DISPLAY WEEK PREVIEW / TOPICS IN APPLIED VISION

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Information DISPLAY

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Outstanding Achievements: SID's 2015 Honorees

UNCONVENTIONAL APPLICATIONS OF LIGHT-FIELD DISPLAYS

2015 CONSUMER ELECTRONICS SHOW REVIEW

OPPORTUNITIES AND CHALLENGES OF SOLID-STATE LIGHTING

DISPLAY WEEK 2015 PREVIEW

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MARCH/APRIL 2015
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ON THE COVER: *This year's winners of the Society for Information Display's Honors and Awards include* ***Dr. Junji Kido****, who will receive the Karl Ferdinand Braun Prize;* ***Dr. Shohei Naemura****, who will receive the Jan Rajchman Prize;* ***Dr. Ingrid Heynderickx****, who will be awarded the Otto Schade Prize;* ***Dr. Jin Jang****, who will be awarded the Slottow–Owaki Prize; and* ***Dr. Allan Kmetz****, who will receive the Lewis and Beatrice Winner Award.*

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In the Next Issue of *Information Display*

Display Week Show Issue and Automotive Displays

- 2014 Display Industry Awards
- Products on Display
- Automotive Overview
- Touch in Vehicle Displays
- *ID* Magazine Retrospective

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For Industry News, New Products, Current and Forthcoming Articles, see www.informationdisplay.org

editorial

The Pace of Innovation

by Stephen Atwood

It seems that everywhere I turn I hear or read something referring to the rapidly increasing "pace of innovation." Any reasonable person could look at the breadth of technology developed over the last few decades and compare that to a comparable period of time a couple of centuries ago and see the difference. It is not just in electronics but all fields of science, including agriculture, medicine, atmospheric studies, astronomy, geology, genetics, and on and on. In a *Wired* magazine essay (November 2013), Bill Gates said key innovations such as synthesizing ammonia and immunizing against polio are reasons why as much as 40% of our world's population is alive today.[1] Certainly among those 40% are some really good innovators themselves, helping to feed the growing trend with their own achievements.

A question we might pose is how to quantify this increasing pace and in so doing derive a model similar to Gordon Moore and his "Moore's Law" about the rate of increasing density of transistors in integrated circuits. Possibly, one could start with a similar premise that some arbitrary metric of human-science output could or would double every X years. Pick a field, pick a problem area, and start measuring.

In any attempt to model a system, you need to define the inputs and outputs in some rational way. The outputs are relatively easy to define and measure: better weather forecasts, lower mortality rates, cleaner air, improved quality of life, *etc*. In terms of inputs, innovation is fueled by the need to solve a problem, the human drive for creativity and achievement, and the availability of vital resources. Those resources almost always include money and time – both of which can be in short supply. But, as anyone at a high-tech company can tell you, the right innovation, properly monetized and nurtured, can become a veritable flood of additional income that can then be re-invested to solve all kinds of future problems.

Of course, true innovation can happen without regard to money but in many cases, and especially in our industry, money is a necessary input to the process and that money usually must come from the commercial success of ongoing efforts. In other words, we need our current ideas to make money so we can invest in the commercialization of our new ideas. Because of this reality, it would be great if we could apply some form of empirical model that would tell us which ideas will be commercially successful and which will not – so we could focus our resources on the best ideas first. But, clearly, history has shown that it is practically impossible to know in advance which ideas will lead to commercial success and which ones will not.

The challenge develops when people try to predict the future potential of ideas based on the framework they have in the present time. Without being able to "see" the future, we are stuck in a tug of war between our imaginations and our practical senses. Being practical means it is almost always easier to see what can go wrong, to understand how an idea can fail, and to say "no" when asked for support. It is harder to take risks (especially financial ones) by saying "yes" to new ideas. Consider the last hundred years of work on computer technology and all the incredibly creative milestones along the way. At almost every step there were decision makers rejecting the new ideas as either unreasonable or too unlikely to succeed based on what they knew at the time. This negative pressure slowed the pace of computer innovation, but did not stop the true believers who, when met with seemingly endless resistance, went their own way, found their own resources, and proved the conventional establishment wrong.

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industry news

700 Million Apple iPhones Sold to Date

Competitors and industry pundits have been saying for years that Apple's ascendancy is over, but to paraphrase Liberace, Apple is crying all the way to the bank. In March, Apple CEO Tim Cook announced that the company had sold more than 700 million iPhones since the launch of the product in 2007. In the fourth quarter of 2014 alone, according to Apple Insider, Apple sold nearly 75 million iPhone 6 and 6 Plus units, which works out to 34,000 iPhones every hour, 24 hours a day, every day of the quarter.[1] The iPhone 6 and 6 Plus were released in September 2014.

A recent article in *Money* noted that the fourth quarter of 2014 was the first time in 3 years that Apple's iPhones have been the best-selling smartphones in a given quarter. The breakthrough is largely the result of an Apple deal with China's largest mobile provider, China Mobile. Apple's sales in China increased 70% last quarter.[2]

Sales like these are obviously keeping iPhone suppliers happy. While Apple is close-mouthed regarding its supply chain, manufacturers such as LG, Japan Display, and Innolux are widely assumed to be among its display suppliers.[3] One supplier that did not reap the benefits of iPhone 6 sales is GT Advanced Technologies, which Apple, as reported earlier in *ID* magazine, had contracted with in November 2013 to build a new facility to produce sapphire, a scratch-resistant transparent material that can be used for mobile devices. But Apple's iPhone 6 and 6 Plus launched with non-sapphire screens and GT Advanced filed for bankruptcy in October 2014. A settlement agreement between GT Advanced and Apple was announced late in 2014.

The next mobile Apple device to launch will be the Apple Watch, scheduled for release on April 24. According to the feature list making the rounds of the technology press, the Apple Watch will have sapphire glass.

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[1] http://appleinsider.com/articles/15/03/09/apple-shipped-700-million-iphone-6-iphone-6-plus-units-since-launch

[2] http://money.cnn.com/2015/03/03/technology/mobile/apple-iphone-top-smartphone/

[3] http://bgr.com/2014/05/19/iphone-6-display-specs/

. . . All about Those Dots . . .

At CES last January, major TV manufacturers like Samsung and LG were showing LCD TVs enhanced with quantum dots for increased color saturation and gamut. Quantum-dot-enhanced TVs, writes *ID* contributor Ken Werner in his review of CES in this issue, are the 4K TVs of last year, meaning that 4K has become more commoditized, and quantum dots are the current high-priced differentiator for TVs. Certainly, 2015 is the year that QDs move from something a few people know about to something a lot of people know about.

"As is typically the case," says display industry analyst Paul Semenza, "the development of quantum dots was an instance of technology push, not market pull. However, once the materials became available, they came to be viewed by some as a way for LCD to improve its color performance relative to that of OLED."

A few quantum-dot facts and updates:

- Quantum dots, which are tiny nanocrystals, were discovered in the 1980s by Russian scientists Alexander Efros and Aleksey Ekimov, as well as by Louis Brus at Bell Labs.[4]
- Quantum dots are somewhat controversial from an environmental standpoint because many contain heavy metals such as cadmium. Even the extremely small size of cadmium dots (thousands of times smaller than the width of a human hair) makes them potentially more hazardous to humans than larger particles. However, in a typical display the quantum dots would be so encapsulated as to pose negligible risk to humans, according to a recent report from phys.org. Of greater concern are manufacturing safety and end-of-life issues.[5]
- Quantum-dot-maker QD Vision is addressing these concerns and received a Presidential Green Chemistry Challenge Award last year from the EPA for its use of quantum-dot technology in energy-efficient commercial display and lighting products. QD Vision's processes involve fewer hazardous building blocks and solvents, reduce solvent waste, and increase yields in such a way as to ensure a net positive environmental benefit. In addition, TVs using the company's quantum dots use substantially less power than non-QD counterparts.[5]
- Nanoco Technologies makes cadmium- and heavy-metal-free quantum dots. Last fall, the company entered into a partnership with Dow Chemical Company in which Dow was to manufacture quantum dots using technology licensed from Nanoco at a facility Dow was building in Korea. In January 2015, LG and Dow announced that LG would be using the Dow/Nanoco quantum dots to produce TVs.
- The Vermont-based company VerLase won a patent last year for quantum-well technology that it hopes will replace phosphors and quantum dots in multiple LED applications. Its Versulite G material incorporates wurtzite ZnCdSe quantum wells on 2-D layered semiconductor crystal. Product development is still in early stages.

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[4] http://en.wikipedia.org/wiki/Quantum_dot

[5] http://phys.org/news/2015-01-quantum-dot-tvs-toxic-ingredients.html

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guest editorial

Properly Controlling Light Is a Human-Factors Engineering Problem

by Jim Larimer

The idea that through every point in space rays of light are traveling, carrying information about the surfaces of objects the light has interacted with as it ricochets through space, is a concept as old as the camera obscura. Leonardo da Vinci referred to the light passing through a point in space as a "radiant pyramid."[1] It has only been possible recently to use the insights da Vinci had 500 years ago to build imaging products that can capture and replicate some of the information contained in these radiant pyramids. Today, we stand on the threshold of that possibility. Light-field imaging, or as it is also called, computational photography, is now the future for cameras and displays.

To effectively use these ancient insights requires an understanding of how optics, computing, and human vision work together. To create stereo-pair imagery that requires no head gear and that will work at any head orientation relative to the display requires two different images for each head position separated by 6 cm and containing information unique to each eye location. A light-field display holds the promise that this may soon be feasible.

It is even possible to imagine a future where every aspect of looking through an ordinary window, including focusing your eye anywhere that attracts your attention, can someday be replicated on a display. Several seemingly solvable technical hardware problems need to be worked out to do this. Equally important will be determining how many rays must pass through the observer's pupils from every point on the virtual objects for the rendered scene to seem real to the observer.

One of the articles in this issue of *Information Display*, by Gordon Wetzstein, delves into those insights and relates how this new and exciting technology will work. Compressive light-field ideas tap the advantage provided by the relatively long temporal integration time of the human eye compared to the speed of electrical devices.

Da Vinci was aware that if several pinholes are placed in the front surface of a camera obscura, several radiant pyramids will form images on the rear surface of the camera.[2] These images are slightly different from each other due to parallax, and they are not in register. As the number of pinholes is increased, the resulting projections lose the distinctive sharpness of the camera obscura image and tend towards blur.

The entrance aperture of a camera, and the pupils in our eyes, collect a connected set of pinholes, *i.e.*, a finite sample of the light field; without a lens the rays passing through the aperture would form a blurry image on the retina or on the projection surface of a camera. A larger aperture allows more light to reach the projection surface, making the resulting image brighter but also less sharp. With a lens placed in the plane of the aperture, objects in the visual scene that are at the focal distance of the lens are brought into register on the retina or projection surface. Objects that are nearer or farther away from this focal distance remain blurry in projection. The distances within which the edges formed in the image are sharp-appearing define the depth of field of the camera and lens. Lenses were discovered within a couple of hundred years of the camera obscura and were soon incorporated into these cameras to form a brighter image, trading off brightness for depth of field.

At the time of the discovery of the camera obscura and the lens, there was no way to exploit the sharpness and parallax information contained in each pinhole camera

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2015 SID Honors and Awards

This year's winners of the Society for Information Display's Honors and Awards include ***Junji Kido,*** *who will receive the Karl Ferdinand Braun Prize for his outstanding contributions to the science and technology of OLEDs and pioneering contributions to commercializing white OLEDs for general lighting applications;* ***Shohei Naemura,*** *who will be awarded the Jan Rajchman Prize for his outstanding achievements in the chemical physics of liquid crystals and contributions to research on LCDs;* ***Ingrid Heynderickx,*** *who will receive the Otto Schade Prize for her outstanding contributions to the measurement, specification, and improvement of the image quality of electronic-display technologies;* ***Jin Jang,*** *who will be awarded the Slottow–Owaki Award for his major contributions to display education and active-matrix-display development, including AMOLED displays, AMLCDs, and flexible displays; and* ***Allan R. Kmetz,*** *who will receive the Lewis and Beatrice Winner Award for his exceptional and sustained service to the Society for Information Display.*

by Jenny Donelan

ONCE AGAIN, the Society for Information Display honors those individuals who have made outstanding contributions to the field of displays, with awards in the category of Fellow and Special Recognition, as well as the Braun, Rajchman, Otto Schade, Slottow–Owaki, and Lewis and Beatrice Winner awards. Recipients are nominated by SID members and selected by a process involving the Honors and Awards Committee and SID's Board of Directors. Fan Luo, chairman of the awards committee, notes that it is always difficult to select the award winners because there are so many candidates who have made major contributions to the display industry. Therefore, this year's winners represent the best of the best.

A striking commonality among this year's award recipients is their willingness to pass along their knowledge and enthusiasm in order to perpetuate the display industry. Four of the five awardees are professors. Junji Kido from Yamagata University not only teaches graduate students, but works with junior-high and high-school students so they can gain hands-on experience with OLED devices. Ingrid Heynderickx found that a teaching environment permitted her to gain valuable insights from students. Jin Jang has advised 183 graduate students at Kyung Hee University, and the vast majority of these have moved on to work in the display industry not only in Korea, but all over the world. These are but three examples of how this year's award winners are nurturing the next generation of display professionals.

Another way to grow the display industry is to become involved in the Society for Information Display, and all of this year's winners have engaged in SID activities over the years. As a young researcher, Shohei Naemura helped promote his career by presenting at SID's technical symposium. As he matured and became more successful, he "paid back" SID through volunteer activities. Lewis and Beatrice Winner award recipient Allan Kmetz has held numerous roles within SID, from president to editorial advisor (he still serves in the latter capacity to this magazine). Although these activities represented work above and beyond his regular job, "I never really considered not volunteering," says Kmetz.

This comment illustrates something else this year's winners have in common – their willingness to take action, whether through research, teaching, or volunteering. When asked what his advice would be to a young person looking to start a career in display research, Naemura says, "I would convey messages from two great persons out of the Western and the Eastern worlds:

> *What we have to learn, we learn by doing.*
> *– Aristotle*
>
> *I see and I forget. I hear and I remember.*
> *I do and I understand.*
> *– Confucius*

Jenny Donelan *is the Managing Editor of* Information Display *Magazine. She can be reached at jdonelan@pcm411.com.*

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Karl Ferdinand Braun Prize

This award is presented for an outstanding technical achievement in, or contribution to, display technology.

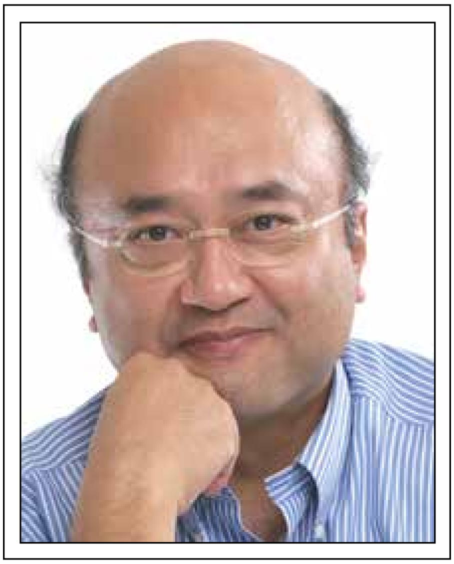
Dr. Junji Kido, SID Fellow and Professor in the Department of Organic Device Engineering at Yamagata University, will receive the Karl Ferdinand Braun Prize "for his outstanding contributions to the science and technology of OLEDs and pioneering contributions to commercializing white OLEDs for general lighting applications."

Junji Kido has spent a lifetime researching OLED technologies and applications. Among his major accomplishments are the invention of the first white-light-emitting OLED and the invention of tandem OLEDs that result in very long lifespans at high luminance levels with an internal quantum efficiency that can exceed 100%.

"In Japan," explains Ching Tang, a Professor at the University of Rochester and the Hong Kong University of Science and Technology, "Junji Kido is not only a towering figure among OLED researchers, he is probably the best known public spokesman and the strongest advocate for everything related to OLEDs."

Kido is the primary pioneer of the development of white OLEDs. His first white OLED used a polymer emitter layer dispersed with several kinds of fluorescent dyes. The second was fabricated with successive vacuum deposition of blue, green, and red emitter layers so that the resulting emission became white. These latter results were so notable that they were reported by major international publications. In 1995, *The Wall Street Journal* described his work in an article entitled "Japanese Light Researcher May Turn LED into Gold."

Tang also points out another important aspect of Kido's work. "It is widely acknowledged that the tandem device structure holds the key to solving the short-lifetime problem in OLED devices, which has been a major obstacle in the development of practical OLED technology. Because the tandem structure essentially allows an arbitrary number of individual OLED devices to be connected in series, a tandem OLED device can therefore produce high luminance (at a low current density) without compromising the operational stability. This invention has made possible a wide range of applications from large-area HDTVs to lighting based on OLEDs."



Dr. Junji Kido

Kido is also training and inspiring future generations of display and organic electronics scientists. "He is an eager educator, not only for his students at Yamagata University, but also for younger generations," notes Toshio Suzuki, Vice-President of R&D at Kuraray America. "He invites junior-high and high school students to his laboratory to let them experience the preparation and characterization of their own OLED devices. Many students become inspired by organic electronics and some of them eventually join Kido Lab in order to further their interests."

Kido has also founded commercial enterprises such as Lumiotec, Inc., created in 2008 as a joint venture with Mitsubishi Heavy Industry, Toppan Printing, Rohm, and Mitsui Company to manufacture white OLED panels for lighting. He is a co-founder of Organic Lighting Corp., which manufactures OLED lighting fixtures. He is also the recipient of many prizes, including, in 2013, the Medal with Purple Ribbon from the Emperor of Japan.

Jan Rajchman Prize

This award is presented for an outstanding scientific or technical achievement in, or contribution to, research on flat-panel displays.

Dr. Shohei Naemura, SID Fellow and Guest Professor at Tottori University, will receive the Jan Rajchman Prize "for his outstanding achievements in the chemical physics of liquid crystals and contributions to research on LCDs."

Shohei Naemura first discovered liquid crystals as a student at Kyoto University in 1968. He didn't know what they were – they just sounded interesting to him. His initial hunch paid off. Forty-seven years later, he is still finding out interesting things about liquid crystals, and these discoveries have forwarded the industry.

Naemura's results include the operation mechanism of liquid-crystal displays (LCDs) by focusing on the interfacial region between the liquid-crystal (LC) material and the display panel substrate, and also the relationship between the macroscopic physical properties and the chemical structures of LC materials.

His achievements in these areas were indispensable to the development of LC materials and their commercialization as well as to the research and development of modern LCDs with improved picture quality.

According to Hoi-Sing Kwok, Director of the Center for Display Research at the Hong Kong University of Science and Technology: "His research is both theoretically interesting as well as important to practical applications. This is the hallmark of a good applied physicist."

Looking back on his research career, Naemura says: "The biggest challenge was to make organic materials (liquid-crystalline compounds) functional in electronic devices (display devices, especially active-matrix LCDs)." Going forward, he says, "[The fields of] chemistry and physics, including electronics, should work cooperatively in developing LC materials, which work together with thin-film transistors in display panels, for instance."

Dr. Shohei Naemura

Naemura notes that his involvement with SID was essential to his career. "When I started my research as a young engineer, it was my target to present a paper every year at the SID technical symposium, and thus I may say that I was developed by SID as a researcher. Later, in gratitude, I became involved in the society in order to make SID more attractive and instructive, especially for young engineers in the display science and technology field."

To that end, he served as General Chair of IDW '02, Chair of SID's Japan Chapter, General Chair of Asia Display/IDW '01, Executive Chair of IDW '00, Program Chair of IDW '98, and President of the Japan Chapter, as well as in numerous other roles.

Otto Schade Prize

The Otto Schade Prize is awarded for outstanding scientific or technical achievement in, or contribution to, the advancement of functional performance and/or image quality of information displays.

Dr. Ingrid Heynderickx, SID Fellow, and Dean of Industrial Engineering and Innovation Sciences at Eindhoven University of Technology, "for her outstanding contributions to the measurement, specification, and improvement of the image quality of electronic-display technologies."

Ingrid Heynderickx has played a leading role over the last two decades in the application of psychophysics and human subjective testing to the optimization of image quality in electronic displays. In particular, she has produced pioneering work in the areas of psychophysical methods, saliency and attention measurement, eye-tracking, and large subjective rating databases. It is difficult to find an aspect of display image quality to which she has not made a contribution. She has also shepherded these research results into practical commercial advances, such as the technologies Pixel Plus, Ambilight, and LifePix at Philips Research Laboratories, a company she has been affiliated with for her entire career.

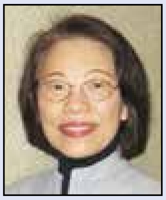
According to Scott Daly (Senior Researcher at Dolby Laboratories and previous Otto Schade winner): "Professor Heynderickx's research career has included a wide range of topics, with results that have found significant usage by engineers in the display-industry pipeline – from capture and generation to transmission and display."

2015 SID Fellow Awards

The grade of Fellow is conferred annually upon SID members of outstanding qualifications and experience as scientists or engineers whose significant contributions to the field of information display have been widely recognized.

Hidefumi Yoshida, *"for his many significant contributions to LCD technology, especially wide-viewing multi-domain vertical-alignment LCDs, including protrusion geometry, photo-alignment process, halftone technology, and fast-response architecture."*

Dr. Yoshida is a Department General Manager with Sharp Corporation. He earned his Ph.D. in engineering from the Tokyo Institute of Technology.



Anne Chiang, *"for her pioneering contributions to electrophoretic display technology and significant innovations in the development of polysilicon-TFT technology."*

Dr. Chiang is Principal of Chiang Consulting. She received her Ph.D. in physical chemistry from the University of Southern California.

John F. Wager, *"for his pioneering contributions to the development of oxide TFTs."*

Dr. Wager is a professor and holds the Michael and Judith Gaulke Endowed Chair in the School of Electrical Engineering and Computer Science at Oregon State University. He has a Ph.D. in electrical engineering from Colorado State University.

Ryuichi Murai, *"for his outstanding contributions to the research and development of PDPs, CRTs, flat CRTs, and OLED displays and nurturing and leadership in the PDP as well as other display communities.*"

Mr. Murai is a researcher with Panasonic Corporation. He has a B.S. from Osaka University.

Fujio Okumura, *"for his pioneering contributions to the research and development of LTPS-TFTs and SOG devices and significant contributions to the advancement of the display community."*

Mr. Okumura is a Senior Manager with NEC Corporation. He has an M.S. in electrical engineering from Yokohama National University.

The 2015 winners will be honored at the SID Honors & Awards Banquet, which takes place Monday evening, June 1, 2015, during Display Week at the Fairmont Hotel in San Jose. Tickets cost $95 and must be purchased in advance – they will not be available on-site.

Visit www.displayweek.org for more information.

Dr. Ingrid Heynderickx

Heynderickx's degrees are in physics, but she discovered human factors early on in her career. Her first task at Philips Research, where she began working in 1987, was to find a solution for the poor image quality of LCDs under oblique viewing angles. She developed an electro-optical model for LCDs and used it to evaluate the performance of an LCD under different viewing angles. But she immediately realized that she needed visual-perception knowledge in order to understand which deviations from optimal performance would be visible to humans. So she visited the Institute for Perception Research (then at Eindhoven University of Technology) to find out more. It was a lightbulb moment for her. "From the first, I envied their research area," says Heynderickx, who afterwards gradually but steadily became more involved in the applied visual perception of displays and lighting systems.

In 2005, she began teaching at both the Southeast University of Nanjing in China and at the University of Technology in Delft, The Netherlands. She eventually moved to full-time teaching in part so that she could pursue the kinds of long-term research more commonly found at universities than at private companies. She has also found it inspiring to work with students. "They force you to carefully think through and formulate your reasoning and to continuously look at your findings from a different perspective."

Heynderickx has been an active member of SID for many years, having served as chair of the applied-vision subcommittee and also as chair of the European Program Committee. "I really learned a lot from the interaction with various committee members and regular visitors of SID. I yearly met people that I admired a lot for their expertise in the field of applied visual perception, and they were always willing to listen to my research and give advice. Especially for me, being rather isolated in this area of research here in Europe, it was great to have the opportunity to meet other members of the global visual-perception research community."

Slottow–Owaki Prize

The Slottow–Owaki Prize is awarded for outstanding contributions to the education and training of students and professionals in the field of information displays.

Dr. Jin Jang, SID Fellow and Professor at Kyung Hee University, will receive the Slottow-Owaki Prize "for his major contributions to display education and active-matrix-display developments including AMOLED displays, AMLCDs, and flexible displays."

To date, Jin Jang has advised the thesis and dissertation research of 183 graduate students (43 Ph.D. and 144 Master's degrees.) Most of these graduates are now working in the display industry, with 54 at Samsung Display Co., 40 at LG Display, and others at numerous companies in Korea as well as in Japan, the U.S., the U.K, France, Taiwan, and China. "I have met many students from Jin Jang's group," says Heiju Uchiike, a former colleague of Jang's at Kyung Hee University. "They are very hard working and have a wide vision of display research. In particular, the students that have graduated from his laboratory are making great contributions by developing displays in many areas of the private sector."

At the graduate school of Kyung Hee University, where he is currently a professor, Jang established a display major in 1997 and then a Department of Information Display in 2004. The latter now accepts 60 students every year and has 12 professors.

In addition to being a prolific teacher, Jang is also known for research. Among his discoveries have been a novel technique to crystallize a-Si at low temperatures as well as well-received research on self-organized deposition, flexible displays, oxide TFTs, QLED displays, and more.

Jang says that he has been lucky enough to pursue both teaching and research because his department at the university performs practical research and creates manufacturing prototypes – the teaching is automatically combined with those activities. His advice to young students anywhere currently considering a career in displays: "Flexible displays have been a hot area recently, so job opportunities would be good for students who study oxide TFTs on plastic, LTPS TFTs on plastic, thin-film encapsulation for OLEDs, and plastic AMOLEDs."

Dr. Jin Jang

Jang himself started out in the display industry as a doctoral student in physics, working on TFTs and thin-film solar cells. Shortly after graduating, he collaborated with Samsung on TFT-LCD research; this experience, he says, set him solidly in the direction of display research.

Jang also became involved with SID early on, joining the organization in the late 1980s and becoming a program committee member in 1995. He has served in many other roles as well since then, including program chair of the SID symposium and general chair of Display Week and IMID. He estimates that he has attended all the SID symposia in the U.S. and all the IDW conferences in Japan for the last 20 years. "I have made many friends in Japan, Taiwan, the U.S., and Europe by attending SID-sponsored conferences," says Jang.

Lewis and Beatrice Winner Award

The Lewis and Beatrice Winner Award for Distinguished Service is awarded to a Society member for exceptional and sustained service to SID.

Dr. Allan R. Kmetz, SID Fellow and display-industry consultant, will receive the Lewis and Beatrice Winner Award "for his exceptional and sustained service to the Society for Information Display."

Forty years of involvement with SID began in graduate school for Lewis and Beatrice Winner recipient Allan R. Kmetz. "My thesis advisor at Yale was an officer of the IEEE Magnetics Society and he dragged me along to conferences he organized," explains Kmetz. "After switching to displays in my first year at Texas Instruments, it just seemed natural to submit two papers to the first joint IEEE/SID conference on displays. I was a new face in a new field and the SID program committee invited me to join them. I agreed and apparently couldn't stop."

He has not stopped yet. Kmetz is currently on the editorial board of this magazine, having assisted for more than 10 years in helping *ID* to be technically (and also grammatically) accurate. He has served SID in a multitude of capacities, including lecturer and seminar organizer, program committee member, chair of the SID Technical Symposium, Honors and Awards Committee member, bylaws chair, and last but not least, president of the Society.

In this last capacity, "Allan was wonderful to work for and with," says Jenny Bach, former SID Data Manager and previous recipient of the Lewis and Beatrice Winner Award. "As president of SID from 2002 to 2004, Allan made fantastic achievements," says Shigeo Mikoshiba, also a past-president. "His superclear and systematic way of thinking clarified the path to progress for SID. Academic as well as financial activities were significantly promoted through his efforts."

Many who worked with Kmetz over the years are quick to cite his work on the organization's bylaws. Says Past-President

2015 SID 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.

Jun Ho Song, *"for his invention and product development in simplifying the TFT process for LCD devices and the development of 22-in. TFT-LCD TV in 1995 and integrated a-Si gate driving in TFT-LCDs in 2005."*

Dr. Song is a master researcher at Samsung Display Company. He has a Ph.D. in quantum optical physics from Korea University.

Byoungho Lee, *"for his leading contributions to three-dimensional display technologies based on integral imaging and holography."*

Dr. Lee is a professor in the Electrical Engineering Department at Seoul National University. He has a Ph.D. in electrical engineering and computer science from the University of California at Berkeley.

Byeongkoo Kim, *"for his leading contributions to the research and development of AH-IPS technology for high-end displays including smartphones, tablets, notebooks, monitors, and automotive displays."*

Dr. Kim is Vice-President of LG Display. He has a Ph.D. in electrical and computer engineering from Pohang University of Science and Technology.

Toshio Kamiya, *"for his outstanding contribution to the material science of amorphous-oxide semiconductors."*

Dr. Kamiya is a professor and the Vice-Director of the Materials Structures Laboratory at the Tokyo Institute of Technology. He earned a Ph.D. in engineering at the Tokyo Institute of Technology.

Yasuhiro Koike and ***Akihiro Tagaya***, *"for their leading contributions to the research of zero-birefringence polymers, highly birefringent polymers, and highly scattered optical-transmission polymers and their applications in LCDs."*

Dr. Koike is a professor with the Faculty of Science and Technology at Keio University. He has a Ph.D. in engineering from Keio University.

Dr. Tagaya is a Project Professor at the Graduate School of Science and Technology, Keio University. He has a Ph.D. in engineering from Keio University.

Shunpei Yamazaki, *"for discovering CAAC-IGZO semiconductors, leading their practical application, and paving the way to next-generation displays by developing new information-display devices such as foldable or 8K x 4K displays."*

Dr. Yamazaki is president of Semiconductor Energy Laboratory. He received his Ph.D. in engineering from Doshisha University.

Dr. Allan R. Kmetz

Munisamy Anandan: "Allan was bylaws chair during my term as president. He examined in detail the bylaws of the student branches and new chapters. He spent an enormous amount of time editing the drafts of bylaws submitted by student branches from regions where English was not the first language. Allan was also responsible for defining different categories of membership accurately in SID bylaws."

From Kmetz's own standpoint, one of the more rewarding aspects of his volunteer career at SID has been the annual paper-selection process with the liquid-crystal subcommittee. "This has been one part of SID that has put me face to face with the very brightest in the field of displays," says Kmetz. "The value I gained from this has been both professional and personal."

Kmetz received his doctoral degree in engineering from Yale University in 1969 and went on to work for Texas Instruments, Brown Boveri Research Center in Switzerland, Bell Laboratories, and Agere Systems before retiring in 2003 to become an independent display consultant. He is the author of numerous technical papers and co-editor of the book *Nonemissive Electrooptic Displays*. He holds 16 U.S. and 45 foreign patents. His active display technology and intellectual-property consulting duties include aiding in portfolio evaluation and serving as an expert witness. ■

DISPLAY WEEK 2015
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SID International Symposium, Seminar & Exhibition

May 31–June 5, 2015

San Jose Convention Center
San Jose, California, USA

Rolling Out the Red Carpet

I-Zone

Competition of live demonstrations regarding emerging information-display technologies, such as not-yet-commercialized prototypes and proof of concepts.

Individual Honors and Awards

The SID Board of Directors, based on recommendations made by the Honors & Awards Committee, grants several annual awards based upon outstanding achievements and significant contributions.

Display Industry Awards

Each year, the SID awards Gold and Silver Display of the Year Awards in three categories: Display of the Year, Display Application of the Year, and Display Component of the Year.

Best in Show Awards

The Society for Information Display highlights the most significant new products and technologies shown on the exhibit floor during Display Week.

Journal of the Society for Information Display (*JSID*) Outstanding Student Paper of the Year Award

Each year a sub-committee of the Editorial Board of *JSID* selects one paper for this award which consists of a plaque and a $2000 prize.

Solid-State Lighting for Illumination and Displays: Opportunities and Challenges for Color Excellence

Solid-state light sources are transforming luminaires and information displays, enabling screens to illuminate rooms and luminaires to form images. Maintaining color excellence, from all perspectives, will be challenging but worthwhile.

by Lorne Whitehead

IT is interesting to compare the simple incandescent lamps that dominated the early days of lighting with today's flat-screen televisions. TVs are impressive, but in two important ways the lowly incandescent lamp "outshines" them: first, incandescent lamps emit more than 10 lm of visible light for each watt of electrical power, whereas a typical LED-illuminated LCD TV emits less than 1 lm. Second, incandescent lamps emit very high-color-quality light, yet most TVs emit light that has unacceptably poor color quality for illumination purposes. In short, today's displays make for great televisions but terrible lamps! Some find this quite surprising since LEDs themselves are now much more efficient than incandescent lamps and they can be blended to make high-color-quality light.

Of course, some may feel this comparison is irrelevant because screens are rarely used for illumination, but that is bound to change. After all, for decades, screens have become cheaper, brighter, larger, clearer, and more commonplace and that trend is certainly continuing. We can anticipate that image displays will soon start making significant contributions to general illumination, similar to the way windows contribute significantly to indoor illumination while also making rooms more interesting. Another way to think of this is that we should reasonably expect our electric light sources to provide more than just light – why shouldn't they also provide the added value of visual information?

As the blending of illumination and information display gets under way, society will face some important human-factors issues involving color perception. These relate to the spectral power distribution (SPD) of light and its impact on the accuracy and range of color reproduction in displays, as well as the color-rendering quality and photo-biological influences of the light emitted by displays. As it becomes practical to produce light with almost any desired SPD, designers will have the freedom to adjust these factors, but in doing so they will face design trade-offs because what is best from one perspective is often not best from another. Often the parties influencing an overall design may have differing views of the relative importance of these factors. For this reason, it is important to achieve a shared understanding of them. Lighting designers and display designers will need to coordinate closely for optimal success as their areas of work begin to overlap.

The purpose of this article is to make a contribution toward that shared understanding. It provides an overview of the key design factors in both fields and suggests that soon there may be improved solutions for optimally satisfying all of the main requirements.

The Significance of Solid-State Lighting

By now, people are well aware that solid-state lighting devices, such as light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs), are a revolutionary addition to the field of lighting. A common assumption is that their primary distinguishing feature is high efficiency. But while these devices are indeed efficient, they do not dramatically surpass the efficiency of previous sources such as high-intensity discharge and mercury fluorescent lamps. The characteristic of LEDs that may be the most transformative is their ability to efficiently produce light in a narrow band of wavelengths and for the center of that output band to be selectable, during manufacture, at almost any desired points in the visible spectrum. As a result, it is possible to combine the light from a number of LEDs to produce almost any desired SPD. For the first time, engineers have spectral design freedom. Here, it is argued that they also have a responsibility to exercise this freedom wisely.

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Figure 1 shows an SPD for each of three light sources: a typical non-LED lamp (a fluorescent lamp that contains numerous peaks associated with the underlying mercury-vapor discharge) and two quite different LED lamps. Note that the vertical axis in Fig. 1 is dimensionless because the curves in this figure depict, for each lamp, the ratio of the light intensity at each wavelength to the peak value, which, by definition, is 1.0. In order to explore the key perceptual phenomena arising from a very wide choice of SPDs, it will first be helpful to review some basic concepts of human color vision.

Key Characteristics of Human Color Vision

In human color vision, wavelength information concerning light is detected by means of three types of light-sensitive retinal cone cells (labeled L, M, and S), which have peak wavelength sensitivities in, respectively, longer, medium, and shorter wavelength regions of the visible spectrum. Their sensitivity functions are shown in Fig. 2.

It is important to note that the response functions shown in Fig. 2 are relative. One way to think of this is that if a certain degree of stimulation of a particular cone cell is produced by one unit of radiant power at that cone's wavelength of peak sensitivity, then two units of radiant power would be required to produce the same stimulation using a radiation wavelength for which that cone sensitivity is half of its peak value. When calculating a cone's response to light consisting of a blend of wavelengths, the radiant power at each wavelength must be multiplied by the cone's sensitivity at the same wavelength and so these individual contributions can then be added up. Thus, the response of each cone contains no information about specific wavelengths that caused its stimulation; color information is known to the visual system only by means of the relative degree of stimulation of the three cone types. For example, longer-wavelength light will stimulate the L cones to a greater degree than the M or S cones because L cones have greater sensitivity at longer wavelengths than do the M or S cones. In turn, this pattern of cone stimulation (which creates the sensation of red light) indicates that the stimulus must have consisted of predominantly longer-wavelength light.

Overall, this means that the brain can obtain information about the spectral distribution of

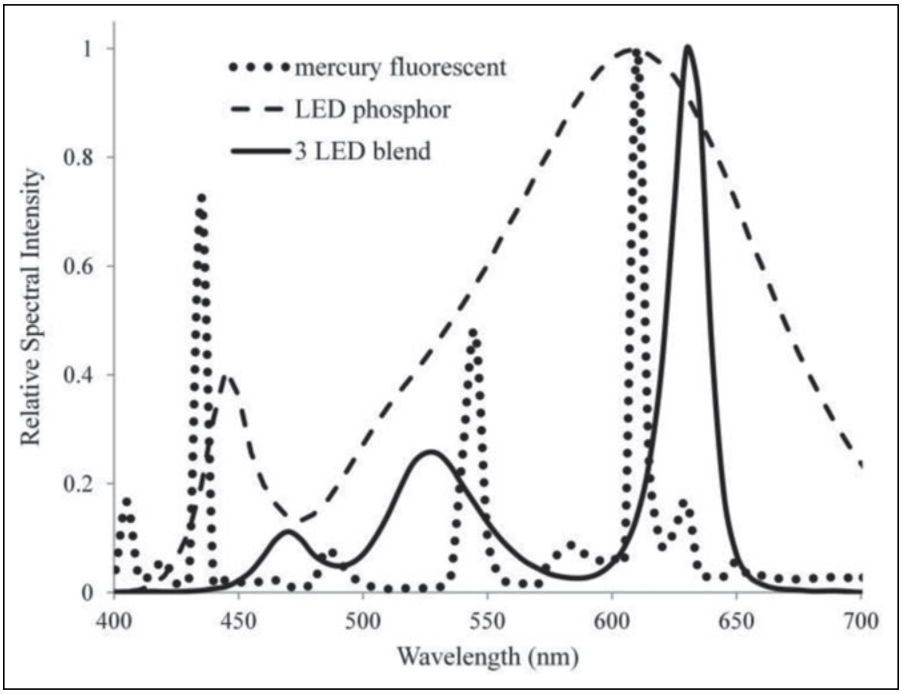

***Fig. 1:** Shown are spectral power distribution (SPDs) for a mercury fluorescent lamp, a white phosphor LED, and a lamp that blends three narrow-band LEDs.*

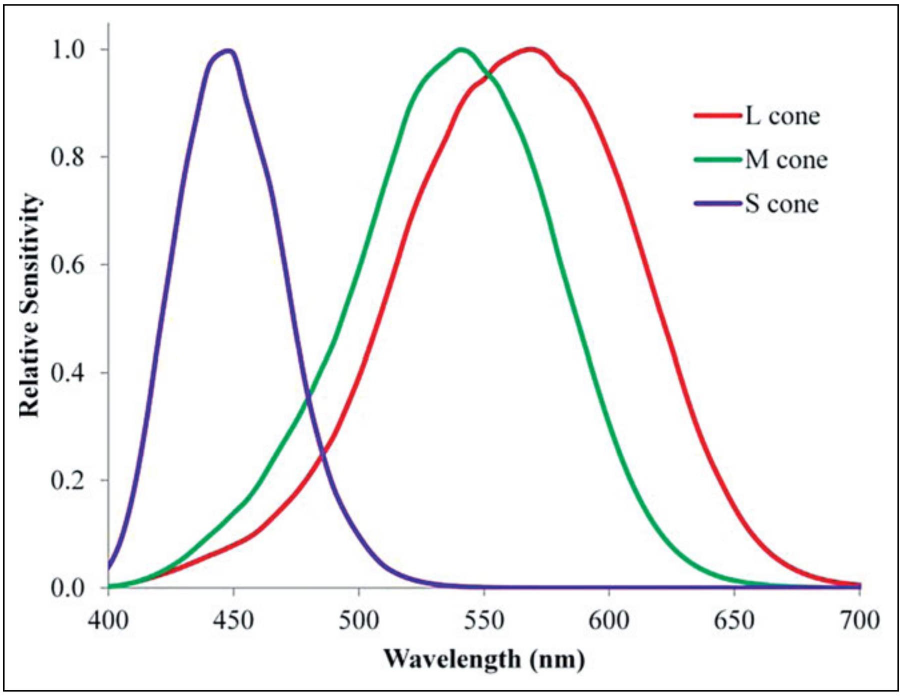

***Fig. 2:** The relative spectral sensitivity functions for the L, M, and S retinal cone cells appear in red, green, and blue, respectively.*

light by observing the pattern of stimulation of the three cone cell types. Interestingly, this need to assess the intensity of cone stimulation is somewhat problematic because of the very wide range of lighting conditions that the eye routinely encounters. In rough terms, the intensity range over which color vision operates spans a factor of 1,000,000[1] (from sunlight to moonlight). However, the optic nerve (a bundle of nerve cells that carry information from the eye's retina to the brain) can only convey a limited number of signal levels. The number of discernable signal levels probably depends on the kind of optical information being transmitted and is not precisely known, but there are clues that can provide a rough idea.

One of these clues is that, as recognized by typical reference books of sample colors,[2] there are only about 40 distinguishable hues around the color circle. The exact number is not critical to the following comparison: Using 40 levels as an example, if one attempted to evenly represent the required million-fold range of intensity in just 40 equal ratiometric steps, each of those steps would represent about a 40% intensity change. But the typical just-noticeable difference in light intensities is actually a lot less – often on the order of 8% for shades of gray, and in certain cases of color perception as little as a 1% difference in relative cone stimulation may be noticeable.[3]

Clearly, this sensitivity would not be possible if the intensity of cone stimulation was directly communicated by the optic nerve, and yet the color-vision system does exhibit this high sensitivity over most of the million-fold range of illumination intensity previously mentioned. This remarkable perception accuracy is achieved through sophisticated signal processing, beginning with adaptive non-linear compression within the cones[4] followed by sophisticated signal processing in the retina.[5]

Furthermore, after the resultant processed information is received by the brain, even more complex processing takes place,[6] providing to our conscious awareness a remarkably stable and reliable depiction of color information. The last processing stages are so important that some say we "see" mainly with our brain,[7] not our eyes. In other words, what we consciously perceive is an image generated by a massive computer (the brain), based upon many factors, including information from the eyes about how objects in the world are influencing the incident light field.

Fortunately, in this article, it is not necessary to fully describe this remarkable perception process and indeed that is not even completely possible since there are still a number of unanswered questions. The primary point here is that color vision is an extremely sophisticated system. In evolution, sophisticated systems develop when they enhance survival over vast time periods.[8] In modern times, people generally greatly value aspects of life that were necessary for survival, such as health and fitness, good food, and security. From this perspective, it makes sense that the beauty and subtlety of color perception is very important to many people, and this is further evidenced by the vast color-related businesses in paints, dyes, fabric, cosmetics, industrial design, and marketing. Therefore, it is very important to maintain high color quality both in information displays and interior illumination, and it stands to reason this will matter even more as the two fields begin to overlap.

Studies of how people use color information have led to the realization that color vision serves two purposes that are related but different. In the first, people perceive color as an informative property of light.[9] In the second, people perceive color as an informative property of the manner in which a surface reflects light[10] (a distinction that will be made clearer shortly).

We'll begin with the first – assessing the color of light. Not only is it the simpler of the two, but also it is a building block for the perception of surface color. Figure 3 shows symbolically how the eye assesses the color of light landing on the retina.

The top row in Fig. 3 is simply an arbitrarily selected SPD; it is a graph of spectral power intensity *vs*. wavelength, which is useful information. For example, moonlight and firelight have quite different spectral distributions, as do a clear and cloudy sky. Therefore, information about the intensity and spectral distribution of a light could help a person determine the source that emitted it. The same can be true in the human-made environment. For example, we are familiar with the idea that a red traffic light is a universal symbol for "Danger! Stop!" The visual system can recognize a red light through the corresponding heightened stimulation of L cones, which are the most sensitive to the long wavelengths associated with the color red.

The next row in Fig. 3 shows the L, M, and S cone responses while the remaining rows depict the way they are effectively multiplied by the light SPD, and the results, summed to give the resultant L, M, and S values for the SPD in question, are shown in the last row. (The numbers shown are real – they were calculated using this procedure with the SPD shown and the L,M,S sensitivity functions, a process that is repeated in Figs. 4 and 5.) The numerical values show roughly how closely the light-source spectrum matches the sensitivity function for the L, M, and S cones. Sources with predominantly longer wavelengths stimulate the L cones the most, while predominantly shorter wavelengths stimulate the S cones most.

Since we only have three cone types, this information is only approximate, but nevertheless it can be very useful in distinguishing between different light sources. (It should also be noted that the raw L, M, and S values shown here represent information at the beginning of the signal-processing stages mentioned earlier, and the subsequent stages leading to what we actually perceive are more complex, but fortunately not needed for the present discussion.)

While information about light-source color is useful, that is not the most important, nor the most sophisticated use of color vision.

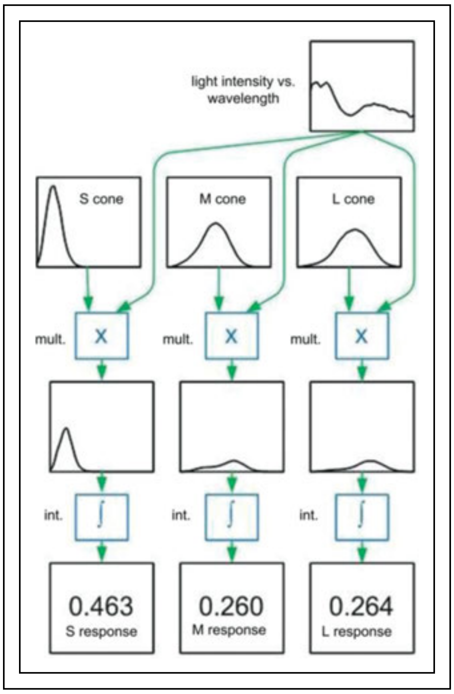

Fig. 3: *The stimulation of the S, M, and L cones is determined by spectral power distribution (SPD).*

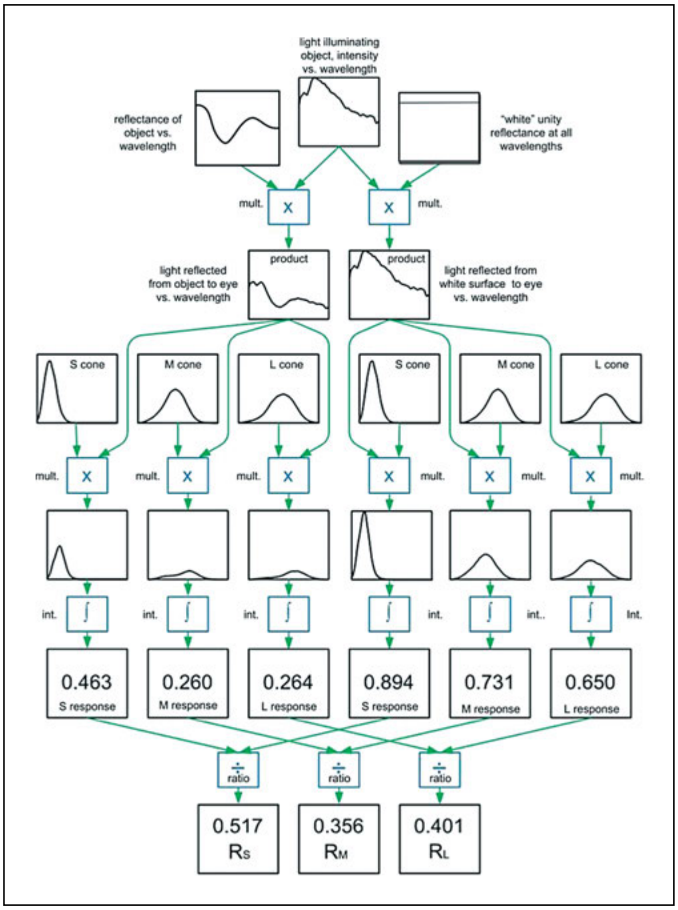

Fig. 4: **Fig. 4:** *Surface color is determined by comparing the S, M, and L cone stimulations arising from light reflected from an object of interest to the S, M, and L cone stimulations arising from light reflected by a white surface, when both the object of interest and the white surface are illuminated by the same light source.*

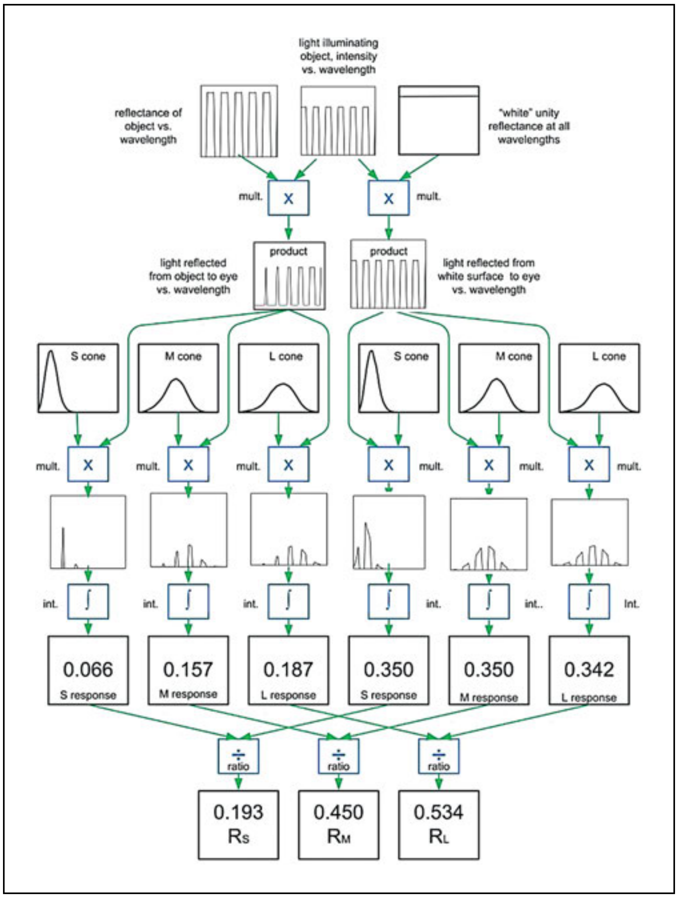

Fig. 5: *The schematic represents an extreme case of poor color rendering in which a white source illuminates a normally gray surface and causes it to appear orange.*

Color vision's second purpose, the assessment of surface color, is depicted in Fig. 4. (Do not worry if you find Figs. 4 and 5 too complex to easily follow in detail – just getting the gist of them will enable you to easily follow the remainder of this article.)

The main point in Fig. 4 is that surface color perception involves two separate assessments of light color that happen at the same time. The left half of Fig. 4 is concerned with light reflecting toward the eye from a surface of interest, and the right half is concerned with light reflecting toward the eye from a white surface. Importantly, both surfaces are illuminated by the same light source, depicted as the SPD shown at the top center of the figure. On both sides of the figure, the SPD of the reflected light is the product of the surface reflectance at each wavelength multiplied by the source intensity at that wavelength, and the color of that reflected light is then assessed, resulting in the listed L, M, and S values. That is, on the left we have L, M, and S values for the surface of interest and on the right side the larger L, M, and S values for the white surface.

The last two rows of Fig. 4 show the unique and important characteristic of surface color perception: The L, M, and S values for the surface of interest are divided by, respectively, the L, M, and S values for the white surface, yielding effective reflectance values weighted by the L, M, and S sensitivity functions. (It should be pointed out that, in general, the processing is not nearly as simple as depicted here, but this simple division calculation is often a good approximation and is sufficient for the purposes of this article.)

The process of effectively referencing the color of a surface to the color of the illuminant is called chromatic adaptation, and it is very important because it provides reliable determination of surface color, somewhat independent of the color of the illumination. For example, people can accurately judge the ripeness of a banana, based on its color, when it is illuminated by daylight or by incandescent light. Even though the color of the incandescent light is pale orange in comparison to daylight, the perceived subtle shades associated with a ripening banana are not substantially changed. Without the sophistication of chromatic adaptation, the accuracy and reliability of our perception of surface color would be severely diminished.

In turn, diminished color-perception accuracy would be problematic because accurate assessment of surface color is useful – it gives us information about spectral reflectance function of the surfaces around us. That is, over large portions of the visible spectrum, we can estimate roughly what fraction of the incident illumination is reflected by an object, and this can then tell us about the materials that are present within the object's surface. For example, the spectral reflectance function of human skin is affected by degree of oxygenation of hemoglobin molecules, which relates to health.[11] Similarly, such information can help us know if various foods are fresh.[12]

The reason for distinguishing between the assessment of light color and surface color is that they depend in very different ways on the SPD of light, which, in turn, places different constraints on color excellence in displays and in illumination. Let's now consider these relationships, first for the case of illumination and then for displays.

Color-Perception Quality Issues with Illumination

Since color perception evolved with daylight as the dominant source of illumination, and daylight remains unchanged and universally available today, it makes sense that people prefer to have artificial lighting provide the same color appearances that we see under daylight. This requirement is not terribly constraining because daylight itself comes in a wide variety of SPDs. Generally, all of these different daylight SPDs have the common characteristic of a fairly smoothly varying SPD. In some cases, there is a relatively smaller intensity at longer wavelengths (as with illumination from blue sky) and in others relatively more (as with sunlight near sunrise or sunset), yet in both cases white objects look white and the appearance of other objects appear consistent and natural, largely as a result of the chromatic adaptation taking place within the visual system.

Let us now consider a very important concept known as color rendering. To help understand it, we'll consider an example of a source SPD under which colors can appear extremely distorted. Consider Fig. 5, which is almost identical to Fig. 4, showing the observation of a surface color. The only change is that a special SPD has been selected for the light source, and also a different special function has been selected for the spectral reflectance function of the object of interest. In both cases, the function alternates from high to low as a function of wavelength, which is unusual but possible.

The light source shown in the top row appears white (because it stimulates the L, M, and S cones approximately equally), and the surface represented here, when illuminated by daylight, would appear gray (because in that case its reflected light stimulates the L, M, and S cones equally). However, the simple arrangement in Fig. 5 has a perplexing outcome: When this particular white light shines on this particular gray surface, it appears orange! (This can be seen in Fig. 5, where the bottom-row ratios RS, RM, and RL correspond to those normally found for an orange surface color.) This is because both the source SPD and the surface spectral reflectance function have narrow features in the wavelength dimension that interact, *via* the reflection process, in a way that distorts surface color. This is an extreme case, but many common electric lamps cause smaller, but still unpleasant, distortions of surface color. As real life examples, some popular energy-efficient lamps make tomatoes seem pale, while purple petunias appear blue.

Overall, there are two desirable features of natural illumination that we would like to preserve indoors. First, surface colors indoors should appear similar to their natural color outdoors. Second, if two objects have matching surface color under natural illumination, they should also have matching surface color indoors. This reliability gives meaning to the idea of surface color; it enables people to consider the precise shade of surface color to be a property of a surface. Therefore, we should try to minimize surface color distortion. Light sources that fulfill this requirement are said to have high color rendering.[13] This idea is quantified by the CIE Color Rendering Index.[14]

So, how do LEDs impact color rendering? Well, on the positive side, the spectral design freedom provided by solid-state lighting makes it fairly easy to produce smoothly varying SPDs that do not distort color, and so it would seem reasonable, going forward, to expect no further problems with color rendering. Ironically, the opposite is the case, as a result of a simplistic response to a fundamental trade-off between color quality and luminous

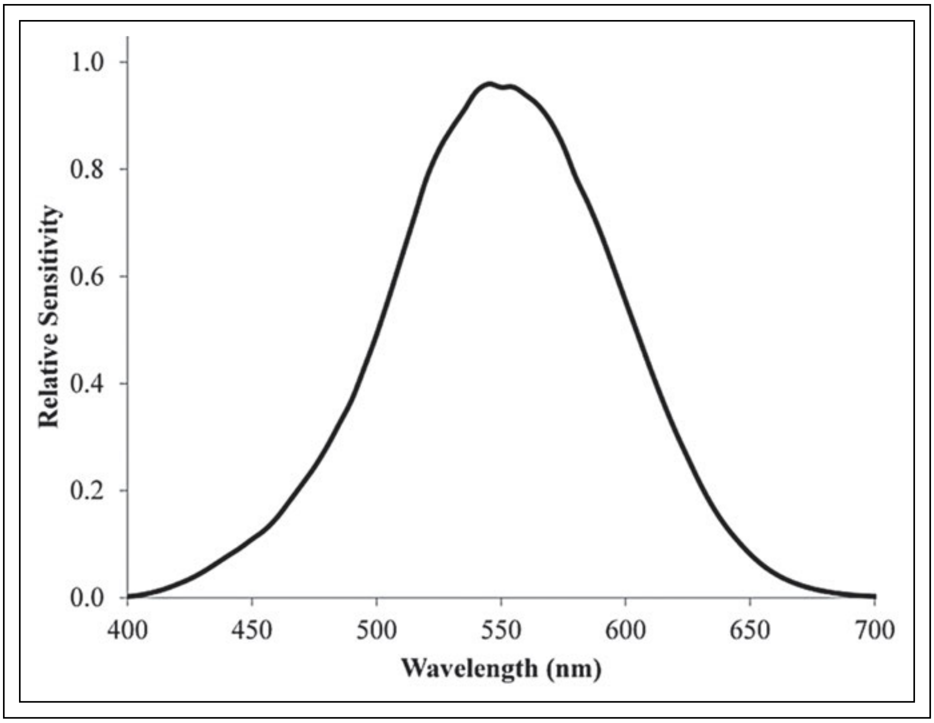

Fig. 6: *Depicted is the the photopic luminous-efficacy function.*

efficacy. To help explain this, consider Fig. 6, which shows the overall light sensitivity of the human color-vision system, showing a peak response at 555 nm and a smooth fall-off to either side.

The average luminous efficacy of a lamp will be greater if its SPD has more of its energy close to the peak of Fig. 6. Put the other way around, an SPD will have less average luminous efficacy if a significant portion of its intensity lies near the ends of the distribution. Unfortunately, that is what is needed for high color-rendering quality. In other words, in designing a lamp's SPD, we are forced to choose between producing more visible light or higher color quality; we cannot maximize both at the same time. Fortunately, this turns out to be a very mild tradeoff – in most practical cases only a 10% reduction in luminous efficacy is needed to maintain reasonably high color quality. And, importantly, this requires no power increase; the power can be kept constant while reducing the illuminance by 10% – a decrease that is essentially imperceptible – while providing an improvement in color quality that is very noticeable. Once this trade-off is properly understood, it is clear that color rendering can take priority without any negative consequences. High-color-rendering light is simply better for people, overall. Nevertheless lighting color quality is currently threatened by the widespread misunderstanding of the relative importance of luminous efficacy and color rendering.[15]

A related issue is that the current method for assessing color rendering (the aforementioned CIE Color Rendering Index) has certain inaccuracies when rating narrow-band light sources.[16] Fortunately, a new improvement for that metric is under development by the CIE[17] and is expected to overcome that difficulty. This will be helpful because phosphor-free narrow-band LEDs have the potential to be the most efficient light sources, and achieving high color rendering with them will require accurate design.

Another critical requirement for high-color-quality lighting is the avoidance of undesirable color variations between the various sources illuminating a room. Between rooms, people are comfortable with a range of lighting conditions (just as daylight comes in a range of colors), but within a given room even small color differences can distort the color appearance of objects, so such variations should be avoided.

Lastly, for completeness, it is important to bear in mind another quality factor that is not directly color related but that does influence the best choices for LED lamp design. This is the topic of the photo-biological impact of light. In the human retina, there is an important recently discovered class of photoreceptors known as intrinsically photosensitive retinal ganglion cells (IPRGCs). They have been shown to send signals to the brain that do not directly cause visible sensation but which influence the diameter of the eye's pupil[18] and have also been linked to reduction of seasonal affective disorder and synchronization of circadian rhythm.[19] Recently, significant circadian rhythm disturbances have been observed to result from late-night use of e-Readers[20] with backlighting. The IPRGC relative spectral sensitivity function has a similar shape to that of cone cells, with a peak response located between those of the M and S cones. Given these important effects, it would seem wise to ensure that the relative amount of IPRGC stimulation approximately match what is normally found in daylight during the day and what is found in dim incandescent sources during the evening. Generally, this will be the case for fairly uniform spectral distributions, but it will require careful design consideration when working with narrow-band LEDs.

Color-Perception Quality Issues with Information Displays

Let us now consider how the principles of color vision influence the design of displays. Color reproduction has been practical for a

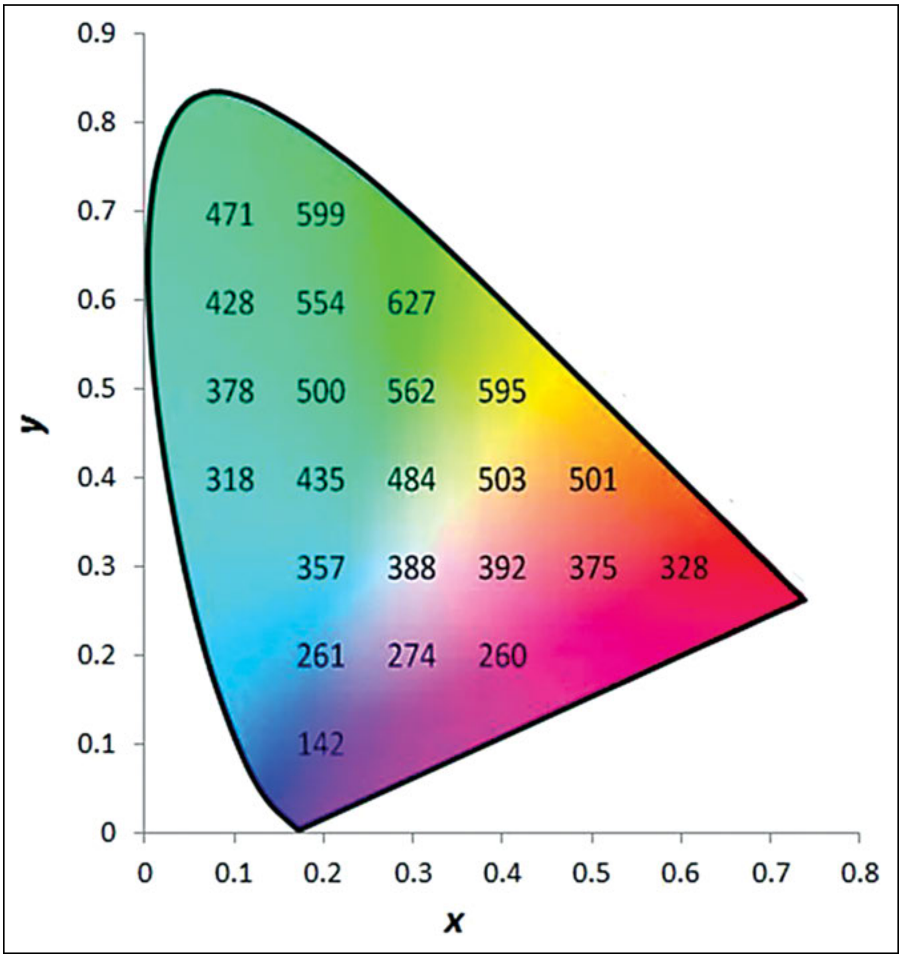

Fig. 7: *This CIEx,y chromaticity diagram also shows the maximum possible luminous efficacy of radiation at selected x, y coordinates.*

long time because of a key simplification arising from the fact that we only have three types of cone cells. Two SPDs that cause the same level of stimulation of the three cone cell types will have the same color appearance, even though they may have very different intensities at various wavelengths. (In this case, the SPDs are described as metameric.) Generally, the overall shapes of metameric SPDs are somewhat similar, but at a detailed level they may be very different. Because there are only three cone cell types, it follows that for most SPDs, an SPD of matching color appearance can be generated by adding together a selected amount of three so-called "primary" SPDs. Typically in information displays, the three primaries used appear red, green, and blue.

From this perspective, a convenient way to characterize any given SPD is by the relative degree to which they excite the three cones. Generally, these can be described by a pair of numbers that are determined from the ratios of the cone excitations, and there are many different ways to do that. Here, we will use the most common one – the familiar CIEx,y chromaticity coordinates,[21] as shown in Fig. 7.

The curved envelope shown in Fig. 7 depicts the x,y chromaticity coordinates of all of the individual spectral wavelengths, ranging from about 400 nm at the bottom left to about 700 nm at the bottom right. Connecting the two ends of the spectral points is the so-called purple line segment, coordinates that can only be achieved by blending monochromatic blue light from one end with monochromatic red light from the other.

The primary significance of this diagram is as follows: Consider a first SPD that corresponds to a first point in the diagram and a second SPD that corresponds to a second point. Any mixture of the two distributions will correspond to a point in the diagram lying somewhere on the straight-line segment connecting the first point with the second point. Furthermore, if there is a third distribution corresponding to a third point, all mixtures of these three distributions will correspond to points located within the triangle formed by the three points. There are two key practical implications – first, the only possible coordinates are those lying in the colored region within Fig. 7. Second, most chromaticity coordinates can be made through mixtures of three primary stimuli, the first of which has chromaticity coordinates in the red region, the second in the green region, and the third in the blue. This is the standard well-known concept of additive color mixing as used in most electronic image displays.[23]

Less well-known are some key color-vision issues associated with the choice of additive primaries. One of these relates to the tradeoff between gamut and efficacy. The numbers shown within the colored region of Fig. 7 depict the maximum possible luminous efficacy of SPDs with that chromaticity coordinate, shown in lm/W. (These values were obtained by numerically optimizing a source SPD subject to the constraint that it have the specified x,y coordinate.) The maximum possible efficacy is 683 lm/W, which occurs with monochromatic light with a wavelength of 555 nm and appears yellow. All other chromaticity coordinates have lower values, tending toward zero at the extreme red and blue ends of the spectrum.

The net result is that there is a fundamental trade-off when selecting primary stimuli for color displays. On the one hand, we would like them to be as far as possible into the "corners," so as to encompass the largest triangle of possible colors. (This is called the "gamut" of the display and generally it is felt that a larger "gamut area" is better because it allows a wider range of colors to be reproduced.) This forces us to use primaries that have low efficacy, thus wasting energy or sacrificing brightness, or both.

Another difficulty with wide-gamut displays is that they intensify natural differences between human observers. The L, M, and S cone response functions shown in Fig. 2 result mainly from special light-sensitive molecules that differ in the three cone types but are the same in the great majority of people with normal color vision, which is why three primary systems work fairly well for most people. However, the eye has light transmission losses that modify the cone response functions to some degree, and these losses are more variable from one person to another and even over a person's life.[23] As a result, the accuracy with which a blend of primaries will match the appearance of a real scene varies somewhat from person to person, an effect sometimes called metameric error. It is not a large problem, but it can be bothersome, and, unfortunately, the severity of this problem grows with the gamut area of a display. Finally, from a practical point of view, it is more difficult to accurately reproduce subtle pastel colors if the underlying primaries are extremely vivid – greater control precision is then required. For these reasons, there has always been a tug of war involved in designing primary-color stimuli for information displays.

Finally, there is a new concern that relates to the image content that a wide-gamut display can show. In recent decades, researchers have

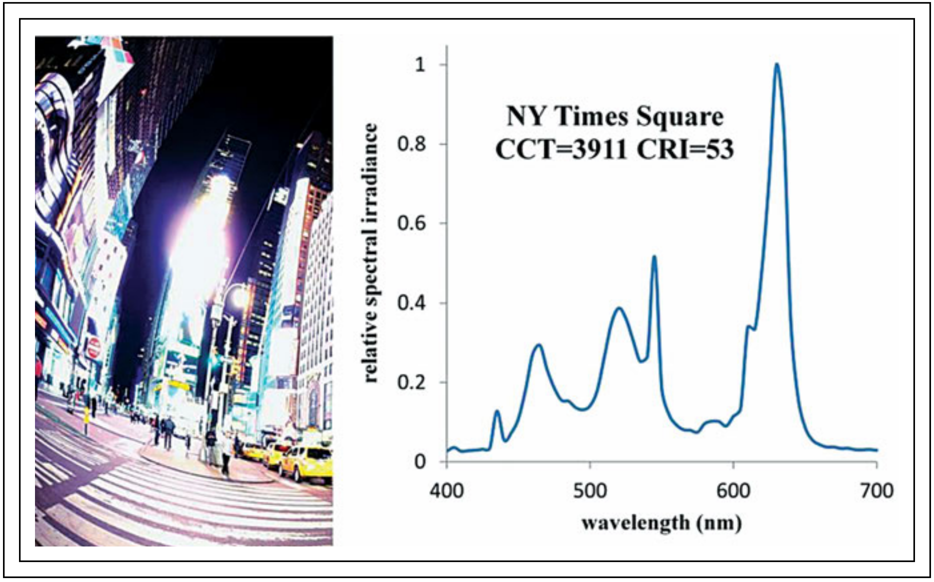

Fig. 8: *In Times Square in New York City, most of the night-time light comes from displays. The chart at right shows the SPD and the CRI of the resulting ambient lighting.*

learned that long-term adaptation mechanisms take place in the human-visual-perception system in response to exposure to extreme stimuli. For example, exposure to significant amounts of intense red light can distort the balance of red-green response of an observer, and this effect can persist for days or weeks.[24] It is possible that similar adaptation could occur to exposure to extremely high-color-contrast stimuli, which would normally be extremely rare in ordinary life. The adaptation could take the form of reduced contrast sensitivity, meaning that day-to-day colors could appear less colorful after such exposure. In this sense, high-color-contrast displays could be habit forming. There could be troubling psychological consequences of such exposures, and we should be particularly wary of exposing children to excessive amounts of such stimuli. Now we can take a look at how these factors will become more important as the anticipated blending of information display and illumination proceeds.

Human-Factor Trade-Offs As Information Displays and Illumination Blend

As a concrete example, consider Fig. 8, showing a recent night-time photo of New York's Times Square and a graph of the SPD of the ambient lighting.[25]

That ambient lighting comes almost entirely from the surrounding LED video displays, and its Color Rendering Index is only 52, which is unacceptable for conventional lighting. Ironically, while the people shown on those screens appear in their natural color, the people illuminated by the screens may not.

It is apparent that the challenges of the existing lighting design trade-offs will worsen as displays become providers of light as well as imagery. The problems fall into three categories:

Gamut: The display industry push toward higher gamut will cause further problems as displays provide illumination because three-primary wide-gamut lighting has very poor color rendering, thus distorting the color appearance of familiar illuminated objects.

Color balance: Typically, the average chromaticity of the light produced by televisions is bluer than the usual values for indoor illumination. Unless handled well, this can cause color-appearance distortion even if the screen output light is intrinsically of high color quality. There will need to be reasonable limits on the size of the color difference between the light output of displays and ambient lighting.

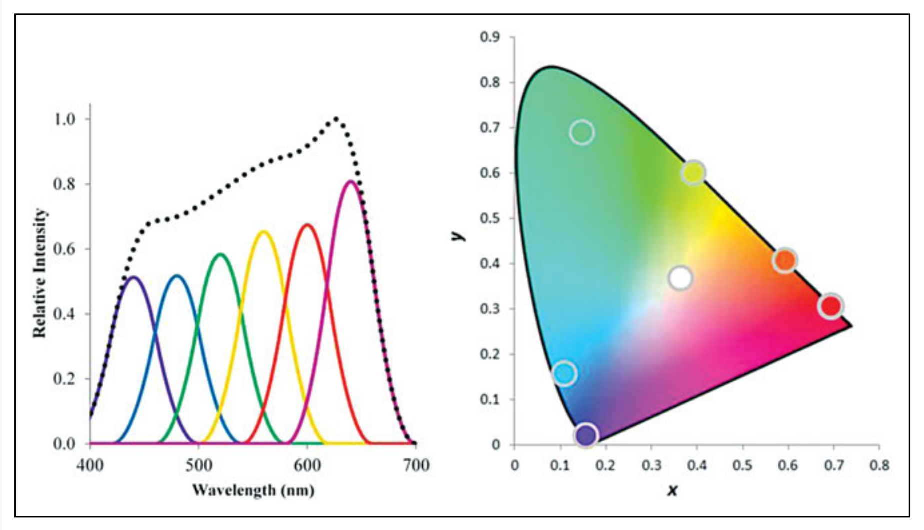

Fig. 9: Chromaticity coordinates and SPDs for a hypothetical six-primary-color display system are shown.

Emotional and photo-biological effects: It is important to understand that color vision is one of the most sophisticated human senses and that our visual experiences, both conscious and unconscious, have a profound impact on our sense of well being. We do not yet have a good understanding of these issues, and this calls for caution. Pending greater understanding, we should at least minimize exposure to stimuli that differ dramatically from the sorts of visual conditions under which our eyes evolved. It is possible to produce impressive and dramatic color experiences with solid-state lighting, but their excessive use is unlikely to be good for people.

Conclusion and a Look to the Future: Six-Primary Displays?

When faced with difficult trade-offs, it is natural to ask if there can be a breakthrough that lets us have our cake and eat it too. Indeed, for some time an idea has been floating around the display industry that could be a major step forward – the use of a larger number of primaries.[26] Figure 9 depicts this idea conceptually within the x,y chromaticity diagram and through graphing the SPDs for a theoretical six-primary display system.

The primary reason that such displays have been proposed in the past is to achieve even greater gamut than can be achieved with any three-primary system. Any color can be produced that lies within the six-sided polygon defined by their six x,y coordinates. What has been less well appreciated, but is now becoming a strong driving force for this improvement, is the way in which this design overcomes the other key concerns that have been mentioned above. Unlike wide-gamut three-primary systems, the six-primary system ameliorates the following previously mentioned problems:

Efficacy: The inefficient deep-red and deep-blue primaries are responsible for a small portion of the light, so overall efficacy is excellent.

Metamerism: The deviations from viewer to viewer are very significantly reduced with this system because the typical SPDs are smoother, so more people will see better color most of the time.

Color rendering: The smooth spectral characteristics can yield excellent color-rendering properties without significantly reducing efficiency or gamut.

Looking toward the future, we now have much greater motivation to achieve all of these desirable outcomes simultaneously. Fortunately, it seems likely that color excellence, from all perspectives, can be practically maintained as the fields of illumination and image display gradually overlap.

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Why People Should Care About Light-Field Displays

Light-field displays have a wide range of potential applications, including 3-D television and projection systems, technologies for vision assessment and correction, and small form factors with support for focus cues in head-mounted displays.

by Gordon Wetzstein

MANY PEOPLE believe that the recent hype about stereoscopic 3-D displays is over, at least for the moment. Part of the reason why 3-D television, in particular, has not been widely adopted by consumers may be the lack of a truly unique or useful enhancement of the 2-D viewing experience. At the same time, light-field displays are expected to be "the future of 3-D displays." So what makes people believe that a new technology delivering an experience that consumers have not adopted in the past will work in the future?

This article does not attempt to outline possible future scenarios for 3-D television applications. Instead, we discuss a range of unconventional display applications that are facilitated by light-field technology that perhaps would benefit much more than conventional television from emerging capabilities. Whereas glasses-based stereoscopic displays present two different views of a scene to the eyes of an observer, light-field displays aim for a multiview solution that usually removes the need for additional glasses. Conceptually, a light-field display emits a set of all possible light rays (over some field of view) such that the observer can move anywhere in front of the display and his eyes sample the appropriate viewing zones (Fig. 1). The next section outlines a short historical review of light-field displays and recent trends toward compressive light-field displays, followed by a discussion of applications in projection systems, vision assessment and correction, wearable displays, and a brief comparison to holography.

From Integral Imaging to Compressive Light-Field Displays

The invention of light-field displays dates back to the beginning of the last century. In 1908, Gabriel Lipmann built the first integrated light-field camera and display using integral imaging.[1] He mounted microlens arrays on photographic plates, then exposed and developed these plates with the lens arrays in place such that they could be viewed as a light field or glasses-free 3-D image after the fact. Over the course of more than

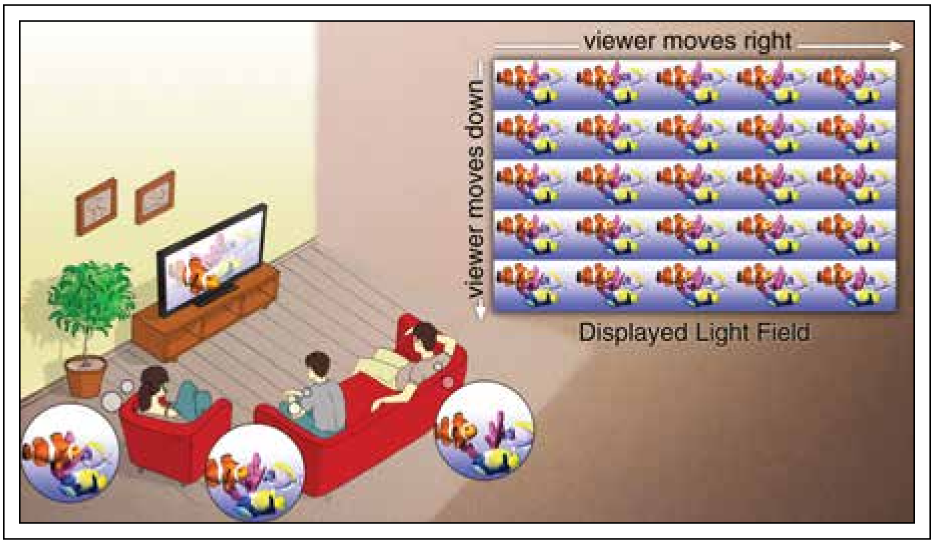

Fig. 1: In this conceptual sketch of a light-field display, several people enjoy glasses-free 3-D television. The emitted light field (top right) is a collection of images depicting the same scene from slightly different horizontal and vertical perspectives. These images are all very similar, hence compressible. Image courtesy Wetzstein et al. (Ref. 10).

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100 years, many alternative technologies have emerged that deliver a glasses-free 3-D experience;[2] for example, holography, volumetric displays,[3,4] multi-focal-plane displays,[5–7] and multi-projector arrays.[8,9] However, extreme requirements in feature sizes, cumbersome form factors, and high cost are some of the reasons why none of these technologies has found widespread use in consumer electronics.

With an ever-increasing demand on image resolution, one of the major bottlenecks in the light-field-display pipeline is the computation. Consider the example of a high-quality light-field display with 100 × 100 views, each having HD resolution streamed at 60 Hz. More than 1 trillion light rays have to be rendered per second, requiring more than 100 terabytes of floating-point RGB ray data to be stored and processed. Furthermore, with conventional integral imaging, one would need a display panel that has a resolution 10,000× higher than available HD panels.

To tackle the big data problem and relax requirements on display hardware, compressive light-field displays have recently been introduced as a modern take on Lippmann's vision. They exploit two simple insights: (1) light fields are highly redundant high-dimensional visual signals and (2) the human visual system has limitations that can be exploited for visual signal compression.

Rather than pursuing a direct optical solution (*e.g.*, adding one more pixel or voxel to support the emission of one additional light ray), compressive displays aim to create flexible optical systems that have the capability to synthesize a compressed target light field. In effect, each pixel emits a superposition of light rays; through compression and tailored optical designs, fewer display pixels are necessary to emit a given light field (*i.e.*, a set of light rays with a specific target set of radiances) than would be demanded with a direct optical solution.

Implementations of compressive light-field displays include multiple stacked layers of liquid-crystal displays (LCDs) (see Fig. 2), a thin "sandwich" of two LCDs enclosing a microlens array, or, in general, any combination of stacked programmable light modulators and refractive optical elements.[10] The main difference between stacked LCDs and conventional volumetric displays is the non-linear image formation. Cascading LCDs have a multiplicative effect on the incident light,[10-13] with the polarizers between panels in place or a polarization-rotating effect without the polarizers.[14] Volumetric displays, such as spinning disks or multi-focal-plane displays, are inherently additive, and hence provide a linear image formation. By using a 4-D frequency analysis,[10,11] one can show that multiplicative non-linear displays, at least in theory, support high-resolution virtual content to be displayed outside and in between the physical layers with high resolution. This is not the case for additive multi-focal-plane displays.

The human visual system is a complex mechanism. In addition to all the depth cues, two of its characteristics are particularly important for 3-D display design: visual acuity and the critical flicker fusion threshold (CFF). Usually, 3-D display capabilities are created by reducing either the resolution of the screen or multiplexing information in time. These are fundamental tradeoffs that cannot be easily overcome; basically, "there is no free lunch."

The most reasonable thing to do would be to make tradeoffs where an observer would not perceive them. Resolutions available in commercial panels are now at, or at least close to, the "retina" level. Adding 3-D capabilities through spatial multiplexing, as is the case for integral imaging, reduces the resolution by a factor that is equal to the number of light-field views. If only a few views are desired, this may be a reasonable approach, but for wide field-of-field multiview displays, the loss in resolution is unacceptable for an observer.

With currently available panel resolutions, adding 3-D capabilities through spatial multiplexing may actually decrease the overall viewing experience because the gain in 3-D capabilities may not be justified by the loss of resolution. However, the critical flicker fusion threshold of the human visual system is much lower than display refresh rates offered by consumer displays. LCDs can achieve about 240 Hz, and MEMS devices run in the kHz range. This is already widely exploited in active shutter-glasses-based 3-D displays, field-sequential-color displays (*e.g.*, in projectors), and also in time-sequential volumetric

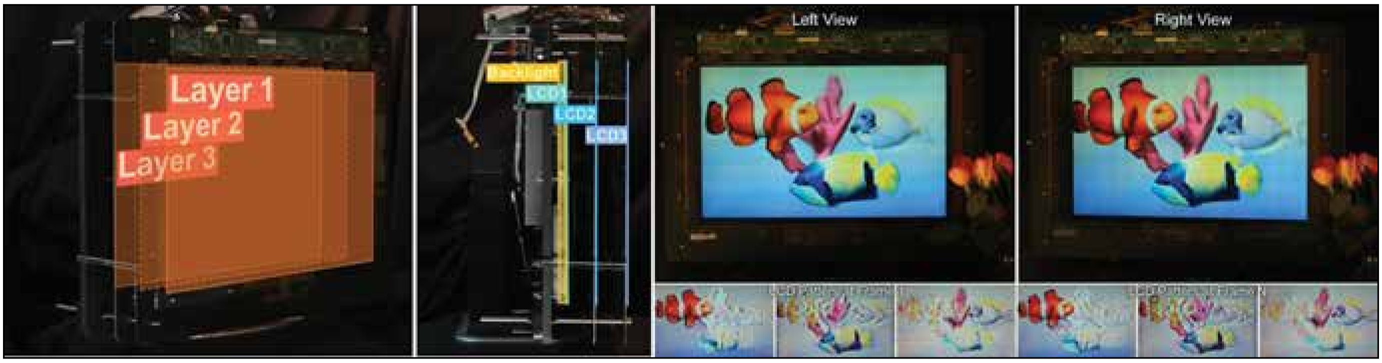

Fig. 2: *This compressive light-field prototype uses three stacked layers of LCDs (left) that are rear-illuminated by a single backlight. A non-negative light-field tensor factorization algorithm computes time-multiplexed patterns for all LCD layers (bottom right), which are then displayed at a speed exceeding the critical flicker fusion threshold of the human visual system. Perceptually, these patterns fuse into a consistent high-resolution light field that supports binocular disparity and motion parallax without the need for glasses (right). Image courtesy Wetzstein et al. (Ref. 10).*

displays. Although not perfect, it appears to be the most reasonable choice if making tradeoffs cannot be avoided. Compressive light-field displays usually are also time-multiplex visual signals, but some incarnations[10,15] are designed such that the same hardware configuration allows for dynamic tradeoffs in resolution, image brightness, 3-D quality, *etc.*, to be made in software in a content-adaptive manner.

And although compressive light-field displays have so far only been demonstrated in the form of academic prototypes (Fig. 2), the promised benefits make further research and development worthwhile: traditional resolution tradeoffs can be overcome, device form factors can be reduced, requirements for display refresh rate and resolution can be relaxed, and visual discomfort introduced by the vergence-accommodation conflict can be mitigated. The design and implementation of such displays is at the convergence of applied mathematics, optics, electronics, high-performance computing, and human perception.

3-D Projection: Toward the Holodeck

Large-scale glasses-free 3-D displays have a wide range of applications in collaborative learning, planning and training, advertisement, scientific visualization, and entertainment. Over the last decade, light-field projection systems that provide an impressive image quality and extreme depth of field have emerged.[8,9] For horizontal-only parallax systems, a one-dimensional array of projectors is mounted in front of or behind a vertical-only diffusing screen. The diffuser ensures that the generated image is independent of the vertical viewing position, whereas the horizontal directionality of individual projector rays is preserved by the screen. As a viewer moves in front of the displays, his eyes sample the emitted light field. As with any 3-D display, there are tradeoffs. The number of required projectors directly scales with the desired field of view and angular density of emitted rays. In practical applications, dozens

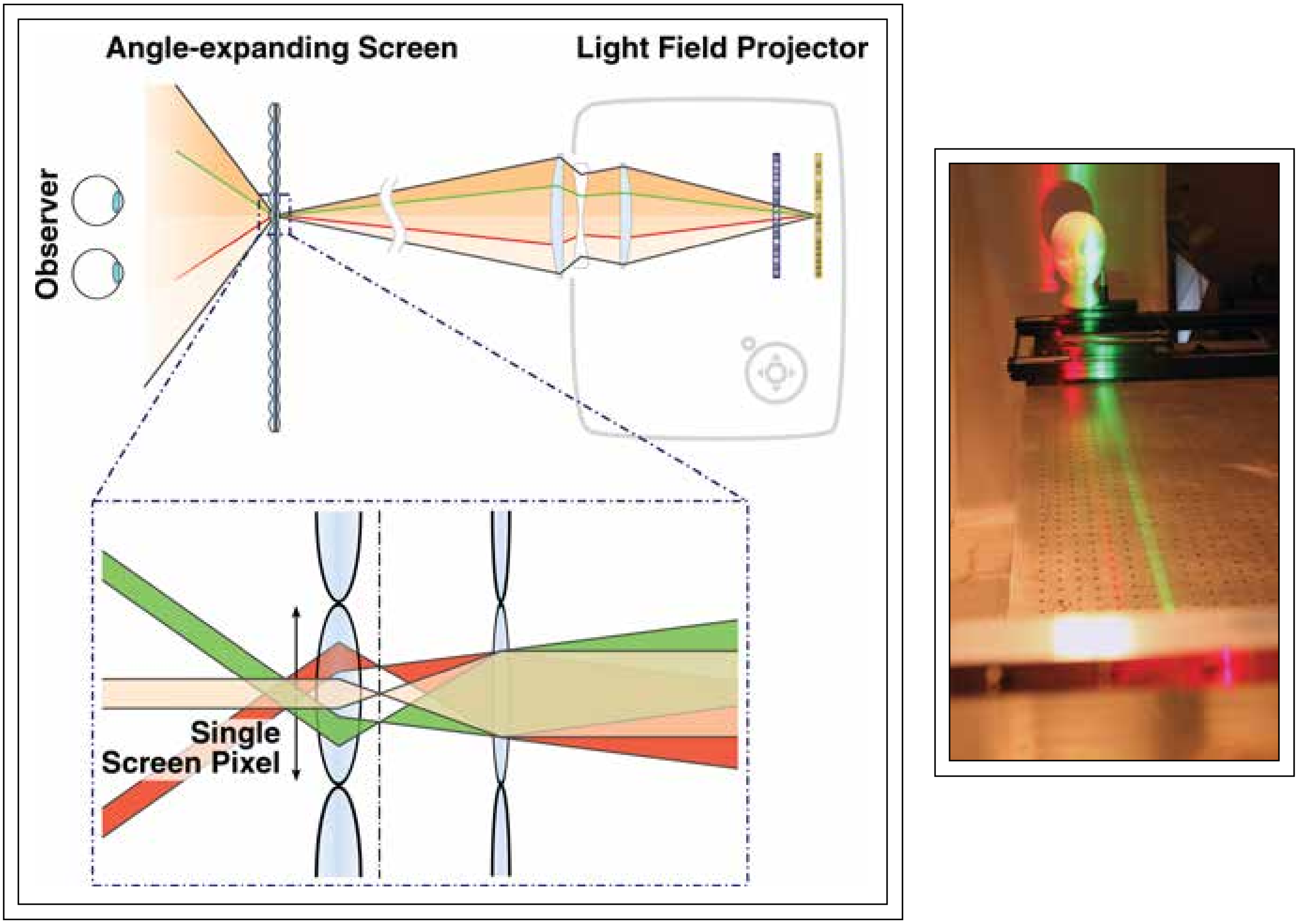

Fig. 3: At left is a schematic of a compressive light-field projection system comprised of a passive angle-expanding screen and a light-field projector. On the right is a photograph of a prototype system demonstrating a field of view and viewing zone separation suitable for a 3-D display. Image courtesy Hirsch et al. (Ref. 16).

of projectors are often employed, which makes multi-projector light-field displays expensive, difficult to calibrate, power hungry, and sometimes bulky. These limitations may not be restrictive for some applications – for example, military training – but it could be argued that they make consumer applications currently unfeasible.

The compressive light-field methodology also applies to projection systems.[16] In this case, the goal is to "compress" the number of required devices, thereby increasing power efficiency, form factor, and cost of the system. The basic idea behind compressive light-field projection is intuitive: ideally, one would only use a single projector that generates a light field inside the device and emits it on a screen that preserves the angular variation of the light field. Diffusers would not be suitable for that task. Furthermore, the field of view of the emitted light field would only be as large as the projector aperture, so at first glance this does not seem like a feasible option.

A possible solution to this problem was recently presented[16]: a light-field projector that employs two cascading spatial light modulators (SLMs) and a rear-illuminated passive screen that not only preserves angular light variation but actually expands it such that the perceived field of view is much larger than the projector aperture. This angle expansion can be achieved by a screen that is composed of two microlens arrays with different focal lengths, mounted back-to-back. Each of the microlenses covers the area of a single pixel, thereby not compromising image resolution. As illustrated in Fig. 3, each of the screen pixels is a beam expander (or tiny Keplerian telescope), which expands the field of view but inherently shrinks the pixel area on the other side. The tradeoff is now between pixel fill factor and desired angle amplification. A prototype system providing a field of view 5° for a monochromatic light field was recently demonstrated by Hirsch *et al.*[16] This is a promising direction that may lead to practical and low-cost 3-D projection systems, but high-quality manufacturing techniques for angle-expanding screens providing a significantly higher angle expansion factor have yet to be developed.

Assessing and Enhancing Human Vision

Perhaps one of the most unconventional applications of light-field displays is the assessment[17] and correction[18] of visual aberrations in a human observer (see Fig. 4). In essence, the light-field display presents a distorted light field to the eyes of the viewer such that her aberrations undistort the light-field imagery, resulting in the desired image. The idea is very similar to wavefront correction with coherent optics. The requirements on the light-field display are extreme in this case.

For conventional 3-D displays, as discussed above, stereoscopic depth cues and motion parallax are usually sufficient. Hence, the emitted light field has to provide views that are densely packed such that each of the eyes of the observer always sees a different image. For vision assessing and correcting displays, one not only needs to emit two different images into the observer's eyes, but multiple different images into the same pupil. At least two different views have to enter the same pupil to produce a retinal blur that triggers accommodative responses.[19] Although researchers have attempted to produce faithful focus cues – accommodation and retinal blur – in addition to binocular disparity and motion parallax,[13] it is very challenging to achieve high image quality, and diffraction places an upper boundary on the achieved resolution. The diffraction limit is critical in this context because transparent LCDs are high-frequency pixel grids that filter visual signals (or additional LCDs) physically located behind the former LCDs such that those are optically blurred via diffraction. The smaller the pixel structures, the more blurred the spatial content of farther display planes becomes. Hence, there is a type of uncertainty principle at work: adding more and higher-resolution LCDs to the stack ought to increase the 3-D capabilities of the device, yet it comes at the cost of reduced spatial resolution of other device components.

Ignoring stereo cues and motion parallax, however, allows for practical light-field displays to be built that support only focus cues.[17,18] To assess visual aberrations, a light field containing a pair of lines can be presented to an observer such that the retinal projections exactly overlap when the viewer has normal or corrected vision but appear at spatially distinct locations when that is not the case. By interactively aligning the lines, one can manually pre-distort the light field until the pre-distortions are canceled out by the refractive errors of the eye. The amount of manually induced pre-distortion then gives

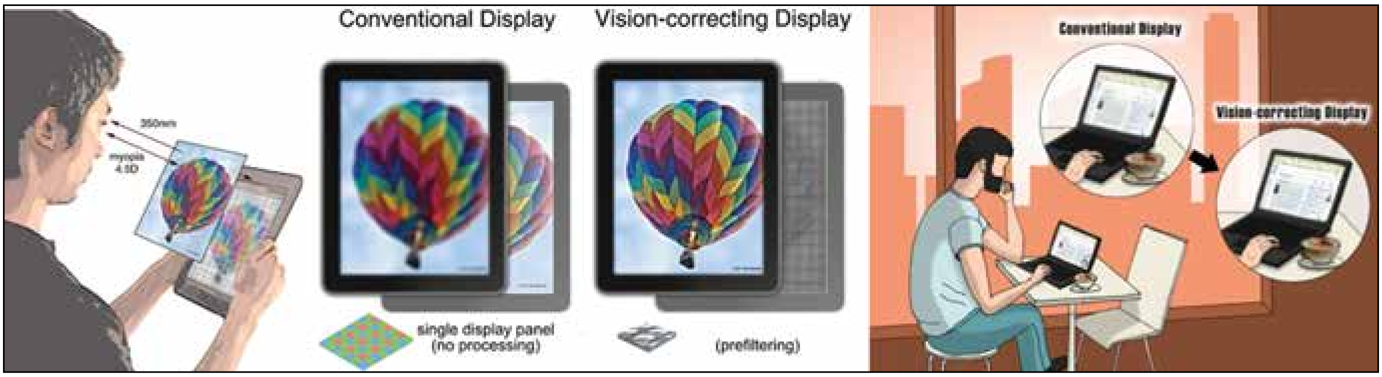

Fig. 4: *At left is a comparison between a conventional display and a vision-correcting light-field display. On the right are some application scenarios. Vision correcting displays could be integrated into existing displays and used in laptops, cellphones, watches, e-Readers, and cars to provide a comfortable eyeglasses-free experience. Image courtesy Huang et al. (Ref. 18).*

insights into the distortions in the eye. The procedure can be repeated for lines at varying rotation angles, allowing for astigmatism to be estimated as well as defocus.

Assuming that the refractive errors in the eye are known, either from an eye exam or through self-diagnosis, one can also emit arbitrary light fields that are pre-distorted for a particular viewer. This approach creates a vision-correcting display. Instead of correcting vision with eyeglasses or contact lenses, the same can be done directly in the screen, allowing for myopia, hyperoptia, astigmatism, and even higher-order aberrations to be corrected.

The main technical insight of recent work on vision-correcting displays is this: the image presented on a conventional display appears blurred for a viewer with refractive errors. One could attempt to deconvolve the presented image with the point-spread function of the observer, such that the image and the observer's visual defects together optically cancel out,[20] but it turns out that this is usually an ill-posed mathematical problem. Employing light-field displays, however, uses the same idea but lifts the deconvolution problem into the 4-D light-field domain, where it becomes mathematically well-posed. Current vision-correcting displays require the prescription of the viewer to be known (no changes to the hardware are necessary; different prescriptions can be corrected in software) and the pupil positions and diameters to be tracked. The latter is an engineering challenge that would have to be implemented to make vision-correcting light-field displays robust enough for consumer devices.

Near-to-Eye Displays

One application of light-field displays that has received a lot of attention recently are wearable displays. With the emergence of Google Glass, the Oculus Rift, and, more recently, Microsoft's HoloLens near-to-eye displays for virtual reality (VR) and augmented-reality (AR) applications in the consumer space have become one of the most anticipated emerging technologies.

Unfortunately, no existing near-to-eye display supports correct focus cues, which are crucial for comfortable and natural viewing experiences. For immersive VR, this lack of support results in the well-known vergence-accommodation conflict,[21] which can lead to visual discomfort and fatigue, eyestrain, diplopic vision, headaches, nausea, compromised image quality, and even pathologies in developing visual systems. Only a few display solutions exist that support correct or nearly correct focus cues;[5,6] *i.e.*, accommodation and retinal blur. These are multi-focal-plane displays that closely approximate volumetric displays.[3,4] Volumetric displays can be interpreted as one special type of light-field display that is capable of producing light distributions that are a subset of the full 4-D light-field space.

Lanman *et al.*[22] have recently shown that a different implementation of a near-to-eye light-field display (*i.e.*, integral imaging) is also suitable for supporting focus cues within some range and at a reduced image resolution (see Fig. 5). The focus of their paper was the design of a very thin device form factor rather than an in-depth evaluation of the range in which focus cues are actually supported. This idea is very similar to vision-correcting

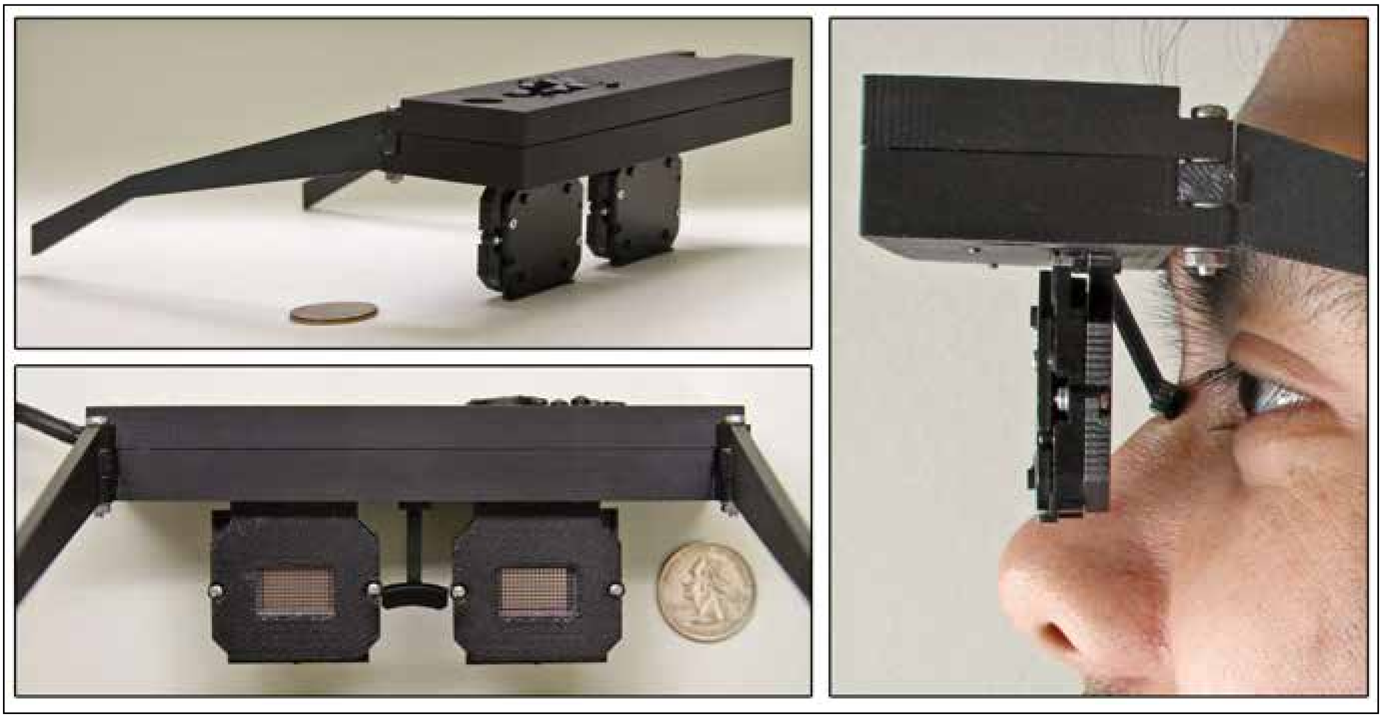

Fig. 5: *The shown near-to-eye light-field display provides a very thin form factor and correct or nearly correct focus cues within a limited depth range. Image courtesy Lanman et al. (Ref. 22).*

light-field displays: a virtual image is shown outside the physical device enclosure. In principle, both could be combined into a single, slim near-to-eye display that supports focus cues and simultaneously corrects myopia, hyperopia, astigmatism, and higher-order aberrations in the eye. However, such a device has not been demonstrated yet. The requirements for focus-supporting near-to-eye light-field displays are the same as for vision-correcting displays: at least two different views have to enter the same pupil.[19] In display applications, the algorithms doing digital refocus in light-field cameras ("shift and add light-field views") are optically performed in the eye. Overall, near-to-eye light-field displays hold great promise in overcoming some of the most challenging limitations of head-mounted displays today and helping to create more-comfortable and natural viewing experiences. Perhaps this is one of the most promising and at the same time unexplored areas of light-field displays in general.

Light Fields and Holography

The difference between light fields and holograms is a subject for evening-filling philosophical discussions and cannot easily be answered. The author's take on it is this that both effectively create similar viewing experiences, but a fundamental difference is that light fields usually work with incoherent light and holograms are based on coherent illumination. However, partially coherent or incoherent holograms exist as well and light-field displays can also account for diffractive phenomena.[24] The boundaries between these fields are fluid, but traditionally holograms are modeled using wave optics, whereas light fields are modeled as rays or geometric optics. As pixels get smaller, the image formation of light-field displays will have to incorporate diffractive effects, so the areas are expected to merge eventually. Nevertheless, it is advantageous to think about light fields in the ray-space because it makes connections to advanced signal processing and optimization algorithms, such as computed tomography[11] and a non-negative matrix[12] and tensor factorization,[10] very intuitive.

A Potential As Yet Unrealized

In summary, light-field displays have a wide range of applications in 3-D television and projection systems; they enable technologies for vision assessment and correction, and one of the "hottest" areas at the moment are applications to small form factors and the support for focus cues in head-mounted displays. Even if public interest in any of these applications may diminish in the long term, light fields provide a fundamental framework that allows almost all existing display technologies to be analyzed and compared in a unifying mathematical framework. The same framework also makes it intuitive to leverage modern signal processing and optimization algorithms, which has led to the emergence of compressive light-field displays. Finally, very similar strategies can be employed to design and build 2-D super-resolution and high-dynamic-range displays.[15,16,23]

Thus far, all of the recent advances in computational and compressive display technology have been made using standard optical and electronics components, including LCDs, liquid-crystal–on–silicon (LCoS) microlens arrays, *etc.* Future designs, however, may incorporate completely new optical designs that are not only tailored to a particular application (wearable, mobile, television) but also to specific algorithms driving these devices. We have entered an area in which advanced computation has become an integral part of the image formation in many emerging display technologies. The synergy between computation, optics, electronics, and human perception is expected to become even more important in the future.

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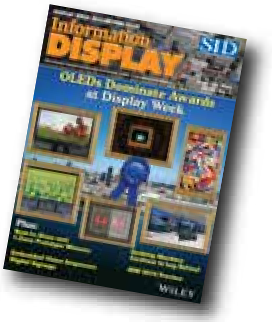

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Inspiration and Innovation Abound at Display Week's Annual Technical Symposium

This year's technical program at Display Week features more than 450 papers on topics ranging from quantum dots to light-field displays.

by Jenny Donelan

THE display industry is never static, and the annual SID International Symposium at Display Week both reflects and informs that state of constant change. Last year, backplane technology took center stage at the symposium, with 12 papers devoted to the topic of Oxide vs. LTPS TFTs alone. This year, backplanes remain an essential focus, but other topics, including materials that promise to disruptive the industry as we know it, are strongly represented. Program Chair Seonki Kim also points to an increased number of papers on vehicle displays and also displays being produced in curved and non-rectangular form factors.

This year, the technical symposium features 75 sessions and more than 460 papers. That's more than any one person can take in during the four days (June 2–5) of the program, but you can take in a lot if you plan ahead by accessing the preliminary program online at http://displayweek.org/2015/Program/Symposium.aspx and also by reading this article, in which we point out some of the highlights.

Each year, the papers presented are organized by their major technical focus – Active-Matrix Devices, Applications, Applied Vision/Human Factors, Display Electronics, Display Manufacturing, Display Measurement, Display Systems, Emissive Displays, e-Paper and Flexible Displays, Liquid-Crystal Technology, OLEDs, Projection, and Touch and Interactivity – then assigned to sessions designated by topic, such as Wearable Display Systems. Each session consists of three to five 20-minute paper presentations. This year, four special focus areas – Oxide and LTPS TFTs, Wearable Displays, Disruptive Display Materials, and Curved and High-Resolution Displays – and three Mini-Symposia on Lighting [in cooperation with the Illuminating Engineering Society (IES)], Vehicle Displays and Trends, and Imaging Technologies and Applications were also included.

The peer-reviewed papers chosen for presentation at Display Week represent the best of the best. Here are just some of the highlights from this year's sessions.

Quantum Dots and Other Disruptive Materials

Even if you can't see quantum dots (QDs) – these tiny nanocrystals range from 2 to 10 nm (10–50 atoms) in diameter – they have been hard to miss lately. QDs are not new to the symposium or the exhibit hall at Display Week – companies such as 3M, Nanosys, and QD Vision have been named by SID's awards committee several times since 2012 for their quantum-dot technology. Last year's technical program featured three sessions dedicated to quantum dots, and, at the time, this magazine noted that the technology was gaining momentum. What's new this year is that quantum dots are rapidly showing up in a whole range of LCD-based products, such as Amazon's Kindle Fire tablets and in LCD TVs shown at CES last January. "It's nice to see this technology moving from the experimental phase to the lab and now to product fruition," says Qun "Frank" Yan, co-chair of the Emissive Displays subcommittee.

Quantum dots have many potential uses, as will be discovered in this year's symposium, again offering three dedicated sessions on QDs. "Quantum dots have the potential to disrupt the display industry," says Seth Coe-Sullivan of QD Vision, Vice-Chair of the Disruptive Display Materials special topic. Despite the aforementioned commercial forays, many of the improvements to the technology are still at the research stage, he says, adding: "The next question is: Can we reduce that science to practical innovations that lead to improved products?"

There is a great deal of interest in how QDs can help achieve Rec. 2020, the new ITU color specification for UHD broadcasting, says Coe-Sullivan. Jame Thielen of 3M will be presenting an overview of that effort in the paper "Optimizing Quantum-Dot LCD Systems to Achieve Rec. 2020 Color Performance." Another recommended paper is "Next-Generation Display Technology: Quantum-Dot LEDs" from Jesse Manders of NanoPhotonica. The NanoPhotonica team achieved extremely high external quantum efficiency for green and blue quantum-dot LEDs, as well as high performance for red QD-LEDs.

Quantum dots are but one technology classified as disruptive by this year's technical

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Display Week 2015 Symposium at a Glance

2015 SID Display Week Symposium at a Glance – San Jose Convention Center

Day	Times	Ballroom 220B	Ballroom 220C	Room LL20A	Room LL20BC	Room LL20D	Room LL21EF	Room LL21D
Tuesday, June 2	8:00 – 10:20 am	SID Business Meeting and Keynote Session (Ballroom 220A)						
	10:50 am – 12:10 pm	3 Wearable Display Systems (Joint with Display Systems and Projection)	4 Flexible Display Manufacturing	5 Image Quality of Displays	6 Novel Display Applications I	7 OLED Driving Techniques	8 Quantum-Dot Materials (Joint with Disruptive Materials)	Imaging Technologies and Applications I
	2:00 – 3:20 pm	9 Wearable Displays: Direct View (Joint with e-Paper/Flexible)	10 OLED Encapsulation and Reliability	11 Hunan Factors and Applications	12 Novel Display Applications II	13 Advanced Displays and Imaging	14 Photoluminescent Quantum Dots	Imaging Technologies and Applications II
	3:40 – 5:00 pm	15 Applied Vision and Applications of Wearable Displays (Joint with Applications)	16 OLED Deposition and Patterning	17 Color Appearance of Displays	18 Applications of Flexible Display Technology (Joint with e-Paper/Flexible)	19 Image Processing for Display Enhancement	20 Electroluminescent Quantum Dots (Joint with Disruptive Materials)	Imaging Technologies and Applications III
	5:00 – 6:00 pm	Author Interviews						
Wednesday, June 3	9:00 – 10:20 am	21 Oxide-TFT Manufacturing	22 OLED Materials I	23 e-Paper	24 3D Light-Field Displays and Imaging	25 Laser-Phosphor Light Sources for Projectors	26 Micro LED Displays and Electroluminescence	
	10:40 am – 12:00 pm	27 Advanced Manufacturing Technologies	28 OLED Materials II	29 TFTs and Circuits for Flexible Devices (Joint with e-Paper and Flexible Displays)	30 3D Applications	31 Disruptive LCD Materials (Joint with Disruptive Materials)	32 Front Lighting and Reflective Displays (Joint with e-Paper/ Flexible and Lighting)	
	2:00 – 3:30 pm	Designated Exhibit Time (Exhibit Hall)						
	3:30 – 4:50 pm	33 Novel Devices	34 Disruptive OLED Materials (Joint with Disruptive Materials)	35 Projetion Optics	36 Holographic 3D Displays	37 Blue-Phase LCDs	38 OLED Lighting (Joint with Lighting)	
	5:00 – 6:00 pm	Author Interviews (Ballroom 210)						
Thursday, June 4	8:30 – 9:00 am			Vehicular Displays and Trends Morning Plenary Talk				
	9:00 – 10:20 am	39 Advanced TFTs	40 OLED Devices I	41 Automotive Display Applications and Systems	42 Curved and High-Resolution Display Metrology (Joint with Curved and High-Resolution Displays)	43 FFS/IPS I	44 Advanced Light Sources, Components, and Systems I	
	10:40 am – 12:00 pm	45 High-Performance Oxide TFTs I	46 OLED Devices II	47 Next-Generation Automotive Display Technologies I: HUDs (Joint with Display Systems)	48 Display Standards and Their Application to Transparent Displays	49 FFS/IPS II	50 Effect of Lighting on Health and Perception	
	1:00 – 1:30 pm			Vehicular Displays and Trends Afternoon Plenary Talk				
	1:30 – 2:50 pm	51 High-Performance Oxide TFTs II	52 OLED Devices III	53 Touch, Interactivity, and Human-Machine Interface (Joint with Touch and Interactivity)	54 Transparent Display Systems	55 LC Beyond Displays	56 Advanced Lighting Applications	
	3:10 – 4:30 pm	57 Oxide and LTPS TFTs	58 OLED Displays I	59 Next-Generation Automotive Display Technologies II: Flexible, Curved, Coatings	60 Capacitive Touch	61 Liquid-Crystal Lenses	62 Advanced Light Sources, Components, and Systems II	
	4:30 – 5:30 pm	Author Interviews (Ballroom 210)						
	5:00 – 8:00 pm	Poster Session (Ballroom 220A)						
Friday, June 5	9:00 – 10:20 am	63 High-Resolution Displays	64 OLED Displays II: Curved and High-Resolution (Joint with Curved and High-Resolution Displays)	65 Flexible Display Technology	66 Stereoscopic 3D Displays (Joint with Projection)	67 Photo Alignment	68 Touch Systems and Materials (Joint with Manufacturing and Vehicular)	
	10:40 am – 12:00 pm	69 Oxide-TFT Reliability	70 OLED Displays III	71 Flexible Encapsulation	72 Curved and High-Resolution Large Displays (Joint with Curved and High-Resolution Displays)	73 Ultra-Low-Power LCDs	74 Touch Applications	

TECHNOLOGY TRACKS KEY

Active-Matrix Devices	Applications	Applied Vision	Curved and High-Resolution Displays		Display Electronics	Display Measurement
Display Systems	Disruptive Materials	Emissive Displays	e-Paper/Flexible	IES Lighting	Imaging	Liquid-Crystal Technology
Manufacturing	OLEDs	Oxide and LTPS TFTs	Projection	Touch and Interactivity	Vehicular	Wearable Displays

program organizers. Other technologies include new material innovations in LCDs and in OLEDs, according to Coe-Sullivan. "OLED is very materials-innovation heavy right now," he says. One example is the invited paper, "Combinatorial Design of OLED-Emitting Materials," by Alán Aspuru-Guzik of Harvard University, which looks at a particular example of recent developments in thermally assisted delayed fluorescence (TADF) emitters that are enabling novel classes of OLEDs using technology that may be better for the environment and, possibly, longer lasting than OLEDs using phosphor emitters. A representative paper on potentially disruptive LCD developments is "Evolution of Cellulose Triacetate (TAC) Films for LCDs: Novel Technologies for High Hardness, Durability, and Dimensional Stability" by Ryo Suzuki of Fujifilm Corp., which describes the development of different films that could solve stability problems caused by reductions in the thickness of polarizers and reduce warping in IPS-LCD TV panels.

An even more disruptive technology, notes Yan, are micro-sized LEDs, which he says could be the display industry's "next big thing." These LEDs integrate light source and optics, enabling high-pixel density and may be well-suited to 3-D displays, he says. Ostendo, last year's Innovation Zone winner at Display Week, has a very interesting paper on this technology: "Quantum Photonic Imager (QPI): A Novel Display Technology that Enables more than 3D Applications," by Hussein S. El-Ghoroury, which describes the QPI, a 3D-IC semiconductor device comprising a high-density array of digitally addressable micro-LED pixels.

OLEDs

The biggest trend in OLEDs, according to subcommittee chair Sven Zimmermann, are the TADF emitters mentioned in the disruptive materials section above. He believes these may soon be competitive with normal phosphorescent emitters (which contain heavy metals and have lifespan issues). TADF OLEDs also have a more uniform spectral distribution, which could make them strong candidates for lighting applications in particular.

Zimmermann notes that there are also several symposium papers on OLED TV. The current state of the art can be found in the paper "High-Performance Large-Sized OLED TV with UHD Resolution" from Yu-Hung Chen of AU Optronics Corp., in which the author and his team describe the architecture and fabrication of a high-performance 65-in. ultra-HD OLED TV with excellent visual quality that utilizes stable arrays and cutting-edge OLED processes.

Flexible, Foldable, Wearable

Flexible technology continues to be a hallmark of Display Week, and the most outstanding trend here is that flexible displays are entering a more mature phase, according to subcommittee chair Kevin Gahagan of Corning, who cites commercial examples that contain flexible displays, such as LG's G Flex phone. Flexible papers this year reflect that relative maturity, he says, in that issues like scaling are more of a focus, as well as encapsulation and the integration of features such as touch and transparency. "The [whole] system has to be flexible," he says.

Looking farther ahead, Gahagan thinks that foldable is the next frontier for flexible devices. "We're seeing demos of foldable displays that are high resolution, with many bend cycles." One example is "Foldable AMOLED Displays with a Touch Panel" from Jia-Chong Ho of ITRI. "There is a growing consensus that foldable is the ultimate form factor," says Gahagan. "It's easy to interact with." Although the flexible display that can be rolled up and popped into a purse or briefcase has been the form factor most people imagine for the ultimate flexible display, the scroll can be problematic because when you write on it, it's unsupported in the middle, explains Gahagan. "This might be speculation," he says, "but foldable is where I think we're headed."

The category of flexible often meshes with wearable, and a case in point is the paper "Stretchable 45 × 80 RGB-LED Display Using Meander Wiring Technology" by Hideki Ohmae of Panasonic Corp. This paper describes a foldable and stretchable (up to 10%) fabric-like display that incorporates LEDs. Another wearable paper to look for is "High-Image-Quality Wearable Displays with Fast-Response Liquid Crystal" by Zhenyue Luo at the University of Central Florida. Luo reports on two ultra-low-viscosity liquid crystals with a field-sequential-color LCOS. The LC's fast response time offers vivid color, a high ambient contrast ratio, low power consumption, and mitigated color breakup even in extremely low temperatures.

Touch, Liquid Crystals, and Projection

Touch technology has been an integral part of the display industry and Display Week for several years. Subcommittee chair Jeff Han notes that even though there may not seem to be as much touch news as there has been in the past: "Touch is still hot. People just don't want to talk about it because companies integrating touch would have to describe their own stacks, *etc*." In terms of trends: "In-cell is what it's all about," says Han. "I feel like the tide is turning in this regard [in the direction of vertical integration]." There are still plenty of touch papers at the symposium, with four separate sessions. The invited paper "Panel-Structure Evolution of In-Cell Capacitive Touch Sensor" by Qijun Yao of Shanghai Tianma Microelectronics Co. will look at various integration schemes for in-cell capacitive touch panels and review ongoing efforts being made to eliminate the interference between display and touch-sensor structure. That paper will also present an in-cell LCD module with an integrated self-capacitance touch sensor.

In terms of liquid crystals, besides the disruptive materials papers mentioned earlier, fringe-field switching (FFS) and in-plane switching (IPS) are current trends in the industry, according to subcommittee chair Philip Chen, as are suggested breakthroughs for blue phase involving a new structure. Look for the papers "A High-Transmittance IPS LC Mode Using a New Self-Aligned Structure" by Sun-Hwa Lee, of LG Display Co., "A Fast-Response A-film-Enhanced FFS LCD from AU Optronics Corp., and "A Blue-Phase LCD with Wall Electrode and High-Driving-Voltage Circuit" by Cheng-Yeh Tsai, also of AUO.

The biggest trend in projection this year is that solid-state light sources are replacing lamps, according to projection co-chair Dave Eccles. LEDs were much vaunted for projectors a few years ago, but are not really bright enough for most applications beyond pico projectors, explains Eccles. Laser phosphors, which have been described in papers at Display Week for some years, are now being used in commercial products. They can be employed for everything from pico projectors to digital-cinema projectors, says Eccles, though in digital-cinema applications, laser phosphor projectors are referred to as "non-coherent light" for public-relations purposes. A particularly educational and interesting

Display Week 2015 Overview

San Jose Convention Center, San Jose, California, USA

May 31–June 5, 2015

TIMES	Sunday May 31	Monday June 1		Tuesday June 2				Wednesday June 3			Thursday June 4				Friday June 5
	Short Courses	Seminars	Business Conf.	Symposium	Mini-Symposium	Exhibits Exhibitors Forum Sessions / I-Zone	Investors Conf.	Symposium	Exhibits Exhibitors Forum Sessions / I-Zone	Market Focus Conf.	Symposium	Mini-Symposia	Exhibits Exhibitors Forum Sessions	Market Focus Conf.	Symposium
7:45 AM			Business Conference	Session 1: SID Business Meeting											
8:30 AM		Seminars M1 - M3		Session 2: Welcome / Keynote Addresses								Vehicular Displays and Trends Sessions 41, 47, 53, 58			
9:00 AM	Short Courses S-1 & S-2							Oral Sessions 21-26	Exhibits / Exhibitors Forum / I-Zone	Market Focus Conference: Touch	Oral Sessions 39-44	SID/IES Lighting Sessions 44, 50, 56, 62	Exhibits / Exhibitors Forum	Market Focus Conference: Wearable - Flexible	Oral Sessions 63-68
9:30 AM															
10:00 AM															
10:30 AM		Seminars M4 - M6		Oral Sessions 3-8	Imaging Technologies and Applications Sessions I, II, III	Exhibits / Exhibitors Forum / I-Zone	Investors Conference	Oral Sessions 27-32			Oral Sessions 45-50				Oral Sessions 69-74
11:00 AM															
11:30 AM															
12:00 PM			Bus. Conf. Lunch					DIA & Best-in-Show Awards Luncheon			Lunch				Author Interviews
12:30 PM				Lunch											
1:00 PM		Seminars M7- M9									Oral Sessions 51-56				
1:30 PM			Business Conference												
2:00 PM				Oral Sessions 9-14				Designated Exhibit Time							
2:30 PM															
3:00 PM	Short Courses S-3 & S-4	Seminars M10 - M12									Oral Sessions 57-62				
3:30 PM				Oral Sessions 15-20				Oral Sessions 33-38							
4:00 PM															
4:30 PM											Author Interviews				
5:00 PM		Seminars M13 - M15	Bus. Conf. Recept.	Author Interviews			Inv. Conf. Recept.	Author Interviews							
5:30 PM											Poster Session				
6:00 PM								Special Networking Event San Jose Museum of Art							
6:30 PM															
7:00 PM															
7:30 PM															
8:00 PM		Honors and Awards Banquet													
8:30 PM															
9:00 PM															
9:30 PM															

paper to catch is "The Progress in International Safety Standards for Laser-Illuminated Projection Systems" by Greg Niven of LIPA. "This is a good one for people to hear because it will explain current standards for both the U.S. and the rest of world," says Eccles.

Light-Field Displays

Yet another key technology not to be missed at Display Week is light-field displays. This is an area that is growing, says displays systems chair Kalil Käläntär. "Everyone is being challenged to 'solve' light-field displays, including 3D displays," he says. "Light field would be a great candidate for next-generation displays." To find out more, catch the invited paper "Design Principles for Light-Field Image Capture and Display" by Kathrin Berkner of Ricoh Innovations Corp., in which the author and her team discuss design principles for task-specific light-field camera systems and outline how such principles can be applied to the design of personal light-field displays.

Special Mini-Symposia

New to Display Week in 2015 is the addition of three Mini-Symposia in the form of Special Technology Tracks on Lighting, Vehicle Displays and Trends, and Imaging Technologies and Applications.

SID/IES Lighting: There has always been a great deal of overlap in the technology behind lighting and displays. In recognition of the newly signed Friendship Agreement between SID and the Illuminating Engineering Society of North America (IESNA), the SID/IES Lighting Track aims to deliver in-depth coverage in a diverse range of topics of common interest to both lighting and display professionals. This Mini-Symposium is scheduled for Thursday, June 4, and will consist of the following four sessions:

- Advanced Light Sources, Components, and Systems I
- Advanced Light Sources, Components, and Systems II
- Effects of Lighting on Health and Perception
- Advanced Lighting Applications

There will be additional OLED lighting sessions outside of this 1-day event for more in-depth discussions on OLED device physics and materials. Access to this 1-day Mini-Symposium is included for those attending the Display Week Symposium. It is also available as a stand-alone event to our guests from IESNA. For further registration information, go to www.displayweek.org/2015/Attendee/Registration.aspx.

Vehicle Displays and Trends: This program will bring together scientists, engineers, market analysts, and industry leaders from the display, touch, photonics, and vehicle systems communities for a unique one of a kind event exploring the recent developments and trends of vehicle displays. This Mini-Symposium is also scheduled for Thursday, June 4, and will consist of a morning and afternoon plenary talk and the following four sessions:

- Next-Generation Automotive Display Technologies I: HUDs
- Automotive Display Applications and Systems
- Touch, Interactivity, and Human-Machine Interface
- Next-Generation Automotive Display Technologies II: Flexible, Curved, Coatings

Access to this 1-day Mini-Symposium is included for those attending the Display Week Symposium. It is also available as a stand-alone event. For further registration information, go to www.displayweek.org/2015/Attendee/Registration.aspx.

Imaging Technologies and Applications: The Mini-Symposium on Imaging Technologies and Applications will feature invited papers covering the areas of imaging technologies, products, applications, advanced developments, and emerging trends. This focused track will bring together scientists, engineers, business professionals, market analysts, academic, and industry leaders pioneering the end-to-end chain of imaging to display technologies and applications. Scheduled for Tuesday, June 2, it will consist of three sessions of invited papers that include:

- "On the Duality of Compressive Imaging and Display"
  Gordon Wetzstein, Stanford University
- "Image Systems Simulation"
  Joyce Farrell, Stanford University
- "The Importance of Focus Cues in 3D Displays"
  Martin Banks, University of California at Berkeley, Berkeley, CA, USA
- "Light-Field Imaging"
  Kurt Akeley, Lytro
- "Interactive Systems and Applications Based on Depth-Imaging and 3D-Sensing Technology"
  Achin Bhowmik, Intel Corp.

Access to this 1-day Mini-Symposium is included for those attending the Display Week Symposium. For further registration information, go to www.displayweek.org/2015/Attendee/Registration.aspx.

Keep Up the Pace

As always, there is more to see and hear at the Display Week Symposium than one person can see and hear, and we've only been able to mention a few examples here. Other recommended presentations include the special lighting sessions, vehicle display sessions, display measurement papers that look at metrics for curved displays and transparent displays, near-to-eye display presentations – the list is nearly endless. Whatever you do, don't miss the technical symposium at Display Week. It's the best way to keep up with the pace of the display industry. ■

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2015 EDITORIAL CALENDAR

January/February

Flexible Technology, e-Paper, Wearables
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March/April

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May 4: Editorial Content Proposals due
Sept 2: Ad closing
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Related Technologies and Markets: OLEDs, LCDs, TVs, Retail Electronics
July 1: Editorial content proposals due
Nov 3: Ad closing

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CES 2015: The Show of Everything (SoE)

For a consumer-electronics show, CES 2015 was noticeably shorter on traditional consumer-electronic products than in previous years. Enterprise solutions – such as automotive electronics and displays – received as much attention as TVs.

by Ken Werner

WITH 170,000 registered attendees, the International Consumer Electronics Show in Las Vegas this year was once again the biggest in history, but the show feels increasingly strange. For an event that is nominally about consumer-electronic products, a surprising number of the products shown were not for consumers – and many were not primarily electronic.

Cars, batteries, and electric appliances, both small (as in personal-grooming products) and large (as in home appliances), were just some of the products on exhibit that did not fall under the traditional "CES" umbrella. Some of these products (cars, appliances) had displays; some did not. A significant portion of Panasonic's booth was devoted to a men's grooming salon where male attendees were being barbered for free, with Panasonic grooming devices. Not far away was a beauty salon, where female attendees were being beautified, again with Panasonic products. Samsung, LG, and others showed stoves, refrigerators, washing machines, and dryers.

Panasonic also emphasized batteries, promoting the huge battery plant it is building near Reno with Tesla Motors, which Panasonic called "the largest investment in electric automotive technology anywhere." Also in Panasonic's booth was the new Tesla Model X crossover SUV, which has a 0–60 acceleration time of 5 sec and a very large center-stack display (Fig. 1).

Panasonic certainly was not hiding the industrial thrust of its exhibits. At the company's big press event at the beginning of the week, the company proudly announced it is the "Number 1 supplier of Li-ion batteries for automobiles" and "the Number 1 supplier of automotive infotainment systems worldwide." If there was any doubt about the direction Panasonic is pursuing (outside of grooming products), company executives removed it by saying, "You will increasingly see Panasonic create enterprise solutions as our B2B business grows."

Consider the energy with which TCL, Hisense, and other Chinese TV set-makers are entering the North American market with sets carrying their own brands, the retreat of Toshiba from the North American market, Sharp's licensing of its brand to Best Buy for the 2K part of its TV business, and JVC's

Fig. 1: *Tesla's new Model X, shown in Panasonic's booth, contains an impressively large center-stack display. Photo courtesy Ken Werner.*

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licensing of its direct-view North American TV business to AmTRAN; and then consider Panasonic's statements. It is reasonable to speculate that Panasonic will be the next company to drop out of the consumer TV business.

Automobiles, and Some Electronics

Not many years ago, the North Hall at CES looked like a compact version of the annual show put on by the Specialty Equipment Market Association (SEMA). The hall bristled with garish but beautifully executed custom vehicles, and the air pounded with powerful custom audio systems exquisitely integrated into those vehicles. Some of the SEMA aesthetic could still be seen in North Hall this year, but the show's vibe was more like a toned-down New York (or Detroit or Los Angeles) auto show, with the center of gravity shifted heavily toward vehicle manufacturers instead of after-market customizers.

A JVC Kenwood rep stated his company commanded 50% of the U.S. market for in-deck navigation systems. The Model DDX9702S, in addition to sophisticated audio features such as time alignment and crossover adjustments, provides touch control, phone mirroring and control, optional wireless HDMI, Android Auto, and Apple CarPlay. Android Auto supplies Google Maps, music streaming, "Ok Google" speech recognition, and auto-optimized apps on the Android Auto site. The DNN992 "connected DVD receiver with navigation" incorporates a 6.95-in. hi-res capacitive touch screen, built-in WiFi, a wireless link for in-car content sharing, and a "route collector" trip planner. In the Kenwood booth was a McLaren 650S with its (presumably) Kenwood-based five-display digital cockpit system (Fig. 2).

Fig. 2: *How many displays can you fit in the cockpit of a two-seat car? If you're McLaren, the answer is five. Photo courtesy Ken Werner.*

FCA (Fiat Chrysler Automobiles) showed its RAM 1500 Eco-Diesel light truck. Its large infotainment screen is approximately square and well-integrated into the center stack, but FCA's main interest seemed to be its new U-Connect infotainment system that will present a nearly uniform interface across all of FCA's global markets. FCA's primary interest seems to be the cost savings it can obtain from a (nearly) universal platform.

BMW was emphasizing its electric i3 and stunningly designed i8, along with inductive charging and a key fob for the i8 with multiple control and information capabilities via a small display. The display can provide nuggets of information, such as oil level, battery-charge level, or remaining electric range, and you can code a central button to do something useful, such as flashing the headlights. It will also tell you if you forgot to lock a door. You can check the battery status of your i3 on your smart TV and plan your route before you leave your bed – if you ignore your sleep therapist and keep a TV in your bedroom.

In its large press conference on Press Day and in its booth in Central Hall, Sharp showed its IGZO-driven free-form displays, which feed both column- and row-driving signals in from the bottom edge of the display, so the rest of the display can be curved in various ways to fit the design for an automobile's instrument cluster, or a designer's whim for other locations (Fig. 3). Sharp has shown the concept at display-oriented shows, including SID's Display Week last year, but presenting it at CES implies that Sharp is ready to roll the innovative displays out in volume. Given typical automotive design cycles, it is unlikely we will see these displays in cars for at least 3 years, but see them we will.

Ford stated explicitly that CES is very important to them, and the company wanted to be accepted as part of the CES community. A Ford executive suggested that Ford's sizeable presence at CES this year is likely to grow. Although other manufacturers may not have made that statement explicitly, several traditional makers of consumer electronics, Panasonic among them, implied that they were emphasizing their automotive electronic products.

The logic behind this is clear. As consumer electronics continues to be a difficult business with low margins and many competitors, automotive electronics is a rapidly growing

Fig. 3: *This "free-form" automotive display from Sharp was shown at CES. Photo courtesy Ken Werner.*

market with significant opportunities for innovation and profit.

Displays at CES

Despite the automotive distractions, there were still a lot of consumer-electronic products at CES. A major trend in TV this year is the increasing commoditization of UHD (4K) TV. The speed with which 4K has gone from expensive to cheap continues to surprise many people in the industry.

Quantum-dot-enhanced TVs are at the same stage this year as 4K was last year. Many major manufacturers announced QD-enhanced TVs for release this year, including Samsung, LG, and TCL. Unfortunately, they will probably be called "QD TVs." But we survived "LED TVs," and we can probably survive "QD TVs" too (Fig. 4).

Viewed side by side with conventional LCD TVs, the increased color saturation and gamut produced by QDs provide an obvious improvement in image quality and allow TV makers to exceed 90% of REC.2020. Combined with 4K, QDs produce really compelling images. Samsung went so far as to say that QD enhancement provides image quality that is superior to OLED.

In its suite, QD Vision had a side-by-side demo that went a long way toward providing credibility for Samsung's claim. The QD TV using QD Vision's Color IQ optical element exhibited greater luminance and color gamut than the OLED TV next to it. The QD TV could not match the OLED's inky blacks, but one could make a credible case that the QD TV had a better image overall. Not everybody will agree with that case, but it is defendable.

When LG announced its line of QD-enhanced TVs, its marketing people were forced to walk a very tricky tightrope. On the one hand, the company said its new QD-enhanced TVs offer a huge improvement over conventional LCDs, that the new sets are beautiful, and that everybody should buy one – but they are not as good as OLED TVs, which is the technology of tomorrow. That's a tightrope on which they might not be able to balance for long.

Panasonic and Sharp were using non-quantum-dot phosphor sheets to enhance color gamut instead of sheets or linear elements containing quantum dots. Panasonic described its approach in some detail, claiming up to 98% of the DCI color space (which is considerable smaller than Rec.2020) and high color accuracy within the space thanks to "professional-level 3D lookup tables" and "six-color reproduction." Strangely, Sharp was not straightforward about its approach, calling it "Sharp's version of quantum dots." I would guess that Sharp will be moving to a true quantum-dot solution in the relatively near future.

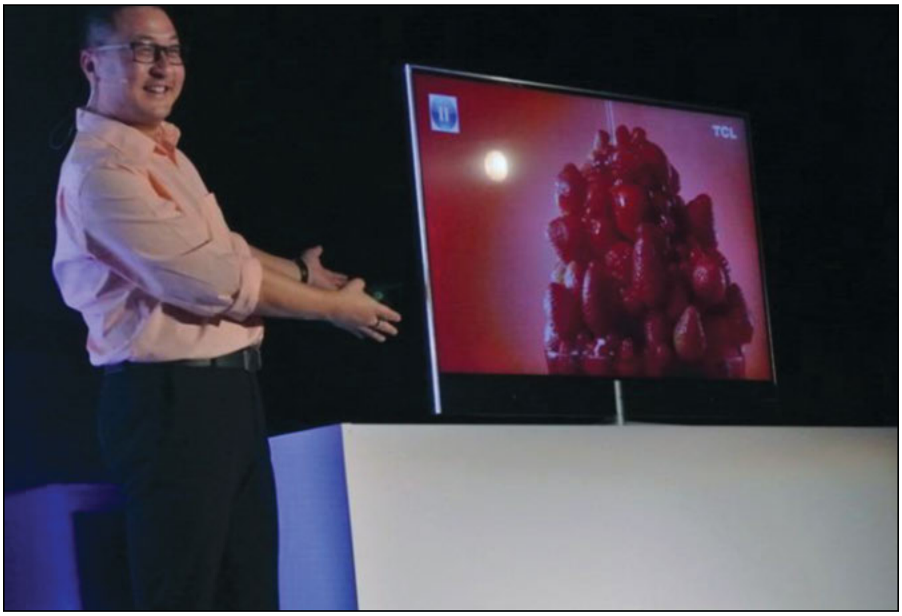

Fig. 4: *A TCL executive gleefully introduced TCL's new quantum-dot-enhanced TV and the company's relationship with QD Vision. Photo courtesy Ken Werner.*

This year QD will be for premium sets, with TCL saying it will have a UHD 65-in. set with QD for $3000 later in the year. Next year, these sets will enter the pricing mainstream.

As usual, LG had a very large exhibit for customers, analysts, and the press in a hotel suite. Of course, LG was featuring its mid-to-very-large-sized curved UHD OLED-TV panels, but I was taken by the flat 55-in. UHD OLED TV with its impressive pixel density and typical OLED color saturation and contrast ratio. For those inclined to say at this point that you cannot see the difference between 2K and 4K on a 55-in. screen at normal viewing distance, I can only respond that the Snellen visual-acuity chart in your optometrist's office does not begin to describe what goes on when you view moving images sampled by a fixed pixel matrix. But that is the subject of another article.

LG had some good demonstrations of high dynamic range (HDR), which was a feature in premium sets promoted by all major set-makers. LG, of course, argued that OLED technology is ideal for implementing HDR, but LCDs with local-area dimming and good algorithms can do very nicely.

LG also had a good 8K demo, with a 98-in. 8K set showing 2K, 4K, and 8K images on different portions of the screen. To my eye, the subjective difference between 4K and 2K was obvious and impressive, but the difference between 8K and 4K was subtle.

Smart TVs are no longer exclusive to premium sets, and at least one market-intelligence firm said the market penetration is already at 50%.

Not surprisingly, LG was also promoting flexible OLEDs for mobile electronics and automotive applications. The company also showed its "M+" LCD technology for commercial displays, which adds a white subpixel to each conventional RGB triad, with signals converted from RGB inputs and optimized with a chip-based algorithm (Fig. 5). An unusual feature is that the white subpixel is smaller than its RGB siblings. The idea is to provide increased pixel density, lower power consumption, better color rendition, and higher luminance at low incremental cost. Side-by-side demos were impressive.

Fig. 5: LG's M+ technology (in image at right) provides some of the benefits of QD enhancement at relatively low incremental cost for industrial displays. Photo courtesy Ken Werner.

Materials and Components

You might not expect materials and components to be a major topic at CES, and on the show floor, they were not. But with much of the electronic, and now automotive, world congregating in Las Vegas in January, it is an excellent opportunity for materials and component makers to rent hotel suites and meet with their customers – both current and potential.

Pixelworks introduced its "Iris" mobile display co-processor, which improves mobile display quality while reducing system cost, the company says. Graham Loveridge, Senior Vice-President of Strategic Marketing and Business Development, says Iris is the world's first mobile-display co-processor. Many of Iris's functions have been performed by television video-processing chips and cores for years. But incorporating those functions and others in a chip that takes up sufficiently little space and consumes sufficiently little power for a mobile device is new. Pixelworks calls the display performance that results from Iris processing "True Clarity."

One of the more obvious things Iris does is up-convert mobile-display video from 15 or 30 frames per second (fps) to 60 fps. In side-by-side demonstrations in the suite, this provided motion images with far less judder, much smoother scrolling, and motion that had much less blur. This should not be a surprise since we have seen the same evolution in large-screen television, and Iris uses motion estimation and motion compensation (MEMC) algorithms to do its work, which is also used for TV. Loveridge said that Iris is unique in that it does MEMC without producing a halo around moving images.

Pixelworks also claims enhanced colors and wider gamut through the use of a 3-D look-up table, better contrast, better high-ambient visibility, and custom color tuning. The color tuning, Loveridge said, can be used to make sure that all displays in a production run look the same. But more than that, the OEM can buy displays from different manufacturers and tune them so they all look alike.

What is surprising is that all of this can be done with a power reduction of roughly 25%. Some of the savings come from the Iris chip off-loading functions from the GPU and CPU and performing them more efficiently.

Because the Iris chip permits savings elsewhere in the display electronics, it can save $6 on panel cost, says Loveridge. The power savings permit a smaller battery, which can save another $2. Depending on order size, the chip can be had for less than $6. So, says Loveridge, "if a manufacturer is savvy he can improve system performance and simultaneously lower cost."

TV-quality LCD cells are increasingly common in mobile devices. With the addition of TV-quality video processing, it will be even more appealing for viewers to do more of their movie and "TV" viewing on mobile devices.

Quantum-Dot Makers

Nanosys: Jason Hartlove, CEO of Nanosys (Milpitas, California) says Samsung has licensed Nanosys's cadmium-free quantum dots, which Nanosys has been developing under the radar. The license agreement gives Samsung access to the Nanosys technology and specifies that Samsung will be manufacturing the dots. In addition, Nanosys is ramping up its line in Milpitas. Capacity is now 25 tons/year, enough for 10-million TVs.

Hartlove was understandably pleased that Samsung had a major demo in its booth comparing quantum-dot-enhanced LCD TVs to other technologies, including plasma and OLED. Samsung's conclusion, boldly stated in the booth, is that quantum dots are better than OLED for television.

This position represents a solid strategy for Samsung. Samsung has abandoned OLED TV as not being a feasible high-volume technology, at least for the present, leaving LG in possession of the OLED field. But it's a field whose value is debatable. By taking a strong position on the outright superiority of QD-enhanced LCD – rather than saying, as LG is, that it is the best technology until OLED is ready for the mainstream – Samsung is attempting to reduce the value of LG's OLED field even more. Nanosys's media guru Jeff Yurek added, "We're very excited by HDR. OLED has troubles."

Nanosys supplies 3M with the quantum dots it uses in its Quantum Dot Enhancement Film (QDEF). (Although "QDEF" is consistent with the names of other 3M optical enhancement products, Nanosys actually owns the name.) Hisense is using QDEF for its ULED TVs and is fully committed to continuing the film-based approach. Changhong and LG are also using the film approach, as will Samsung when it begins manufacturing this year.

Hartlove said that QDEF sets are now delivering 90% of Rec. 2020. Nanosys, working with Dolby and the chip vender, customized the dots to do this. With a better blue filter, they can do 97% of Rec.2020, says Hartlove, and this has been shown in a demonstration unit.

Some vendors have spoken of "QD on chip" – putting the quantum dots directly on the LED chip – as the ideal solution. Hartlove thinks there is lots of work that needs to be done before this can be achieved. For Hartlove, the ultimate solution is the emissive quantum-dot display, in which the QDs are energized by an electric field instead of optically. He feels this is more interesting than QD on chip. The emissive QD display is sometimes called "QLED," a name that has been copyrighted by QD Vision. In the nearer term, Nanosys is aiming to make QD-enhanced systems cost-neutral.

Although Nanosys started out producing cadmium-based QDs, the company is now developing cadmium-free materials as well. The underlying equipment is similar for both products, Hartlove said. Cadmium is a bit more efficient and provides a larger color gamut, so it is needed for Rec. 2020. Samsung's new QD-enhanced sets will display the DCI P3 gamut, which is used for digital cinemas. (Although generous, DCI P3 is not as large as Rec. 2020.)

QD Vision: Steve Ward is the new Executive Chairman of QD Vision (Lexington, Massachusetts). He was formerly with ThinkPad and Lenovo (until 10 years ago), was former CIO at IBM, and spent time with E Ink. Advanced Development Manager John Ho says the company finds the QD-on-chip approach very interesting and that QD Vision's quantum dots are particularly suited for the approach. Ho says, as the company has said repeatedly in the past, that QD Vision has spent significant effort to make its dots more resistant to heat and luminous flux than its competitors' dots because using the dots in the company's Color IQ element, which sits close to the LEDs and experiences high levels of heat and flux, requires it. These are just the characteristics, in enhanced form, that are required for the QD-on-chip approach.

Ho showed me a side-by-side demo of a QD-enhanced TV and an OLED TV. The OLED set indeed had deeper blacks, but the QD-enhanced set was brighter and had a larger color gamut, while still having black levels that were quite good.

QD Vision is obtaining new customers for its Color IQ approach, says CMO John Volkmann. The company believes the economies of this approach over the film approach will eventually result in it dominating the market.

Quantum Materials Corp.: Steve Squires, founder and CEO of Quantum Materials Corporation (San Marcos, Texas), and Toshi Ando, Senior Director of Asian Business Development, wanted to talk about micro-reactors. The continuous production from micro-reactors is much more economical than the batch processing of other manufacturers, Squires says. "Continuous production is disruptive without a doubt."

Late last year, Quantum Materials VP for R&D David Doderer said, "One continuous-flow microreactor can produce 100 kg of highly uniform tetrapod quantum dots/day, or around 30,000 kg/year. Assuming a design that coats the entire display surface with QD film, this is enough to create approximately 10-million QD-LED TVs, outpacing projected market demand over the next few years." At CES, Squires announced the company is increasing its annual production capacity to 2000 kg beginning in Q2.

Squires thinks the QD-in-photoresist approach is very interesting. In addition to displays, Squires is attracted to applications in anti-counterfeiting and lighting, and says there are so many interesting possibilities that the company must be disciplined and not try to chase too many of them. "I think we are in an enviable position as a company right now," he says.

ITO Alternatives at CES

There has been much development and even more talk about new transparent-conductor technologies to replace the brittle and not-all-that-conductive indium tin oxide (ITO), which has been the dominant display technology for many years and remains so today.

The most commercially advanced alternative is the ClearOhm silver nanowire (AgNW) ink from Cambrios. Very-fine nanowires as small as a few atoms in diameter are dispersed in a carrier. This ink is applied to either a glass or polymer substrate and can then be patterned.

In the Cambrios suite, CEO John Le Moncheck told us the market has expanded in the last half-year, as has Cambrios production. In 2013, the company could produce 22,000 liters/year; in 2014, it was 175,000 liters. The company announced that its collaboration with the chemical and electronic materials business division of LG Electronics had produced a production rate of more than a million units of AgNW touch panels per year.

LG is shipping large volumes of touch panels to Tier One OEMs in the U.S., China, Taiwan, and Korea. Le Moncheck says that the use of AgNWs had "real champions at LG, who wanted to sell [touch sensors] outside the company." And the fact that LG already had a roll-to-roll manufacturing facility helped a lot.

The company also announced that CN Innovations (CNI), a company known for making touch sensors using laser technology with both roll-to-roll and sheet manufacturing, is delivering touch panels based on ClearOhm to Tier One OEMs. LeMoncheck said that the laser patterning CNI is known for is hard to do with ITO, but is easy with AgNWs.

He also says that the single-layer film (GF1) touch sensors that can be made with AgNWs are very interesting to cost-conscious Chinese manufacturers whose products are targeted at the value end of the spectrum. GF1 delivers a small amount of crosstalk, but it is well suited to value-oriented products. Other architectures deliver higher levels of performance. The two-layer architecture is effective for large displays. One customer is making a 65-in. touch display.

Le Moncheck notes that the current "Jupiter" ink produces a little haze in the OFF-state in bright ambients because the ambient light reflects from the wires. The new "Mercury" wires are thinner – only a few atoms thick – and these provide a "jet-black OFF-state in bright light." This allows Cambrios to go after high-end applications, Le Moncheck says.

In addition, the touch-sensor-maker TPK has a joint venture with Cambrios. The JV is ramping up and could produce hundreds of thousands of units this year.

Le Moncheck notes that the capital equipment cost for AgNW-based touch sensors is perhaps one-tenth that for ITO. Thus, he is hopeful that when sensor makers have to add capacity or replace worn-out equipment, they will turn to AgNW. "A robust supply chain is in place," Le Moncheck says, "and AgNWs are the obvious technology to use for the coming wave of flexible devices."

Cima NanoTech

This company takes a different approach to transparent conductors, using a conductive nanoparticle technology that self-assembles into a random mesh-like network when coated onto a substrate. In addition to touch screens, Cima is targeting capacitive proximity sensors, transparent antennas, wearables, transparent microwave and EMI shielding, OLED lighting, and transparent heating. In its suite at CES, Cima planned to showcase a 58-in. interactive tabletop and 42-in. interactive digital signage. "For large-format touch screens to become a mainstream product, we knew we needed to provide a cost-effective solution that can be easily integrated and creates an engaging user experience," says Cima CEO Jon Brodd.

Back in the laboratories, other approaches – including organic conductors and graphene – are being investigated, but it is technologies such as Cambrios and Cima NanoTech's that will be leading the charge against ITO for the foreseeable future.

The Future of CES

So, what is CES? CES is morphing from a consumer-electronics show to a show of everything (SoE). It's still a place to see consumer-electronic products that will appear in stores very soon, as well as display technology that has found its way into real products, but the focus has definitely broadened. Given the commitment of its sponsoring organization, the Consumer Electronics Association (CEA), to growth above all, we can expect this evolution to continue. Will CES evolve into a brontosaurus and eventually collapse from its own weight? Many of us have been predicting that for years, but it has not happened yet. ■

Display Week 2015

Innovation Zone (I-Zone)

June 2–3, 2015

The prototypes on display in the Innovation Zone at Display Week 2015 will be among the most exciting things you see at this year's show. These exhibits were chosen by the Society for Information Display's I-Zone Committee for their novelty, quality, and potential to enhance and even transform the display industry. Programmable shoes, interactive holograms, the latest head-up displays, and much more will not only fire your imagination, but provide an advance look at many of the commercial products you'll be using a few years from now.

SID created the I-Zone as a forum for live demonstrations of emerging information-display technologies. This special exhibit offers researchers space to demonstrate their prototypes or other hardware demos during Display Week, and encourages participation by small companies, startups, universities, government labs, and independent research labs.

Don't miss the 2015 I-Zone, taking place two days only: Tuesday June 2, and Wednesday June 3, on the show floor at Display Week.

I-Zone 2014 Best Prototype Award Winner:
Ostendo Technologies, Inc.

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Planar Announces Transparent OLED

Planar Systems, Inc., a maker of display and digital-signage technology, announced a new transparent OLED technology at Integrated Systems Europe (ISE) in Amsterdam last February (Fig. 1).

According to Planar, the 55-in. prototype's OLED technology improves on the transparency of LCD-based see-through displays because OLED displays are self-emitting, thus eliminating the need for a backlight or enclosure. (Planar also makes transparent LCDs.) According to the company, transparent OLED technology also offers brilliant picture quality and contrast and wide viewing angles. Planar anticipates adding the transparent OLED technology as a product offering in early 2016.

Fig. 1: *Planar's transparent OLED display expands signage possibilities because it doesn't need a backlight.*

Instrument Systems Intros New Photometer/Colorimeter

Instrument Systems, which develops, manufactures, and markets turnkey solutions for light measurement, has introduced the LumiCam 1300 Advanced, a new imaging photometer and colorimeter (Fig. 2). The LumiCam 1300 Advanced has been designed for extremely high accuracy in analyzing the characteristics of displays and electronic-panel graphics.

The new device is based on six filters. Alongside the four optical filters used in the company's LumiCam 1300 Color, the new camera has been expanded by two filters. The system allows very accurate adjustment to eye-sensitivity functions using the data recorded from the six channels. The LumiCam 1300 Advanced provides excellent accuracy for color coordinates, particularly when taking LED color measurements.

Fig. 2: *The LumiCam 1300 Advanced is designed for high accuracy in analyzing display metrics.*

SID New England Chapter Members Brave Snow to Hear About Advanced Television Display Technology

by Steve Atwood

It was January 29th, just two days after a record-setting storm had delivered over 3 feet of snow to the Boston area, and no one was sure if the roads would even be clear. Yet, roughly 30 hearty SID New England Chapter members made their way safely to Waltham, Massachusetts, for a lively dinner and evening of technical discussions around the topic of advanced television displays. This annual event was made possible in part by the generosity of 3M Company.

Leading the technical bill was longtime *Information Display* contributor and current industry analyst Ken Werner, who presented a survey of a number of key innovations being utilized by the television industry to entice consumers and squeeze more value out of their products. Some new features like 4K resolution, quantum dots, and OLEDs are being met with almost universal applause, while others, like curved TVs, are facing some skepticism. Ken delivered his engaging and very informative analysis of all of these areas with emphasis on which ones people should pay the most attention to in the coming years.

Following Ken was a presentation from John Van Derlofske, Senior Research Scientist at 3M, who drilled into some key technical areas of LCDs, including backlighting efficiency, color-gamut expansion, and high-dynamic-range (HDR) capabilities. These subjects generated a great deal of audience discussion during the Q&A periods, with listeners asking specific questions about quantum-dot technology and video encoding and distribution for 4K and HDR platforms.

It wasn't long after this evening that the snow came again, and the shovels and plows were once more the order of the day, but everyone was glad for the chance to re-connect with old friends, make some new ones, and learn something along the way. The New England chapter will carry on with at least two more technical meetings this spring, and all are welcome, members or guests, to participate. Meeting announcements are posted on the SID NE webpage: http://www.sid.org/chapters/americas/newengland.aspx. ■

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A great book about this subject is *The Innovators* by Walter Isaacson, in which he illustrates how teamwork and spirit among truly visionary teams have consistently overcome the negative pressure of conventional wisdom. Imagine how much faster the pace of computer-science innovation might have been if every leader had been truly "on-board" from the beginning.

Clearly, we cannot create a simple model to measure the pace of innovation any more than we can define the success of innovation itself in simple terms. But we all can understand innovation as a process of inputs (efforts and resources) producing (hopefully) productive and profitable outputs.

As leaders in our own spheres of influence, are we providing the right inputs by effectively evaluating and promoting the best in creative thinking? Are each of us truly open-minded to the types of radical ideas and unconventional thinking that have made so many great technological achievements happen? If so, are we communicating that every day to our teams and re-enforcing it with the right support? Or are we the ones who shy away from risk, hold on to conventional norms, and put negative pressure on the pace of innovation?

As I learned from reading Isaacson's book, really great ideas will break through no matter how much negative pressure exists. And if your organization does not provide the right environment, those great ideas may spring up somewhere else instead. If the people in your organization cannot find an avenue to explore their ideas and fuel their creative spirits, they will go elsewhere to do it. The annals of history are full of once-great companies that failed to adapt and embrace innovation – for a myriad of reasons. Many times they had it all within their grasp – the ideas, the resources to develop them, even the infrastructure to commercialize them – but for familiar reasons they chose to ignore those ideas and play it safe.

In contrast, we can all probably cite numerous examples of businesses that have exceeded our wildest expectations through innovation and great leadership. There are many more of these examples today than ever before. These businesses know how to take risks, provide the necessary fuel for innovation, and remain open minded about what comes out. Sometimes what you get out of the process has even more value than what you originally expected. The results can be seen in our industry every day as new technologies combined with new ways to enable human–machine interaction to create stunning and in some cases life-changing new products. The incredibly rapid penetration of smartphones and tablets into our everyday lives over the last few years shows how a simple idea can become a whole new paradigm.

Did any of us really foresee the impact that an embedded digital camera in a handheld phone would have on the world? Similarly, I do not think anyone could have predicted that a political mandate for space exploration in the 1960s would have fueled semiconductors and integrated circuits innovation for decades to come, along with all that those innovations then enabled. It is clear, however, that along the trajectory from transistors to smartphones there were countless people with truly innovative ideas and some visionary leaders who had the imagination to embrace and nurture those ideas with whatever it took to succeed.

Our own industry is proof that the pace of innovation continues to accelerate. Each of us should strive to bring the same creative open-minded cultures to our own teams in our own spheres of influence – whether business, academic, or social – as those who came before us. The rewards will far outweigh the risks.

So, with that in mind, welcome to our latest issue, in which we preview Display Week 2015, announce the winners of the annual SID Honors and Awards, and also explore some interesting topics in applied vision. As you all know, the annual gathering of the display industry is just a few months away and this year it's back to Silicon Valley for us all. We'll get to some of those specifics shortly but first we begin with our cover story announcing the annual SID Honors and Awards. Each year, the Society for Information Display honors those individuals who have made outstanding contributions to the field of displays, and if anything symbolizes the spirit of innovation, this year's honorees certainly do. Read about "SID's Best and Brightest" for 2015 (written by Jenny Donelan) and you will see in each case examples of true creative energy combined with commitment to problem solving and furthering the success of our industry. These are people who lead by example and continue to give so much back to help fuel innovation not only today but for future generations to come. Congratulations to all the honorees.

It has been a privilege to work with our guest editor for this month, Jim Larimer. Jim is a leading consultant in the field of applied vision and has been a trusted advisor to many of us in SID over the years. In his guest column for this issue, he introduces two Frontline Technology features, the first an article written by Gordon Wetzstein of Stanford University and addressing a self-imposed question, "Why Should People Care about Light-Field Displays?" During Jim's introduction, he takes the time to explain exactly what is meant by the term "light-field Display" in a way that is better than any other explanations I have read. Gordon's article then paints the complete picture about the potential future and present day capabilities of the technology. We've been covering light-field displays in *ID* for a while now but this one is one of the best overall views we have had to date. The next article is a very interesting presentation on various aspects of solid-state lighting and human-vision considerations titled "Solid-State Lighting for Illumination and Displays: Opportunities and Challenges for Color Excellence" by Lorne Whitehead of the University of British Columbia. In both cases, I urge you to read Jim's excellent introduction first and then enjoy the articles with his perspective as a starting point.

Now we come to our other major feature for this issue, the preview of the annual technical program known as the International Symposium at Display Week 2015. If you are looking for proof that innovations are plentiful in the world of displays, this will certainly do it. Aside from the sheer numbers – 450+ papers in 72 technical sessions and a poster session – the rich array of technical focus areas such as disruptive display materials (including quantum dots), OLEDs, flexible and foldable Displays, and light-field technology will surely make for one of the most exciting symposiums ever. Starting with the seminars on Sunday, May 31 at the San Jose Convention Center, this year's Display Week will pack more technical and business content into one week than any other display-industry event in the world. To start planning your visit, consult the Display Week Web site http://www.displayweek.org/2015/2015.aspx to register, then sit back and enjoy our preview, "Inspiration and Innovation Abound at Display Week's Annual Technical Symposium."

Another good barometer for display innovation each year is the Consumer Electronics

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Show (CES) in Las Vegas, which features the latest in actual products, including all manner of TVs, portable devices, wearables, and everything else you can think of that might use a display. This year we asked Ken Werner to chronicle it all for us and he responded with a wonderful story about all the highlights titled “CES 2015: The Show of Everything (SoE).” If you have been waiting to see new innovations in automotive electronics and more form factors for automotive displays, this was your year. It makes sense, since this is an area where display makers can generate a lot of value with their capabilities and the volumes are very attractive. I think many of us have been wondering why it has taken so long for electronic dashboards and truly new user interfaces to make it to the marketplace. This year may be the turning point. Of course, there was also no shortage of great TV products featuring quantum-dot backlights, ultra-high-definition (UHD) and many more new innovations. Clearly, CES continues to prove there is no finish line for the pace of innovation, at least in the display world.

This wraps up another issue of *Information Display*. I hope to see every one of you in San Jose for Display Week in just a few short months. ■

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[1] http://www.wired.com/2013/11/bill-gates-wired-essay/

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projection; today, that is no longer the case. The technology to do this is now becoming rapidly available. These innovations would not be possible, however, without high-speed powerful graphical computing and without important insights into how we perceive the world. These insights began to be clearly understood a little fewer than 20 years ago.

Adelson and Bergen[3] characterized the light passing through a pinhole or any arbitrary point in space as a function of the location of a point in space, the azimuth, and elevation angles of each direction through the point and the spectral power distribution of the light coursing through the point in each direction. They called this the plenoptic function; a contraction of plenus for full or complete and optics – full optic. Their plenoptic function corresponds to da Vinci’s radiant pyramids. The Russian scientist Arun Gershun coined the term “light field” in a classic 1936 paper[4] describing the radiometric properties of light. The idea is even older and was introduced by Faraday in a lecture given in 1846 entitled “Thoughts on Ray Vibrations.” The light field is a connected set of plenoptic functions – all the points on the surface of a window or within the plane of a camera’s entrance aperture, for example.

Adelson and Bergen went on to describe the many ways biological vision has evolved to exploit the information in the light field. We sample the parallax information contained in the blurry image formed by our eye to give us cues about the distance to objects.[5] In a single eye’s image, this information is contained in the blur and sharp regions of the image.

When the two eyes of an animal have overlapping visual fields, then the displacements of objects in one eye’s image relative to the image formed in the other eye is another cue to distance called disparity. Many animals, such as sheep, have only a small region in which the visual fields of their two eyes overlap. These animals have eyes looking to both sides simultaneously. In these eyes and for the non-overlapping portions of the visual field, focus yields important information about distances. Some animals, such as sheep, have apparently evolved different shaped pupils to use blur information in one axis to estimate depth in one plane while maintaining sharpness in the orthogonal plane.[6]

The psychologist J. J. Gibson[7] described the light field passing through a volume in space as the “. . . permanent possibilities of vision . . ,” meaning all of the information at the location of an observer’s eyes that can be perceived or used by the observer. Gibson believed that perception is based upon our sensory apparatus being capable of detecting information in the immediate environment that can be acted upon by the perceiver. According to Gibson, “. . . what we perceive when we look at objects are their affordances, not their qualities,” and later he said, “ . . . what an object affords us (actions we can take) is what we normally pay attention to.” This suggests that evolution has produced sentient mechanisms to extract information from the environment and a cognizance capable of acting on it.

We use our eyes to avoid hazards such as spoiled food and dangerous substances and to judge the health and therefore the risks presented by people near us. These actions need not be conscious and willful. Without thinking, for example, we avoid stepping on something that appears yucky. The color and textures of surfaces are how we conceive and recognize these hazards. The light imaged on the retina depends upon the reflectivity of the surfaces of objects in the visual field and the spectral content of the light illuminating them. What we perceive can be dramatically altered by changes in either of these two important variables.

A second article in this issue, by Lorne Whitehead, probes the quality of light emitted by displays and from ordinary lighting fixtures as it impacts our ability to see surface colors. Our color sensibilities evolved in an environment in which the illuminants were skylight, starlight, or firelight. Today, we illuminate our work and home spaces with artificial light sources that will soon be mostly based upon solid-state technologies, *i.e.,* LEDs and OLEDs. Will the colors of familiar objects look right in this light? Whitehead’s article describes the engineering trade-offs that are being made to produce light from displays and from solid-state luminaries. Some of these trade-offs will confuse our senses. His article describes how to fix this problem for both ordinary room lighting and for displays.

There is mounting evidence that information in the light field, *i.e.*, the intensity and spectral properties of daylight over the course of the day, is used to synchronize our biological clocks or circadian rhythms.[8] A recent report finds that light emitted from backlit e-Readers when used in the evening can have a negative effect on sleep and morning alertness.[9] When

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modern electronic-imaging systems leave out important information, distort it, or exaggerate naturally occurring signals embedded in the light field that we sense to relate our bodies, the consequences can be unexpected. We now have to consider the possibility that signals in the light may cause not only sleep loss, but possibly depression and even, some speculate, the early onset of puberty. These are emerging concerns for the display and lighting industries. Not fully capturing all of the critical information, *i.e.*, affordances, in the light field, can be pleasing, misleading, or actually bad for us.

Whitehead's article describes how solid-state light emitters can be engineered to address these problems. As new understanding of light's role in human vision and biology emerges, so does new technology that can remedy problems we are just now discovering. Whether it is making objects look "right" or controlling the spectral content of the light to get a better night's sleep, the evolution of technology now allows us to manipulate light so that it is consistent with the evolution of human vision.

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