3-D Displays for Home Entertainment

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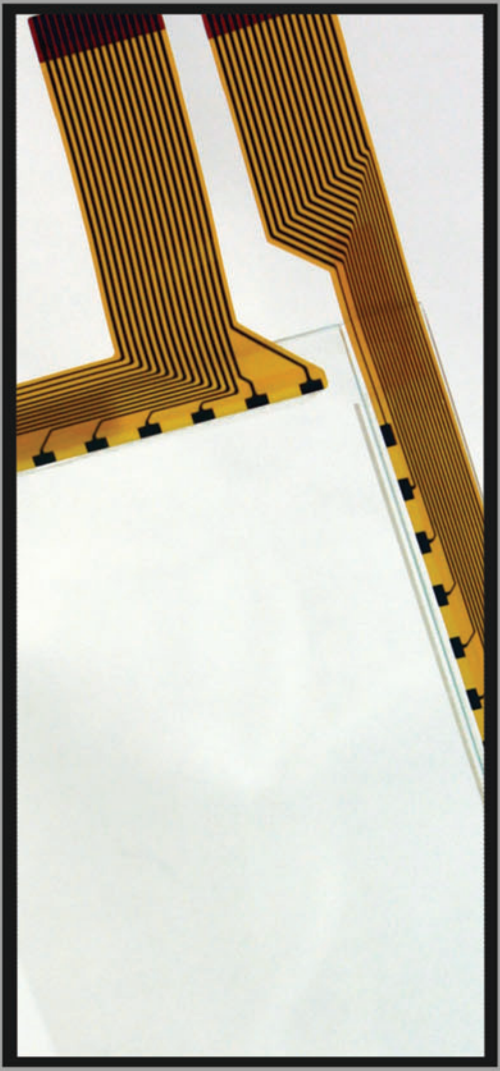
Home Theater 3-D Technology

- Standards for 3-D TV
- 3-D Displays for Home Entertainment
- Luminance, Brightness, and Gamma
- Increasing Dynamic Range in Displays
- Smaller Electrophoretic Displays
- *Journal of the SID* July Contents



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COVER: *Although 3-D displays targeted for home use have been commercially available for quite some time, they have not achieved widespread consumer adoption nor has there been a successful system put into place to generate sufficient high-quality 3-D content and distribute it into the home. However, the recent commercial success of 3-D in the theater has once again fueled interest in bringing 3-D entertainment into the home.*

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  - LCD Technology
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  - Projection
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- Beijing Olympics Projection Technology
- *Journal of the SID* August Contents

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editorial

A Gamut of Opinion

by Steve Atwood

When Martin Kytka, Senior Research Scientist with Uni-Pixel Displays, first approached me with the idea of writing an article that would tackle the complexities of dynamic range in displays, gamma correction, and viewer perception of brightness and luminance, I was really excited. While the current North American Digital TV standard provides for a maximum of 256 gray levels per primary color, there are many new TV displays capable of 1024 or more levels per primary. With some type of temporal dithering scheme in high-frame-rate systems, this dynamic range can be extended even further.

Many in the display industry, as well as those on the content creation side, think there is a real opportunity to create a better user experience with extended-dynamic-range systems. Author Walter Allen of WalVisions summarizes this point of view well in this month's opinion piece, "An Appeal for More Bit-Depth in Displays." So naturally, if we are going to design systems with wider dynamic range, how are we going to map those levels to luminance values that will provide the best viewer experience? Well, that's the question Kytka is attempting to answer with his article "Gamma, Brightness, and Luminance Considerations for HD Displays" in this issue. Drawing on his experience with the DICOM standard, which is used to calibrate medical radiology displays (with well over 2000 distinct gray levels) for diagnostic purposes, he proposes that the same standard has some distinct advantages as a potential baseline for commercial high-dynamic-range HDTV displays.

What I did not know when I first discussed the article with Kykta was the wide range of opinions that exist with regard to this topic. It is complex and encompasses several fundamental fields of science, ranging from classical signal processing and display optics to human vision science and psychophysics. The science itself, the math, the prior art, and the previously published experimental research all weave a complex fabric of understanding as well as misunderstanding, allowing for many differing interpretations. Because the end result boils down to what we "see" and how we feel about it, we cannot avoid attempting to personalize the science and draw on our own experiences, either professional or personal, to rationalize the data. A natural bias often emerges, and some aspects of the science are therefore harder to digest than others.

We asked many knowledge experts in this field, including our mutual colleagues, for their points of view and we got them! I am grateful to everyone who took the time to weigh in on this topic. Our subsequent goal was to present an analysis, draw some conclusions, and provide an opinion about how this information can help guide future system designs. I am very pleased with the result and I think it will help drive discussion for further development and possibly a new baseline for future work. Additional analysis and differing points of view are always welcome and I look forward to this being a continuing subject in future issues of *ID*.

Meanwhile, I've had a lot of other things keeping me awake lately, and contrary to what you might think, the recent DTV transition in the U.S. is not one of them. My thoughts are on a different aspect of TV – 3-D TV, in fact, because that is the topic of our cover feature stories for this month; two compelling articles addressing the future for 3-D entertainment in the home – your home, my home, and anywhere else you could envision. Guest Editor Brian Schowengerdt has worked with us before and we

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industry news

E Ink to Be Acquired by Prime View International

One of the biggest news items to come out of Display Week in San Antonio in June was E Ink's announcement that it would be acquired by Prime View International (PVI) for approximately $215 million. E Ink is the main supplier of digital ink technology for e-readers (such as the Amazon Kindle), and PVI is a leading provider of small- and medium-sized displays and a major supplier of e-paper display modules. Together, E Ink, based in Cambridge, MA, and PVI, based in Taiwan, currently support nearly 20 e-book manufacturers worldwide.

"Combining E Ink and PVI creates a single public company that is dedicated to electronic paper," said Russ Wilcox, co-founder, President, and CEO of E Ink Corp. "With a common ownership structure, we can get closer to customers around the world, streamline the supply chain, and speed up new product development."

The acquisition, in other words, is a complementary one. E Ink can gear up to produce more in response to demand, and PVI now has closer access to E Ink technology. "For Prime View, it allows them to occupy a larger space in the e-reader supply chain," says Sarah Rotman Epps, Media Services Analyst with Forrester Research. Up until now, she explains, "E Ink has been the hub of the e-reader ecosystem." Its digital ink represents step 1 in the e-reader supply chain. Three companies have been involved in step 2, making backplanes for e-readers: LG, Chi Lin Technology, and Prime View, she continues. Step 3 involves "people like Amazon" and its manufacturing partners, which assemble the final products. "Now that Prime View has acquired E Ink," she says, "they essentially occupy steps 1 and 2 of the process. Instead of being one company in step 2, they are now a major player in steps 1 and 2."

In fact, the mutual benefits of the acquisition have led some critics to voice concern over a possible monopoly that could keep e-reader prices high and choices limited, says Rotman Epps. "But, personally, I think that demand with regard to both price and product will keep supplies plentiful [and reasonable] for consumers."

E Ink sales were $18M in the first quarter of 2009, up 157% over the same quarter in 2008. The company's future as a Massachusetts-based entity seems secure at the moment. At the press conference at Display Week last month, Sri Peruvemba, Vice President of Marketing at E Ink, said that the company will remain headquartered in Cambridge, Massachusetts, for at least the near future and plans to expand its employee base from 127 to 150 people during 2009.

— *Jenny Donelan*

guest editorial

3-D Closer to Home

by Brian Schowengerdt

More than a year ago at Display Week 2008, the Society for Information Display highlighted the renaissance of 3-D cinema with a number of talks from speakers at the forefront of the technical development and content generation that has been enabling this resurgence. Since then, the continued commercial success of 3-D in the theater has fueled interest in bringing 3-D entertainment into the home. Accordingly, this year's Display Week saw a number of technical presentations and demonstrations featuring enabling technologies for 3-D home entertainment.

In the exhibition hall, LG Display demonstrated a bevy of advanced 3-D displays targeting the 3-D home-entertainment sector, joining ongoing efforts by Samsung, Mitsubishi, and Hyundai to provide displays to this growing market. In addition to a number of talks on general 3-D display technologies in the technical symposium, a session entitled "Advanced TV and 3-D" featured presentations by Samsung, Toshiba, and others that provided a preview of 3-D-television solutions on the horizon.

Although 3-D displays targeted for home use have been commercially available for quite some time, they have not achieved widespread consumer adoption – nor has there been a successful system put into place to generate sufficient high-quality 3-D content and distribute it into the home. This has posed a bit of a chicken-and-egg problem, with adoption of 3-D display technologies hampered by a paucity of stereoscopic content, and creative teams reluctant to invest resources in the production of 3-D content without widespread consumer adoption of the technology necessary to display that content. A number of factors are helping to break this deadlock, with the most salient being the success of 3-D cinema.

The recent proliferation of 3-D-capable theaters, spearheaded by Real D, has convinced filmmakers that there is now sufficient infrastructure to allow 3-D movies to reach a broad audience, and the demonstrated increased revenue from 3-D screenings has provided assurance that there is money to be made in stereo. Animation studios such as DreamWorks Animation have been among the first to embrace the transition to 3-D, largely because existing computer-generated content can be readily adapted to render the two camera views needed for stereoscopic presentation. Following on the heels of the box-office successes of 3-D animated films, many live-action studios have started to film their movies with stereoscopic cameras.

The 3-D movies that are being generated for cinematic presentation promise a wealth of stereoscopic content that can be tapped for home entertainment. With revenue from DVD and Blu-ray Disc sales far outstripping box-office revenues for the movie industry as a whole, there is a strong motivation to expand the market for 3-D films by creating a compelling 3-D home-theater experience. Success depends on two critical factors. First, home-movie watchers need televisions that can display high-quality stereoscopic imagery with good viewing comfort. Second, the full-content generation and distribution pipeline must be streamlined to deliver great 3-D content from the filmmakers to the consumer's home-theater system.

This issue of *Information Display* features articles by two experts ideally suited to addressing each of these components. Our first article, entitled "3-D Displays in the Home," is written by Andrew Woods, research engineer at Curtin University and co-chair of the annual Stereoscopic Displays and Applications Conference. Woods provides a broad survey of stereoscopic display technologies available for use in the home – past, present, and those just entering the market. Good options for viewing 3-D content are already available, and the new crop of displays promises an even better viewing experience.

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Tweet!

by Paul Drzaic
President, Society for Information Display

Well, let me cut to the chase. If you are inclined, you can now follow me on Twitter. I am located at *twitter.com/theSIDPrez*. Those of you who know what this means can skip the next couple of paragraphs, but please come back toward the middle after I provide a short introduction to those who don't know what the fuss is about.

So what is Twitter? The tag line at Twitter.com is *What are you doing*? The service makes it easy to blast a quick note on "what I'm doing" to the Internet for anyone to see. There is a 140-character limit, and this limitation forces notes to be short and focused on a single topic. A twitter note is called a tweet or perhaps more formally a micro-blog post.

The basic structure of Twitter is to sign up followers, as well as pick up people you are following. Followers automatically get to see your tweets; you automatically get sent the posts of the people you are following. You can send and receive links to web pages and pictures, and you can tweet from your computer or from a smart phone. That is pretty much it for the basics.

So why bother? For me, it's not going to be *what am I doing*? You are not going to be hearing about what I had for breakfast or that I am waiting in line at some restaurant. Rather, I will be sending out tweets more in line with *what I have noticed* or sometimes *what am I thinking*, organized around some topic in electronic displays. I do have a habit of spending some time each day searching out interesting tidbits on displays on the web; for me, Twitter provides a means for me to share the news that I find interesting. I may also slip in some SID-related news from time to time.

So what have I tweeted in the last several weeks? Posts include some notes from a recent trip to Korea, some good economic news from Corning, a new entry in the electronic-paper space, an immersive touch-display demonstration, noting a few things that caught my eye at the SID show, mention of an article I wrote for the journal *Nature Photonics*, and a debate on the size of the screen on the Enterprise bridge in the new Star Trek movie.

My current following list include tech blogs, SID members, friends, and assorted display enthusiasts tweeting about digital signage, electronic paper, and OLEDs. During the time leading up to the SID show, I followed the U.S. Centers for Disease Control, which provided real-time updates on the swine-flu situation. Having the latest news regarding the H1N1 influenza was extremely helpful in SID's decision to proceed with our meeting, and to communicate authoritative information to our members. For real-time information, Twitter can be very useful.

So, *what am I thinking*? If you sign up and have interests similar to mine, you will probably find the tweets interesting and perhaps entertaining. If your interests are different, then you can promptly unfollow me, and that's OK too. In any case, you might consider sending out a few tweets of your own and see who might be listening. ■

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3-D Displays in the Home

There are many predictions that the next stage in the commercial evolution of consumer display technology is the widespread availability of stereoscopic 3-D content for viewing on home 3-D displays. This article describes the types of 3-D displays that are currently available, as well as what technologies are on the horizon.

by Andrew Woods

IN PARALLEL with the widespread deployment of digital 3-D cinema systems and an explosion in the release of 3-D movies into those theaters, there has also been a concerted effort from several consumer-electronics manufacturers to release 3-D TVs and 3-D displays into the consumer marketplace. This article looks at the technologies behind these high-quality 3-D displays that have been released into the consumer marketplace and also answers the often-repeated question: can my existing home TV be used for high-quality 3-D viewing (*e.g.*, by bringing home the 3-D glasses from the movie theater)? While the focus will be mainly on the home-display marketplace for HDTVs or computer monitors, there are a great many more 3-D display products available if the professional-display marketplace is also taken into consideration.

When cathode-ray-tube (CRT) monitors became less commonplace in retail outlets, there was great concern in the stereoscopic-imaging community about what displays could be used for stereoscopic purposes in the future. Up to that point, CRTs had been the mainstay of stereoscopic display (using active shutter glasses), and the alternative displays such as plasma-display panels (PDPs) or liquid-crystal displays (LCDs) were not directly stereoscopic 3-D compatible. Fortunately, several display manufacturers rose to the challenge. Explanations of how those systems work follow later in this article.

In April of 2007, Samsung became the first to release a stereoscopic 3-D-capable large-screen high-definition television (HDTV) into the home marketplace. The displays used a rear-projection digital-light-processing (DLP) engine designed by Texas Instruments.[1] Several things were remarkable about this product: the very competitive pricing (much less than an equivalent 2-D LCD or PDP); the 3-D capability was included at no extra cost (apart from the 3-D glasses, which had to be purchased separately); the very high quality of the stereoscopic image; the high-definition resolution; and, further, the use in some models of an innovative LED light engine that offered richer colors, longer lamp life, and removal of the rainbow effect. Samsung released a selection of models ranging in size from 46 to 72 in. in 2007 and 2008. Mitsubishi also released a selection of these displays in 2007, 2008, and 2009. Over 2 million of these displays are reported to have been sold into homes in North America to date – the only market in which these particular displays have been directly marketed. It is an open question as to how many of these displays have been used for 3-D purposes – possibly less than 1% – but there are still some very happy 3-D users out there!

These displays essentially house a single-chip DLP projector that projects onto the rear of a special screen mounted in the front of the display. A color-sequential technique is used to produce full-color images – as with all single-chip DLP solutions. The stereoscopic 3-D method used by these displays is the time-sequential technique, which involves showing left and right images alternately (in this case at 120 Hz) that are viewed using liquid-crystal-shutter (LCS) 3-D glasses that blank the left and right eyes alternately in synchronization with the left and right images shown sequentially on the display. The fast switching time of a DLP (~2 μsec) makes it particularly well-suited to the time-sequential 3-D method. The 3-D input format accepted by these displays, commonly known as the checkerboard format (see Fig. 1), involves multiplexing the left and right images into a single frame in a checkerboard-like layout. This innovatively allows the two left and right image streams to enter the display within a single regular bandwidth video input (albeit at half-resolution per view).

These rear-projection DLP TVs use a half-resolution digital micromirror device (DMD) to achieve a full-resolution image by way of a process called "wobulation."[2] As shown in Figs. 1(b) and 1(c), in 2-D display mode each frame is broken down into two sub-frames – half of the pixels are displayed in the first sub-

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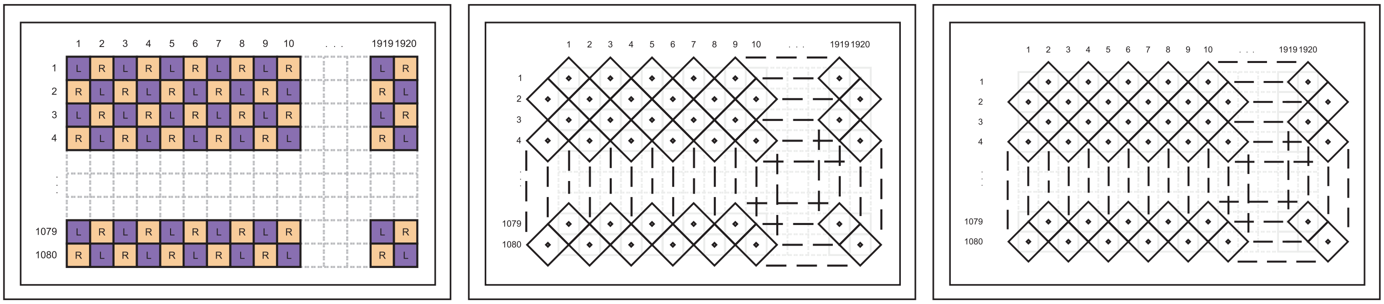

(a) Checkerboard 3-D input format

(b) Wobulated 3-D DLP display format – sub-frame 1; 3-D left image

(c) Wobulated 3-D DLP display format – sub-frame 2; 3-D right image

***Fig. 1:** An illustration of the 3-D input and 3-D display formats of the DLP 3-D HDTVs includes (a) the checkerboard 3-D input format and (b) and (c) the half-resolution DMD with diamond-shaped mirrors that oscillate between two optical positions at 120 Hz to display the full resolution.*

frame and the remaining pixels in the second sub-frame. The mirrors of the half-resolution DMD used in these DLP TVs are oriented in a diamond pattern (as opposed to square pixels in a regular DMD), and the centers of the mirrors match the checkerboard pattern shown in Fig. 1(a). The image of the DMD is optically shifted (wobulated) between the two sub-frames in order to display the full-resolution image. In 3-D mode, the two sub-frames are used for the left and right images, respectively. The pixel arrangement of each sub-frame directly corresponds to the checkerboard pattern used for 3-D input, so, in effect, the display internally converts the checkerboard 3-D input to time-sequential 3-D for display, allowing the viewer to wear LCS 3-D glasses to view the 3-D image.

Also in 2007, another class of 3-D displays started to become more widely available and at price points that were affordable to some home users. The micro-polarizer (μPol) technique was invented by Sadeg Faris in the early 1990s[3] and involves the attachment of a special optical filter to the face of an LCD (Fig. 2), which results in alternate rows of pixels of the display being polarized in two different polarization states – usually left-handed circular and right-handed circular. When the display is viewed using the appropriate passively polarized 3-D glasses, one eye sees all the odd-numbered rows and the other eye sees all the even-numbered rows. When the left and right images are spatially multiplexed onto the odd and even rows respectively, the observer can see a high-quality stereoscopic 3-D image. These types of 3-D displays are now commonly available around the world from manufacturers including Zalman, Hyundai, Pavonine (under the brands Dimen and Miracube), and JVC in sizes ranging from 22 up to 46 in. The smaller monitors are mainly aimed at the stereoscopic 3-D gaming market, whereas the larger sets are intended for 3-D video or movie viewing. In 3-D mode, these displays have half the 2-D resolution in the vertical axis, and there is also some vertical viewing-angle sensitivity. Some products use a μPol variant called Xpol that includes a black mask between rows of pixels to increase the vertical range of the viewing zone and reduce crosstalk. The price premium for the 3-D capability on these sets starts from about 200% on the smaller models and higher for the larger models, so market penetration has not been high.

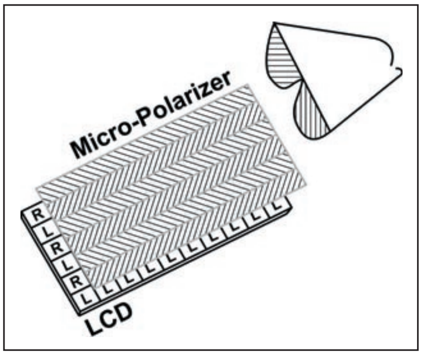

***Fig. 2:** Shown is an optical layout of a μPol 3-D LCD. A micro-polarizer layer over the front of the LCD polarizes alternate rows of pixels into two different polarization states. (Illustration based on Faris.[3])*

In 2008, Samsung achieved another world's first with the consumer release of two stereoscopic 3-D-capable plasma HDTVs (42 and 50 in.) These displays use the time-sequential 3-D display method and the stereoscopic 3-D images are viewed through LCS 3-D glasses – operating at 120 Hz. Unlike the 3-D DLP HDTVs, which were only released in North America, the 3-D plasma HDTVs were released in many international markets. Recently, Panasonic has been demonstrating time-sequential stereoscopic 3-D-capable plasma displays at various trade shows, and many commentators anticipate they will release a product based on this technology in the near future.

Another 3-D LCD product that has been gaining popularity, particularly in the 3-D gaming market over the last couple of years, uses an innovative dual-panel LCD technique – also known as a variable-polarization-angle display – and is viewed using passive polarized 3-D glasses.[4] In a conventional LCD, each subpixel in the LCD panel is used as a light-valve controlling the amount of light that travels from the backlight to the observer. But in these 3-D LCDs, the optical function is very different – the optical layout is illustrated in Fig. 3. The first (back) panel (Mod LCD) operates in a somewhat conventional light-valve approach to modulate the brightness of the light at each pixel, except that the image sent to this first panel is an amalgam of the left and right images. Essentially,

$$\sqrt{L^2 + R^2}$$

[see Figs. 4(a)–4(c)]. The second (front) panel (Ang LCD) acts to control the output polariza-

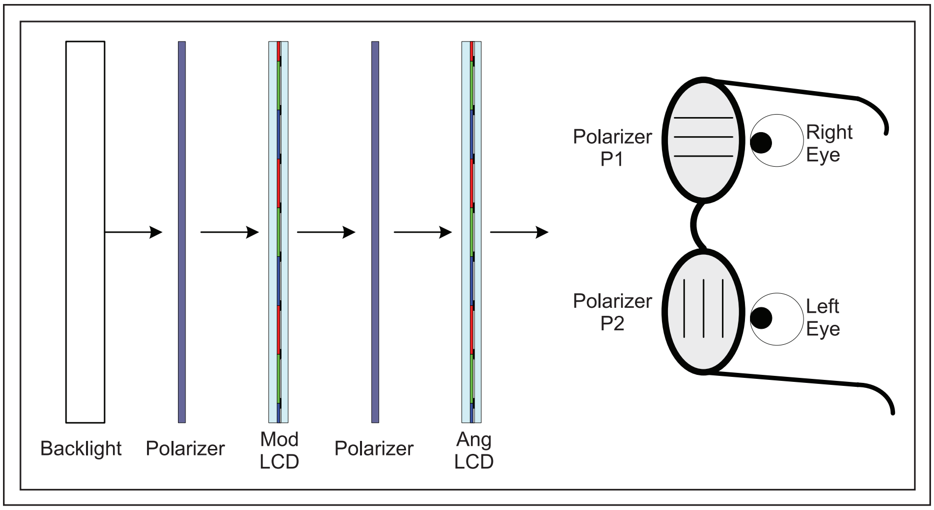

Fig. 3: *A basic optical layout of a variable-polarization-angle display is depicted. The modulo LCD controls pixel brightness and the angulo LCD controls the polarization angle of each pixel. (Illustration based on Gaudreau.[4])*

tion angle of each subpixel (using the fundamental function of a liquid-crystal cell as a polarization rotator) and by virtue of this, sending the light from each subpixel to one eye, the other eye, or a mixture of both. The drive signal to the second layer is calculated for each pixel and is approximately $arctan(L/R)$.[5] As can be seen in Fig. 4(d), if the image on this second panel was viewed individually, it would be a rather strange experience, but when the display is viewed using the appropriate passive polarized 3-D glasses, the resultant stereoscopic 3-D image can be remarkably good. In 3-D mode, these displays are full resolution (no resolution is sacrificed), but some models do suffer from relatively high amounts of crosstalk (ghosting). Consumer displays using this technique are available from iZ3D, and displays intended for professional applications are available from MacNaughton, Inc., and Polaris Sensor Technologies.

The most recent consumer 3-D display to hit the market was masterminded by NVIDIA and released as 22-in. 3-D LCDs from Samsung and ViewSonic. These displays use the time-sequential 3-D-display technique and have been specially engineered to be viewed in 3-D by using custom LCS glasses – operating at 120 Hz. The developers had to make some fairly smart changes to the LCD design to allow them to work with LCS 3-D glasses – most LCDs cannot. Again, these displays have been mainly aimed at the 3-D gaming market and they also retain the full resolution of the LCD panel in 3-D mode.

There is also a selection of 3-D displays aimed at the professional and semi-professional markets, available from suppliers including Planar, Christie, DepthQ, projectiondesign, and others. Large-screen autostereoscopic displays (3-D displays not requiring glasses) are also available in the professional marketplace, but they are believed to be a long way off from being a home consumer-deployed product (especially with Philips having abandoned this market in March 2009[6]). Mobile devices with autostereoscopic displays have been released in Asia by Sharp, Samsung, and Hitachi – but not as yet in the U.S. This article does not even touch on 3-D projection, which is starting to get very exciting with consumer/prosumer product offerings and announcements from ViewSonic, Mitsubishi, Infocus/DepthQ, BenQ, Sharp, and others. (A full summary of all the 3-D displays mentioned above is available from: www.3dmovielist.com/3dhdtvs.html.)

It should be noted that there is a considerable variation in image quality and resolution between these various 3-D displays. For some of the displays, the 3-D resolution is half that of the 2-D resolution. Other image-quality aspects to consider include the amount of crosstalk or ghosting present in the display, display brightness in 3-D mode, as well as regular 2-D measures of image quality.

Can Existing Home TVs Be Used for 3-D Purposes?

A parallel phenomenon with the increased penetration of 3-D displays, and the general consumers' recognition of 3-D TV in the home, is the regular question as to whether a consumer's existing home display(s) can be used for 3-D purposes. For the time being, the short answer is that unless the display is advertised as being "3D-Ready" or "3-D compatible" (see www.3dmovielist.com/

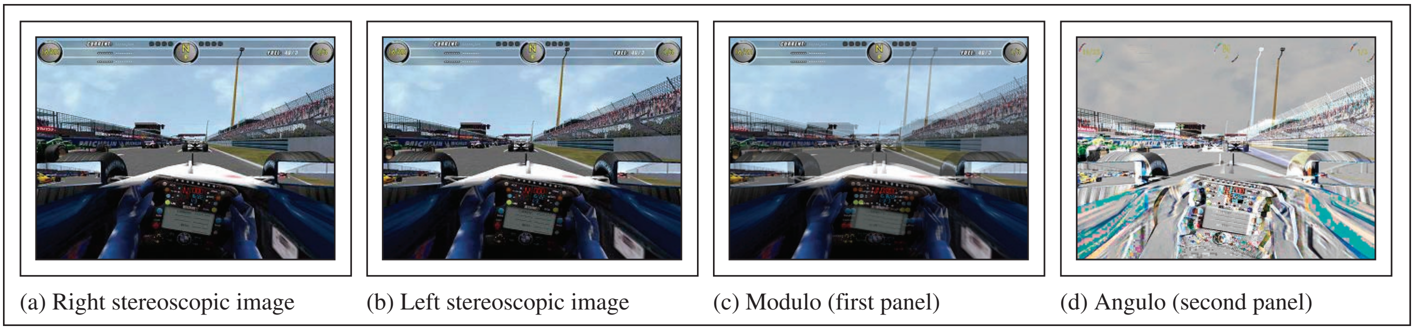
(a) Right stereoscopic image (b) Left stereoscopic image (c) Modulo (first panel) (d) Angulo (second panel)

Fig. 4: *A left/right stereoscopic image pair [(a) and (b)] is converted to modulo/angulo [(c) and (d)] for display on a variable polarization angle display. (Drive images from Gaudreau.[4])*

3dhdtvs.html) it unfortunately will not be able to be used for high-quality flicker-free full-color stereoscopic 3-D viewing (except in the case of older CRT monitors). Consumers may be tempted to take home the 3-D glasses from the various high-quality 3-D movie screenings, but unfortunately they simply will not work on their conventional home TV. Ignoring the displays that are advertised as being stereoscopic 3-D capable, here is why conventional displays cannot be used for high-quality stereoscopic 3-D viewing.

First, consider the three types of 3-D glasses being used in the theaters – passive polarized glasses, active LCS glasses, and Infitec (Dolby 3-D) glasses.

Polarized 3-D glasses will not work with conventional displays because they output light either in a single polarization direction (*e.g.*, LCDs) or they are unpolarized (*e.g.*, PDPs). An optical filter would need to be added to these displays to provide two polarization states (for the left and right views) – but currently this is not a customer-deployable solution.

LCS 3-D glasses do not work with conventional LCDs for a range of reasons,[7] but the most significant reason is the image-update method. Unlike CRTs, LCDs are a hold-type display, meaning that each pixel of the display outputs light over the entire frame period – *i.e.*, there is no blanking period. But similiar to a CRT, the image on an LCD is updated row by row from the top of the display to the bottom. The time taken to address the entire display is almost one frame period. What this means is that there is no one time, or period of time, when the display shows one image exclusively across the entire display; *i.e.*, there is no one time when the shutters in a pair of LCS 3-D glasses could be opened so that a left (or right) image would be seen across the entire screen. Figure 5 shows the image-update method of conventional LCDs, which illustrates the problem. As mentioned above, ViewSonic and Samsung have implemented an as-yet-undisclosed modification in their 3-D LCDs to overcome this problem.

Unfortunately, conventional plasma displays also cannot be used with LCS 3-D glasses to produce a high-quality flicker-free 3-D image.[8] Unlike CRTs or conventional LCDs in which updated pixels are presented sequentially over the course of the frame (see Fig. 5), plasma displays have the nice feature that all of the updated pixels in a frame are illuminated simultaneously. However, the long phosphor persistence of conventional plasma displays means that crosstalk (ghosting) will be high. Additionally, conventional plasma displays can only be driven with a 60-Hz video signal, meaning that even if the crosstalk was ignored, the image seen through the LCS 3-D glasses would flicker excessively. Samsung's 3D-ready plasma displays make use of the checkerboard 3-D input method to deliver the 3-D video signal and presumably use custom phosphors to reduce the amount of crosstalk due to phosphor persistence.

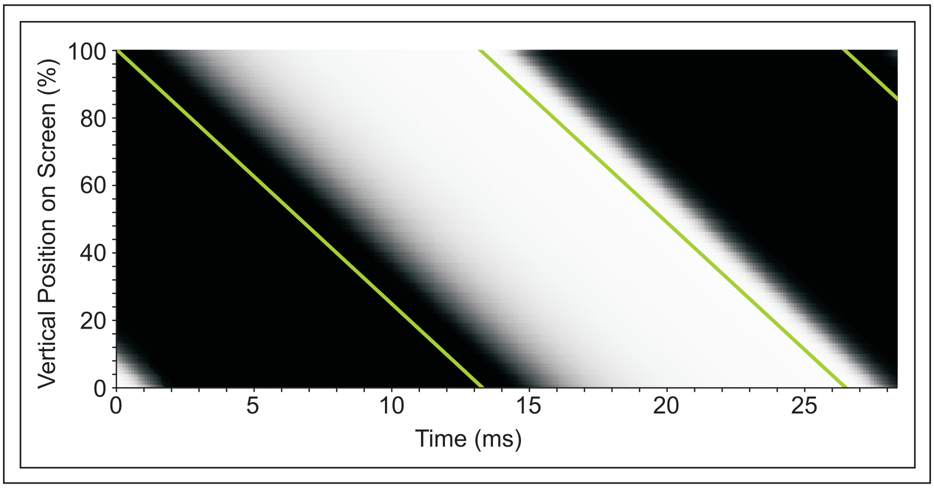

***Fig. 5:** Time-domain response of an example conventional LCD monitor (with 5.7-msec pixel response rate alternating between black and white frames at 75 Hz). The green line represents the time each row is addressed. It can be seen that there is no point in time when the entire screen shows one image across the entire screen.*[7]

Even displays that are advertised as being 120 Hz do not solve the problem – 120-Hz (and 240-Hz) technologies are being implemented with a range of LCDs and plasma displays to reduce the problem of image smear in scenes containing fast image motion. Many people recognize that "120 Hz" is often associated with stereoscopic 3-D viewing, but unfortunately the inclusion of 120-Hz refresh rates does not solve all the problems for successfully using time-sequential 3-D on these displays. The most obvious problem is that there is no way of driving them with a true 120-Hz video signal, containing 120 distinct frames per second. Usually, the display accepts only a conventional 60-Hz video signal and the display internally interpolates extra frames. The inability to send 120 unique frames per second to the display would mean that it could not be used for 120-Hz 3-D purposes. So, unless the display is labeled as "3-D-ready" or "3-D compatible," any mention of 120 Hz currently will not be an advantage to time-sequential 3-D compatibility.[9]

The Infitec system employed in Dolby 3-D cinemas uses special interference filters to divide the visible color spectrum into six narrow bands called R1, R2, G1, G2, B1, and B2 for the purposes of this description.[10] The R1, G1, and B1 bands are used for one eye image and R2, G2, and B2 for the other eye. The human eye is largely insensitive to such fine spectral differences, so this technique is able to generate full-color 3-D images with minimal color differences between the two eyes. Unfortunately, conventional displays lack the ability to modulate light wavelengths at this fine scale, so Infitec/Dolby 3-D glasses also will not work on conventional displays. This may be a possibility in the future with multiprimary-color displays, but there is nothing like this currently in the consumer market.

The only 3-D solution that can be widely deployed to any consumer color display is the anaglyph 3-D method. The anaglyph has been around since the 1800s, and for modern full-color displays involves sending the left and right image views into one or two complementary color channels, respectively. For example, the most common anaglyph technique involves the left perspective image being stored in the red color channel and the right perspective image being stored in the blue and green (cyan) color channels. The viewer wears red/cyan 3-D glasses to decode the correct image to each eye and sees a 3-D image. Other primary color combinations are possible, including blue/yellow and green/magenta. The main advantages of the anaglyphic 3-D method are its simplicity and low cost. All that is required is an anaglyphic 3-D image source, any full-color display, and a corresponding pair of anaglyphic 3-D glasses. Unfortunately, the anaglyph 3-D method usually suffers from fairly low 3-D image quality – due to fairly high ghosting levels, retinal rivalry, and the inability to reproduce a completely full-color 3-D image.[11] Despite these limitations, anaglyph 3-D remains a commonly used format as evidenced by the widespread release of many 3-D DVDs and Blu-ray discs in anaglyph format – albeit leaving many shaking their heads and yearning for something better.

Conclusion

A good (and expanding) range of high-quality 3-D displays is gradually penetrating the home consumer market. The successful roll-out of 3-D cinemas and 3-D movies is probably greatly responsible for the increasing consumer interest in this display category. The next part of the equation that needs attention is the availability of stereoscopic 3-D content for viewing on home 3-D displays. The consumer game market is the greatest source of 3-D content at the present time, with over 300 PC game titles available to be played in stereoscopic 3-D – enabled by 3-D game-software solutions available from NVIDIA, DDD, and iZ3D. There is also talk of game consoles supporting high-quality 3-D displays in the not too distant future. However, probably the most anticipated form of 3-D content is high-definition 3-D movies. Over 300 3-D movies and shorts have been publicly exhibited from 1915 until 2009, but unfortunately only a handful of 3-D movie content is commercially available at the present time (see www.3dmovielist.com) – and none in a high-quality high-definition format. At the present time, most content owners appear to be waiting for the much-talked-about Blu-ray 3-D format to be standardized, which is addressed in another article in this issue. Once that format is standardized, we will probably see another jump in the uptake of stereoscopic 3-D displays.

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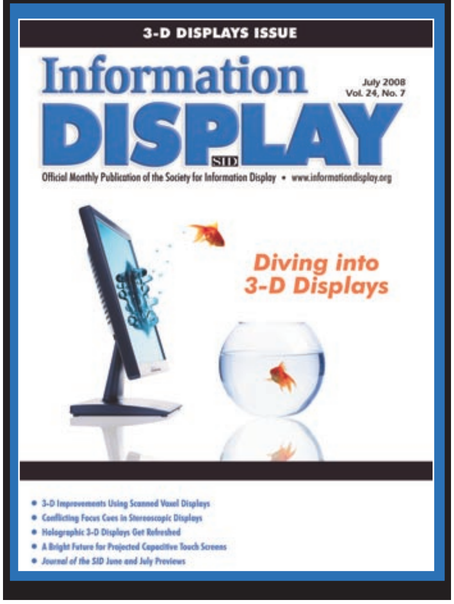

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An Overview for Developing End-to-End Standards for 3-D TV in the Home

Enthusiastic consumer response to recent 3-D theatrical releases is demonstrating users' appetite for 3-D content, and 3-D seems destined to become the next killer application for the home-entertainment industry. Until then, the standardization of 3-D formats for mastering and distribution is critically important for a successful introduction to the consumer market.

by William Zou

TODAY, the most noticeable development in the display industry has been the focus on 3-D. Of course, the use of 3-D for printing, the movies, and even TV is not new. It has been envisioned, promoted, and implemented for more than 100 years. There is no question why 3-D is a natural extension to the 2-D presentations we already enjoy today, and it provides a more interesting and attention-getting medium for viewers. But interest has faded every time 3-D has been promoted, and 3-D movies or TV have never quite moved beyond the gimmick stage – that is until recently. In 2005, particularly after Disney's release of 3-D versions of *Chicken Little* in movie theaters, the industry rediscovered the huge business potential of 3-D.

3-D theatrical releases are now generating more revenue in movie theaters than 2-D releases. For the recent theatrical release of DreamWorks Animation's *Monsters vs. Aliens*, nearly 60% of the revenue in the first week was generated from 3-D cinemas – which comprised only 28% of the total theaters screening the film. Because tickets to 3-D versions of films cost more than their 2-D counterparts, people are clearly willing to pay more for 3-D. The latest generation of digital-cinema projectors and 3-D glasses has enabled the success of 3-D at the box office. With the adoption of the Blu-ray HDTV format for next-generation home entertainment and large-display TV sets in the home, movie studios and other content providers see the potential for huge revenues from 3-D content consumption in the home as well as in theaters.

Meanwhile, consumer-electronics manufacturers see 3-D as a significant differentiator that could encourage consumers to continue investing beyond 1080*p* (full high definition). The advancement of 3-D display technology, including the availability of large screen sizes, high resolutions, and high frame rates (120 Hz and higher) will help enable high-quality 3-D content presentation in the home. 3-D is now being seen as the killer application that will not only bring people back to movie theaters, but also enable a whole range of new services and business to be offered to the home consumer.

***William Zou** is the chairman of the SMPTE Task Force on 3-D to the Home. He is employed by DTS, Inc. in Agoura Hills, CA. The full report on 3-D to the Home from The Society of Motion Picture and Television Engineers (SMPTE) comprises 76 pages, including a 3-D glossary, use cases, minimum requirements, recommendations, appendices, and references. It is recommended for anyone seeking a comprehensive introduction to many aspects of 3-D systems and the issues that need to be considered in planning for 3-D to the home and is available for download from the online SMPTE Store (https://store.smpte.org) for $20.*

3-D End-to-End Systems

This article provides an overview of 3-D end-to-end systems, as well as the issues and challenges involved in developing solutions. It will focus on industry efforts toward 3-D standards development and offer a glimpse into the substantial work remaining in those standardization efforts.

Figure 1 shows the process flow for delivering 3-D to end users, be it to movie theaters (top of diagram from left to right) or to mobile phones and home TVs (lower part of diagram from left to right). The issues involved in getting 3-D into the home, including content creation, mastering, distribution, and the displays themselves, will be discussed in the following.

Content Creation. There are three main approaches to creating 3-D content:

- *Live camera capture: capturing stereo paired images simultaneously.* Live events require the use of stereo cameras. In addition to the conventional stereo-camera rigs, a new class of 3-D cameras has been developed for capturing 2-D and depth mapping in real time using rangefinders. Rangefinders are usually

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laser or infrared camera devices that are used to provide depth maps for a given scene. Depth maps can also be calculated on a pixel-by-pixel basis in real time or offline.

- *Computer-generated images (CGIs): creating a stereo pair of views by rendering two views in parallel with a small angular separation in the two views.* Computer-generated content is typically considered the easiest method of stereo generation. The rendering system can render one or more related views depending on the application.
- *2-D–to–3-D conversion: processing of existing 2-D imagery and extraction of depth information from non-stereo depth cues to create a polygon-based image.* This process deconstructs the 2-D image into a series of objects (also known as segmentation), assigning relative depth to each object, then filling in occluded areas. The conversion can be either real time or non-real time. 2-D converted material may prove to be essential for a successful transition from 2-D to 3-D.

Mastering. Mastering involves formatting and packaging original 3-D content in a standardized format for post-production and down-stream distribution. It is ideal that a single master is used for all distribution channels. Generally, the master package will undergo additional processing (compression, storage, and physical transport) before being delivered into the distribution system. The master format is ideally in an uncompressed domain so that the highest quality can be maintained for downstream process and distribution.

Distribution/broadcast/emission: For 3-D distribution/broadcast/emission, the master (either from live camera or play-out systems)

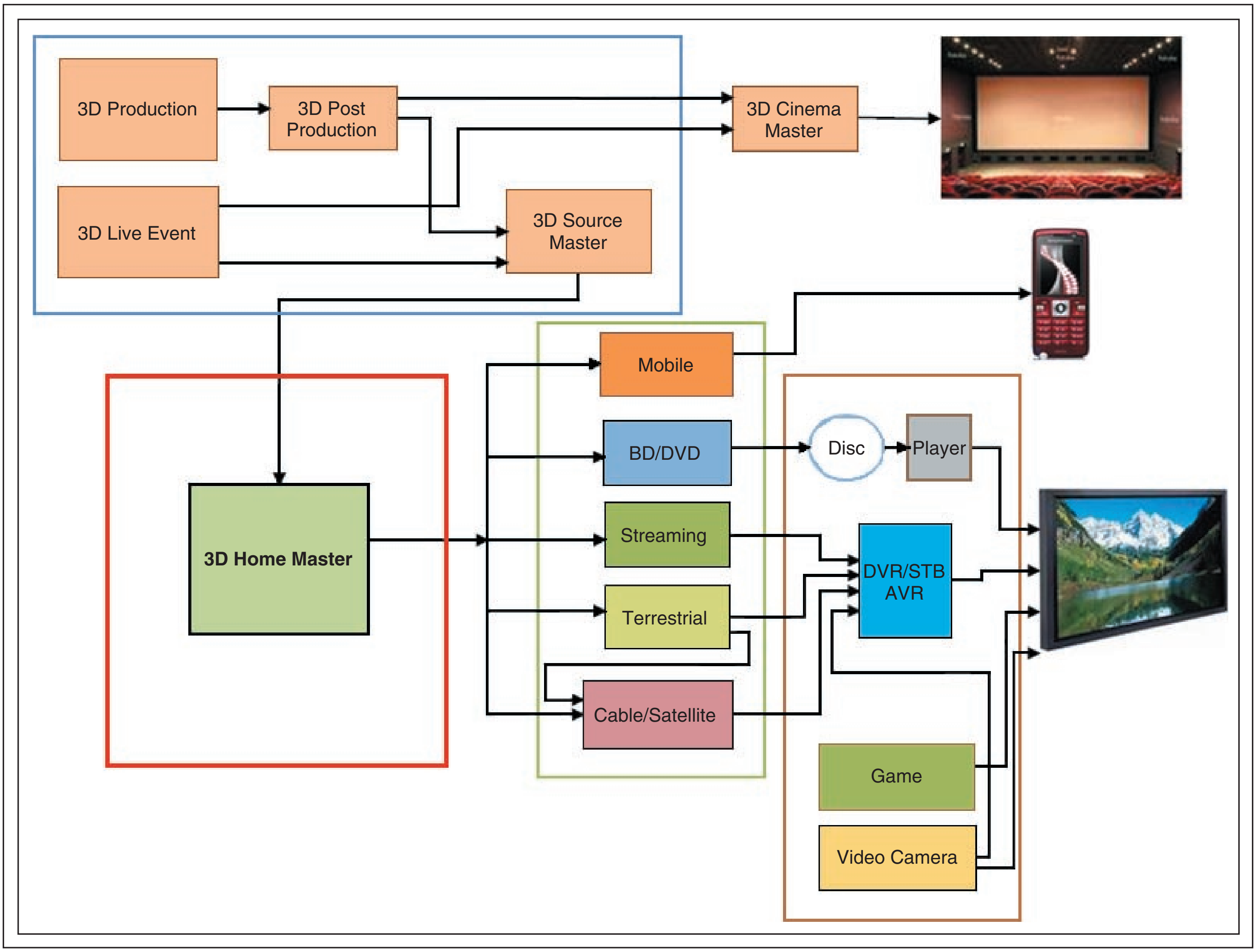

Fig 1: A conceptual model for delivery of 3-D content illustrates the role of the 3-D Home Master (lower left in red-outlined box) with regard to standardizing content and delivery for end-user devices (at right). Source: "Report of SMPTE Task Force on 3-D to the Home," pp. 11 © 2009 by SMPTE.

is taken into the distribution systems for delivery to the home. Because of bandwidth constraints, the signal is typically compressed to reduce the data rate to meet specific channel requirements. A stereoscopic image pair consists of a left-eye image and the corresponding right-eye image. Therefore, the support of stereoscopic 3-D content for distribution to homes requires two times more bandwidth than 2-D content. In order to reduce the bandwidth requirement while preserving visual quality as much as possible, and also supporting 2-D device compatibility, various 3-D formats have been developed:

- ***Spatial compression.*** In order for stereoscopic content to fit into existing transmission/storage infrastructures, one simple approach is to use spatial compression. This can be done by sub-sampling left- and right-eye images and then compressing them into a single 2-D image frame. The sub-sampled left and right images can be packed in a top/bottom, side-by-side, line/column interleaved or checkerboard fashion. All these formats achieve the goal of using no more than 2-D bandwidth. However, the downside is loss of spatial resolution and incompatibility with conventional 2-D displays. Embedding and transmitting additional side information with the formats and using a post-process such as pixel interpolation/smoothing could mitigate the problem of loss of spatial resolution.
- ***Time multiplexing.*** By multiplexing left- and right-eye images in the time domain, 3-D content becomes 2-D, but the frame rate is increased 100%. This approach could be implemented using some existing standards and interfaces, and possibly be supported by some consumer devices already in the home. The advantage of time multiplexing is that full spatial resolution for each eye can be provided. For some distribution platforms such as packaged media, the high bandwidth/bit rate of using time multiplexing might not be an issue, while for others the 100% increase of bandwidth/bit rate is prohibitive.
- ***2-D + depth map/delta/metadata.*** The key benefit of this approach is the support of 2-D device compatibility – display, set-top box (STB), *etc.* The format consists of 2-D images plus associated depth maps for each 2-D image.

  A conceptually similar approach using a single 2-D video stream with added metadata can be used for stereo image pairs. Instead of encoding two separate 2-D image streams, conventional video data can be used to represent, for example, the left half of the stereo pair, while metadata in the form of a difference map or delta map is used to encode the right half as a function of the left. The 2-D + depth map/delta/metadata can be encoded with standards-based compression techniques (*e.g.*, MPEG-2, AVC) for distribution. At the receiver, the 2-D portion can be decoded by conventional 2-D STB/TV while the data of depth map/delta or 3-D metadata is ignored. New 3-D devices (*e.g.*, STB, 3-D TV set) can decode the complete 3-D stream and render it on a 3-D display.
- ***Color coding.*** Using color-coded images for left-/right-eye presentation (such as with the anaglyph method) for 3-D TV has been with us for decades. It is the only format that can be used for 3-D presentation with a pair of color-coded glasses on any 2-D display. Certainly, color coding produces poor quality and does not provide a compelling 3-D viewing experience.

3-D Displays in the Home

There are many different types of 3-D display technology and each has a different set of advantages and disadvantages. Currently, there are three types of 3-D displays commercially available on the market.

- DLP-based rear-projection TV using the checkerboard format.
- Plasma TV using checkerboard or line/column interleaving.
- LCD TV using page-flip (120-Hz frame rate with time multiplexing) or a line-alternative micro-polarized screen.

The companion article to this piece, “3-D Displays in the Home” by Andrew Woods, describes these devices in more detail, but they all require wearing glasses (either passive or active) for 3-D viewing. Autostereoscopic 3-D displays do not require viewers to wear glasses and can also provide multiple viewing spots with good spatial resolution. Although glassless 3-D viewing is considered the future, large screen multi-view autostereoscopic displays will not be commercially available in the short term.

All of the 3-D display technologies mentioned above will be co-existent and consumers will have to deal with the choices of quality, price point, and the question of whether they will accept the wearing of glasses for long-term 3-D viewing. The adoption of well-researched standards can help minimize consumer confusion and the need to educate the end-user by facilitating the most viable options.

Issues and Challenges for Delivering 3-D Content to the Home

The key issues and challenges for delivering 3-D content to the home include a lack of industry standards for content mastering and distribution, high cost of 3-D content production and distribution infrastructure, and multiple incompatible display technologies. Selection of the right 3-D formats for specific distribution channels heavily depends on:

- 3-D quality and extensibility (future quality improvement).
- Efficiency of implementation (storage, transport, computation, rendering).
- 2-D compatibility (distribution requirement and 2-D display).
- Compatibility with the existing consumer devices.
- Production and implementation cost.
- Technology maturity and time to market.

The following is a list of possible distribution channels, including their pluses and minuses:

Terrestrial broadcast. This is the most bandwidth-constrained distribution platform. Each TV station has only a 6 MHz (U.S. and Japan) or 8 MHz (European countries) channel bandwidth. It is also the most regulated and standards-based distribution. With limited RF bandwidth per station, constraint by legacy-transmission standards, and the current state of consumer TV receivers in the home, it is highly desirable to transmit 2-D backward-compatible formats that could be received by both 3-D receivers and legacy 2-D receivers. This approach would require compressed 3-D bit streams for emission in the format of 2-D + metadata (*e.g.*, depth-map, delta, *etc.*) so that a 2-D legacy receiver could decode the 2-D portion and ignore the 3-D side information, while a 3-D receiver could display the 3-D content. An alternative would be to simulcast 2-D and 3-D streams (not necessarily with identical content), so that each uses a fraction of the channel. It will be important to assess the likely transmission bit-rate requirements for terrestrial broadcast and to understand what factors affect the quality of the 3-D experience as perceived by viewers.

The relevant international standards bodies addressing terrestrial broadcast standards are ATSC (Advanced Television Systems Committee), DVB (Digital Video Broadcasting), and ITU-R (International Telecommunication Union Radiocommunications Sector).

Cable. Cable is relatively less constrained with regard to bandwidth than terrestrial broadcast. 3-D services could be treated just like today's Video on Demand (VoD) model or with dedicated 3-D channels for those with a special STB that supports 3-D decoding and presentation. This business model provides a flexible requirement for cable to go to either a 3-D-only or 2-D-compatible format solution. Cable could be one of the distribution platforms that starts offering 3-D early when sufficient 3-D-ready sets are available in the home. Like the broadcast industry, the cable industry follows standards-based implementation. Two standards development organizations playing key roles in defining standards are the SCTE (Society of Telecommunications Engineers) and DVB.

DTH/Satellite to the home. Unlike cable or terrestrial broadcast, DTH (direct to home) is basically a closed system – individual operators such as DirecTV, Dish Network, and BSkyB can do whatever they want. As is the case with cable, bandwidth constraint is less of a problem, although the rollout of HD content, especially the addition of large numbers of local HD channels in the US, consumes large chunks of transponder bandwidth. DTH could offer 3-D as a dedicated channel, either using 3-D-only or 2-D-compatible formats.

Packaged media. It is expected that packaged media such as Blu-ray discs will be the main platform for 3-D home entertainment, as driven by Hollywood studios and their desire to capture the home-entertainment segment by leveraging their growing 3-D theatrical content library and success in the 3-D box office. The Blu-ray disc format has large disc storage space (25/50 GB) and supports advanced video and audio CODECs. The format also supports dual-stream decoding (picture-in-picture and secondary audio features). The video decoding can support up to a 40-Mbps data rate and the 1080*p* format.

IPTV/Internet/Mobile/Cellphone. IPTV (Internet protocol TV) is much like cable service, although some varieties are based on point-to-point switching networks, while others are RF-overlay on fiber or FTTH (fiber to the home). These networks can adopt VoD-like 3-D services or transmit dedicated streams for 3-D content to the home. Mobile TV and cell phones can also provide 3-D content using single-view autostereoscopic screens. There have been announced market trials for 3-D-capable cell phones and services. Internet content download and streaming to PC and TV are now popular and will play a key role in future content distribution and consumption. SMPTE and some industry forums have already started developing standards for broadband distribution, and their 3-D support is expected.

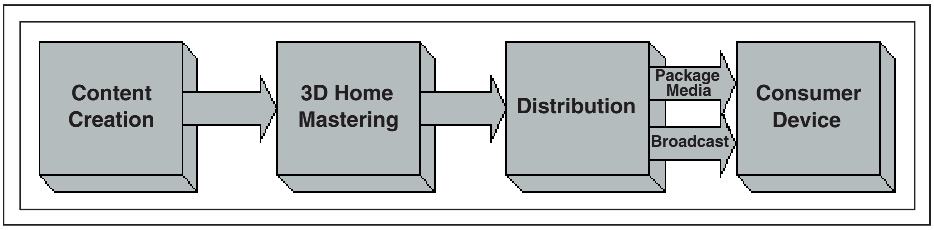

Fig. 2: *The value chain is a simplified version of the flow diagram appearing in Fig. 1.*

What Standards Are Needed?

Standards are playing important roles in developing an end-to-end value chain for 3-D to the home. The key questions to be answered are what standards are needed and when to standardize 3-D TV. The benefits of standardization include interoperability, low-cost consumer devices, and consumer confidence. Ideally, standards should be implemented before any proprietary system becomes the *de facto* standard on the market. The right timing to standardize a technology depends on factors such as technology maturity as well as future-proofing for extensibility.

Another issue is single/worldwide standard *vs.* multiple/regional standards to meet specific requirements. A single worldwide standard is best, and this is certainly possible, especially for 3-D content mastering. The requirements and business models for the distribution platforms are very different, and therefore a one-size-fits-all distribution format might not be feasible. The fragmentation of distribution standards/formats might split and confuse the market and the consumer, and a worldwide standard would go far toward alleviating this problem. The entire value chain can be segmented into four categories as shown in Fig. 2.

With the exception of content creation, standards are needed in each of the following value chain areas:

Content creation. There is no need to standardize content creation. The Society of Motion Picture and Television Engineers (SMPTE) uses the term 3-D source master to refer to the image format or file package where content originates.

3-D home mastering. It is important to standardize a single worldwide 3-D home master format for all distribution channels. (The SMPTE defines "3-D Home Master" as an uncompressed, unencrypted image format or file package derived from a 3-D source master.) The 3-D Home Master is intended to be used in the creation of 3-D distribution data. However, any future standards creation should adequately study whether it is feasible to create a single 3-D home master *vs.* multiple masters (each for a different distribution channel or set of channels).

Distribution. In this case, distribution is considered the last mile to the home. Distribution includes physical transmission channels/platforms such as terrestrial broadcast using RF frequency, cable HFC networks, satellite to home (DTH), packaged media, and the Internet.

Consumer devices. There are many incompatible 3-D display technologies on the market and there is no clear trend indicating that a single display format is emerging in the near future. Furthermore, it is assumed that there might be multiple distribution formats to meet specific uses for distribution. Therefore, it is critical to make sure that any consumer playback device (*e.g.*, Blu-ray player, STB, game console, *etc.*) can communicate with any 3-D display device in the home and that 3-D content from any playback device is displayed properly. This requires developing industry-wide interface standards and signaling specifications.

Worldwide 3-D Standards Development

A number of entities are actively engaged in the development of standards for different portions of the 3-D pipeline. These organizations include the CEA (Consumer Electronics Association), ATSC, DVB, ITU, SCTE, BDA (Blu-ray Disc Association), DVD Forum, ISO/IEC/MPEG, and SMPTE. As the chair of the SMPTE Task Force on 3-D to the Home, the author will focus on SMPTE's effort, while providing a brief survey of some of the activities of other organizations.

Society of Motion Picture and Television Engineers (SMPTE). In August 2008, the SMPTE established a task force to define the parameters of a stereoscopic 3-D mastering standard for content viewed in the home. The project, called 3-D to the Home, was the first step in propelling the 3-D home-entertainment industry forward by setting the stage for a standard that will enable 3-D feature films and other programming to be played on fixed devices in the home, regardless of the delivery channel. With cross-industry participation and contribution, the task force defined the concept of a 3-D home master, identified use cases from the perspective of various entities in the supply chain for 3-D content to the home, and developed requirements for the 3-D home master. In March 2009, the task force completed its assignments and published its report, which will form the basis for developing actual format standards within SMPTE. This report has been distributed to other SDOs (standards development organizations) in support of their development of related distribution and presentation standards.

The task force defined a 3-D home master as follows: "Uncompressed and unencrypted image format or file package derived from a 3-D Source Master. The 3-D Home Master is intended to be used in the creation of 3-D Distribution Data."

Based on the use cases developed by the task force, the minimum requirements for the specification for a single 3-D home master were defined. The key parameters include the following nine categories: image content, audio synchronization, graphical overlays, subtitles, closed captions, backward compatibility with 2-D and 3-D metadata, ancillary metadata, and evaluation criteria.

In addition to the use cases and requirements described in the report, the task force recognized that there are various unknowns, which may (in the future) impact the format of the master package. These include evolving display technologies, future distribution channels, production and authoring techniques and needs, and unexplored psychophysical characteristics of the human visual system.

A group within the SMPTE standards committees started working on defining specifications based on the requirements developed by the task force in June 2009, with core standards expected to conclude within a year. As in the development of the 3-D home master requirements, the SMPTE committee will work closely with other SDOs that will develop companion standards for complete end-to-end interoperability. A brief listing of other standards groups follows. For more information, please see the SMPTE Web site at www.smpte.org.

Consumer Electronics Association (CEA). CEA's Video Systems Committee has launched a new standards activity aimed at establishing standards for 3-D video. It observed that many broadcasters, DVD distributors, and CE manufacturers are moving forward with 3-D, and concluded that establishing a standard for transporting 3-D video over an uncompressed high-speed digital interface was very important.

Advanced Television Systems Committee (ATSC). ATSC is an international organization that is developing standards for digital television and is responsible for developing DTV standards for digital terrestrial broadcast.

Digital Video Broadcasting (DVB) project. DVB is at this stage looking for information on what technologies and capabilities are available. For example, the project committee is examining backward compatibility and looking for commercial requirements for work items that sit within the scope of the DVB expertise.

International Telecommunication Union (ITU). The subject of 3-D TV is currently being considered by Working Party 6C (program production and quality control), as part of the work of ITU-R Study Group 6 (Broadcasting Service). In October 2008, the ITU-R approved a new study question on digital 3-D television broadcasting. This is essentially a call for proposals for 3-D TV. The question calls for contributions on systems that include, but also go beyond, stereoscopy.

Society of Cable Telecommunications Engineers (SCTE). In early 2009, SCTE established a standards project called 3-D Over Cable. This effort will investigate the distribution of 3-D video content over cable networks. One result will be the identification of any changes that are necessary or desirable in existing SCTE standards to facilitate the provision of 3-D content by cable operators.

Blu-ray Disc Association (BDA). BDA is a voluntary membership group creating, upholding, and promoting the BD formats and developing Blu-ray Disc specifications. Due to the large disc storage capacity, 1080*p* picture quality, and 7.1 audio, Blu-ray Disc is the ideal platform for bringing 3-D technology to mainstream home entertainment. The BD format is backed by the Hollywood studios and major CE manufacturers and will be a distribution platform delivering the highest-quality 3-D content to the home in a relatively short time frame. In May 2009, the BDA formed a 3-D task force to add advanced 3-D technology into the Blu-ray format.

DVD Forum. The DVD Forum is an international association of hardware manufacturers, software firms, content providers, and other users of Digital Versatile Discs. It issued an RFI (request for information) on 3-D technology in 2008 and received several proposals with various encoding formats. The DVD Forum then conducted backwards compatibility tests on the legacy DVD players using these proposed formats. In early 2009, SENSIO's 3-D spatial compression format was accepted as an optional DVD standard.

ISO/IEC/MPEG. In the past, MPEG developed standards related to 3-D video. ISO/IEC 23002-3 (also referred to as MPEG-C Part 3) specifies the representation of auxiliary video and supplemental information. This specification supports the well-known 2-D + depth format, including metadata to adjust the rendering of a 3-D scene based on viewing characteristics such as display size and viewing distance.

The 5th Edition of the ITU-T Rec. H.264 | ISO/IEC 14996-10 Advanced Video Coding (AVC) standard, which will be published soon, includes extensions for multiview video coding (MVC). The Multiview High Profile is specified in this edition of the standard, which utilizes existing high-profile tools (excluding interlaced) for inter-view prediction to achieve improved compression of stereo and multiview video. Signaling of scene acquisition information (*i.e.*, camera parameters) and multiview scene information (*i.e.*, maximum disparity) is also specified. Such metadata may be used for 3-D display processing. MPEG is also in the process of developing an amendment of AVC that standardizes additional capabilities in the context of 3-D.

Conclusion

Recent 3-D theatrical releases have demonstrated significant consumer desire for and acceptance of 3-D content. 3-D is poised to become the next killer application for the home-entertainment industry. Standardization of 3-D formats for mastering and distribution is critically important for a successful 3-D introduction to the consumer. The SMPTE 3-D Home Master is being developed as the cornerstone of the entire content chain. It will provide high-level image-formatting requirements for the source materials authored and delivered by content developers. It will additionally provide requirements for the delivery of those materials to all distribution channels; from physical media to terrestrial, satellite, cable, and other streaming service providers. Beginning in 2009 and continuing down the road, the industry needs to work hard to build a complete value chain for delivering 3-D content to the home. With the completion of the above specifications, 3-D home entertainment will become a reality. ■

Gamma, Brightness, and Luminance Considerations for HD Displays

Gamma correction in high-image-quality displays improves the appearance of imagery and is based on an assumed mathematical relationship between luminance and brightness. As the market for new HD technology expands, it is a good time to examine the correct brightness–luminance relatioship for high-definition displays. The DICOM standard represents a possible way of doing this.

by Martin Kykta

EVERY high-quality video display has a built-in gamma correction that makes the imagery look better. Gamma correction allows the picture to appear more natural and realistic by providing the proper number of gray levels and contrast. This correction is based on the assumption that there is a mathematical relationship between luminance and perceived brightness. Because of the growing market for new high-definition (HD) technology, now is the time to examine the correct brightness–luminance relationship for HD displays.

The derived Digital Imaging and Communications in Medicine (DICOM)[1] standard is a potential solution for selecting the correct gray levels for the luminance range of today's displays and also for choosing the correct image scaling and compression. This methodology could allow images to be scaled up and bright images to be scaled down without compressing the high or low gray levels through an improper transformation.

Background: Luminance, Brightness, and Gray Scale

Of particular interest to display designers, or anyone else who wants to choose a display that will deliver the best image, is that the display is able to show a perfect linear gray scale of increasing brightness. Accomplishing this task requires an understanding of luminance, brightness, and gray scale. The eye and brain react in a non-linear manner to constant increases in luminance. Luminance is proportional to the light flux or power, but is weighted only to the visible wavelengths, with green light having the greatest weight. The human perception of brightness is a non-linear response to a linear change in luminance. A gray scale refers to a uniform, increasing black-to-white scale (see Fig. 1).

A gray scale for linearly increasing brightness requires non-linear increasing steps in luminance from the display. The display must be constructed to have or be programmed with an electro-optical transfer function, which generates the approximate output signal that creates the correct eye–brain response when viewing a gray scale. When the electro-optical transfer function is chosen correctly, the signal input to the display causes a linear increasing scale of brightness – gray scale (see plot in Fig. 2) – by a corresponding non-linear increase in the luminance (see plot in Fig. 3). The brightness *vs*. input signal is a linear function; the luminance *vs*. input signal is a non-linear function.

Although the figures for this article show the input signal to have 16 values, which correspond to 16 gray levels, typically the input

Fig. 1: *An image of 16 levels of gray scale from black to white is depicted, showing each gray-level change representing an equal change in brightness. Brightness is a perception that depends on the human eye–brain response.*

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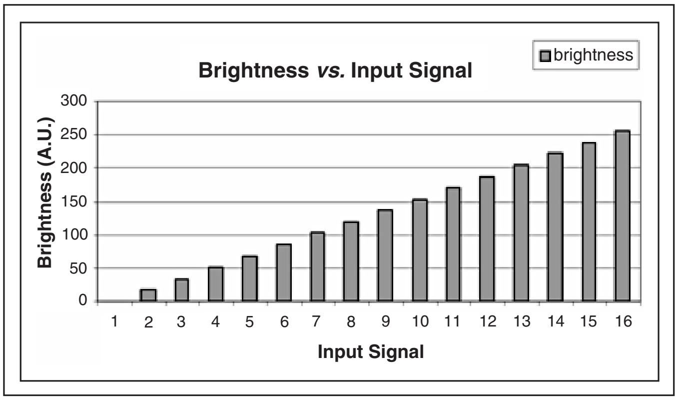


***Fig. 2:** A plot of the 16 levels of gray scale is visually depicted from black to white in Fig. 1. Here, the brightness scale is shown in arbitrary units that demonstrate equal changes in input gray levels, resulting in equal changes in brightness.*

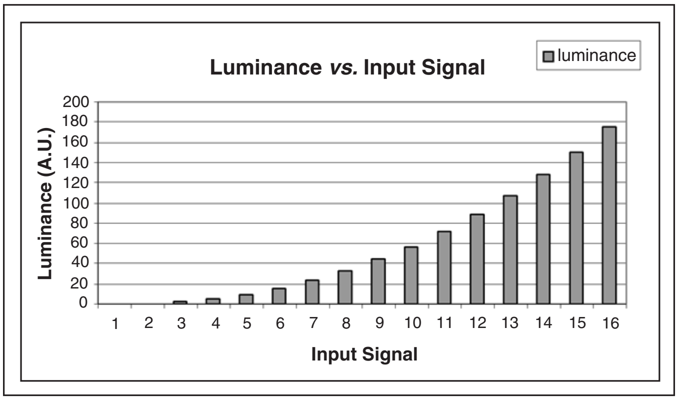


***Fig. 3:** A plot of luminance vs. input signal shows 16 levels of gray scale from black to white (as visually depicted in Fig. 1). Each gray-scale-level change results in an unequal change in luminance approximated by a power relationship.*

range is greater than 16 and extends from 0 to 255 or 256 digital values for a typical video display.

Gamma

Today, gamma correction loosely refers to the electro-optical transfer function that must be applied to the output signal to cause brightness to appear linear with the input signal. Gamma correction is accomplished by forcing the luminance output to obey the gamma relationship shown in Eq. (1). The symbols L, V, and γ refer to luminance, input signal, and an exponent referred to as gamma.

$$L \propto V^{\gamma}. \tag{1}$$

The term "gamma" was originated by cathode-ray tube (CRT) designers that referred to a power exponent of the voltage input signal to the grid of a CRT tube. The grid voltage controlled the electron current density from the electron gun, which determined the screen luminance. CRT output luminance is innately non-linear with linear input. Nowadays, most displays sold are not CRTs and do not contain an electron gun. However, even today, Eq. (1), sometimes called the gamma relationship, still holds true for most video displays. If the luminance output of most any video display is plotted versus the digital input signal (from 1 to 256) on a log–log plot, the slope of the continuous graph would be a constant number called gamma. Without gamma correction, the luminance output from liquid-crystal displays (LCDs) and other displays would not follow Eq. (1).

Gamma correction requires a functional transformation performed with a look-up table (LUT). The LUT is a number matrix that maps the input signal onto itself. The LUT makes the luminance output look like that of Eq. (1). Why do we still make the luminance output look like a power function of input? The reason is based on the brightness–luminance relationship.

Brightness-Luminance Relationship

Early psychophysicists discovered an approximate mathematical relationship between brightness and luminance: brightness perception follows a power law relationship. By neglecting some constants, the perception of brightness, B, is proportional to the cube root of luminance:

$$B \propto L^{1/3}. \tag{2}$$

By substituting Eq. (1) into Eq. (2), we find that $\gamma = 3$, if the brightness appears to be linearly increasing with video signal:

$$B \propto (V^{\lambda=3})^{1/3} = V. \tag{3}$$

This explains why all displays have luminance output signals that grow approximately with the cube of the input signal. The brightness–luminance relationship and the gamma relationship are approximate inverses. But CRT designers of the past usually chose 2.2 instead of 3, and display designers of today do so as well. Does it matter that the exponent is 2.2 instead of 3? No, not really. There are several reasons for not having a cubic dependence. Some leeway must be given for ambient lighting. The perception of brightness depends on all light entering the eye. In the past, the user could also adjust the display with the contrast (which changes the gamma) and brightness knobs. Today, a legacy electronic-signal standard still exists that expects gamma to be 1/0.45. And it also turns out that the brightness–luminance relationship has a power dependence anywhere from 2.2 to 3, depending on the luminance range, which is discussed later in this article.

Medical displays assume a different gamma relationship than shown by Eq. (1). This is called the Digital Imaging and Communications in Medicine (DICOM) standard. The DICOM standard is based on studies of modulation contrast and vision made by Peter G. J. Barten.[2] The author[3] of this article has shown that the power relationship in Eq. (2) approximates the DICOM standard over a limited luminance range. The DICOM standard is a plot of luminance *vs.* just-noticeable difference (JND). The JNDs correspond to video input signal V in the gamma relationship. The assumption in the Barten model is that one unit of JND is the same as any other JND and can be differentiated from a neighboring JND by 50% of the population. The number of gray levels is proportional to the number of JNDs. Given that the gamma relationship and the brightness–luminance relationship are inverses, by inverting the DICOM standard a brightness–luminance relationship where the JNDs are measures of brightness can be derived.

New Display Technology

Now that new HD display technology has entered the marketplace, there is an opportunity to fine tune and choose a better gamma than a simple power relationship. New displays are being built with different luminance ranges. Typical CRT TV displays of the past had a luminance range between 0.01 and 175 cd/m^2. Today's new consumer displays have a luminance range from 0.5 to more than 450 cd/m^2. Digital signals have also brought with them the possibility of more signal levels; however, this change has not yet been implemented for HDTV broadcast. HDTV broadcasts 256 signal levels (actually slightly fewer due to header requirements). Most HD displays are also capable of only 256 signal levels; however, some new displays are capable of 1024 and will be able to show all the gray levels (~637 according to DICOM) that can be seen within a luminance range of 0.5–450 cd/m^2.

Three or four orders of luminance range have the possibility of more gray levels. Theater movies have always taken advantage of the capability of displaying a large number of gray levels. Depending on its quality, analog film is capable of displaying many more than 256 gray levels. Movies played in theaters are certainly not brighter than today's displays. Theaters typically have an average screen luminance of 55 cd/m^2. Movies are shown in dark theaters, so owners allow time before the movie starts for people's eyes to adjust (as well as for showing ads for coming attractions). Letting the eye adjust to a dark room increases the numbers of observable gray levels at the bottom luminance range.

Medical displays have a greater luminance range and make optimal use of gray levels by using the DICOM standard. Doctors need to have the best gray-level discrimination when looking for images of tumors in x-rays. The DICOM standard represents a realization that gray levels depend on the absolute luminance from the display. Consequently, the standard is harder to implement. When displays age, their luminance output changes and feedback is required to adjust the gamma correction.

The Number of Gray Levels

How many distinct, distinguishable gray levels are there? Surprisingly, the answer to this question is still controversial. There are a number of psychological observations that cannot be explained by simple mathematical brightness *vs*. luminance relationships. The existence of these observations is used by some psychologists as a justification for saying that there are no absolute gray levels. They argue that we are not capable of recognizing absolute measurements of brightness but only of a ratio measurement of brightness that is called lightness; that we can make contrast judgments by comparison only. Others acknowledge these observations as real and still say that we still can have distinct gray levels (DICOM standard), but only in a rigidly defined test situation. More complete theories of image and color that explain many vision phenomena have already been formulated. One such theory is the image color-appearance model (iCAM) developed by Mark D. Fairchild and Garret M. Johnson. The theory is semi-empirical with many adjustable parameters and power-relation dependencies.[4]

An explanation for why these observations cannot be explained by simple brightness and luminance relationships is rooted in two main causes: the actual physical structure of the eye and the eye–brain interaction. A close examination of the gray scale shown in Fig. 1 reveals Mach bands, which appear at the edges of each of the vertical bars. The edge of a darker band next to a lighter band appears darker than its center and the edge of the lighter band appears lighter than its center. This effect is due to lateral inhibition that occurs within the cells of the retina – the eye is a great edge detector.

A bigger problem with the idea that we are capable of absolute measurements of brightness is that of simultaneous contrast. The eye and brain will maintain the perception of a gray area as being brighter or whiter when it is surrounded by an area that is darker. An example of this phenomenon is shown with two gray squares of the same luminance, surrounded by white and black areas in a side-by-side comparison (see Fig. 4). The gray square surrounded by the black area appears brighter than the gray square surrounded by the white area. The immediate surrounding area of a point where the eye is focused plays a role in the perceived brightness.

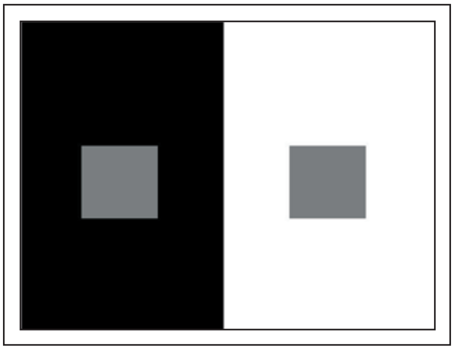


***Fig. 4:** In this example of the problem of simultaneous contrast, two small gray squares have the same luminance. The gray square surrounded by the black area appears brighter than the gray square surrounded by the white area.*

The Weber Fraction

The best answer to the question of the number of distinguishable gray levels can be found by examining the Weber fraction data, $\Delta L/L$, *vs*. luminance plot. The Weber fraction measures the smallest change in luminance that is detectable by the eye at a fixed-background luminance level. The test consists of a target made of two white luminances with one slightly larger than the other. The background luminance is the average of these two luminances. The Weber fraction is the difference between the two luminances, ΔL, divided by the first luminance, L. The change in luminance is associated with a just-noticeable difference, JND. It is assumed that each JND is equivalent. A continuous plot of the Weber fraction taken from data shown in a paper from Selig Hecht[5] appears in Fig. 5, which shows three distinct regions: a threshold, a constant, and a saturation region. In the threshold region, the Weber fraction decreases with increasing luminance. Rod cells are active, and black-and-white vision dominates. As the luminance increases, the cones become active. Color vision is possible, and the Weber fraction is no longer decreasing but is approximately constant. This constant region is linear and about two orders of magnitude and is typically known as the Weber constant. As luminance increases further, the cones begin to become less sensitive to changes in light levels. This is called the saturation region. Any theory that claims to determine the number of gray scales must qualitatively be able to reproduce the shape of the Weber fraction data.

The power law for the brightness–luminance relationship can be derived from the assumption that the Weber fraction for both luminance and brightness is proportional. The power-law relationship, Eq. (5), is a direct consequence of integrating Eq. (4). Both equations are shown below:

$$\left(\frac{\Delta B}{B}\right) = n\left(\frac{\Delta L}{L}\right) \tag{4}$$

$$\Rightarrow B = cL^n. \tag{5}$$

The power relationship has been verified experimentally over a limited luminance range as the equation that shows the correct trend. For example, luminance must increase approximately eight times in order for a doubling in brightness to be observed. Unfortunately, the power relationship used for the luminance–brightness relationship is scale-free. It implies that brightness sensitivity is independent of whether the luminance is high or low. It is not possible to derive the Weber-fraction data curve from this relationship.

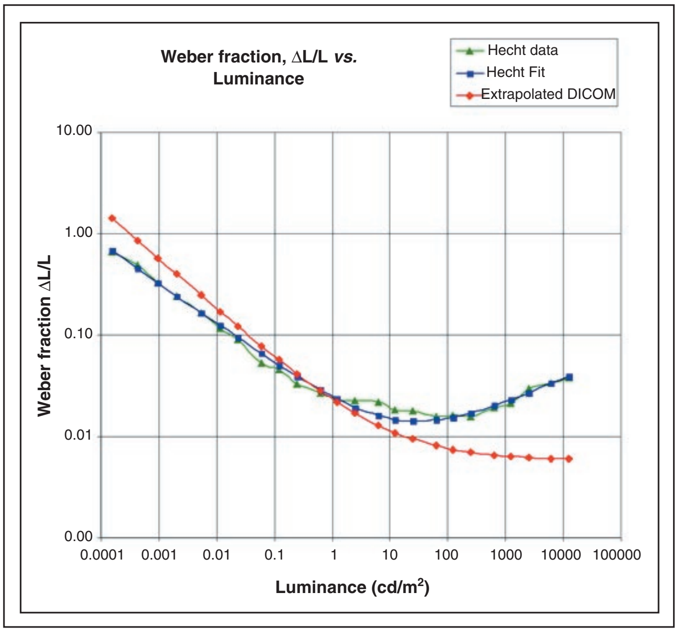
The Weber fraction can be derived from the DICOM standard, as this author has done.[3] The DICOM standard is not based on the Weber fraction data but is experimentally derived from contrast modulation data and experiment measurements. The DICOM standard is based on a 2° × 2° square filled with a horizontal or vertical grating with a sinusoidal modulation of 4 cycles/degree. Figure 5 shows Selig Hecht's tabulated data in a plot, the numerical fit to Hecht's data, and data derived from the DICOM standard by the author.

The Weber fraction data derived from the DICOM standard were extrapolated at the high and low luminance range to overlap the Hecht data. Consequently, the high-level luminance derived from the DICOM data does not show saturation because it was extrapolated from a region that is unsaturated to the saturated region. The Weber fraction of the two curves does not match up but is close. The difference is in the test's special pattern frequency.

The DICOM data was taken at the spatial frequency (4 cycles/degree) where the eye is more sensitive to changes in contrast, while the Weber fraction data was taken over a spatial light modulation frequency based on a test target of an angular field of view of 6° × 4.3° with one cycle of luminance difference (0.17 cycles/degree), where the eye is less sensitive at moderate light levels. The contrast sensitivity as a function of luminance is plotted in Fig. 6.

The contrast sensitivity is the inverse of the Weber fraction. The multiple plots indicate that the sensitivity to contrast at a particular spatial frequency shifts with luminance level. The plot also shows that high and low spatial frequencies are harder to see than middle frequencies. A vertical line on this plot could be converted into a Weber fraction plot using the luminance data. Multiple vertical lines would show that there are different Weber fractions for different spatial frequencies.

Let us reexamine the two gray squares shown in Fig. 4. The two images do not have the same background luminance and are not symmetric in total light content. The background illumination has an effect on the adap-



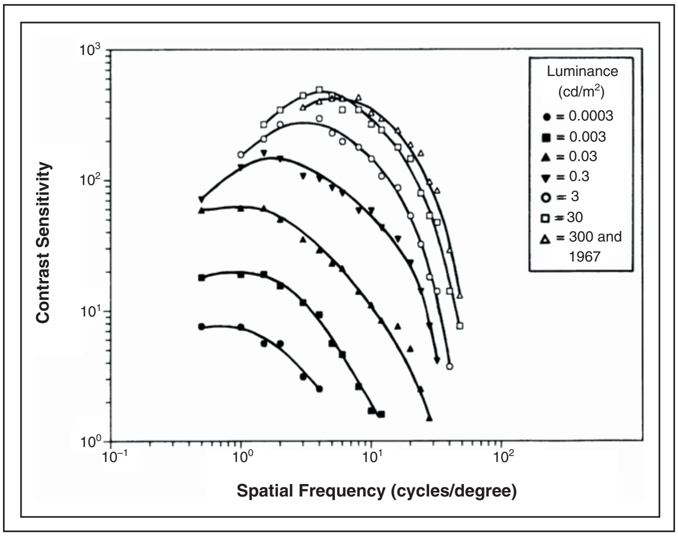


Fig. 5: *This log–log graph depicts the Weber fraction vs. luminance using different data sources. The first data source is taken from Selig Hecht's article. The numerical fit to the Hecht data is plotted. Also, plotted is the derived Weber fraction from the DICOM standard.*

Fig. 6: *This log–log graph shows the contrast sensitivity vs. spatial frequency for various luminance levels. This graph is taken from Louis Silverstein's Fundamentals of Vision and Color Science, SID Short Course, May 20, 2007. The actual graph is adapted from data from Van Ness and Bouman, "Spatial Modulation Transfer in the Human Eye,"* JOSA ***57****, 401-406 (1967).*

tation state. If the Weber test was performed with background luminance much brighter or darker than the two test luminances, the plot shown in Fig. 6 would be very different. Adaptation allows us to explore the full range of luminance for the Weber fraction test, which is 10 orders of magnitude. If we did not have adaptation, we would only see four orders of magnitude.

Derived DICOM

The DICOM-derived Weber fraction data fit Eq. (6), which is a modified Steven's law because it does not show a direct power relationship of luminance to brightness. However, a mathematical relationship for brightness will be shown later.

$$\left(\frac{\Delta L}{L}\right) = kL^n + c \tag{6}$$

For Eq. (6), the difference in the test luminance level and the luminance level, ΔL, corresponds to a JND in luminance, where L is the luminance level and k (= 0.017738) and c (= 0.0058472) are constants that depend on the units used (cd/m^2), and n is an exponent (= – 0.49985). An iteration relationship can be derived from Eq. (6) and is shown in Eq. (7).

$$L_{i+1} = L_i + L_i(kL_i^n + c). \tag{7}$$

The iteration relationshipship and the first threshold luminance (0.00015 cd/m^2) are all that are needed to derive the luminance–brightness relationship that is plotted in Fig. 7. Each indice, i, corresponds to a JND or brightness level. Figure 7 shows that the derived DICOM iteration is approximated by a 2.2 gamma power for the first 200 JNDs and by a 3.0 gamma power relationship for the next 300 JNDs. For a JND greater than 500, neither power function works well. (Note: This DICOM will not match up with the standard DICOM because the first JND starts from threshold.)

The inverses of the plot for Fig. 7, as shown in Fig. 8, are the brightness (JND) *vs*. luminance plots for the DICOM-derived data. The plot shows that brightness at low luminance levels is approximated by a 1/2.2 power function at low luminance levels and can be approximated by a 1/3 power function at higher luminance levels.

Conclusion

In summary, the derived DICOM standard is another choice for gamma that could be used for the new displays that have larger luminance ranges than the ones in the past that used a power relationship. The original DICOM standard is based on experimental data and is already accepted for medical displays. The derived DICOM can be approximated by power relationships 2.2 and 3.0 over different luminance ranges. Not surprisingly, the brightness relationships can be approximated by the accepted 1/3 power over a short luminance range. The derived Weber fraction from the DICOM standard has a shape similar to the Weber fraction data. The data also do not match exactly because the measurements were taken at different spatial frequencies. Spatial frequency affects the number of gray levels. The spatial frequency of video images will vary with image content. The measurable gray-level spacing will also vary with spatial frequency and so should it also vary with image content. It would be tough to vary the gray levels on the fly and we may have to be satisfied with a fixed DICOM gamma correction as the next step in HD technology.

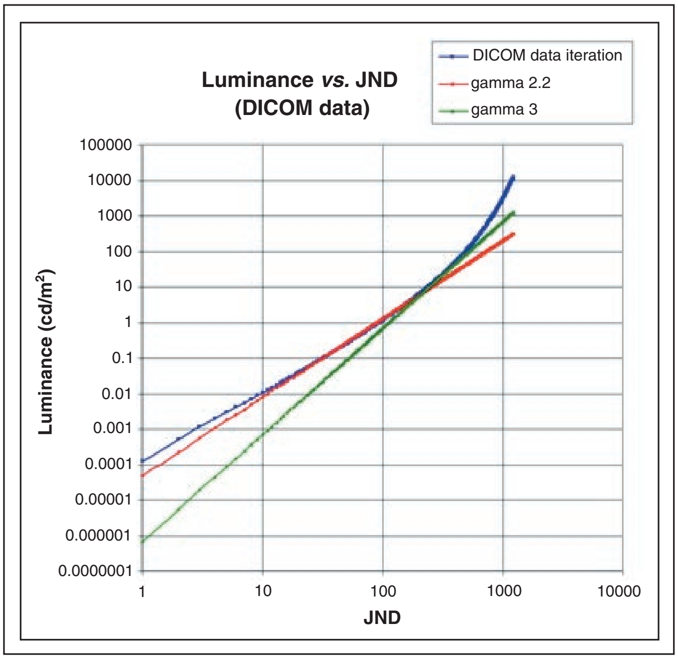


Fig. 7: *A log–log graph depicts the luminance vs. JND using the DICOM data iteration listed in Eq. (7). Also plotted are the gamma 2.3 and 3.0 power relationships that most closely fit the curve.*

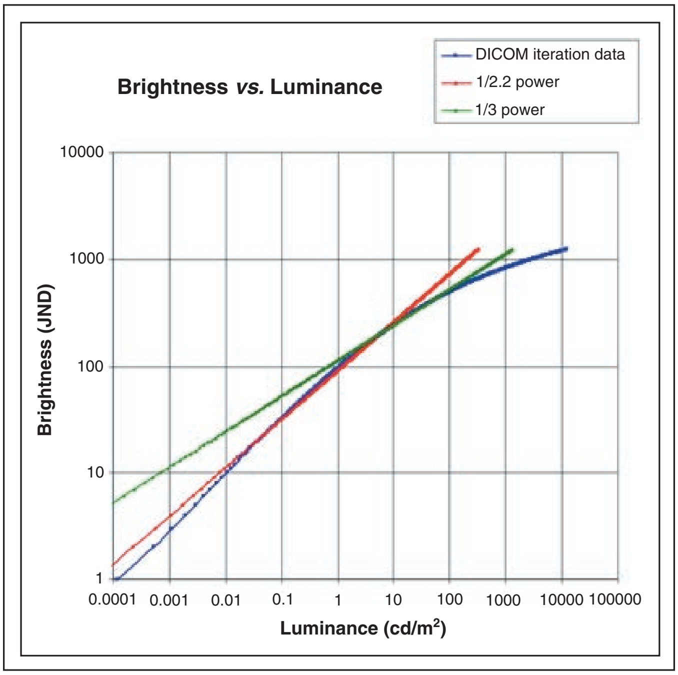


Fig. 8: *This log–log graph shows brightness vs. luminance using the DICOM iteration listed in Eq. (7). Also plotted are the 1/2.2 and 1/3 power relationships that most closely fit the curve.*

Simple power relationships will not reproduce the Weber fraction data, but the extended derived DICOM does reproduce the shape of the Weber fraction data. It should be okay to use for gamma in high-dynamic-range displays that are limited to a luminance of less than 800 cd/m^2 without too much divergence from what is indicated by the Weber fraction data and because of the difference in the spatial frequency at which the data was taken. The high luminance range, 800–10,000 cd/m^2, should be reinvestigated to determine the correct gamma correction.

The derived DICOM covers eight orders of luminance magnitude with about 1000 JNDs. It is unlikely that a display will be used to cover this luminance range because we are only able to view about four orders of luminance magnitude without adaptation. The derived DICOM will be useful for choosing the correct gray levels for the luminance range of today's displays and also for choosing the correct image scaling and compression. Dim images could be scaled up and bright images scaled down without compressing the high or low gray levels through an improper transformation. And, high-dynamic-range images could be compressed proportionally to eliminate shadows or bright spots.

Acknowledgment

I wish to acknowledge the efforts of Charles A. Poynton on behalf of championing the importance of gamma and displays. The motivation to write this article came from reading the article on gamma by Poynton[6] in SMPTE.

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small e-paper displays

Enabling Small-Format Electronic Paper in Smart Surfaces

A new, simplified approach to drive electronics could make electronic-paper displays viable for a wide range of smaller, less-expensive devices.

by Matthew Aprea

OVER THE PAST SEVERAL YEARS, e-paper displays have made their way into the marketplace in the form of e-books and e-readers such as the Sony Reader and the Amazon Kindle. These applications typically rely on active-matrix-display sizes of 6 in. (SVGA) or larger. Electronic-paper displays have been chosen for these applications for a variety of reasons, including low power consumption, paper-like appearance, high image contrast, daylight readability, and 180° viewing angle. Applications requiring smaller active-matrix-display sizes could benefit from these same features; however, the drive electronics typically used to implement e-paper-display systems are more complex and have more features than are necessary or practical for these types of hand-held portable devices. An alternative approach is necessary for small-area displays, one that reduces the complexity necessitated by large-area displays.

A typical e-book or e-reader implementation consists of a host controller that interfaces with a display controller, which handles voltage-bias circuitry and display-driver supply rails, and generates the appropriate timing and data format to drive the display (Fig. 1). Host controllers that have been used in these types of products include application processors such as the Marvel PXA series, the Freescale I.MX series, and the Texas Instruments OMAP series. These host controllers interface with Epson's Broadsheet e-paper-

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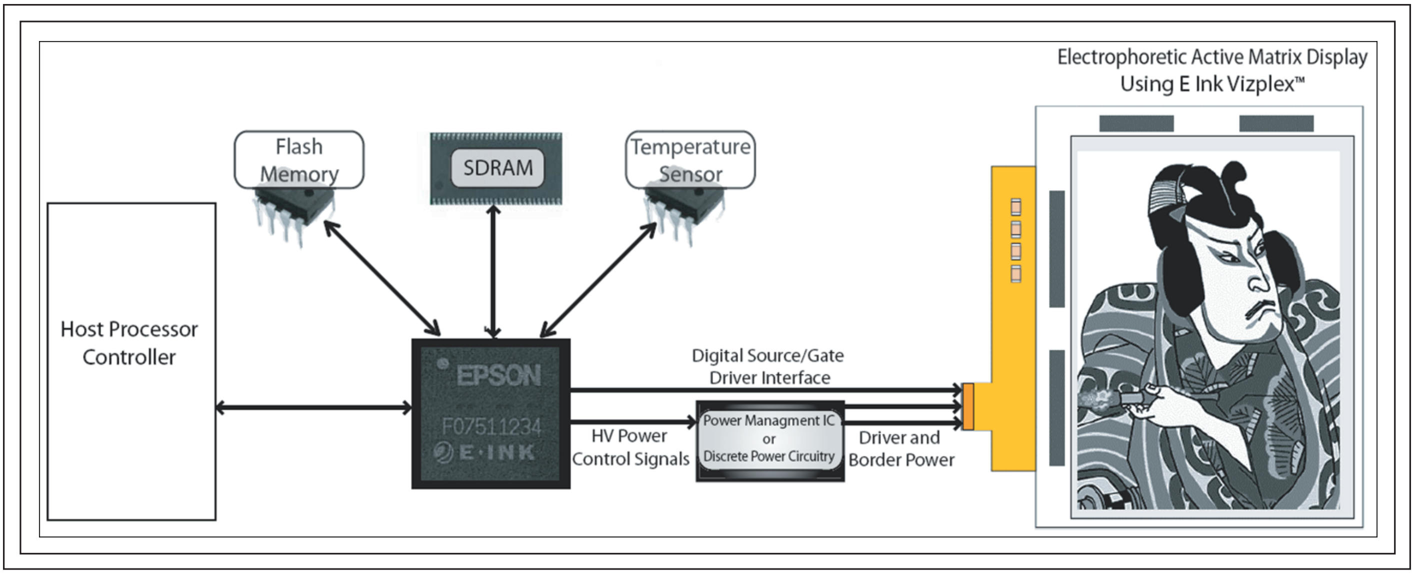

***Fig. 1:** This block diagram shows a typical driver/controller configuration for an e-book application.*

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display controller, designed in partnership with E Ink Corp. (There are other proprietary display controllers on the market, developed for specific device/applications and typically unavailable for general consumption.)

Smaller Solutions

For high-volume portable applications that require a smaller display size (up to QVGA), such as active-matrix smart cards, laptop-computer touchpads, or even hand-held or bicycle-mounted GPS receivers, a separate application processor and display controller is neither necessary nor desired. A new method to drive a small e-paper display would therefore fill a market need.

An approach has been developed that would enable manufacturers to create smaller e-paper displays through leveraging the prevalence of simple ARM-based microcontrollers [previously known as Advanced RISC Machine (ARM), a 32-bit RISC instruction-set architecture developed by ARM Ltd.], which offer a significant advantage in terms of cost over the previously described architecture. This new approach is to use widely available high-volume components that meet the speed, I/O, and power requirements for an e-paper-display-based device. The basic methodology is to drive the source and gate signals directly from the general-purpose I/O on a low-cost processor, thereby eliminating the application processor and display controller chips from the system. A block diagram for this system, which E Ink has named Fiche (after the microfiche technology of yore) is shown in Fig. 2.

This new architecture must be capable of scanning an active-matrix backplane in one pass in under 260 msec, which is the black-to-white monochrome update speed of the e-paper-display material. Scanning an active-matrix backplane requires the controller to shift source data into the source driver for each display column, then pulse the gate line to latch the output of the source driver to the TFT backplane's storage capacitor. This sequence must then be repeated for each display column. For gray-scale resolution, the scan speed must be faster. Gray levels are achieved only when scanning for a fraction of the 260 msec required for full monochrome updates (Fig. 3).

Furthermore, the new design must maintain an image buffer that has at least one bit per pixel representing the current state of the pixel; another bit representing the next state of the pixel is desired for convenience but not actually necessary.

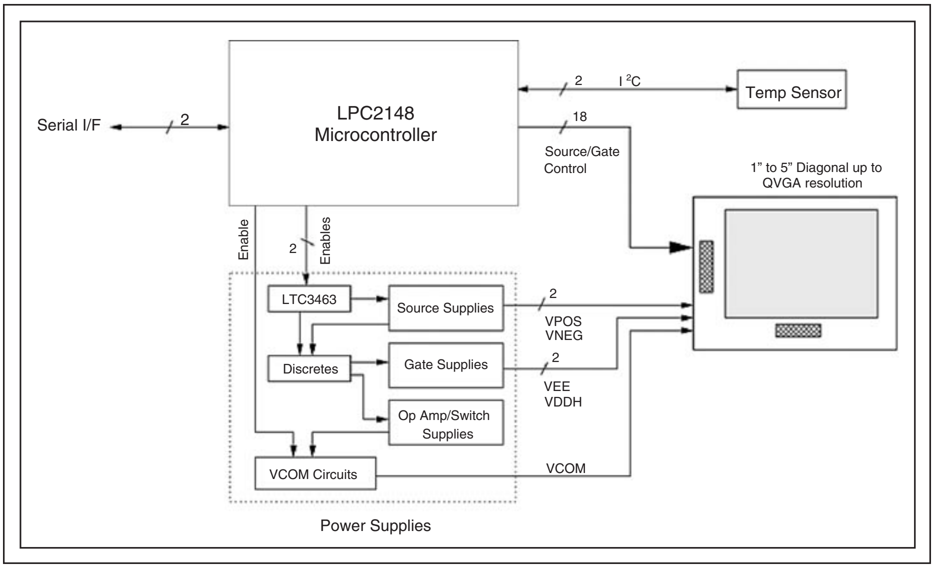

Fig. 2: *The Fiche implementation uses a microcontroller to drive the e-paper display.*

For gray scales, at least two bits are necessary – yielding four gray levels. There are many ways to implement this in software, the

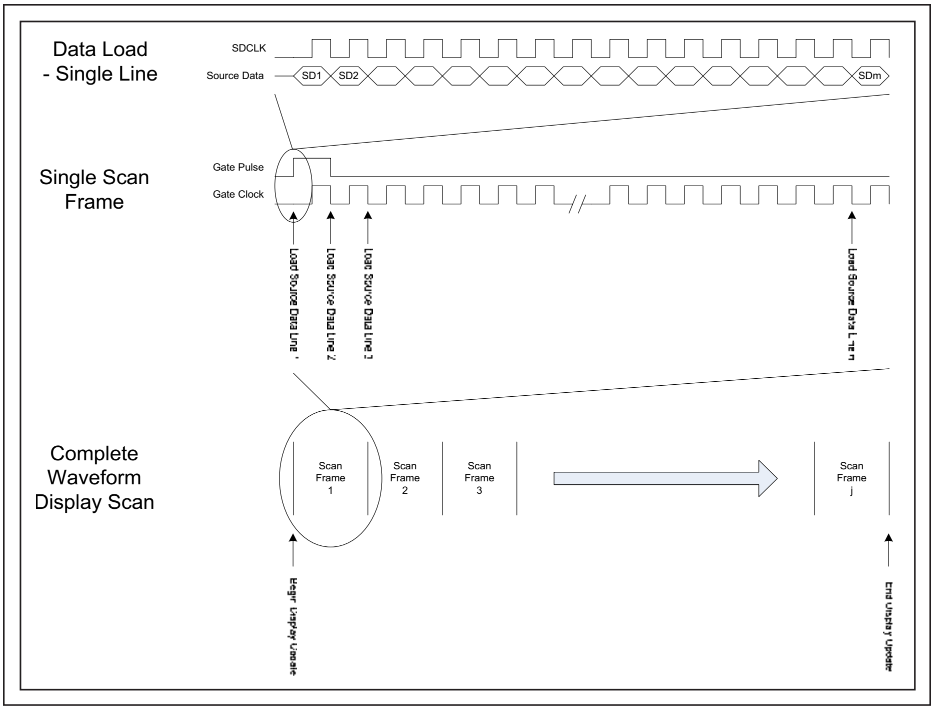

Fig. 3: *Shown is a block diagram of the e-paper-display scan timing. For each line, data for m number of display rows must be loaded. A gate clock must then be provided for each of n number of display lines which define a single scan frame. The process must be repeated for j number of scan frames to achieve the desired optical appearance.*

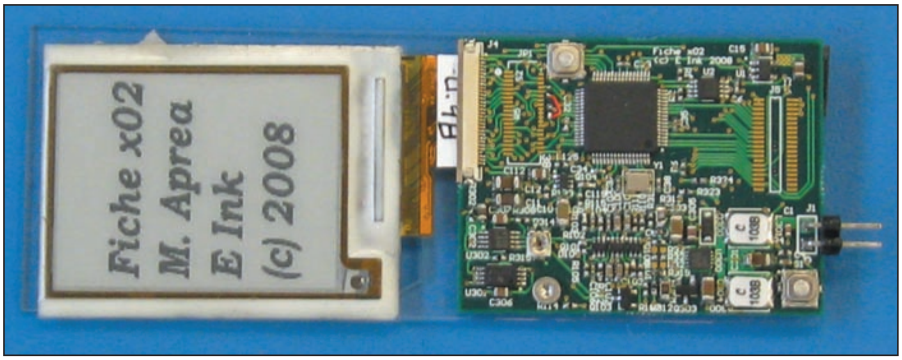

Fig. 4: *In a prototype, a 1.9-in.-active-area-diagonal display appears on the left. The large IC shown on the top is an NXP LPC2148 ARM7 processor. Much of the circuitry on the bottom half of the board generates display supply and bias voltages. The board is the same size as the display, measuring roughly 2 x 1.5 in., so that the board can be folded beneath the display for compactness.*

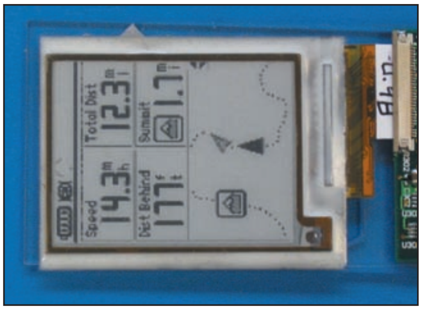

Fig. 5: *This Fiche gray-scale image depicts a potential application for a hand-held or bicycle-mounted GPS unit.*

most straightforward of which is to set aside enough RAM to store the entire image buffer, including the current and next states.

Tradeoffs for this type of design include speed *vs.* power and cost, and memory *vs.* cost. A faster device is capable of driving larger display sizes or greater gray-scale depth on a smaller display. More memory can support larger display sizes and more full-featured applications (Figs. 4 and 5).

Further Refinements

Pulse-width-modulated (PWM) power control from the microcontroller. For simplicity of design, the bias voltages and display supply voltages in the Fiche controller shown in Fig. 4 are generated using a tried-and-true architecture that consists of a switching-voltage regulator to generate the core drive voltages, with discrete charge-pump circuitry to generate additional necessary voltages. An alternative cost-cutting approach is to do away with the voltage regulator chip and generate the core voltages using discrete components, pulse-width modulated (PWM) outputs, and analog-to-digital conversion (A/D) inputs available on many microcontrollers. The PWM outputs can be used to control a field-effect-transistor (FET) switch in a boost regulator design, where the A/D inputs are used to monitor the feedback voltage and modulate the PWM duty cycle to keep the generated voltage within spec, as shown in Fig. 6.

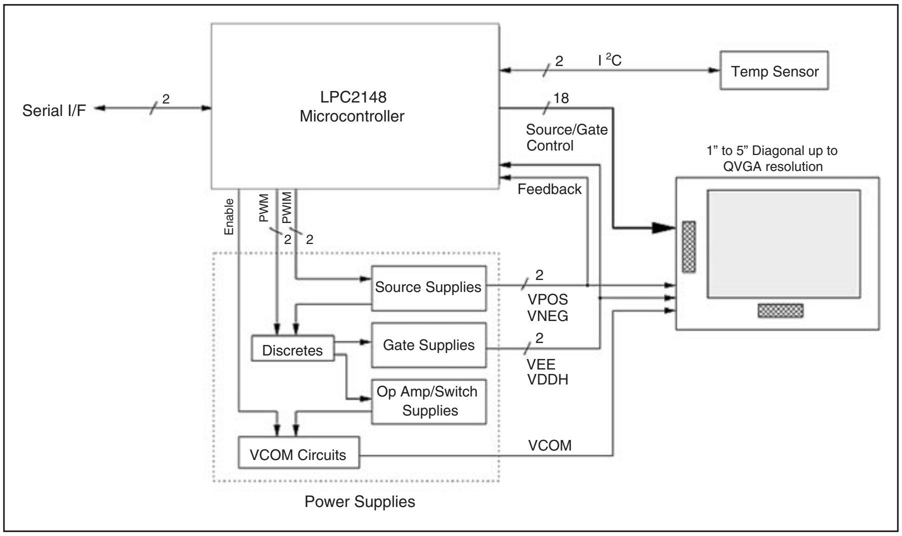

Fig. 6: *This block diagram shows PWM outputs leading from the microcontroller.*

Power-management IC. In the coming years, many of the mainstream e-books and e-readers may begin to use an integrated approach to power management. Soon, a single IC along with a handful of discrete components may be able to replace the many ICs and discrete components now needed to generate the bias and supply voltages necessary to control an e-paper display. For size, simplicity, and cost reasons, this approach may appeal to applications developers. A single IC with a small number of discrete passive components may reduce the area needed for this circuitry, decrease the component count by two-thirds, and potentially decrease the cost by half.

Future Applications

Small-sized e-paper displays with controllers of this nature could be very useful in many mainstream applications for which displays are currently not used. Such applications include the following:

- ***Dynamic Touchpads.*** Laptop-computer touchpads could include an updatable display that could be configured based on the application that is in use. For instance, the scroll-bar touch areas typically on the right side and bottom of the touchpad can be shown on the display. When the user switches applications to something such as a calculator, a keypad can be displayed.
- ***Electronic Shelf Labels.*** Retail shelf labels that can be wirelessly updated to

(continued on page 31)

Journal of the SOCIETY FOR INFORMATION DISPLAY

The following papers appear in the July 2009 (Vol. 17/7) issue of *JSID*.
For a preview of the papers go to sid.org/jsid.html.

Review Paper: **Emerging vertical-alignment liquid-crystal technology associated with surface modification using UV-curable monomer** **(pages 551–559)**
Seung Hee Lee and Sung Min Kim, Chonbuk National University, Korea; Shin-Tson Wu, University of Central Florida, USA

Switchable transmissive and reflective liquid-crystal display using a multi-domain vertical alignment **(pages 561–566)**
Zhibing Ge, et al., University of Central Florida, USA; Wang-Yang Li and Chung-Kuang Wei, Chi-Mei Optoelectronics Corp., Taiwan, ROC

Moving-picture response time (MPRT) of LCDs for the oblique viewing direction **(pages 567–572)**
HyungKi Hong, et al., LG Display, R&D Center, Korea

Fast current programming method for OLEDs using negative capacitor circuit **(pages 573–579)**
Chang-Hoon Shim and Reiji Hattori, Kyushu University, Japan

Image improvement in a laser projection display with a spatial light modulator with a deformable polymer **(pages 581–587)**
Vladimir Kartashov, et al., poLight AS, Norway; Benny Svardal, Cyviz AS, Norway; Tore Svortdal, Setred AS, Norway; Richard Berglind and Gunnar Hedin, Proximion Fiber Systems AB, Sweden

Laser display with single-mirror MEMS scanner **(pages 591–595)**
Peter Schreiber, et al., Fraunhofer Institute for Applied Optics and Precision Mechanics, Germany; Michael Scholles, Fraunhofer Institute for Photonic Materials, Germany

Microdisplay-based industrial 3-D and microstructure measurement systems **(pages 597–602)**
Stefan Riehemann, et al., Fraunhofer Institute for Applied Optics and Precision Mechanics, Germany

Design of a compact projection display for the visualization of 3-D images using polarization-sensitive eyeglasses **(pages 603–609)**
Lawrence Bogaert, et al., Vrije Universiteit, Belgium; Herbert De Smet, Universiteit Gent, Belgium, and IMEC vzw, Belgium

Towards a generic OLED lifetime model **(pages 611–616)**
Alastair R. Buckley, University of Sheffield, Scotland; Chris J. Yates and Ian Underwood, University of Scotland, Scotland

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An Appeal for More Bit Depth in Displays

Technological advances in imaging and content production may render the current standard of 256 gray levels per color in most modern displays inadequate.

by Walter Allen

IN the January 2008 issue of *Information Display* magazine, Aris Silzars authored a thoughtful column on "Technology Asymptotes." At the end of the piece, he suggested that we may have reached the "good enough" point for home-entertainment displays with the current HDTV standard of 1920 × 1080 pixels at 256 levels per color. While I agree that there is little motivation at present to extend that resolution level (even 1280 × 720 pixels is adequate for most home applications), 256 levels per color (8 bits) may not be fine enough as displays and sources evolve and extend their contrast ranges.

Just how good is the 8-bit system? As evidenced by acceptance from the great majority of today's consumers, it appears to be good enough for present-day displays. But on many of these displays the steps between the lower individual discrete levels can be readily detected, and this can manifest itself as posterization in the imagery. Making matters worse, of the 256 levels currently available, in many cases, such as for DVDs, only 220 levels (16–235) are normally used, with the remainder serving as headroom. Thus, while 8 bits may be good enough for today, it is hovering near the "just good enough" end of the range, and new technology on the horizon may push it into the "not good enough" category. These new technological advances are leading to higher-contrast displays and the accompanying ability to display significantly more levels of luminance and color gamut. The big question then becomes how many of the great majority of users will appreciate and demand those additional shades – enough to increase the standard beyond the 8-bit level?

For a little background into the need for range in luminance and contrast, let's travel back to the time when I first became seriously interested in 35mm SLR photography. Initially, life in this image capture and display world seemed so good. I had the tools to compose a picture just the way I wanted, perfectly framed and exposed, and could select the film best suited for a particular photo session. When making an enlargement, I could further refine the process by dodging selected areas to enhance the exposure. But, even then, all too often it seemed there were times that I came upon awe-inspiring sights – spectacular sunsets or sunrises, scenes by a babbling brook in the forest, gorgeous shots at the beach, glorious fireworks, or a winter wonderland – when my camera would fail me. I would take a series of shots, carefully bracketing exposures and precisely composing the images, thinking about the incredible sights I was recording for posterity. After processing the film and viewing the results, either slides or prints or enlargements, the results were all too often a letdown – the impact and depth of the original scene would clearly be missing. The pictures would be good, maybe even very good, but would invariably fail to reproduce the drama of the original moment.

What was the most important ingredient missing from those reproductions? It turned out to be a restricted range of luminance levels and the related overall lack of contrast. The human visual system has evolved to a highly refined and truly amazing dynamic sense. We can perceive an incredible range of luminance levels, from seeing by starlight to viewing clouds backlighted by the sun. The range is well in excess of 1,000,000,000:1! Now, of course, there are caveats – all the range is not available at once, as the eye has adaptive behavior that needs time to be enabled, and within smaller areas of a scene we can discern luminance differences of only about 1%, and anything dimmer than about 1% of an adjacent bright area is seen as black. But the eye can easily detect luminance variations of well over 10,000:1 in non-adjacent areas of larger images.

When I would look at the prints (or slides) that were intended to recreate those original,

If you are interested in exploring a little further using your PC monitor as your display, I invite you to visit **www.walvisions.com/TestPatterns**. There you can select a variety of patterns that will simply display as web pages. The patterns are mostly done in 8-bit color, and there are several related to the above discussion, such as WV-41 (64 Lowest Steps, Vertical Gray Steps), WV-48B (Video Level Arc, 16-48 Levels), and WV-48C (Video Level Arc, 8-Bit Step Differences).

***Walter Allen** is the Principal of WalVisions and works and consults on video projection systems and special video-processing projects. He can be reached at walter@walvisions.com.*

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opinion

awe-inspiring sights, I would be looking at a medium that was probably delivering less than 100:1 in contrast, and certainly well less than 1000:1. Also, in both the brighter areas and the darker areas of the image, the variations in luminance would be compressed and thus appear flat and lack depth. No wonder I was disappointed. The problem could be found in both the capture and display media – not enough luminance range can be captured in a single film exposure, and even if it could be, a conventional print, relying on the absorption of incident light, still could not display the necessary range.

Now let's return to the present, in which the situation is changing. In the world of photography, not only are sensors evolving to capture a greater luminance range, but a bracketed series of captured images can be further combined to create very-high-contrast source material. If we look to computer-generated images, there is virtually no limit to the potential "luminance" range of the content. On the display side, high-contrast-capable displays are showing up on many fronts. We have high-contrast plasma displays, LCDs backlit with arrays of controllable LEDs, LCOS projectors, DLP projectors with outstanding black levels, and the promise of OLED displays. All these displays can render wide contrast ratios and are capable of very-wide dynamic ranges, but in most cases either the display device or the content is limited to 8 bits per color. If more granularity of the luminance levels was provided, with added bits/luminance levels, the images can be significantly enhanced with additional realism and depth. Viewing such displays with current standard (8-bit) programming all too often results not only in posterization, but also in significant areas of the image appearing as completely black, without the "shadow detail" that would have been present in the original scene. As these displays make their way into the mainstream, the source limitations of only 8 bits per color will become more apparent, and just maybe will no longer be considered "good enough." At that point, users may clamor for a little bit (or two or ?) more.

The road to increased bit depth in displays is being paved by developments such as Deep Color in HDMI 1.3, by the Digital Cinema Initiatives, by PC graphics systems, and by capable digital cameras and image-processing software. While the road has potholes here and there, such as the 8-bit constraints of MPEG2 in DVDs and HD, not to mention the fact that most mainstream viewers do not currently perceive a problem with a lack of levels, I hope and expect that this new road to expanded luminance range and depth will be well-traveled in the coming years. Then I, and the overwhelming majority, can look forward to seeing dramatic sunsets and fireworks on our home displays. ■

small e-paper displays

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reflect the most recent prices, or sale prices, as well as a slideshow that provides additional product information such as country/state of origin and product facts. (Such labels are now in use, but not on a widespread basis.)

- ***Portable Hard Drives.*** Electronic-paper displays can be used to display static images that indicate disk status such as bytes available, bytes free, bytes used, folders, and files.
- ***Dynamic Keypad.*** Similar to the previously noted touchpad, but rather for use with a cell phone.
- ***Active-Matrix Smart Card.*** Smart cards for use as a credit card, debit card, train pass, loyalty rewards program, or hotel room key. This card can display a variety of information other than just a passcode. This technology is also useful for displaying icons or the intricate characters in some languages.
- ***Other.*** The Fiche controller and small-area displays can also be used to replace similarly sized LCDs in applications where a premium is placed on ruggedness, readability, and/or low power consumption such as GPS/outdoor fitness devices, cell-phone secondary displays, home thermostats, personal-health meters, and home appliances.

The benefits (low power consumption, paper-like appearance, daylight readability, *etc.*) of using an e-paper display apply to products using a small-area display as much as they do to those that use large-area displays. The Fiche controller can be an effective solution for many high-volume portable-display applications such as those listed above and for many not yet conceived. Readily available components and a simple display update algorithm are all that are needed to integrate an e-paper display into a product for an eye-catching but still cost-effective display solution.

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http://www.epson.com ■

SOCIETY FOR INFORMATION DISPLAY NEWS

SID 2010 honors and awards nominations

On behalf of the SID Honors and Awards Committee (H&AC), I am appealing for your active participation in the nomination of deserving individuals for the various SID honors and awards. The SID Board of Directors, based on recommendations made by the H&AC, grants all the awards. These awards include five major prizes awarded to individuals, not necessarily members of SID, based upon their outstanding achievements. The **Karl Ferdinand Braun prize** is awarded for ***"Outstanding Technical Achievement in, or contribution to, Display Technology."*** The prize is named in honor of the German physicist and Nobel Laureate Karl Ferdinand Braun who, in 1897, invented the cathode-rat tube (CRT). Scientific and technical achievements that cover either a wide range of display technologies or the fundamental principles of a specific technology are the prime reasons for awarding this prize to a nominee. The **Jan Rajchman prize** is awarded for ***"Outstanding Scientific and Technical Achievement or Research in the Field of Flat-Panel Displays."*** This prize is specifically dedicated to those individuals who have made major contributions to one of the flat-panel-display technologies or, through their research activities, have advanced the state of understanding of one of those technologies. The **Otto Schade prize** is awarded for ***"Outstanding Scientific or Technical Achievement in the Advancement of Functional Performance and/or Image Quality of Information Displays."*** This prize is named in honor of the pioneering RCA engineer Otto Schade, who invented the concept of the Modulation Transfer Function (MTF) and who used it to characterize the entire display system, including the human observer. The advancement for this prize may be achieved in any display technology or display system or may be of a more general or theoretical nature. The scope of eligible advancement is broadly envisioned to encompass the areas of display systems, display electronics, applied vision and display human factors, image processing, and display metrology. The nature of eligible advancements is not limited and may be in the form of theoretical or mathematical models, algorithms, software, hardware, or innovative methods of display-performance measurement, and image-quality characterization. Each of these above-mentioned prizes carries a $2000

SID honors and awards nominations

Nominations are now being solicited from SID members for candidates who qualify for SID Honors and Awards.

- KARL FERDINAND BRAUN PRIZE. Awarded for an outstanding *technical* achievement in, or contribution to, display technology.
- JAN RAJCHMAN PRIZE. Awarded for an outstanding *scientific* or *technical* achievement in, or contribution to, research on flat-panel displays.
- OTTO SCHADE PRIZE. Awarded for an outstanding *scientific* or *technical* achievement in, or contribution to, the advancement of functional performance and/or image quality of information displays.
- SLOTTOW–OWAKI PRIZE. Awarded for outstanding contributions to the education and training of students and professionals in the field of information display.
- LEWIS & BEATRICE WINNER AWARD. Awarded for exceptional and sustained service to SID.
- FELLOW. The membership grade of Fellow is one of unusual professional distinction and is conferred annually upon a SID member of outstanding qualifications and experience as a scientist or engineer in the field of information display who has made widely recognized and significant contribution to the advancement of the display field.
- SPECIAL RECOGNITION AWARDS. Presented to members of the technical, scientific, and business community (not necessarily SID members) for distinguished and valued contributions to the information-display field. These awards may be made for contributions in one or more of the following categories: (a) outstanding technical accomplishments; (b) outstanding contributions to the literature; (c) outstanding service to the Society; (d) outstanding entrepreneurial accomplishments; and (e) outstanding achievements in education.

Nominations for SID Honors and Awards must include the following information, preferably in the order given below. Nomination Templates and Samples are provided at *www.sid.org/awards/nomination.html.*

1. Name, Present Occupation, Business and Home Address, Phone and Fax Numbers, and SID Grade (Member or Fellow) of Nominee.

2. Award being recommended:
    Jan Rajchman Prize
    Karl Ferdinand Braun Prize
    Otto Schade Prize
    Slottow–Owaki Prize
    Lewis & Beatrice Winner Award
    Fellow*
    Special Recognition Award

*Nominations for election to the Grade of Fellow must be supported in writing by at least five SID members.

3. Proposed Citation. This should not exceed 30 words.

4. Name, Address, Telephone Number, and SID Membership Grade of Nominator.

5. Education and Professional History of Candidate. Include college and/or university degrees, positions and responsibilities of each professional employment.

6. Professional Awards and Other Professional Society Affiliations and Grades of Membership.

7. Specific statement by the nominator concerning the most significant achievement or achievements or outstanding technical leadership that qualifies the candidate for the award. This is the most important consideration for the Honors and Awards committee, and it should be specific (citing references when necessary) and concise.

8. Supportive material. Cite evidence of technical achievements and creativity, such as patents and publications, or other evidence of success and peer recognition. Cite material that specifically supports the citation and statement in (7) above. (Note: the nominee may be asked by the nominator to supply information for his candidacy where this may be useful to establish or complete the list of qualifications).

9. Endorsements. Fellow nominations must be supported by the endorsements indicated in (2) above. Supportive letters of endorser will strengthen the nominations for any award.

E-mail the complete nomination – including all the above material by **October 9, 2009** –
to cnelsonk@comcast.net or sidawards@sid.org or by regular mail to:
Christopher N. King, Honors and Awards Chairman, Society for Information Display,
1475 S. Bascom Ave., Ste. 114, Campbell, CA 95008, U.S.A.

stipend sponsored by Thompson, Inc., Sharp Corporation, and Philips Consumer Electronics, respectively.

The **Slottow–Owaki prize** is awarded for ***"Outstanding Contributions to the Education and Training of Students and Professionals in the Field of Information Display."*** This prize is named in honor of Professor H. Gene Slottow, University of Illinois, an inventor of the plasma display and Professor Kenichi Owaki from the Hiroshima Institute of Technology and an early leader of the pioneering Fujitsu Plasma Display program. The oustanding education and training contributions recognized by this prize is not limited to those of a professor in a formal university, but may also include training given by researchers, engineers, and managers in industry who have done an outstanding job developing information-display professionals. The Slottow–Owaki prize carries a $2000 stipend made possible by a generous gift from Fujitsu, Ltd., and Professor Tsutae Shinoda.

The fifth major SID award, the **Lewis and Beatrice Winner Award,** is awarded for ***"Exceptional and Sustained Service to the Society."*** This award is granted exclusively to those who have worked hard over many years to further the goals of the Society.

The membership grade of **SID Fellow Award** is one of unusual professional distinction. Each year the SID Board of Directors elects a limited number (up to 0.1% of the membership in that year) of **SID members** in good standing to the grade of **Fellow.** To be eligible, candidates must have been members at the time of nomination for at least 5 years, with the last 3 years consecutive. A candidate for election to Fellow is a member with ***"Outstanding Qualifications and Experience as a Scientist or Engineer in the Field of Information Display who has made Widely Recognized and Significant Contributions to the Advancement of the Display Field"*** over a sustained period of time. SID members practicing in the field recognize the nominee's work as providing significant technical contributors to knowledge in their area(s) of expertise. For this reason, five endorsements from SID members are required to accompany each Fellow nomination. Each Fellow nomination is evaluated by the H&AC, based on a weighted set of five criteria. These criteria and their assigned weights are creativity and patents, 30%; technical accomplishments and publications, 30%; technical leadership, 20%; service to SID, 15%; and other accomplishments, 5%. When submitting a Fellow award nomination, please keep these criteria with their weights in mind.

The **Special Recognition Award** is given annually to a number of individuals (membership in the SID is not required) of the scientific and business community for distinguished and valued contribution in the information-display field. These awards are given for contributions in one or more of the following categories: (a) ***Outstanding Technical Accomplishments,*** (b) ***Outstanding Contributions to the Literature,*** (c) ***Outstanding Service to the Society,*** (d) ***Outstanding Entrepreneurial Accomplishments,*** and (e) ***Outstanding Achievements in Education.*** When evaluating the Special Recognition Award nominations, the H&AC uses a five-level rating scale in each of the above-listed five categories, and these categories have equal weight. Nominators should indicate the category in which a Special Recognition Award nomination is to be considered by the H&AC. More than one category may be indicated. The nomination should, of course, stress accomplishments in the category or categories selected by the nominator.

While an individual nominated for an award or election to Fellow may not submit his/her own nomination, nominators may, if necessary, ask a nominee for information that will be useful in preparing the nomination. The nomination process is relatively simple, but requires that the nominator and perhaps some colleagues devote a little time to preparation of the supporting material that the H&AC needs in order to evaluate each nomination for its merit. It is not necessary to submit a complete publication record with a nomination. Just list the titles of the most significant half a dozen or less papers and patents authored by the nominee, and list the total number of papers and patents he/she has authored.

Determination of the winners for SID honors and awards is a highly selective process. Last year less than 30% of the nominations were selected to receive awards. Some of the major prizes are not awarded every year due to the lack of sufficiently qualified nominees or, in some cases, because no nominations were submitted. On the other hand, once a nomination is submitted, it will stay active for three consecutive years and will be considered three times by the H&AC. The nominator of such a nomination may improve the chances of the nomination by submitting additional material for the second or third year that it is considered, but such changes are not required.

Descriptions of each award and the lists of previous award winners can be found at *www.sid.org/awards/indawards.html*. Nomination forms are available at *www.sid.org/awards/nomination.html* where you will find Nomination Templates in both MS Word (preferred) and Text formats. Please use the links to find the Sample Nominations, which are useful for composing your nomination since these are the actual successful nominations for some previous SID awards. Nominations should preferably be submitted by e-mail. However, you can also submit nominations by ordinary mail if necessary.

Please note that with each Fellow nomination, only five written endorsements by five SID members are required. These brief endorsements – *a minimum of 2–3 sentences* to a maximum of one-half page in length – *must state why clearly and succinctly, in the opinion of the endorser, the nominee deserves to be elected to a Fellow of the Society. Identical endorsements by two or more endorsers will be automatically rejected* (no form letters, please). Please send these endorsements to me either by e-mail (preferred) or by hardcopy to the address stated in the accompanying text box. Only the Fellow nominations are required to have these endorsements. However, I encourage you to submit at least a few endorsements for all nominations since they will frequently add further support to your nomination.

All 2010 award nominations are to be submitted by October 9, 2009. E-mail your nominations directly to cnelsonk@comcast.net or sidawards@sid.org. If that is not possible, then please send your hardcopy nomination by regular mail.

As I state each year: "In our professional lives, there are few greater rewards than recognition by our peers. For an individual in the field of displays, an award or prize from the SID, which represents her or his peers worldwide, is a most significant, happy, and satisfying experience. In addition, the overall reputation of the society depends on the individuals who are in its 'Hall of Fame.'

When you nominate someone for an award or prize, you are bringing happiness to an individual and his or her family and friends, and you are also benefiting the society as a whole."

Thank you for your nomination in advance.

– Christopher N. King
SID Honors & Awards Committee

In Memory of Ronald E. Warden

The avionics and display community will miss the smile and positive attitude of Ron Warden of St. Peters, Missouri, who died at the age of 59 on May 9, 2009. Warden worked in engineering at Boeing for 25 years and was named an Associate Technical Fellow in 2005. He was a member of the Society for Information Display and active in SID as a committee member in Applications, and also as an observer in the ICDM-3D subcommittee. He had been scheduled to serve as subcommittee co-chair for LED backlights at Display Week in San Antonio in June 2009.

"He was a professional and a great friend," says Adi Abileah, Chief Scientist with Planar Systems. "Some of us knew Ron from the time that we worked together at OIS–Optical Imaging Systems in Michigan. In the last 12 years, Ron was the display guru at Boeing in St. Louis and was involved in many projects in the avionics standard group, and more."

You can visit the guest book at *http://obit.baue.com/obitdisplay.html?id=669806&listing=Current* to view inputs from the display community.

SID Organic Electronics UK 2009 Takes Place in London in September

by Alasdair J. Campbell, Imperial College London

The 2009 SID Organic Electronics UK Conference will be held at Imperial College London on September 28 and 29, 2009. This annual meeting is the only one dedicated to organic electronics in the UK. It covers all aspects of this area, including OLEDs, OTFTs, polymers, and small molecules; display electronics; oxides for electrodes and TFTs; OPVs for power generation; device modeling, printing, and fabrication methods.

Last year's conference, which was organized by the UK & Ireland Chapter of the SID, featured a number of invited and submitted papers, as well as the following highlights:

The plenary address, "Organic non-volatile memories," was given by Professor Dago de Leeuw from Philips, Eindhoven. De Leeuw headed Philips's OTFT research and development program from the early 1990s. He discussed Philips's breakthrough in the area of non-transistor/non-MIS capacitor-based memory. These simple bistable devices consist of a metal contact, an oxide layer (e.g., aluminium oxide), an organic semiconductor layer (e.g., a standard light-emitting polymer), and a top metal contact. They work by resistive switching – the application of high- and low-voltage pulses turning the device between high and low conducting states. The organic layer acts as a series resistance allowing soft breakdown of the oxide layer. These resistive-switching organic memory devices can store data for many months and open up a new area of organic semiconductor technology.

Merck offered a £500 prize for the Best Student Poster presented at the meeting. The posters were of a very high quality and the judges found it difficult to determine the winner. It was finally decided to split the prize between Ms. Rupa Das for "A plastic-substrate-based ITO-free multilayer polymer photodiode fabricated using stamp transfer printing" and Mr. Paul Wöbkenberg for "High-mobility low-voltage oxide semiconductor transistors and circuits."

The Ben Sturgeon Award Lecture 2008 is offered annually by the UK & Ireland Chapter to an individual (or group) that has made a significant contribution to the development of displays. For his work on polymer and dendrimer OLEDs over a number of years, Professor Ifor Samuel from the University of St. Andrews received the award. The award was presented by the Chair of the UK & Ireland Chapter, Dr. Richard Harding. Samuel's lecture was titled "Using photophysical measurements to improve organic light-emitting materials and devices."

To find out more about the upcoming SID Organic Electronics UK conference, visit: *www.sid.org/chapters/uki/forthcoming_meetings.html*

New Senior Grade Members

The following SID members were granted Senior Member status on May 31, 2009:

- Hiroki Hamada
- Adrian Kitai
- Alaide Mammana
- George A. Melnik
- Gopalan Rajeswaran
- Stefan Riehemann
- Terry C. Schmidt
- Mike Weaver
- Andrew B. Watson

editorial

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are grateful to welcome him back, and for his extraordinary effort this year in producing these articles. (Be sure to read his guest editorial on the state of the industry.) In "3-D Displays in the Home," author Andrew Woods, a consultant and research engineer at Curtin University's Centre for Marine Science & Technology in Perth, Australia, takes us through an excellent survey of the various television display systems available to consumers today that are capable of showing 3-D content. He also provides an educated glimpse of what may be coming soon. I was surprised to learn that there are a lot more options available right now than I was aware of and that the new innovations could make a compelling experience for consumers quite soon. Meanwhile, author William Zou, chairman of the Society of Motion Picture and Television Engineers Task Force on 3-D to the Home, presents "An Overview for Developing End-to-End Standards for 3-D TV to the Home," which describes in amazing completeness the entire landscape of 3-D content creation and standards to date. Rather than trying to summarize it for you, I'll suggest you dive in and appreciate the unique perspective he brings to the subject. Together, these two articles make me really excited about the prospects for a truly compelling home 3-D experience and I declare once again that there has ***never*** been a more exciting time to be in the display business!

With that along with our regular Industry News on developments announced in and around the Display Week Conference last month, this issue is a wrap. While we do not yet have a way to bring the magazine to you in 3-D, I hope you find it a unique experience nonetheless. As always, we welcome your feedback and suggestions on these or any other topics related to displays. You can reach us by email at press@sid.org. ■

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guest editorial

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The primary bottleneck is delivery of a ready stream of high-quality stereoscopic content into the home. A number of organizations are working on the development of standards for the 3-D formats for mastering and distribution. A leader in this effort is the Society of Motion Picture and Television Engineers (SMPTE). The chairman of the SMPTE Task Force on 3-D to the Home, William Zou of DTS, Inc., has contributed an article entitled "An Overview for Developing End-to-End Standards for 3-D TV to the Home." The article provides a comprehensive snapshot of the current standards development effort under way at SMPTE, as well as at the Consumer Electronics Association (CEA), the Blu-ray Disc Association (BDA), the DVD Forum, ISO/IEC/MPEG, the Advanced Television Systems Committee (ATSC), and the Society of Cable Telecommunications Engineers (SCTE).

While it is clear that it will take time for consumer adoption of 3-D TVs to become widespread and for the finalization of appropriate standards to enable a seamless flow of stereoscopic content from the creators to the viewers, it is also clear that there is a high degree of interest on the part of content producers and display manufacturers to facilitate this process. Most likely, stereoscopic films distributed on Blu-ray Discs will serve as an initial beachhead for the large-scale penetration of 3-D content into the home. As Woods mentions in his article, in many cases manufacturers have included 3-D compatibility in their television sets for little added cost, and many consumers already own a 3-D-ready set. With the promise of an emerging Blu-ray standard, display manufacturers may increase the percentage of sets that are 3-D compatible. There may also be a useful synergy with 3-D gaming, with next-generation video game consoles supporting stereoscopic output, providing consumers an additional impetus to purchase a 3-D-ready TV. It seems like the deadlock has finally been broken and that 3-D TV in the home is only a matter of time. ■

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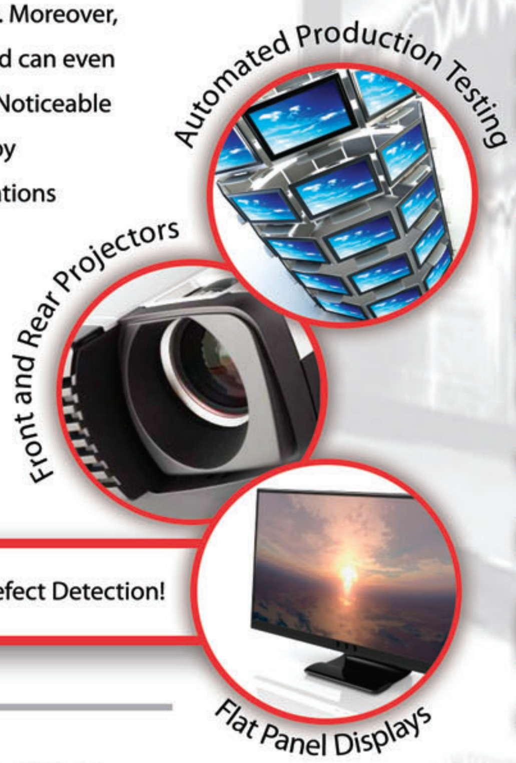
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212 ☐ Engineering Systems (Evaluation, OC, Stds.)
213 ☐ Basic Research
214 ☐ Manufacturing / Production
215 ☐ Purchasing / Procurement
216 ☐ Marketing / Sales
217 ☐ Advertising / Public Relations
218 ☐ Consulting
219 ☐ College or University Education
220 ☐ Other *(please be specific)*

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311 ☐ Electroluminescent Displays
312 ☐ Field-emission Displays
313 ☐ Liquid-crystal Displays & Modules
314 ☐ Plasma Display Panels
315 ☐ Displays (Other)
316 ☐ Display Components, Hardware, Subassemblies
317 ☐ Display Manufacturing Equipment, Materials, Services
318 ☐ Printing / Reproduction / Facsimile Equipment
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