Chapter 7
Creation and Distribution of 4 K Content

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Abstract Until recently, electronics-based video (whether analog or digital) could not achieve the same high-quality motion pictures at comparable cost, as could a 35 mm analog film. But rapid advances in key digital technologies over the past decade have brought digital cinema to effective parity with film-based cinema in terms of image quality. The advent of 4 K digital motion pictures, high-end format of new digital cinema distribution specifications, offers four times the resolution of 2 K digital cinema or broadcast HDTV. But 4 K poses unique technical challenges related to specialized imaging devices like cinema-grade digital cameras and displays capable of this high resolution. Creation and distribution of 4 K in a productive manner also requires access to advanced cyber-infrastructure such as high-speed digital networks, high performance digital storage and powerful computing resources. Creative techniques of cinematography and sound recording, design of performance spaces, and psycho-perceptual optimization of audience viewing/listening environments are also impacted. This also has an effect on the whole notion of what can be done with media remotely via network as opposed to what can only be done locally, in person. These are issues not only for the entertainment industry, but also for scientists, educators, medical researchers and government agencies who are adopting digital media and digital networking for their own demanding applications. There is thus a growing need for professionals with interdisciplinary experience covering media arts/technology, computing/storage systems and digital networking. The members of CineGrid, a non-profit international research consortium, are building advanced media-capable nodes connected by high-speed networks to create a global-scale test bed that can be used by an international community of collaborators working on a variety of projects exploring the future of content creation and distribution in bandwidth-abundant environments while "learning by doing" to train next generation media professionals through hands-on experiments.

D. Gerbarg (ed.), *Television Goes Digital*,

Introduction

Modern society is becoming increasingly media-dense and communications intensive. The future promises both higher quality media experiences and a noisy proliferation of digital media formats, large and small. Content will be created in many places, often by distributed teams linked by high-speed networks capable of transporting professional digital media assets fast enough to satisfy creative workflow. Digital media at very high quality will be distributed ubiquitously and securely, with high-speed networks playing a critical role.

For the past 40 years, numerous forms of media have been undergoing a historic conversion from analog to digital technology. This process started with text and grey-scale graphics, advanced to monochrome and color still photography, then audio, which extended further to digital video – first at standard, and later at high-definition. The adoption of digital technology in both media and communications has spurred a proliferation of media sources, channels and consumption platforms.

Digital imaging technology has got so much better, faster and cheaper in recent years that many imaging applications that traditionally relied on film cameras are converting to electronic cameras. Broadcast television production, which once shot everything on film, converted to video cameras and video tape recorders starting late 1970s – initially using analog electronics – then upgrading to digital electronics in the 1990s. As we approach 2010, almost everything seen on broadcast television is shot using digital video technology.

Until quite recently, electronics-based video (whether analog or digital) could not achieve the same high-quality results at comparable cost as 35 mm analog film. But rapid advances in key digital technologies over the past decade have brought digital cinema to effective parity with film-based cinema in terms of image quality, while at the same time enabling more creative control and offering some commercial advantages over film. This is not to say that film and video will not continue to have differences, including subtle variations in the "look" of the image.

Where once there existed a clear dividing line between film-based motion pictures and electronics-based video imagery, there is now a continuum of creative, technical and budgeting choices that can result in both approaches being used in the same piece of media. It used to be that film was reserved for higher quality, higher budget content with full post-production scheduling, such as cinema, premium television programming and broadcast advertising commercials. Electronics-based video imagery was used primarily for lower quality, lower budget content with little – or in the case of live programming – no post-production, such as television news, sports, reality shows, documentaries, or industrial/educational programs.

Movies, in particular top-quality Hollywood movies, are still shot predominantly using 35 mm film cameras for original live-action photography. But even in the movie business, digital cinema cameras are gaining in popularity.

Modern media is created to be delivered to consumers. With deployment of digital terrestrial television, digital satellite broadcast, digital cable television, digital radio and the Internet, most consumers receive most of their media via digital distribution of some form or another today. Exception has been movies until quite recently.

Historically, films were simply of too high a quality to be handled digitally. In particular, the critical obstacle to digital distribution of cinema was the lack of electronic projectors capable of throwing up a bright enough images on a large enough screen with sufficient dynamic range, rich color, strong contrast and high spatial resolution to satisfy an audience accustomed to seeing 35 mm film projection in a movie theatre.

These sorts of technical limitations have largely been overcome with the development of high-performance digital cinema projectors featuring 2 K resolution (2,048 pixels[1] horizontal × 1,080 pixels vertical) from manufacturers Christie, NEC and Barco, all using the Texas Instruments DLP technology; and digital cinema projectors featuring 4 K resolution (4,096 pixels horizontal × 2,160 pixels vertical)[2] from Sony using its own SXRD technology. (JVC has also introduced a commercial 4 K projector using their own D-ILA technology, but this device features lower light output and is not designed for installation in large cinema theatres.)

In the last few years, movie theatres in North America and elsewhere have begun converting large numbers of screens to digital infrastructure. This has entailed installing digital cinema playback servers and digital projectors designed to handle interoperable digital cinema packages (DCP) containing compressed and encrypted movie in the industry-standard 2 K and/or 4 K image formats.[3] The roll out of digital cinema is allowing cinema distribution without film for the first time in history. But most movie theatres around the world still use film physically threaded through a mechanical projector.

Today, both the “front-end” (motion picture photography) and “back end” (motion picture projection in the theatre) of cinema workflow are moving through a transitional phase wherein both older and newer digital technologies co-exist. But the “middle” of the cinema workflow – creative post-production – started going digital more than 30 years ago and has today almost entirely converted over from film-based editing and optical special effects to digital technology.

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[1] “Pixels” is a term of art for “picture elements,” used when describing computer graphics or digital visual imagery.

[2] The convention in denoting HDTV has been to indicate the vertical dimensions of the image first, whereas projected formats such as 4 K and 8 K (7,680 × 4,320) state the picture height second.

[3] 4 K is a digital format (using dots or pixels across a single line), whereas standard definition television is analog (using scan lines). By way of comparison, HDTV is currently broadcast in the U.S., Japan and Korea at 1080i/30, or 1,080 vertical pixels interlaced/30 frames per second, whereas standard definition NTSC analog TV has 525 scan lines. Panasonic also has created a version of HDTV that’s broadcast (by the ABC network in the USA, among others) at 720 pixels, progressively scanned at 60 frames per second. (Traditional television uses a technology to interlace lines to create an image, whereas computers and digital TV uses progressively scanned lines, repeating from left to right.)

In Europe, standard definition PAL uses 25 frames per second with fewer scan lines than used in the US. If HDTV ever takes off in Europe (slowed by the difficulty of frame rate conversion), it will be broadcast at 1080i/25 frames per second. In general we can state that HDTV has six times more pixels than standard definition TV, and 4 K has four times more pixels, or 24 times the real state of “standard def.”

Faced with a mixed analog/digital "front-end," an all-digital "middle" and a mixed "back-end," the cinema industry has pioneered a hybrid approach to content creation and distribution commonly called the "digital intermediate" (DI). In a DI workflow, 35 mm negative film shot in the traditional manner is run through a high-resolution digital scanner that converts chemically recorded image into a digital image composed of bits of data organized as pixels. Once film frames are converted to digital, all post-production can occur digitally, using file-based workflows and computer-based creative tools for color-grading, editing, visual effects, compositing, etc.

After all creative post-production work is completed in the DI process, the producer/ distributor can choose to output the finished movie, the so-called "digital source master" (DSM), to film via a digital film printer. Digitally controlled lasers are used to precisely "burn," or expose, an analog film negative from which traditional film release prints can be manufactured. Alternatively, they can choose to create a digital cinema package (DCP) for digital cinema distribution. Today, and for the foreseeable future, movies will be distributed using both film release prints and digital cinema DCP in parallel, as the worldwide cinema theaters goes through a multi-year infrastructure upgrade.

The same DSM can be used to generate derivative formats with lesser resolution and/or higher compression to reach non-theatrical markets such as DVD, hotel pay-per-view, conditional-access cable or satellite television, airplane viewing, and eventually, broadcast television. DSM can also be used to generate archival assets for long-term preservation.

Historical Context

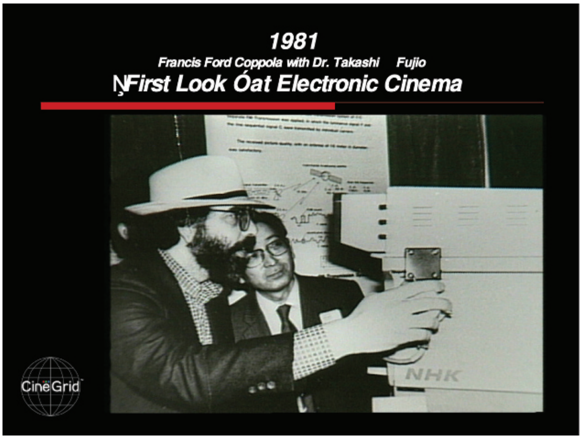
In every period of civilization, the state-of-the-art in visual media has been driven primarily by requirements and funding of three important sectors of society:

- The science/medicine/research/education nexus
- What can be considered cultural interests – entertainment/publishing/art/ advertising
- "The state" – military/intelligence/police/emergency response.

When these different sectors used analog media technology optimized for their particular purposes, there was little need for inter-domain communication regarding media applications. But, this is changing. Even at the highest image quality levels, new digital media technology is becoming acceptable – even desirable – which means that in all three sectors, even the toughest imaging applications formerly only possible with film, can now "go digital."

These different sectors of society are increasingly adopting similar digital platforms, and often buying the same devices. They face similar challenges related to cameras and microphones, recorders and players, speakers and projectors/ displays, data storage, computation and networking, system integration, digital asset management, distribution and preservation, etc.

Photo courtesy of Dr. Takashi Fujio, NHK Laboratories



Convergence of cinema and television is considered by many to have started in 1981 when NHK Laboratories in Japan brought the first generation of analog HDTV devices – cameras, recorders, and monitors – to the SMPTE Engineering Conference in Los Angeles. There, Dr. Takashi Fujio, leader of the team at NHK Labs that developed the first HDTV systems showed them to Hollywood cinema director, Francis Ford Coppola. According to people who were present at the time, Coppola took a long look at this early HDTV gear and encouraged its continued development in order to create a new way of making movies, which he called "electronic cinema." Coppola's vision inspired further development of HDTV for non-broadcast applications. It took almost 20 years to achieve Coppola's and Fujio's shared dream for an "electronic cinema." But eventually, top video equipment manufacturers and traditional motion picture film camera makers introduced HD video cameras that satisfied particular requirements of professional cinematographers.Today, not only cameras, but all computer-based tools and digital devices required to make "electronic cinema" at HD resolutions have become available, at various prices and levels of quality for people from Hollywood professionals to home amateurs.

Meanwhile, other aspects of digital technology were advancing rapidly. By 2001, Nippon Telegraph and Telephone (NTT)'s Network Innovation Laboratory was able to develop the world's first 4 K experimental digital cinema system capable of displaying four times the spatial resolution of HDTV and sending it compressed over digital IP networks.

NTT and the Digital Cinema Consortium of Japan demonstrated this prototype 4 K digital cinema system at the SIGGRAPH 2001 Conference on Computer Graphics and Interactive Techniques in Los Angeles. The demonstration was viewed by thousands of attendees, including representatives of major Hollywood studios and leading post-production houses, most of whom were seeing 4 K motion pictures with their own eyes for the first time.

Since the industry – producers, distributors and exhibitors, and vendors that support them – would have to live for quite a long time with whatever digital cinema standards were adopted, some felt the future of cinema should be limited to resolution of commercial digital projectors available in the year 2001, which was just 1,280 × 1,024 pixels (1.3 K) with 8-bit dynamic range. Others, however, believed that 1.3 K was "good enough" and that waiting for higher quality would unnecessarily delay deployment of digital cinema.

In 2002, the Digital Cinema Initiatives, LLC (DCI) was created as a joint venture of Disney, Fox, Paramount, Sony Pictures, Universal and Warner Bros. Studios. The DCI's primary purpose was articulated as, "establishing and documenting voluntary specifications relevant to an open architecture for digital cinema, thereby ensuring a uniform and high level of technical performance, reliability and quality control."

There were numerous demonstrations, tests and comparative evaluations of digital cinema using various formats running on various technologies in Los Angeles, Rome, London, Tokyo and elsewhere. After considerable technical debate, commercial competition and international wrangling that is beyond the scope of this account, in late 2003 the DCI published its unanimous recommendation for digital cinema. It specified 2 K (2,048 × 1,080) and 4 K (4,096 × 2,160) image formats, both compressed using JPEG2000 and extractable from a common file. The DCI also made recommendations regarding many other specifics dealing with color, sound, packaging, encryption and key delivery security architectures for digital cinema.

Meanwhile, those using very high-quality digital images outside of the "cultural context"— the scientific, educational, military and intelligence communities – welcomed commoditization of HD-quality media and potential access to higher resolution cinema-grade 4 K cameras and projectors. However, these communities did not want to be constrained by existing television formatsor installed movie business infrastructure.

To exemplify the point, scientific visualization pioneers at the University of California San Diego and University of Illinois at Chicago involved in the NSF-funded OptIPuter project were prepared to think in terms of frame buffers with 100–200 megapixels, or more. Their users needed to be able to step back from the display and take in at a glance the largest possible context, and then step closer to study the image at the greatest possible detail. The OptIPuter team understood that no one monolithic display or image format was likely to work for all applications. They developed hardware and software to control tiled displays as an extended frame buffer featuring on-screen windowing, drag-and-drop, and point-and-click graphical user interfaces that had been popularized on personal computers. By 2004, the OptIPuter research vision of the future was gigapixel wallpaper with streaming video at various resolutions mixed with still graphics of arbitrary size and number, augmented by virtual reality implemented without special glasses or tethered glove. All this visualization capability was to be integrated with general purpose computing and storage resources, connected seamlessly by high-speed networks to similar facilities at distant locations.

What Is 4 K?

Generally speaking, the term “4 K” is broadly used to describe any new format for motion pictures with eight or more mega-pixels per frame, which works out to roughly 4,000 pixels horizontal × 2,000 pixels vertical for a widescreen with an aspect ratio of 2.0.

Some content referred to as “4 K” can be more accurately described as Quad HDTV[4] or Super High-Definition (SHD) with a resolution of 3,840 × 2,160 pixels per frame, exactly twice the horizontal and twice the vertical resolution of HDTV (1,920 × 1,080). Quad HDTV frame rates are typically 24, 25/30 and/or 60 fps, with a 1.77 aspect ration (16:9). Quad HDTV is called so because it is comprised of four quadrants each HDTV resolution and often interfaced using four HD-SDI signals encoded as either 4:2:2 YPbPr with 10-bit dynamic range in the Rec. 709 color space, or as 4:4:4 10-bit RGB. A variety of compression techniques can be used and there is no upper or lower limit to the compressed bit-rate for Quad HDTV (*a.k.a*. SHD).

Strictly speaking, however, “4 K” is one of two new motion picture image formats for digital cinema theatrical distribution, as recommended by the DCI in 2003 and subsequently standardized by the Society of Motion Picture and Television Engineers (SMPTE) in 2007–2008. According to the digital cinema standard, “2 K” is defined at 2,048 × 1,080 image container while “4 K” is defined as an image container with 4,096 × 2,160 pixels per frame. Within the 4 K image container, cinema directors can fit images in either of the two aspect ratios most commonly used in cinema: 2.39 (4,096 × 1,716) or 1.85 (3,996 × 2,160). The frame rate of 4 K is fixed at 24 frames per second. Color encoding is always 4:4:4 (equal sampling of the primary colors) with 12-bit dynamic range in the SMPTE XYZ color space for extended color gamut, with progressive scanning and square pixels. Only JPEG 2000 is used for compression in digital cinema, and there is an upper limit of 250 Mbps on the compressed bit-rate for DCI-compliant digital cinema distribution.

Why Is More Resolution[5] Important?

Generally speaking, increasing the spatial resolution of motion pictures allows the audience to sit closer to a larger image display without any degradation in the perceived sharpness of the picture or awareness of the underlying technical structure of the picture. Sitting closer increases the viewing angle. A number of researchers around the

[4] Among the many compression/decompression schemes HDTV, or Quad HDTV uses are MPEG2, MPEG4, HVC (also know as H274), JPEG2000, and numerous proprietary codecs. Some of the latter include VC1 from Microsoft, as well as lossless codecs, low latency, and very fine-detailed codes.

[5] With reference to resolution, visual acuity is assumed to be 20/20.

world have confirmed that an increased viewing angle produces a stronger emotional response in the viewer. So, increasing resolution enables presentation of visual media in larger formats that can elicit a stronger emotional connection with viewers.

For example, a standard definition television format like NTSC used in the USA and Japan (486 active pixels vertical × 720 pixels horizontal) is best viewed at a distance of seven times the picture height, producing a 15-° viewing angle. HDTV with a wider aspect ratio and six times the spatial resolution compared to standard definition TV (1,080 pixels vertical × 1,920 pixels horizontal) is ideally viewed at three times the picture height, producing a 30-° viewing angle. The numbers for 2 K digital cinema format are comparable. Doubling horizontal and vertical resolutions of HDTV brings us effectively to "4 K," which allows for an optimum viewing distance of 1.5 picture heights, yielding a viewing angle of 60°s that significantly increases the sense of visual presence and emotional involvement, especially when accompanied by multi-channel spatialized audio.

Since the early 2000s Japanese national broadcaster, NHK, has been developing a next-generation format in its Tokyo laboratories with "8 K" resolution (7,680 × 4,320), effectively doubling both horizontal and vertical resolution compared to "4 K." Put another way, 8 K is equivalent to 16 frames of HDTV. With an "8 K" format, the viewer will be able to sit just 0.75 of a picture height away from the display, which gives a viewing angle of 100°. Combined with 22.2 digital surround sounds, the 8 K system creates an extraordinary immersive, digital IMAX-like experience.

High-Quality Media, Fast Networking and the Next-Generation Professionals

The ways in which humans use pictures and sounds will evolve to take advantage of communicability and malleability of digital media even at very high quality levels.

To explore this new convergence of high quality media and high speed networking, a non-profit organization, CineGrid, was formed in 2006 with the mission to build an international interdisciplinary community focused on research, development, and demonstration of networked collaborative tools in order to enable production, use and exchange of very high-quality digital media over photonic networks. CineGrid members are organizing themselves to create a prototype infrastructure that can be used as a test-bed for member-driven explorations of new approaches to remote collaboration and distributed project management that can take advantage of the new capability to move very high quality picture and sound at high speed over great distances using advanced photonic networks.

CineGrid is not only about technology challenges. Media education is also at a historical cusp. As today's analog experts and hybrid analog/digital veterans retire over the coming years, and all-digital media come to dominate, there will be increasing demand for inter-disciplinary professionals who understand the whole of networked digital media at high quality. This will require people who can master specific requirements of their particular application areas, as well as the larger legal and economic contexts. They will need to comprehend practical issues of media production, and be able to navigate (or design and administer) complex storage, computation and software architectures. They will have to have had enough experience working with high-speed networking infrastructure to be able to tie all components together into an integrated system that might be distributed around the world. Universities and art schools, research laboratories and movie studios, and government agencies will all need talented, well-trained people with this extremely broad skill set to exploit the full potential of digital media beyond HDTV and DTV.

Characteristics of CineGrid

The essential idea of CineGrid is that its members will build media-capable nodes that are connected by high-speed networks. The aim is to create a global-scale test bed that can be used by an international community of collaborators working on a variety of projects exploring the future of content creation and distribution in bandwidth-abundant environments while "learning by doing" to train next generation media professionals through hands-on experiments.

The networks used by CineGrid are generally part of what's called the Global Lambda Integrated Facility (GLIF), a "virtual" consortium of national research and educational network operators (Fig. 7.1). These operators have agreed to peer their networks at Global Open Lambda Exchanges (GOLEs) under flexible acceptable use policies that allow for various types of experimentation. GLIF members are particularly interested in pioneering what are called Lambda Grids. Lambda refers to light waves used to carry data over fiber optic cables. Lambda Grids is an approach to establish a grid of point-to-point links connecting known and trusted users using light waves over photonic networks. Historically, the GLIF was designed primarily to support scientific applications like high-energy physics, radio astronomy and remote-control electron microscopy, as well as conduct networking research and systems design experiments.

The CineGrid membership is a new kind of self-organizing GLIF user community drawn together by common interest in the convergence of high-quality digital media and photonic networks, with access to next generation networking resources that allow members to be linked to each other at 1 Gbps and 10 Gbps speeds on a global scale.

It is important to clarify that CineGrid projects do not run over the commercial Internet nor even commercially operated private networks. CineGrid uses excess capacity of research and educational networks donated on an *ad hoc* basis by CineGrid's own Network/Exchange members around the world. In many cases, these members operate national networks, such as SURFnet in the Netherlands, or CANARIE in Canada. In other cases, the networks are operated by consortiums of universities, such as the National Lambda Rail and Internet2, both based in the USA. CineGrid members also include regional network operators like the State of California's CENIC.

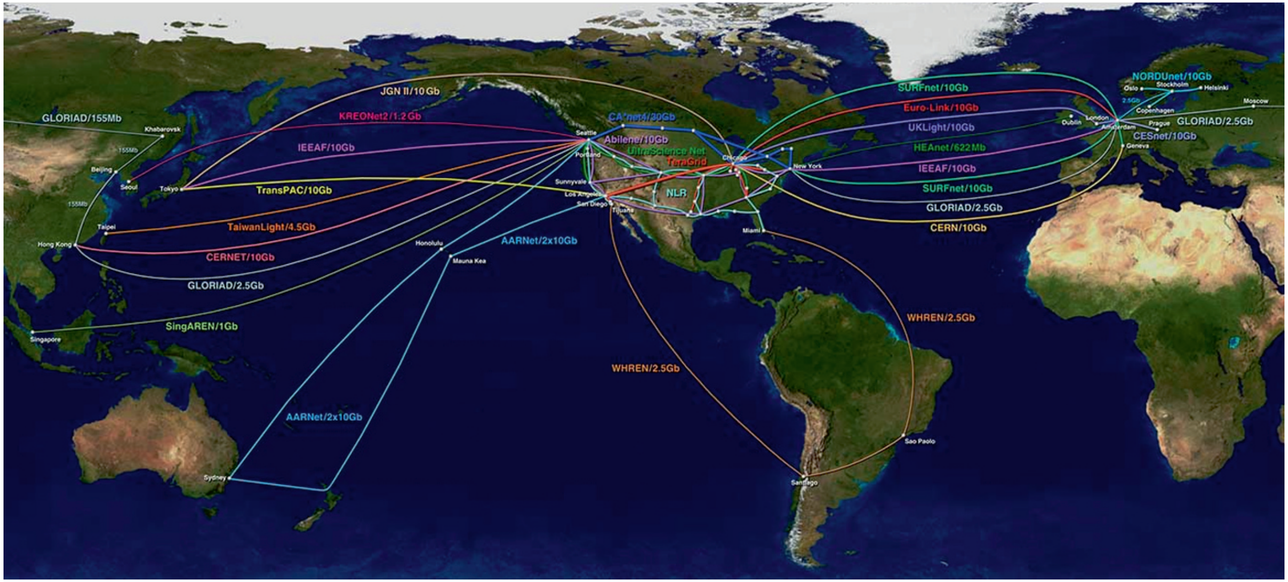


Fig. 7.1 GLIF map 2008 (Courtesy of Bob Patterson, NCSA). The Global Lambda Integrated Facility (GLIF) Map 2008 visualization was created by Robert Patterson of the Advanced Visualization Laboratory (AVL) at the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign (UIUC), using an Earth image provided by NASA. Data was compiled by Maxine D. Brown of the Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago (UIC). Funding was provided by GLIF and US National Science Foundation grants # SCI-04-38712 to NCSA/UIUC and # OCI-0441094 to EVL/UIC. For more information on GLIF, and to download the world map and several close-ups, in a variety of formats and resolutions, see http://www.glif.is/

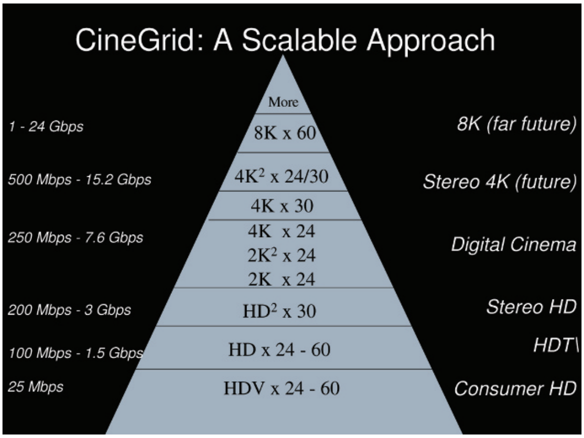


Fig. 7.2 © Laurin Herr, 2005

CineGrid manifests as CineGrid networks/exchanges and CineGrid nodes. The first nodes were established in 2005 at Keio University in Tokyo and at the University of California San Diego's California Institute for Telecommunications and Information Technology (Calit2). Keio's Digital Media Research Center installed Sony 4 K projectors, Olympus 4 K cameras, an IMAGICA 4 K film scanner, and NTT JPEG2000 4 K streaming codecs (compression/decompression), all connected via 10 Gb Ethernet to the Japan Gigabit Network (JGN2). At UCSD/Calit2, a newly constructed 200-seat auditorium was outfitted with an 8.2 Meyer Sound system, a Sony SXRD 4 K projector, a SGI Prism with 21 TB of fast storage, a NTT JPEG2000 4 K streaming codec, all connected via 10 Gb Ethernet to CENIC and NLR. In subsequent years, more CineGrid members have built-up their own CineGrid nodes around the world.

Architecturally and philosophically, CineGrid has a digitally oriented perspective on image formats: There are many media formats in life, with different parameters, quality levels and price/performance trade-offs. From the vantage point of a networked community, bit rates required for a given format relative to available bandwidth and last-mile connectivity are usually decisive constraints on CineGrid projects. As an organization, CineGrid is vendor neutral and format-agnostic. Anticipating future availability of faster networks and more advanced image sensors/displays, CineGrid will take a scalable approach to accommodate higher quality formats with greater frame sizes, variable frame rates, and stereoscopic capabilities that are expected to emerge in coming years.

The pyramid depicted above (Fig. 7.2) represents a basic assumption of CineGrid: The number of users decline as the quality of the format increases, because quality requires more bandwidth (and therefore, is expense) at every step up the pyramid. This refers not just to network bandwidth requirements, but also the performance needed in every device in every system that uses that format.

The CineGrid scalable hierarchy of formats starts at the bottom with consumer HDTV quality recorded heavily compressed on popular HDV digital videotape. The chart goes up through broadcast HDTV to digital cinema in 2 K, 2 K stereoscopic, 4 K and 4 K stereoscopic – and even beyond to 8 K and higher resolutions implemented with tiled displays and camera arrays. On the left of the pyramid, bandwidth is expressed as bit rate (or, if there are two numbers, as compressed/uncompressed rates). In the center of the pyramid is the name of the format and its frame rate(s). The far right of the chart identifies the format in terms of image quality and R&D horizons.

CineGrid Projects

CineGrid members are encouraged to collaborate on CineGrid projects that will "push the envelope" in terms of networking and media technology, while exploring new methods of production, post-production, distribution and presentation. Members choose their favorite formats to accomplish their project goals.

For example, some CineGrid members have long been interested in how 4 K digital camerawork differs when shooting live performance art, as compared to that for standard definition or even high-definition television. Also, they wonder whether these changes in camerawork will affect audio recording techniques or viewing/listening environments.

In 2006, CineGrid members in Tokyo recorded a string ensemble playing Mozart in 8-channel audio using a single 4 K camera placed in the audience with a fixed view of the stage filling the frame. The long-distance audience experience of the recorded performance was uniquely realistic, with enough resolution that enabled the viewer's eyes to naturally flit from place to place on the screen, just as if they were in the audience watching the live performance in person, the high-quality audio filling the auditorium.

Other CineGrid members are more interested in the potential of networked post-production. For example, is it feasible to perform the final mix of sound-to-picture over networks at digital cinema quality when the sound is coming from one location while the picture is coming from a different one, all combined and synchronized in a third location? This was the essence of the CineGrid demonstration at the Audio Engineering Society (AES) 2006 conference in San Francisco. The sound mixer said that he had no sense that the video server and the audio server were thousands of miles from one another, and from him. "I don't feel it," he said. "I am not inhibited in my creative effort." This experiment confirmed a basic premise of CineGrid, that it is possible to use networks to reduce the sense of distance between distributed teams working on digital media at the highest quality.

In June 2007, CineGrid transmitted a 75-min live opera performance in 4 K with 5.1 surround audio from the annual Holland Festival to the 200-seat auditorium at UCSD/Calit2 in southern California, nearly 10,000 km away. There were 700 paying guests in Amsterdam listening to the female singer and seven-piece Baroque ensemble in an all-acoustic hall, so the CineGrid production team was not allowed to turn up the lights nor make any sound that might disturb the performance. CineGrid recorded 24-channels of uncompressed sound that was mixed-down to 5.1 on-the-fly and sent to San Diego synchronized with live 4 K motion pictures at 30 frames per second. The sound and picture were JPEG 2000 compressed to 500 Mb a second for network transmission, twice the maximum bit rate of the DCI specification for digital cinema distribution.

The San Diego audience enjoyed the opera projected in 4 K life-size on a large screen with surround sound just a few seconds after the audience in Amsterdam enjoyed the same performance. Many people commented that they felt as if they were sitting in the actual concert hall listening to the live concert in person. The director of the Holland Festival joked that the audience reaction from San Diego was so positive that perhaps he should put a box office in San Diego the next time.

CineGrid members were even more technically ambitious when conceiving two experiments at the GLIF International Workshop in the Czech Republic in 2007. The first experiment was to use networks for international delivery of 4 K digital “dailies,” the results from each day’s shooting that is typically sent back to studio headquarters for preliminary processing and review. After recording with a 4 K DALSA digital cinema camera in Prague, the CineGrid team sent the selected RAW-format camera shots over the network to San Diego where “de-mosaic” pre-processing was done using a UCSD/Calit2 computer cluster under remote control. Then, Prague commanded San Diego’s server to send the uncompressed RGB frames via network back to Prague for post-production.

For the second GLIF experiment, CineGrid members demonstrated remote color grading of 4 K digital cinema content over a 7,500 km local area network (LAN). The colorist, located in Toronto at the Rogers Communications Centre of Ryerson University, was operating the “control surface” of a Baselight 4 system whose main storage and computation hardware were located at the CinePost’s facility in Prague’s Barrandov Studio. The Baselight4 system in Prague held the uncompressed full-resolution RGB 4 K digital cinema sequences that had been pre-processed the night before in San Diego.

The color grading took place under real-time interactive creative direction of a cinematographer sitting in the Prague screening room experiencing everything the colorist in Toronto was seeing and hearing. The CineGrid team used 10 Gb VLANs to carry multiple parallel payloads between Prague and Toronto: an uncompressed HD “proxy” sent from Prague to Toronto; bi-directional HD over IP video conferencing; and the control signals between the Baselight4 “control surface” in Toronto and the main system in Prague. This ground-breaking test demonstrated how 10 Gb networking infrastructure can be used to create a shared visual workspace rich enough to accomplish real-time interactive collaboration on color grading, which is one of the most expensive and specialized steps in the 4 K digital intermediate cinema workflow.

Several CineGrid members have been particularly interested in 4 K applications because 4 K technology is such a new and challenging format to work with.

Experimentation, prototyping and "learning by doing" within CineGrid are helpful to understanding the real potential of 4 K in various applications. However, that does not mean that CineGrid is focused exclusively on 4 K. Some members are very interested in working with uncompressed low-latency HD, some with stereoscopics, and others with much higher resolutions. Practically, during those years, 4 K represented the newest, highest quality motion picture format for which it was possible to purchase (or rent) devices like cameras, projectors, displays, recorders and playback servers, compression encoders/decoders, etc.

From an engineering perspective also 4 K (and its associated audio channels) generates digital media files of enormous size that can be used to stress test networks, storage and computational infrastructure in useful ways. CineGrid members have had to also learn how to store, transport and exchange their own Terabytes of 4 K digital camera originals, JPEG 2000 encoded versions of selected 4 K clips, and various multi-channel uncompressed audio originals and mixes.

Since 2007, CineGrid members have been actively creating the CineGrid Exchange, a distributed data storage scheme to hold 4 K, 2 K, HD, SD, monoscopic and stereoscopic, digital still and motion picture or digital audio content. The goal is to make CineGrid Exchange assets accessible to CineGrid nodes via secure high-speed networks. CineGrid members contribute networked storage capacity linked by secure fast networks to support member-driven test-beds for research into networked digital media asset management, digital distribution and digital archiving.

Conclusion

These are exciting times for media and networking. The long-term challenge of 4 K content creation and distribution is the coordination of:

- The integration of media devices with computation platforms connected to networks to form distributed systems.
- Workflows that take advantage of the talent and resources connected to the network organizational structures that are aligned with distributed workflows.
- Human resources to staff the organizations that run the workflows which are taking advantage of the networks.