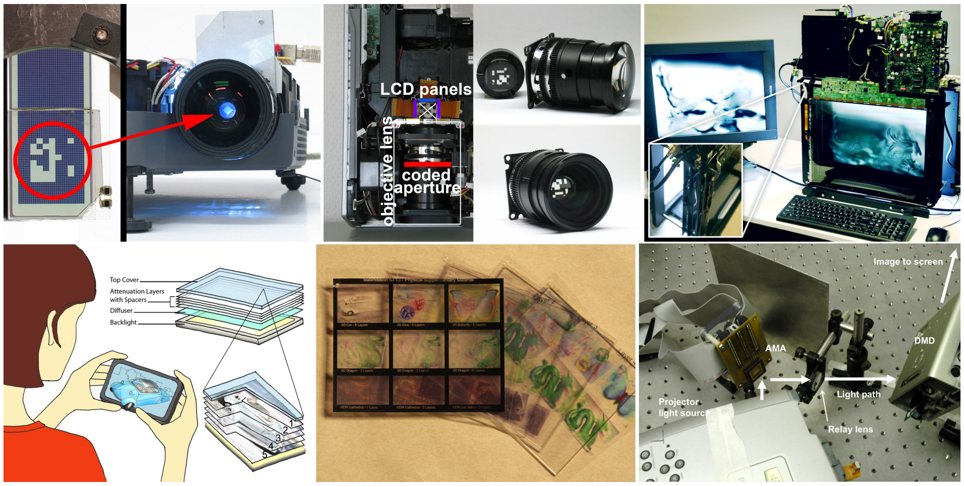
Computational Displays:

Combining Optical Fabrication, Computational Processing, and Perceptual Tricks to Build the Displays of the Future



SIGGRAPH 2012 Course

Sunday, 5 August 2012, 2:00-3:30 pm
Los Angeles Convention Center - Room 408B

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Abstract

With the invention of integral imaging and parallax barriers in the beginning of the 20th century, glasses-free 3D displays have become feasible. Only today —more than a century later— glasses-free 3D displays are finally emerging in the consumer market. The technologies being employed in current-generation devices, however, are fundamentally the same as what was invented 100 years ago. With rapid advances in optical fabrication, digital processing power, and computational models for human perception, a new generation of display technology is emerging: computational displays exploring the co-design of optical elements and computational processing while taking particular characteristics of the human visual system into account. This technology does not only encompass 3D displays, but also next-generation projection systems, high dynamic range displays, perceptually-driven devices, and computational probes.

This course serves as an introduction to the emerging field of computational displays. The pedagogical goal of this course is to provide the audience with the tools necessary to expand their research endeavors by providing step-by-step instructions on all aspects of computational displays: display optics, mathematical analysis, efficient computational processing, computational perception, and, most importantly, the effective combination of all these aspects. Specifically, we will discuss a wide variety of different applications and hardware setups of computational displays, including high dynamic range displays, advanced projection systems as well as glasses-free 3D display. The latter example, computational light field displays, will be discussed in detail. In the course presentation, supplementary notes, and an accompanying website, we will provide source code that drives various display incarnations at real-time framerates, detailed instructions on how to fabricate novel displays from off-the-shelf components, and intuitive mathematical analyses that will make it easy for researchers with various backgrounds to get started in the emerging field of computational displays. We believe that computational display technology is one of the "hottest" topics in the graphics community today; with this course we will make it accessible for a diverse audience. While the popular, introductory-level courses "Build Your Own 3D Displays" and "Build Your Own Glasses-free 3D Display", previously taught at SIGGRAPH and SIGGRAPH ASIA, discussed conventional 3D displays invented in the past, this course introduces what we believe to be the future of display technology. We will only briefly review conventional technology and focus on practical and intuitive demonstrations of how an interdisciplinary ap-

proach to display design encompassing optics, perception, computation, and mathematical analysis can overcome the limitations for a variety of applications.

We will discuss all aspects of computational displays in detail. Specifically, we begin by introducing the concept and discussing a variety of example displays that exploit the joint-design of optical components and computational processing for applications such as high dynamic range image and wide color gamut display, extended depth of field projection, and high-dimensional information display for computer vision applications. We will then proceed to discussing state-of-the-art computational light field displays in detail. In particular, we will focus on how high-speed displays, multiple stacked LCDs, and directional backlighting combined with advanced mathematical analysis and efficient computational processing provide the foundations of 3D displays of the future. Finally, we will review psycho-physiological aspects that are of importance for display design and demonstrate how perceptually-driven computational displays can enhance the capability of current technology.

Prerequisites

For this intermediate-level course, some familiarity with Matlab, C/C++, OpenGL, as well as a general understanding of linear algebra and Fourier analysis is assumed, although the course also functions as a brief, application-driven introduction to each of these tools.

Speaker Biographies

Gordon Wetzstein

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Gordon Wetzstein is a Postdoctoral Associate at the MIT Media Lab. His research interests include light field and high dynamic range displays, projector-camera systems, computational optics, computational photography, computer vision, computer graphics, and augmented reality. Gordon received a Diplom in Media System Science with Honors from the Bauhaus-University Weimar in 2006 and a Ph.D. in Computer Science at the University of British Columbia in 2011. His doctoral dissertation focuses on computational light modulation for image acquisition and display. He is co-chairing the first workshop on Computational Cameras and Displays at CVPR 2012, is serving in the general submissions committee at SIGGRAPH 2012, has served on the program committees of IEEE ProCams 2007 and IEEE ISMAR 2010, won a Laval Virtual Award in 2005 for his work on projector-camera systems, and a best paper award for "Hand-Held Schlieren Photography with Light Field Probes" at the International Conference on Computational Photography in 2011, introducing light field probes as computational displays for computer vision and fluid mechanics applications.

Douglas Lanman

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Douglas Lanman is a Postdoctoral Associate at the MIT Media Lab. His research is focused on computational photography and displays, including light field capture, automultiscopic 3D displays, and active illumination for 3D reconstruction. He received a B.S. in Applied Physics with Honors from Caltech in 2002 and M.S. and Ph.D. degrees in Electrical Engineering from Brown University in 2006 and 2010, respectively. Prior to joining MIT and Brown, he was an Assistant Research Staff Member at MIT Lincoln Laboratory from 2002 to 2005. Douglas has worked as an intern at Intel, Los Alamos National Laboratory, INRIA Rhône-Alpes, Mitsubishi Electric Research Laboratories (MERL), and the MIT Media Lab. He presented the "Build Your Own Glasses-free 3D Display" course at SIGGRAPH 2011, the "Build Your Own 3D Scanner" course at SIGGRAPH 2009 and SIGGRAPH Asia 2009 and the "Build Your Own 3D Display" course at SIGGRAPH 2010 and SIGGRAPH Asia 2010.

Matthew Hirsch
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Matthew Hirsch is a Ph.D. student at the MIT Media Lab. His research focuses on imaging devices that enable new understanding and interaction scenarios. He works with Henry Holtzman and Ramesh Raskar in the Information Ecology and Camera Culture groups, respectively. Matthew graduated from Tufts University in 2004 with a B.S. in Computer Engineering. He worked as an Imaging Engineer at Analogic Corp. from 2004 to 2007, where he designed threat detection algorithms for computed tomography security scanners. He presented the "Build Your Own Glasses-free 3D Display" course at SIGGRAPH 2011, and the "Build Your Own 3D Display" course at SIGGRAPH 2010 and SIGGRAPH Asia 2010.

Diego Gutierrez
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Diego Gutierrez is a tenured Associate Professor at the Universidad de Zaragoza, in Spain, where he leads the Graphics and Imaging Lab. His research interests include applied perception in graphics and visualization, global illumination and computational photography. Since 2006, he has already presented eight courses at both SIGGRAPH conferences. He's currently Papers Chair for EGSR 2012, and has previously chaired other international conferences like APGV 2011. He has served on many Program Committees, including SIGGRAPH, SIGGRAPH Asia and Eurographics, and is also an Associate Editor of three journals (IEEE Computer Graphics & Applications, ACM Transactions on Applied Perception and Computers & Graphics).

Course Outline

3 minutes: Introduction and Overview

Gordon Wetzstein

This part will introduce the speakers, present a motivation of the course, and outline the individual parts.

22 minutes: Computational Displays as a Next-generation Technology

Gordon Wetzstein

This part will introduce the emerging field of computational displays. We will discuss the fundamental building blocks of computational displays: optical components, computational processing as well as the human visual system. This part will also serve as an overview of computational displays, such as adaptive coded aperture projection, high dynamic range displays, and emerging projection systems. In addition to displays intended for the human visual system, we also plan to provide an overview of computational probes: high-dimensional displays targeted toward computer vision applications rather than the human visual system.

35 minutes: Computational Light Field Displays - Hardware Architectures, Fabrication, Content Generation and Optimization

Douglas Lanman and Matthew Hirsch

The combination of numerical optimization, display fabrication, and efficient computational processing provides the foundation of future glasses-free 3D display design. This part will present the latest light field display designs exploiting high-speed LCDs as well as stacked layers of light-attenuating and polarization-rotating LCDs. We will present detailed instructions on how to build arbitrary combinations of high-speed see-through LCD panels and refractive optical elements from off-the-shelf parts. In addition, we will provide source code and instructions for driving these with efficient GPU-based implementations of the most important algorithms: tomographic light field synthesis, non-negative matrix factorizations as well as non-negative tensor factorizations. Furthermore, this part will discuss how important display characteristics, such as depth of field, field of view, and contrast, are theoretically analyzed. This analysis along with hardware and software-related implementation details will be presented as step-by-step instructions so as to provide other researchers with intuitive tools that facilitate them to get started in this exciting new field and build their own computational light field displays.

20 minutes: Perceptually-driven Computational Displays

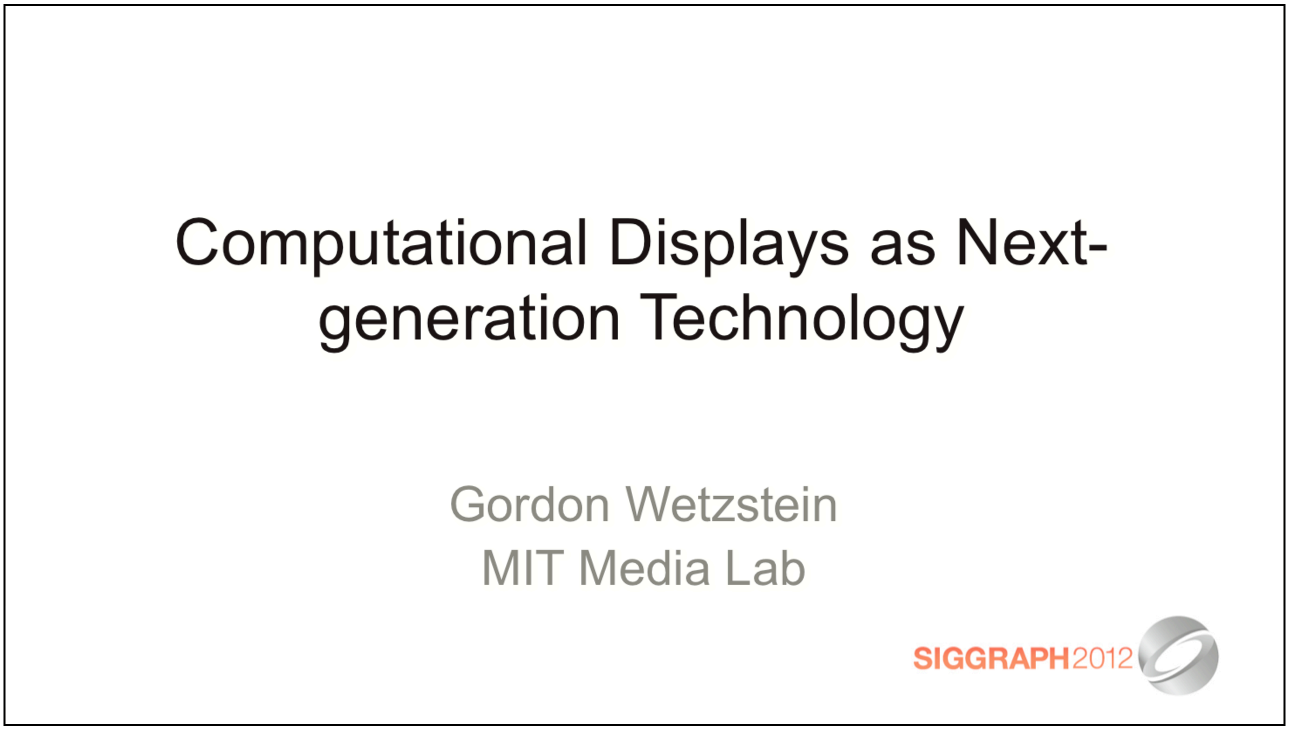
Diego Gutierrez

This part will review aspects of the human visual system that are of particular importance for designing displays. In particular, we will discuss sensitivity to contrast, spatial frequencies, stereo disparities and other depth cues as well as temporally-multiplexed signals. The goal of this part is to emphasize how the limitations of the human visual system can be exploited to enhance the perceived capabilities of computational displays.

10 minutes: Summary and Q & A

All

This part will summarize how computational displays are changing current display architectures by exploiting the co-design of display optics and computational processing targeted toward human observers. We will outline future directions of this emerging field and allow for sufficient time to answer questions and stimulate discussions.

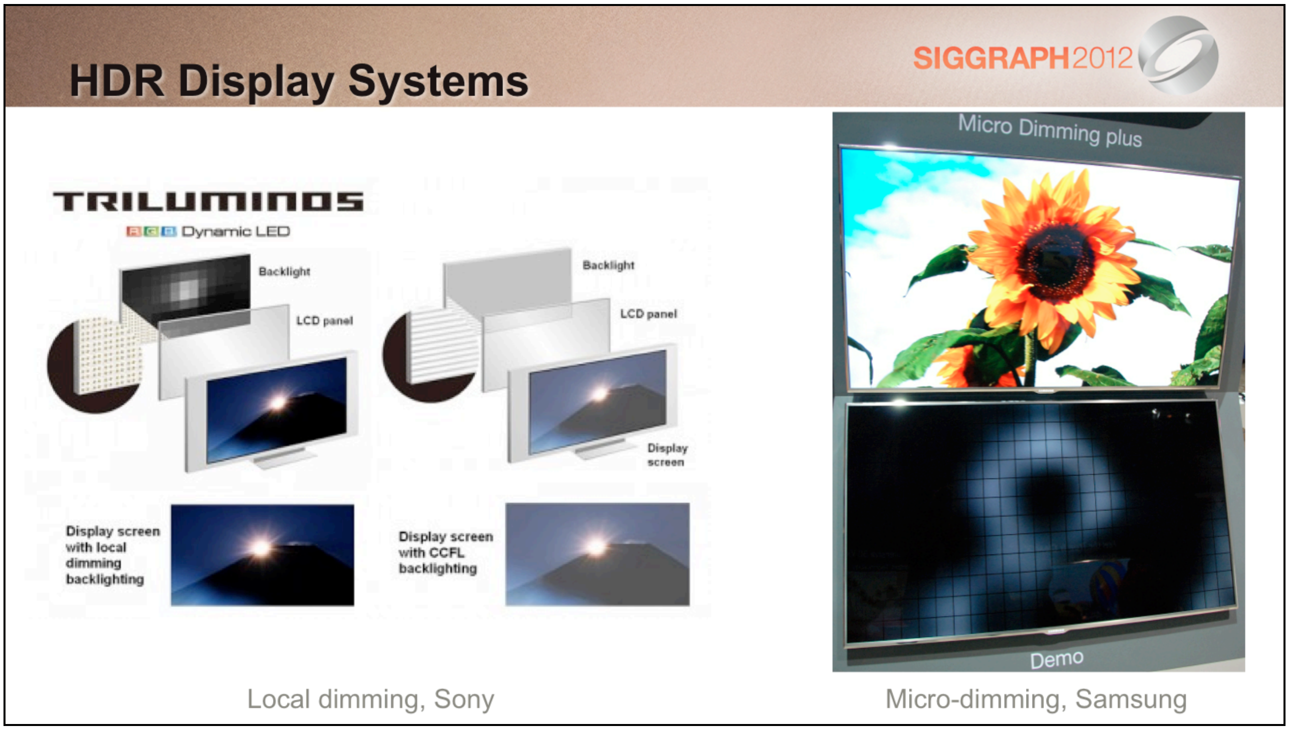


Computational Displays as Next-generation Technology

Gordon Wetzstein
MIT Media Lab

SIGGRAPH2012

This part of the course is meant to give an overview of computational displays. Rather that focusing on a few different approaches, the next 20 minutes will be more of a fast-forward of much of the research in the area that has been conducted within the last decade or so.



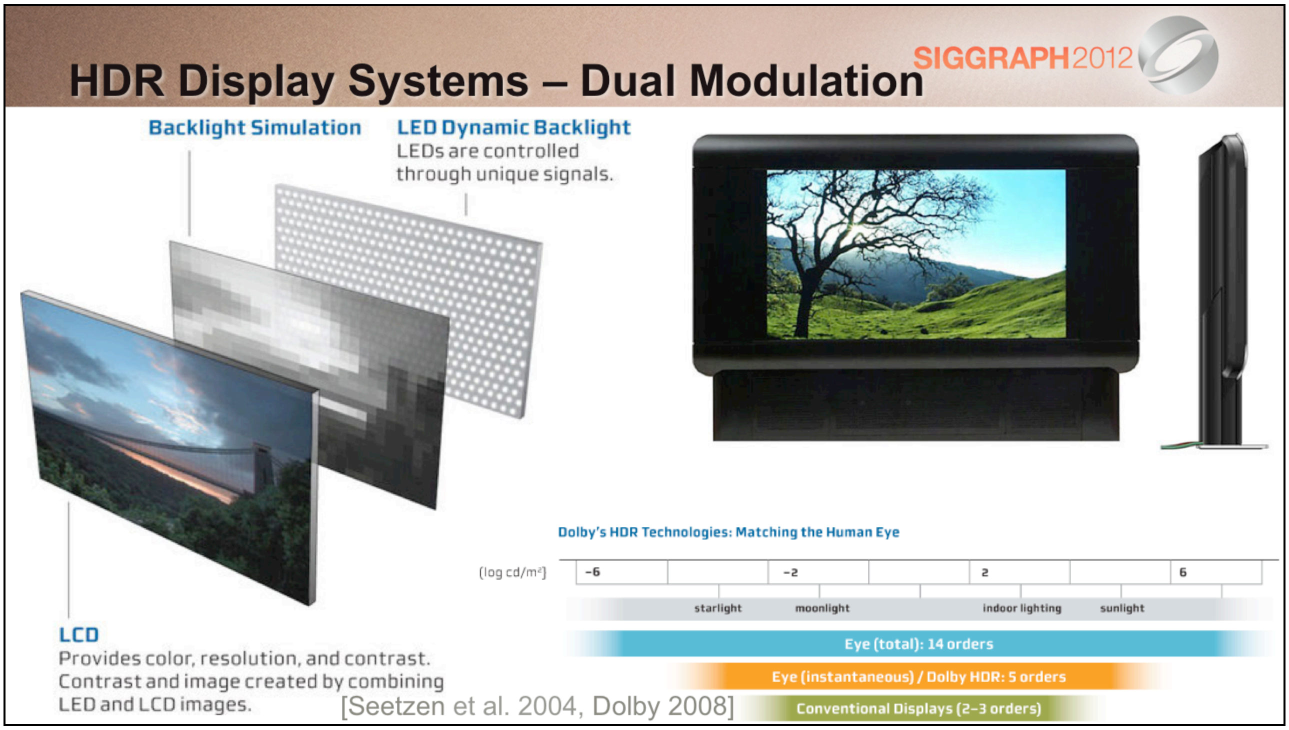
HDR Display Systems

SIGGRAPH2012

Local dimming, Sony

Micro-dimming, Samsung

Let’s start out with a technology that most people have at home: a television. Within the last few years, most TVs that you buy in the store today have local dimming or micro dimming integrated. That is an approach to creating high contrast imagines by combining a low-resolution LED-based backlight with a high-resolution LCD.



HDR Display Systems – Dual Modulation

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Backlight Simulation

LED Dynamic Backlight
LEDs are controlled
through unique signals.

LCD
Provides color, resolution, and contrast.
Contrast and image created by combining
LED and LCD images.

Dolby's HDR Technologies: Matching the Human Eye

(log cd/m²) -6 -2 2 6

starlight moonlight indoor lighting sunlight

Eye (total): 14 orders

Eye (instantaneous) / Dolby HDR: 5 orders

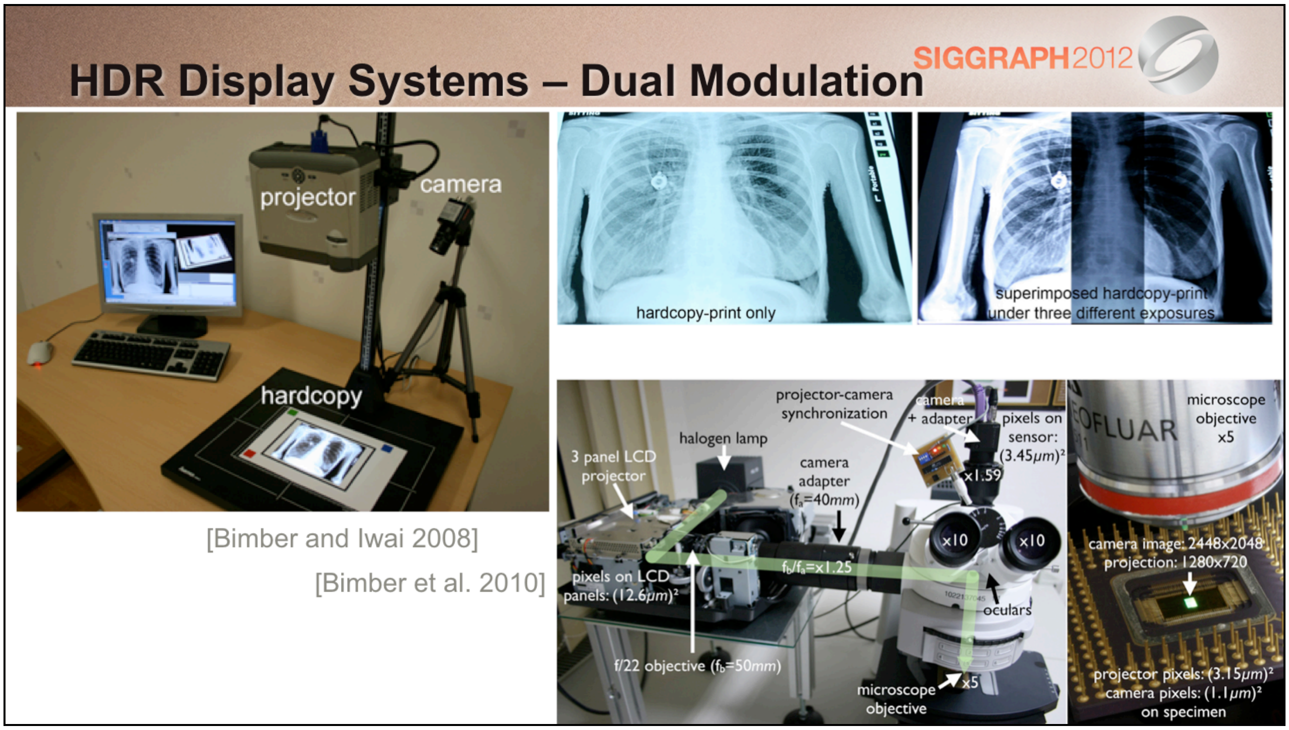
Conventional Displays (2–3 orders)

[Seetzen et al. 2004, Dolby 2008]

The underlying technology was invented in 2004 and presented here at Siggraph for the first time. HDR displays tackle the problem of conventional LCDs having a limited contrast by replacing old-school CFL backlights with an array of programmable LEDs. This provides programmable rear-illumination that can be locally dimmed or even turned off, while illuminating the LCD with full brightness in other image parts.

The necessary pre-computation, usually carried out on the device in real-time, decomposes a target HDR image into a low-resolution but high contrast pattern displayed on the LED array and a corresponding high-resolution LCD image that adds sharp image details and colors on top of the LEDs.

The concept allowing for a significant increase in contrast for these displays is dual modulation. By using two layers of displays that act in a multiplicative fashion, in this case an LCD and a LED array, the overall contrast of the display is increased.



HDR Display Systems – Dual Modulation

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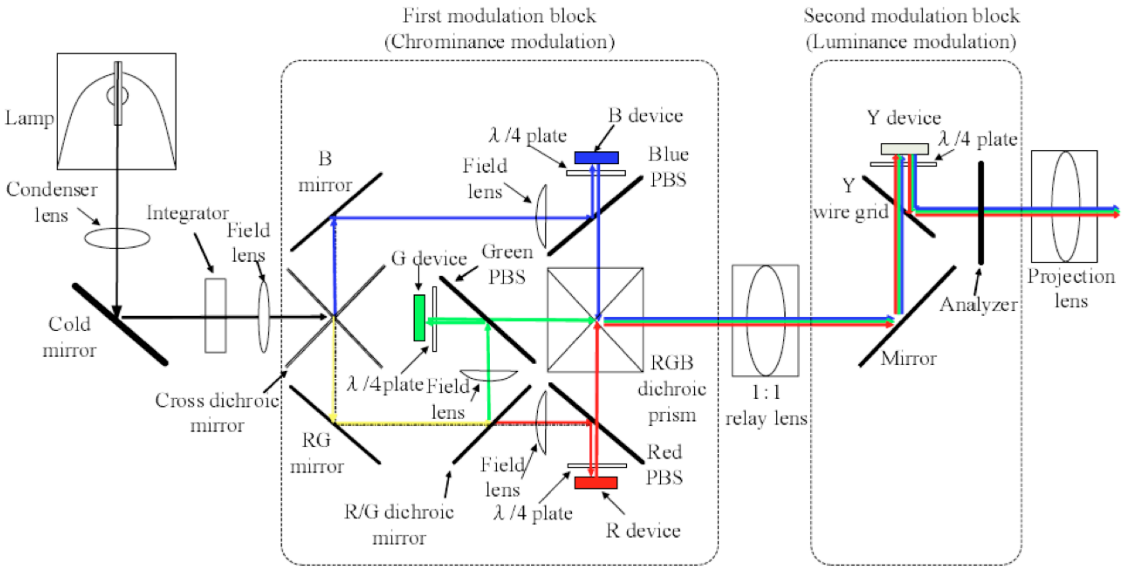
[Bimber and Iwai 2008]

[Bimber et al. 2010]

Similar ideas have also been applied to increasing the contrast of static prints or other hardcopies. For this purpose, a projector can be used to illuminate the print, an e-reader, x-ray transparencies, or any other type of low-contrast display. As long as the projector is registered with the secondary display, it can just illuminate it with the exact image shown on the hardcopy to increase its dynamic range as seen in these examples on the top.

Oliver Bimber also explored the concept of dual modulation for microscopy. The optical design is more involved than for simple printouts, but the idea is the same: a camera observes a specimen and the optics are built so that a programmable light source illuminates it so as to optically enhance the observed contrast. With live camera feedback, the projected images can also be adjusted to allow for dynamic content such as live specimen.

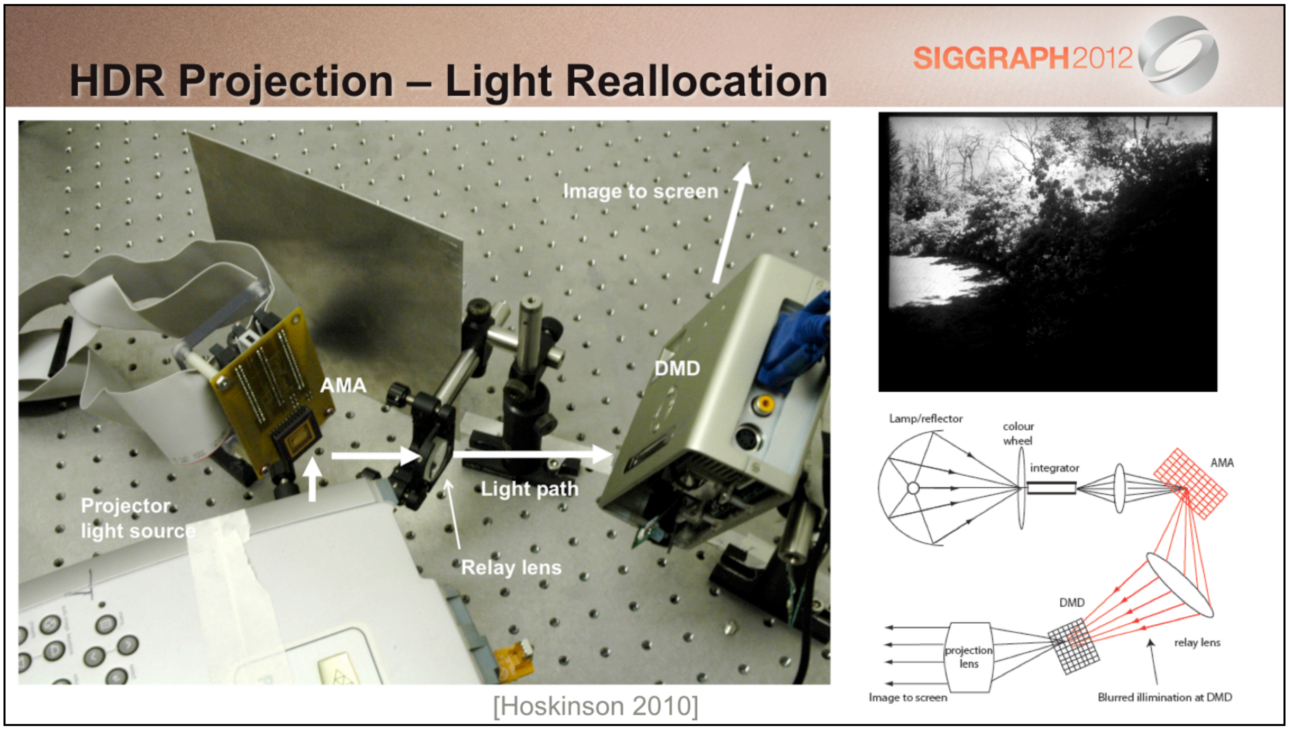
HDR Display Systems – Dual Modulation



[Kusakabe 2009]

Dual modulation has the potential to increase the dynamic range of a variety of other displays as well. As seen in this schematic, the dynamic range of projectors can be extended through dual modulation. What we see is the design of an HDR projector that basically consists of a light source on the left, a conventional reflective or transmissive spatial light modulator for each color channel in the center, and an additional modulator on the right. While the latter only allows for the modulation of the luminance channel, the dynamic range for displayed luminance values is increased as the blacklevel is decreased.

Please note that the human visual system is most sensitive to contrast for luminance perception and not very sensitive to chrominance contrast. In effect, the optical projector design enhances the capabilities of the device in a perceptually optimal manner. Exploiting the limitations of human perception for display optics design and the corresponding computational processing is the spirit of computational displays.



HDR Projection – Light Reallocation

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[Hoskinson 2010]

A somewhat more sophisticated approach to high dynamic range projection was recently presented at Siggraph Asia. While the previous HDR projector blocks a lot of the light inside the device to achieve a lower backlevel, this projector recycles excessive background light in dark image areas. Using an analog micro-mirror array in the optical path, excessive light is steered to other image areas and basically increases the maximum image brightness there.

Light re-allocation or recycling in projectors is an idea that not only increases the contrast of the devices but also reduces the heat and cooling power consumption because the produced light is steered out of the physical enclosure rather than dumping it inside.

This particular project is a great example of how a similar functionality, in this case high dynamic range imaging, can require very different optical designs and corresponding processing depending on whether it's a projector or a TV. In one case dual modulation may be a great idea because one can mostly control where light is being emitted whereas in a projector one usually does not have that luxury, so reallocation may be a much better option.

Computational Projectors – Multi-device Systems

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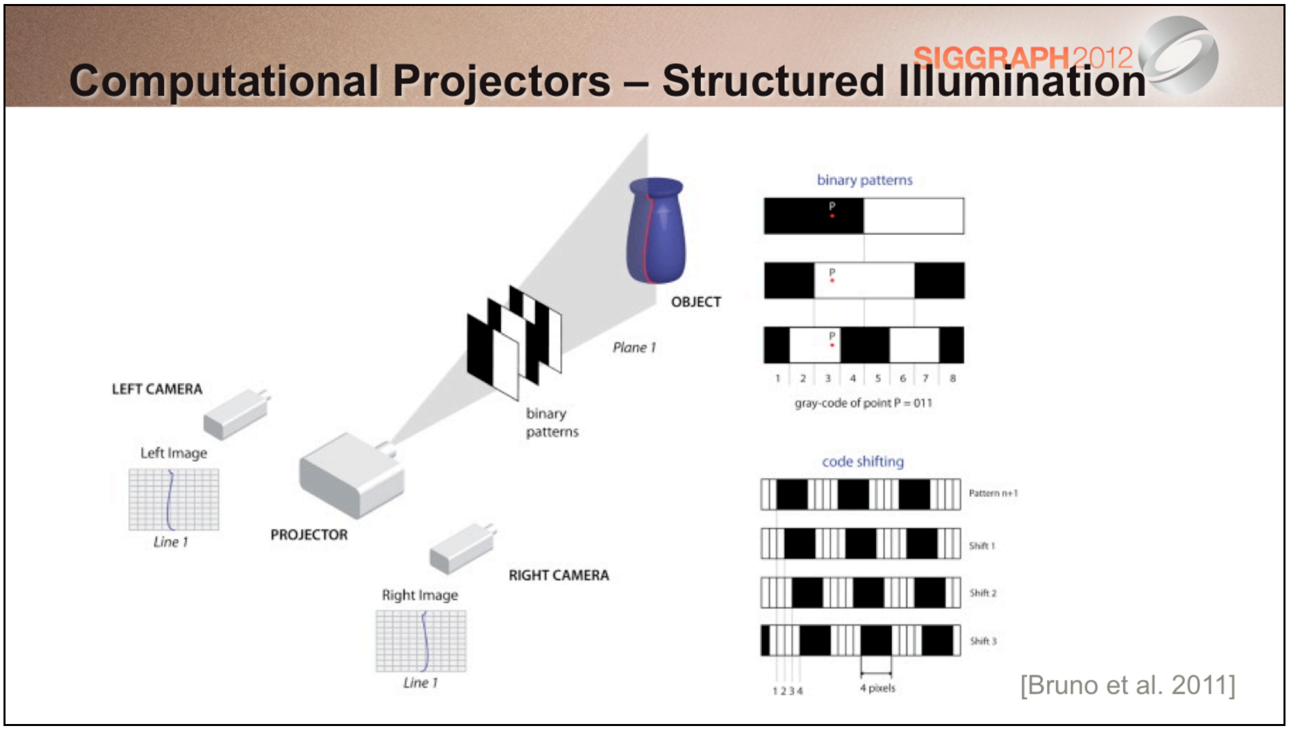
[Raskar et al. 1998]

[Majumder and Brown 2007]

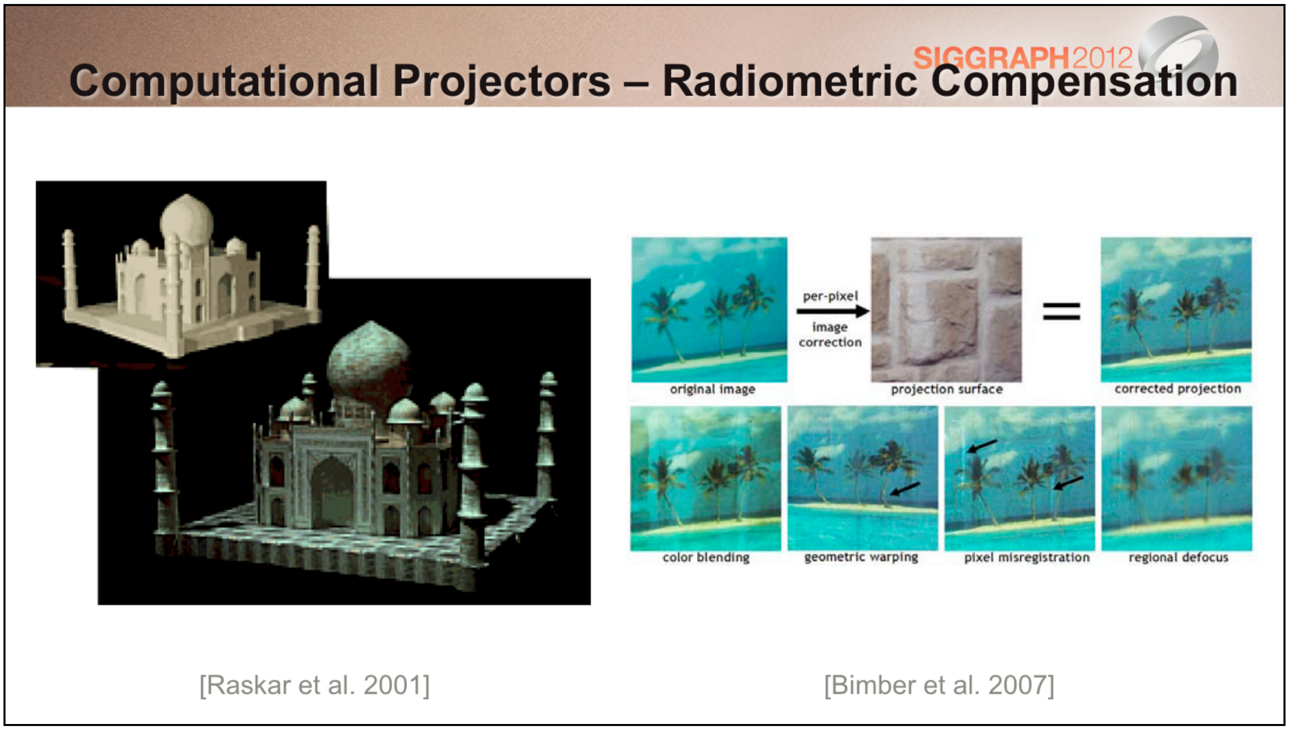
In a much broader sense, projectors have been used for unconventional applications for more than a decade. “The Office of the Future” is probably one of the seminal papers envisioning seamless integration of multi-projector systems into our daily workspaces. Even now, more than a decade later, fully-immersive teleconferencing systems and spatial interfaces allowing us to augment the world with virtual information are still an active area of research. Many of the practical problems associated with multi-projector systems, such as photometric and geometric calibration, however, are solved. Textbooks, such as that by Aditi Majumder cover the topic exhaustively.



Computational Projectors – Structured Illumination

[Bruno et al. 2011]

Another well-known use of computational imaging is structured illumination. The joint design of projected optical codes and computational reconstruction of the underlying data has been a standard technique in computer visions for years. Usually, these approaches encode a one-to-one mapping between projector and camera pixels which allows for diffuse geometry acquisition when the devices are calibrated.



Computational Projectors – Radiometric Compensation

[Raskar et al. 2001]

[Bimber et al. 2007]

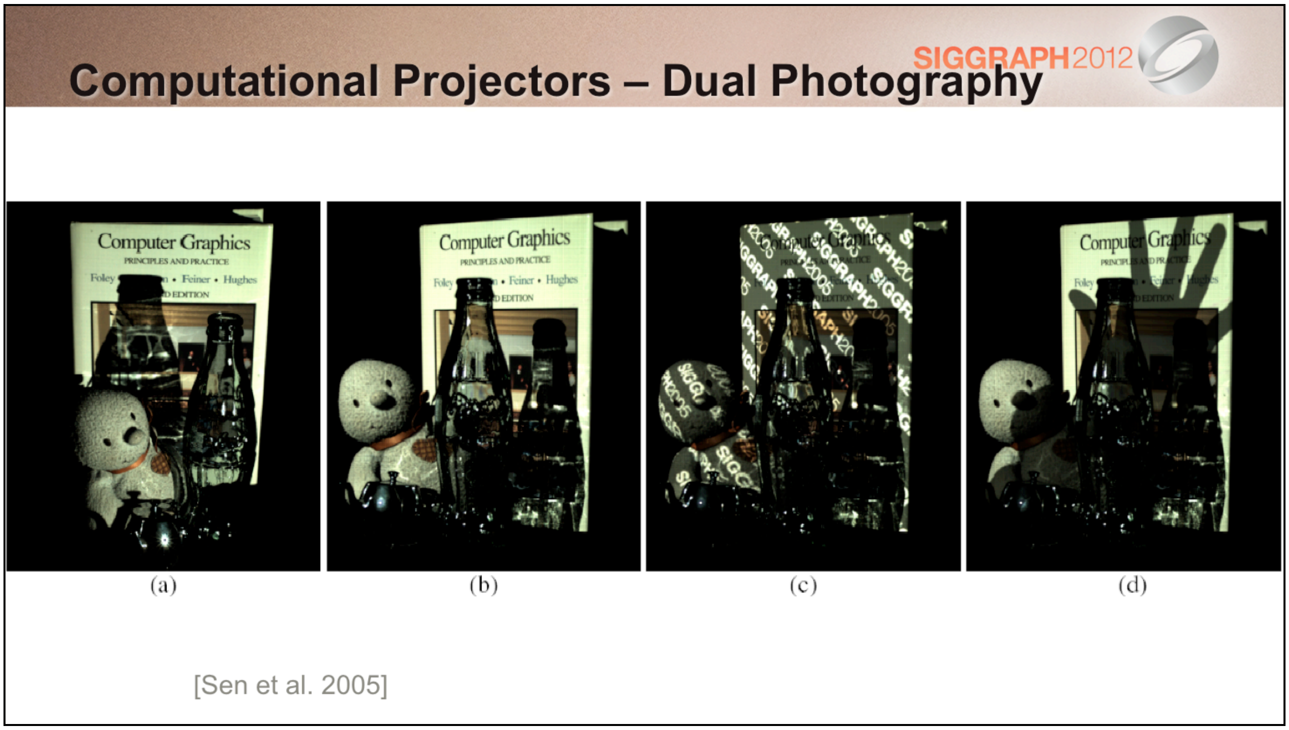
Spatial augmented reality, such as shader lamps and radiometric compensation, allow projectors to manipulate the appearance of objects turning brick walls into planar, white canvases or plain white objects into colorful miniatures of the real world. These approaches require the geometry and reflectance of the surfaces to be known and registered to the projectors; the computational pre-distortion of displayed images can then easily be performed using standard projective texture mapping or other forms of image distortion.

Computational Projectors – Inverse Light Transport

[Wetzstein and Bimber 2007]

[O'Toole and Kutulaks 2010]

While most projector camera systems make strong assumptions on the imaged scene, such as Lambertian-ness, inverse light transport with applications to radiometric compensation and synthetic relighting has been explored as well. The involved illumination patterns and their decoding are more involved than for diffuse scenes, but the general idea of compensating for optical effects using computational pre-processing is the same as simple structured illumination.

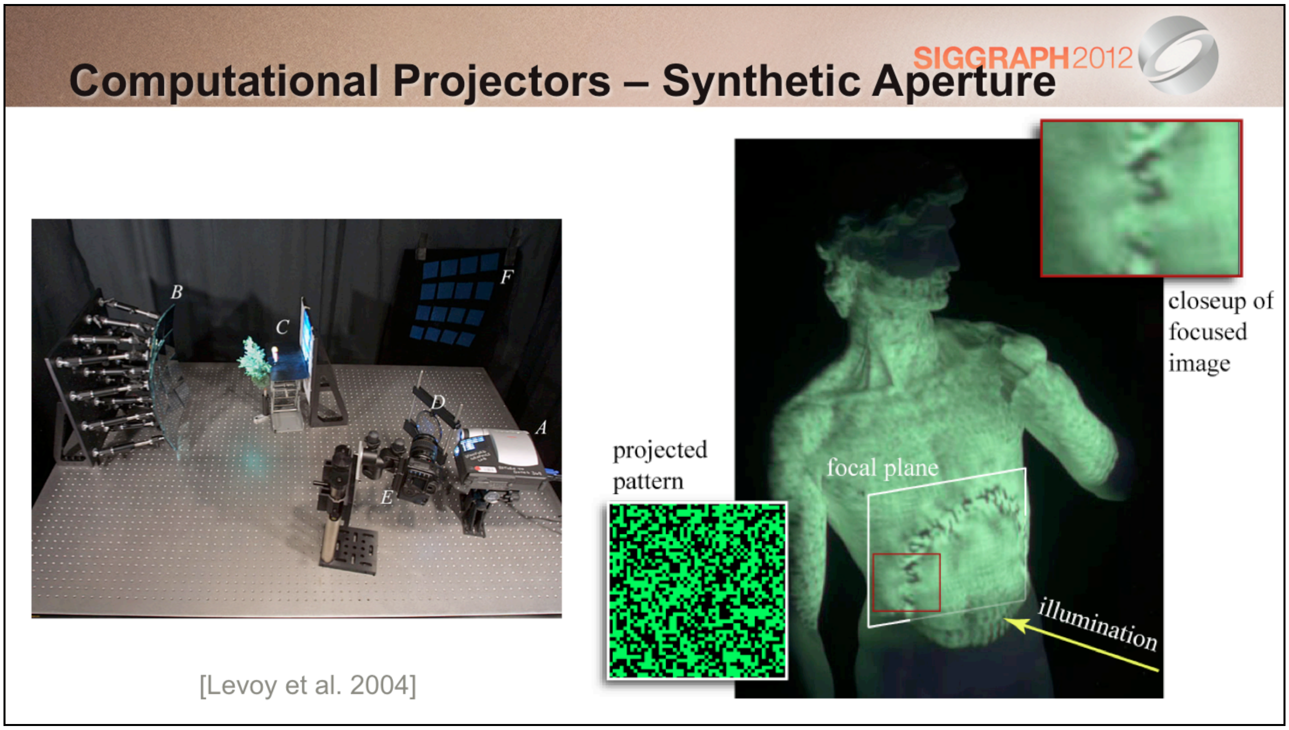


Computational Projectors – Dual Photography

(a) (b) (c) (d)

[Sen et al. 2005]

Light transport does not always have to be inverted, it can also be transposed. Pradeep Sen and colleagues have shown that the transpose of the light transport matrix can be useful for generating dual images showing the scene from the point of view of a projector illuminated by a light source at the point of view of a camera. This allows for novel view generation, even unveiling parts of the scene that were only visible by the projector and never by the camera. Relighting a complex scene with novel illumination patters, such as seen in these images, is another application.



Computational Projectors – Synthetic Aperture

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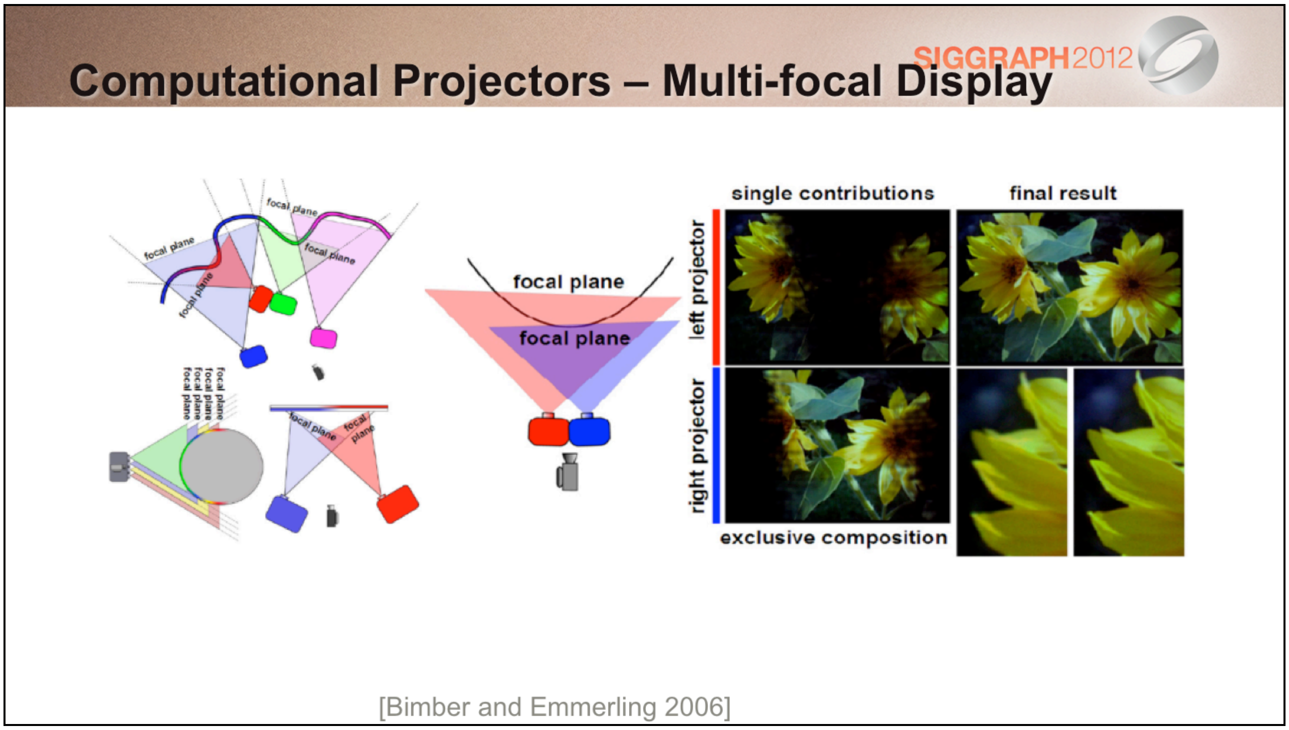
[Levoy et al. 2004]

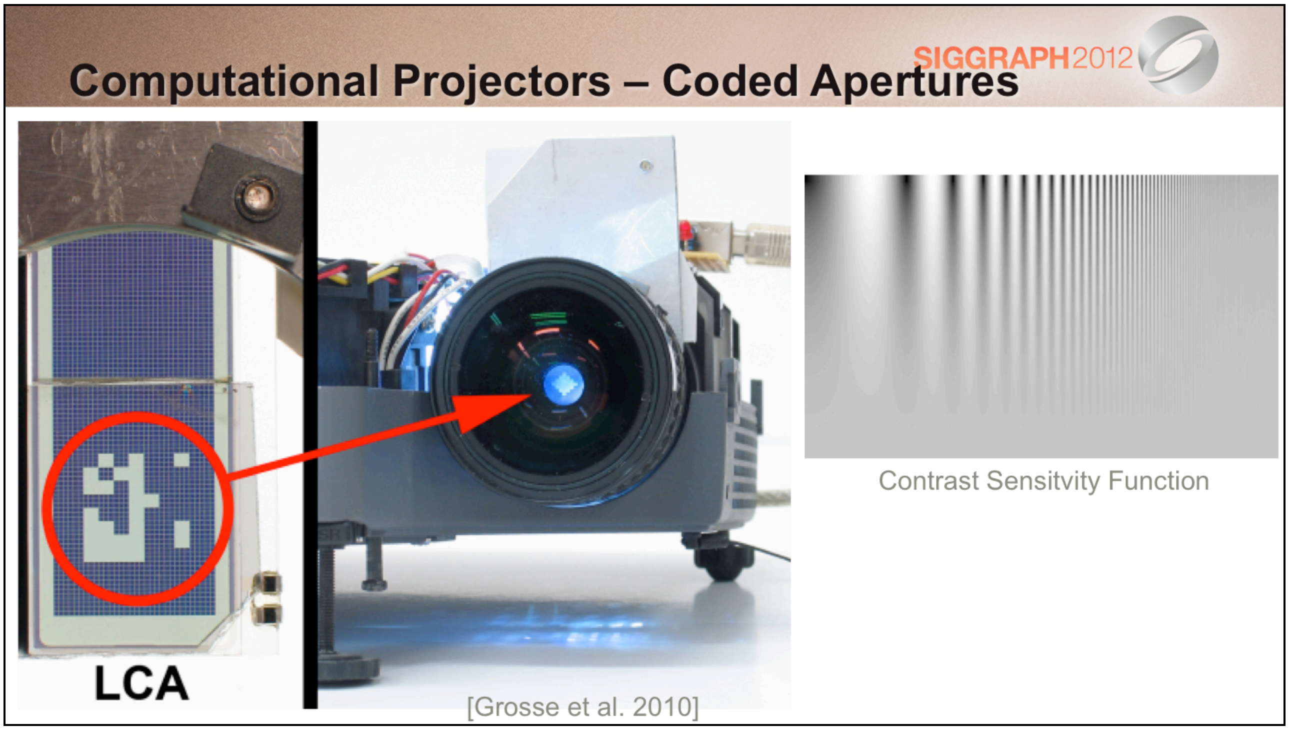
Arrays of projectors, here simulated with a single device illuminating an array of mirrors, in combination with random illumination patterns can create a large synthetic aperture projector. As is the case for cameras, large apertures for projectors create a very shallow depth of field. In this particular application, individual depth slices of the scene can selectively be illuminated such as seen for the David statue on the right.



Computational Projectors – Multi-focal Display

[Bimber and Emmerling 2006]

While a shallow depth of field is sometimes desirable, when projecting on complex screens an increase in depth of field is actually required to guarantee focused image projection on all parts of the screen. Multiple overlapping projectors, each adjusted at a different focal length can be used to extend the depth of field of a single, virtual projector. Using a camera in the loop, the surface geometry can be scanned and a composite image from all devices computed that allows for the minimal amount of overall defocus in the system.



Computational Projectors – Coded Apertures

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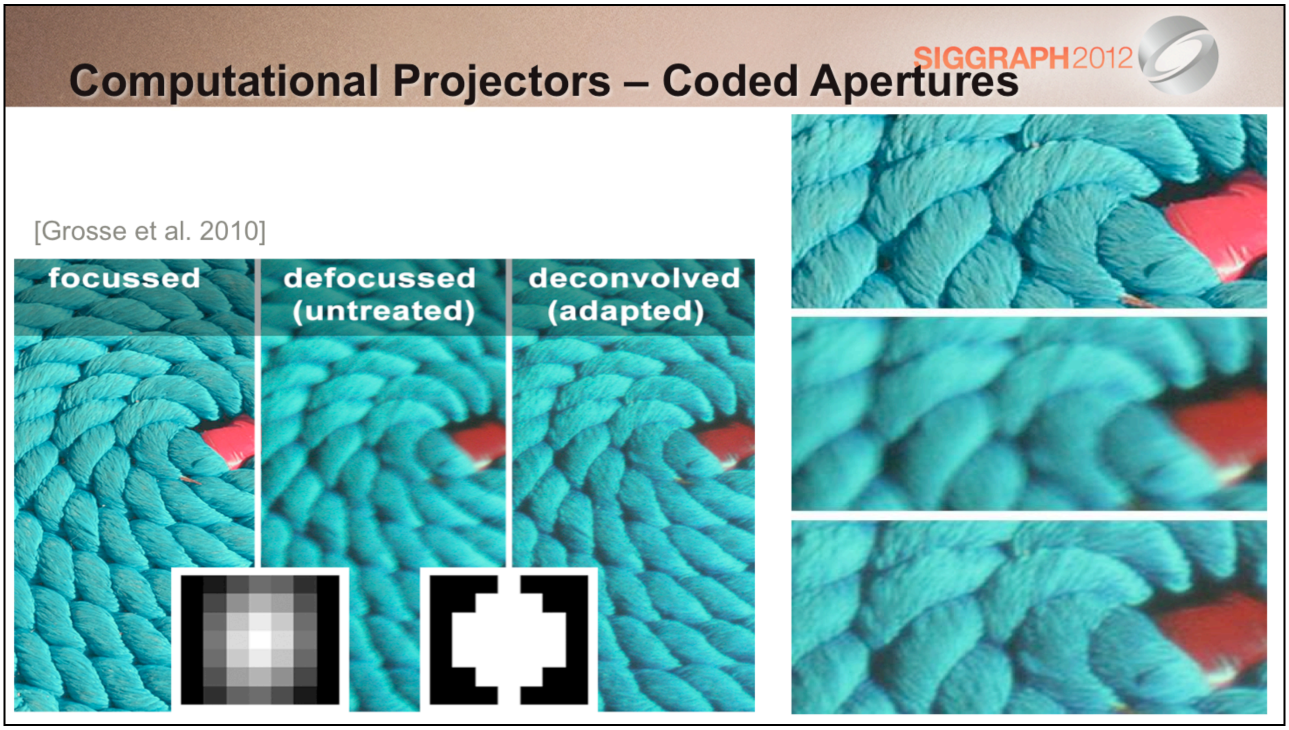
[Grosse et al. 2010]

Contrast Sensitvity Function

An alternative, single device approach to extended depth of field projection has been proposed by us a few years ago. We replace the circular aperture of a projector with programmable liquid crystal array to build a coded aperture projector. The purpose of this device is an extended depth of field. We achieve this by jointly optimizing the display image and aperture pattern taking the contrast sensitivity of the human visual system into account. On the right you can see an image that has an increasing frequency on the x-axis and an increasing contrast on the y-axis. The underlying pattern should be a linear gradient in both axes, but looking at it we actually see the a curve that visualizes our frequency-dependent contrast detection threshold.



Computational Projectors – Coded Apertures

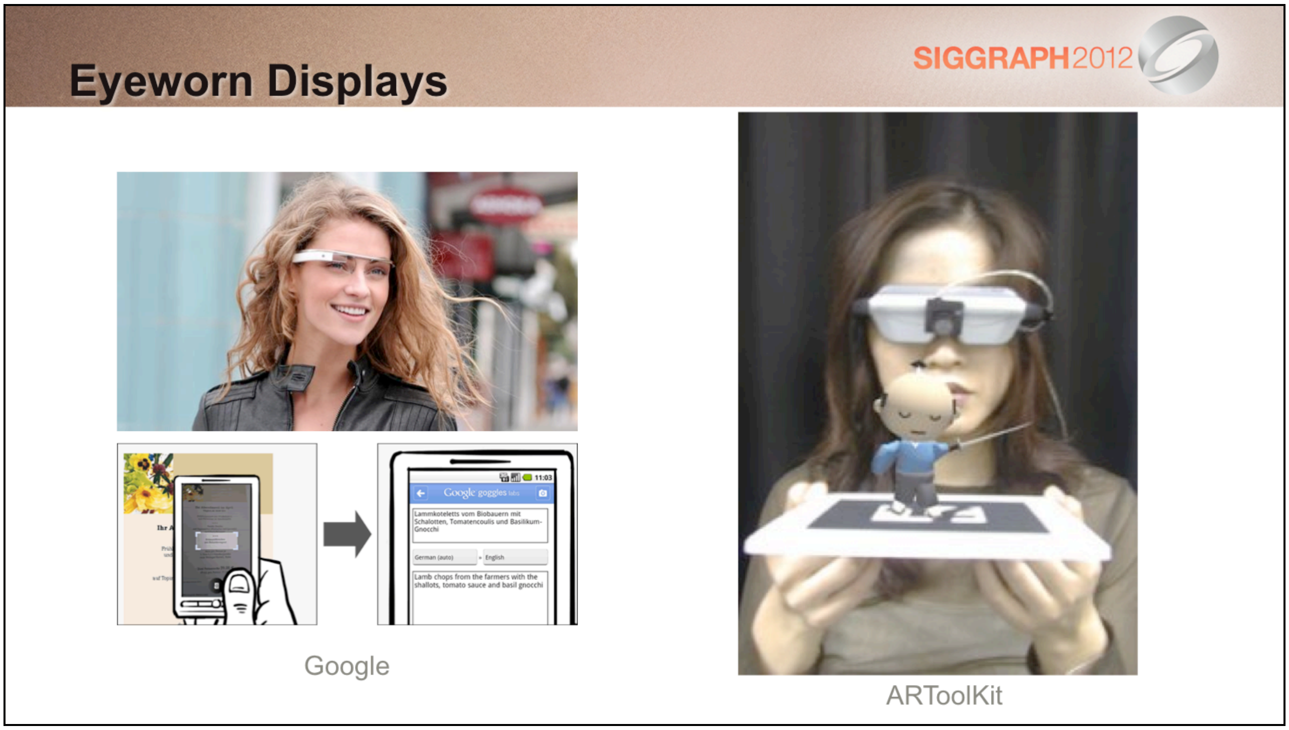
[Grosse et al. 2010]

focussed

defocussed (untreated)

deconvolved (adapted)

Here are some results, the focused image on the left, an optically defocused projection in the center right, and the compensated image in the center. Corresponding close-ups are shown on the right. The aperture codes seen in the insets are computed so as to preserve the image frequencies that are most important for a human observer. Given this pattern, the projected image is computed by deconvolving it with that pattern as a blur kernel.



Eyeworn Displays

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Google goggles

Lammkoteletts vom Biobauern mit Schalotten, Tomatencoulis und Basilikum-Gnocchi

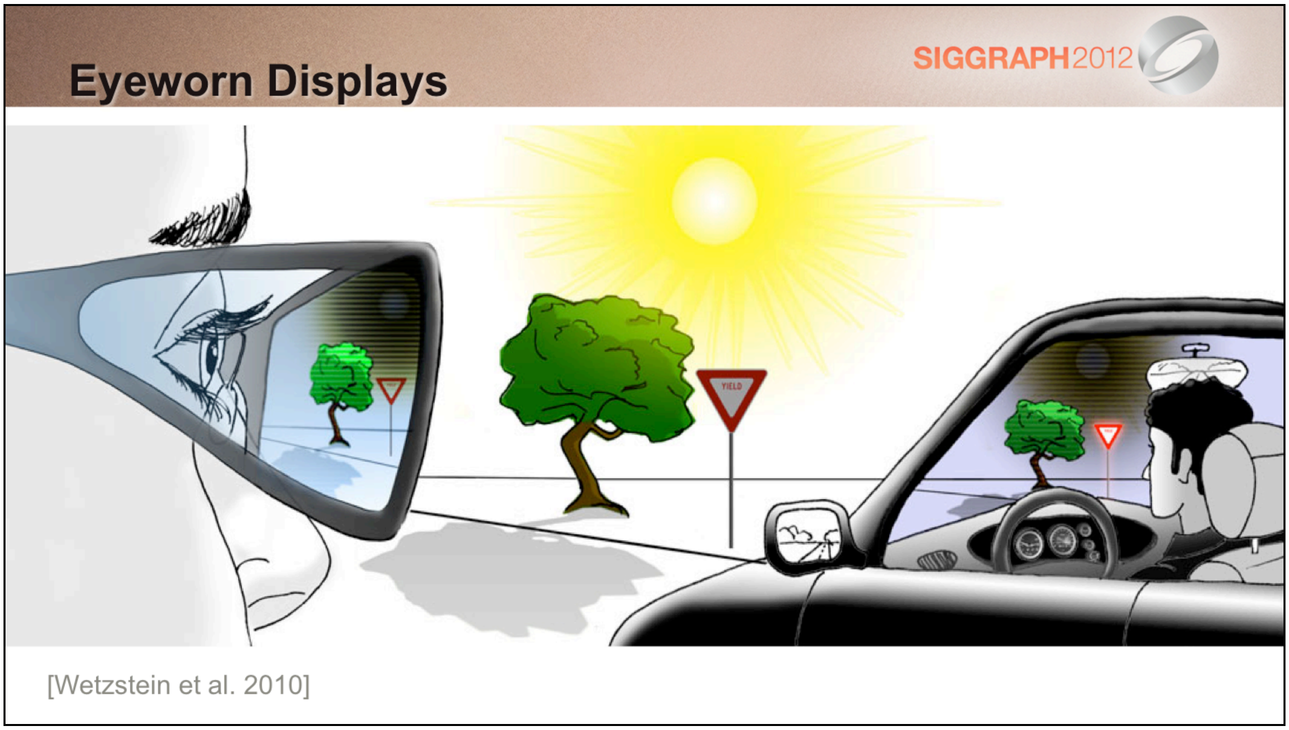
German (auto) » English

Lamb chops from the farmers with the shallots, tomato sauce and basil gnocchi

Google

ARToolKit

Let us also look at a completely different family of displays: head or eyeworn devices. With google goggles and project glass, these ideas finally start to emerge in the consumer market. The field of augmented reality, however, has been exploring the potential of head-mounted displays both optical see-through and video-based for decades.

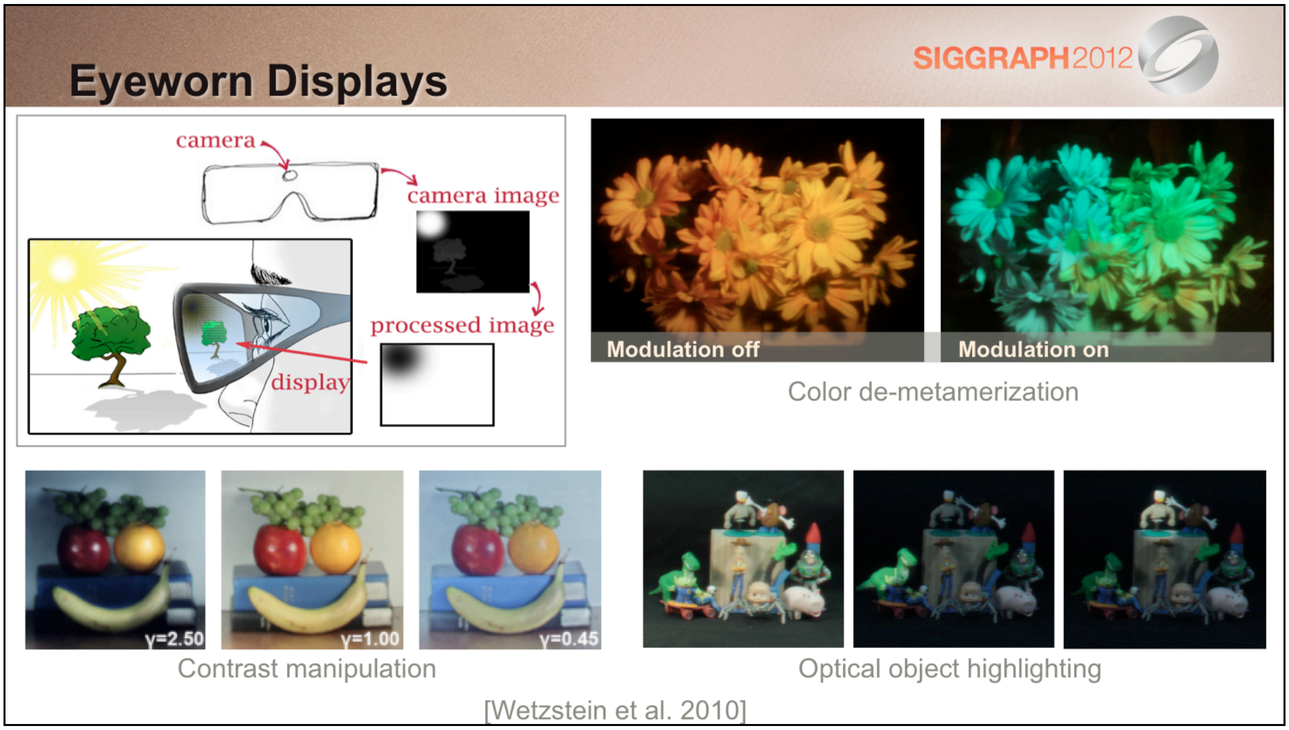


Eyeworn Displays

SIGGRAPH2012

[Wetzstein et al. 2010]

I would just like to highlight one display that has recently been proposed, which is not really an AR approach. We envision sunglasses, car windshields, and other commonly used see-through screens to have spatial light modulators integrated. Sunglasses of the future will be able to dim the environment light where it is actually bright, while preserving the visibility of shadows and other low-light parts of the scene. The underlying physical mechanisms require all-optical image processing by selectively blocking light that reaches the observer’s eyes.



Eyeworn Displays

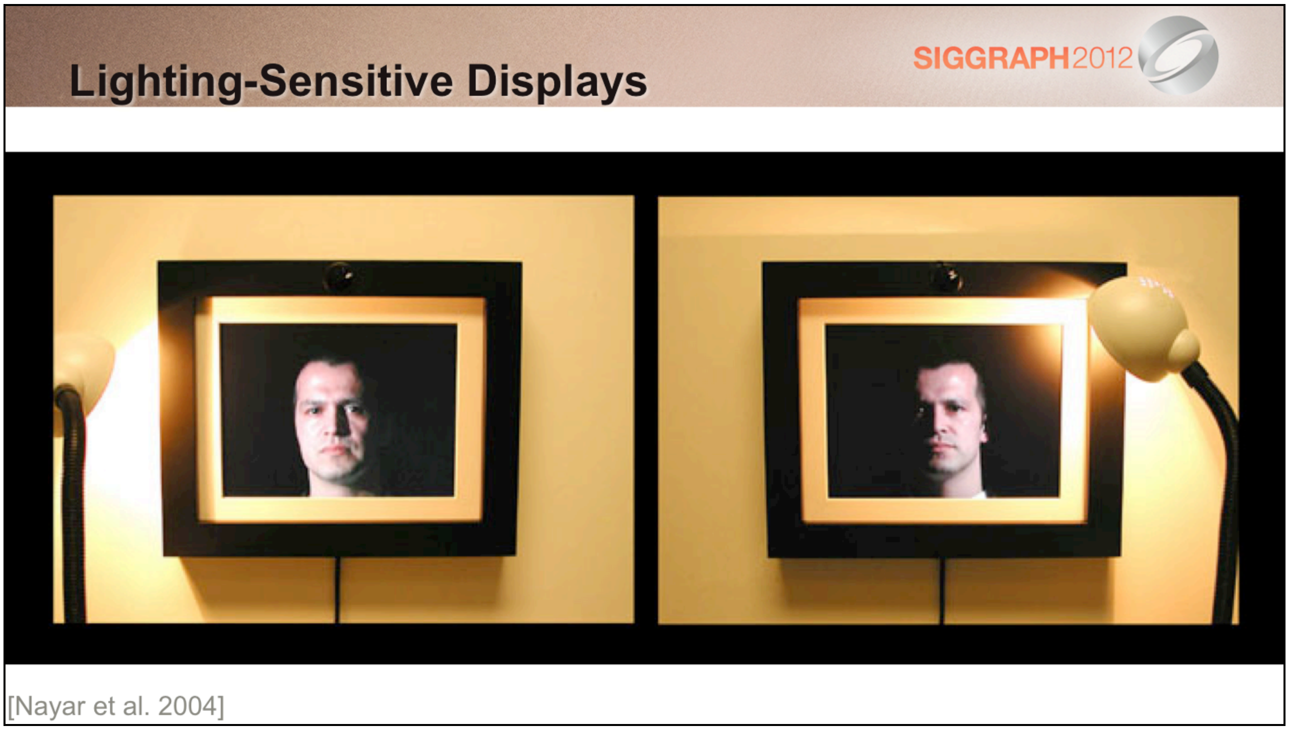
Color de-metamerization

Contrast manipulation

Optical object highlighting

[Wetzstein et al. 2010]

This can be done by integrating a small camera into the sunglasses, processing the recorded video stream, and computing a modulation patterns for the see-through screen. We demonstrate applications to contrast manipulation, which can be used as optical tonemapping. Furthermore, we can optically highlight specific objects of interest by dimming the other parts of the scene. The human visual system pre-attentively processed this kind of information – high level visual processing is not required. We also show that colors of the observed scene can be modulated, allowing for color de-metamerization or even recoloring objects to enhance the vision of color-deficient viewers.



Lighting-Sensitive Displays

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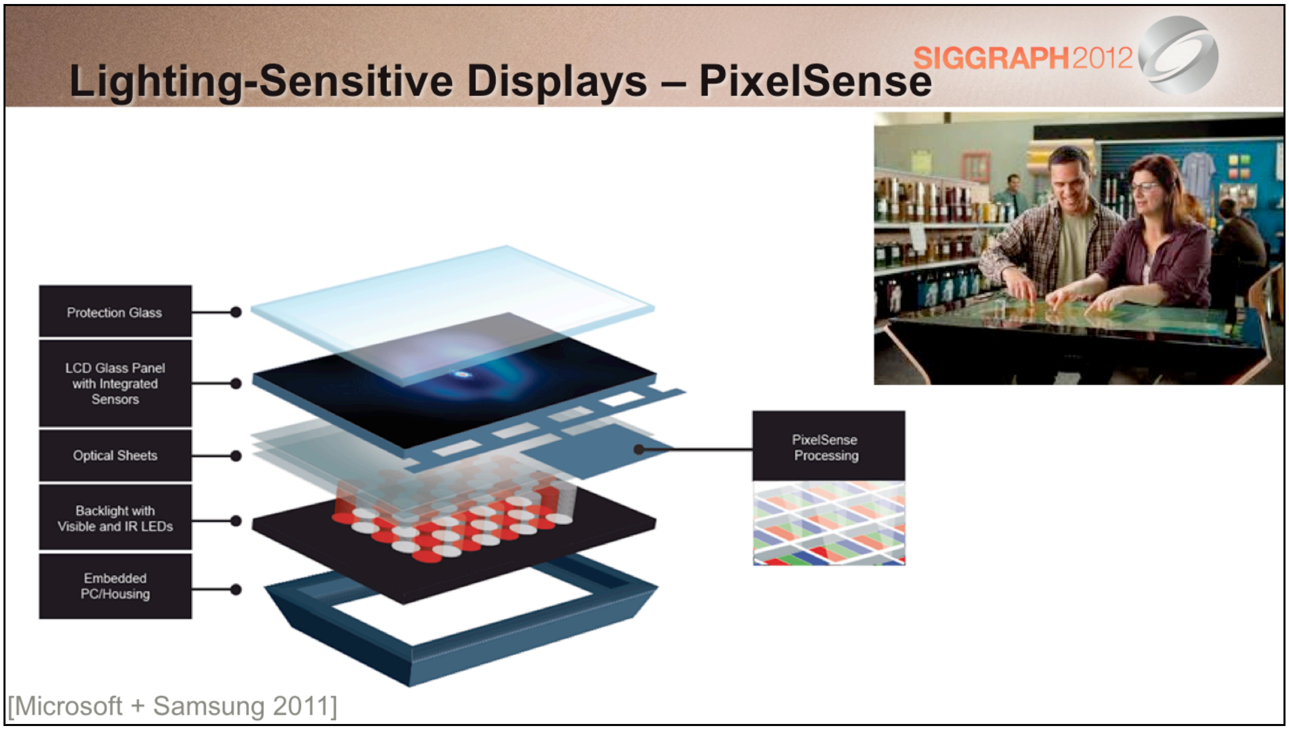
[Nayar et al. 2004]

Lighting sensitive displays have also been an active area of investigation. Shree Nayar proposed such a display in 2004. The presented virtual content reacts to the environment illumination and, in this example, can be lit by a real light source. In a way, the displays acts as a window into a virtual world that is a seamless extension of the physical world with light interacting between the two.

The underlying technology is actually rather simple: a wide field of view camera is integrated in the display frame and captures an environment map. This allows for real-time relighting of the content.



Lighting-Sensitive Displays – PixelSense

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Protection Glass

LCD Glass Panel with Integrated Sensors

Optical Sheets

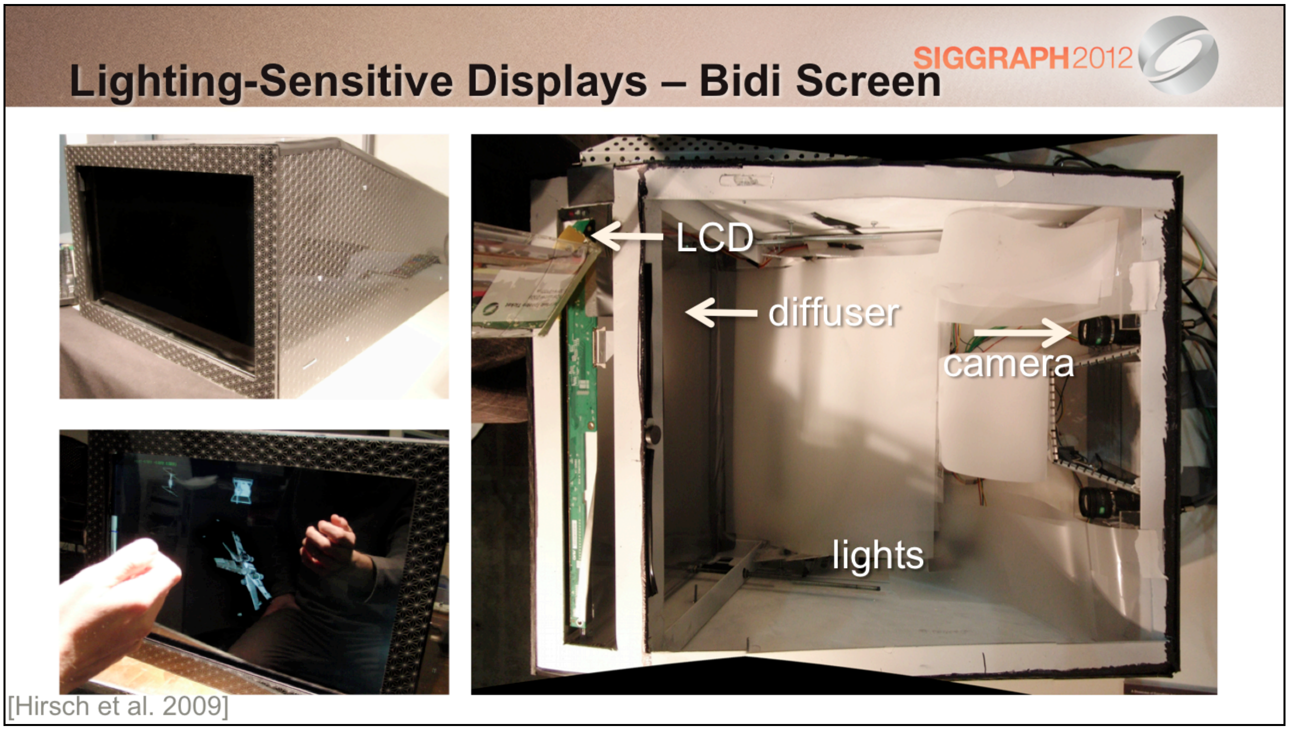
Backlight with Visible and IR LEDs

Embedded PC/Housing

PixelSense Processing

[Microsoft + Samsung 2011]

Recently, Microsoft Research and Samsung have introduced PixelSense or sensors in pixels as part of Microsoft Surface 2.0. Thus is basically a big multi-touch LCD screen. What's special about is is that it has, just as regular LCDs, three subpixels for the individual color channels but in addition this screen has a fourth subpixel that acts as a sensor. Combined with infrared background illumination, an unprecedented resolution of the touch interaction can be captured. Please note that the captured images are only in focus when the fingers actually touch the surface.



Lighting-Sensitive Displays – Bidi Screen

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[Hirsch et al. 2009]

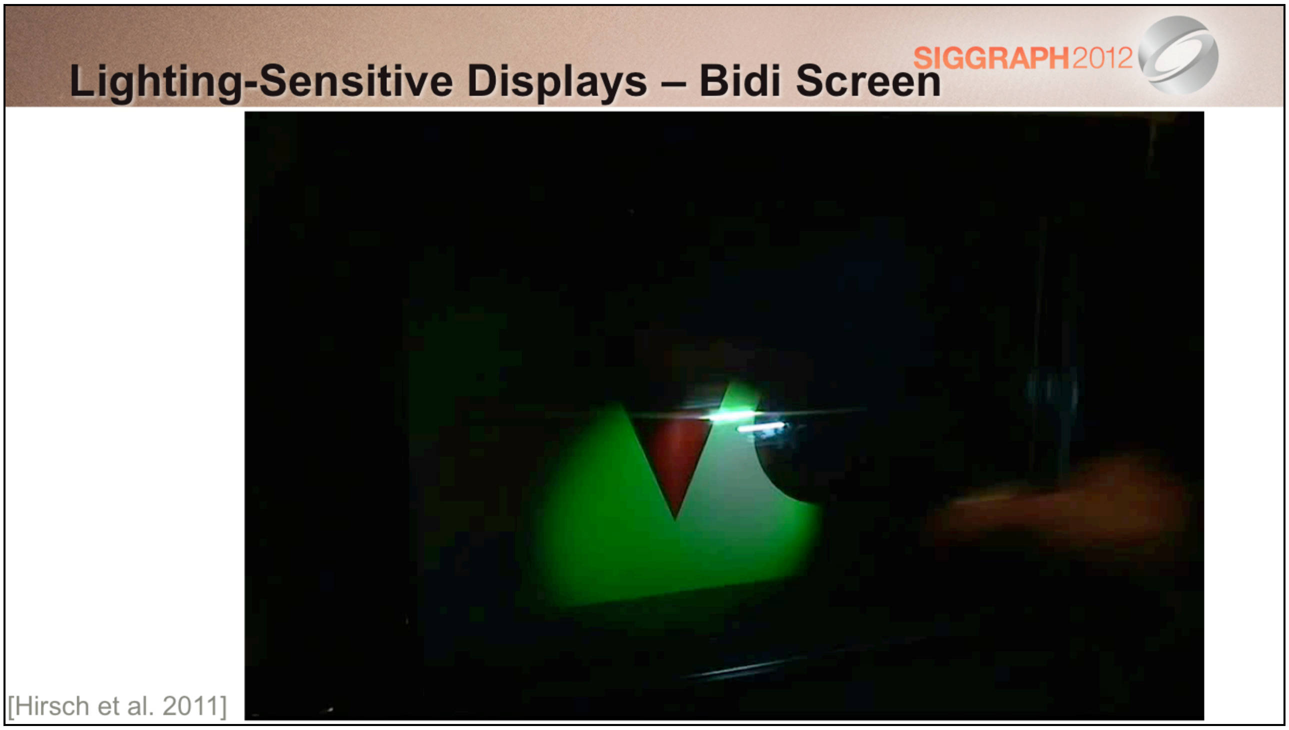
Years before pixel sense was announced by Microsoft, Matthew Hirsch and Douglas Lanman published a very related research project - the Bidi screen. Here, a screen is envision that also acts as a camera but captures a 4D light field rather than a 2D image as the Surface 2.0 does. This capability is achieved by placing the light sensitive elements at a slight offset from the actual LCD pixels. The LCD switches, at a very high refresh rate, between standard image display and a mask-pattern that allows the underlying sensor cells to capture the light field.

These images show the prototype Bidi screen that implemented the concept using a camera and a diffuser behind the screen, hence it's a litter bigger.

Lighting-Sensitive Displays – Bidi Screen

[Hirsch et al. 2011]

One application for such a depth-sensing screen is hovering gestural interaction - multi-touch in 3D.



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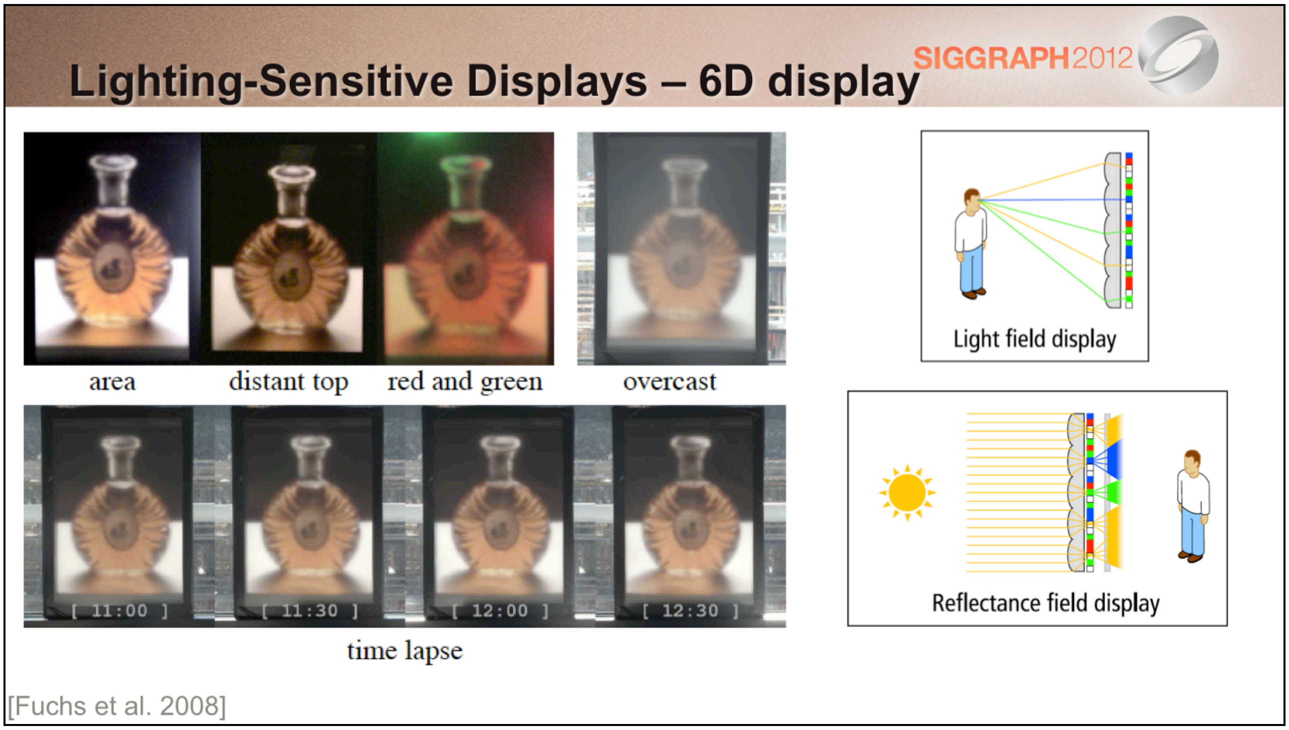
Lighting-Sensitive Displays – Bidi Screen

[Hirsch et al. 2011]

Another application is light-sensitive image display, just like Shree Nayar’s original idea. In this implementation, however, the screen acts as the light sensing device and captures the 4D incident light field which allows for much more accurate relighting as compared to a conventional 2D camera.



Lighting-Sensitive Displays – 6D display

SIGGRAPH2012

area distant top red and green overcast

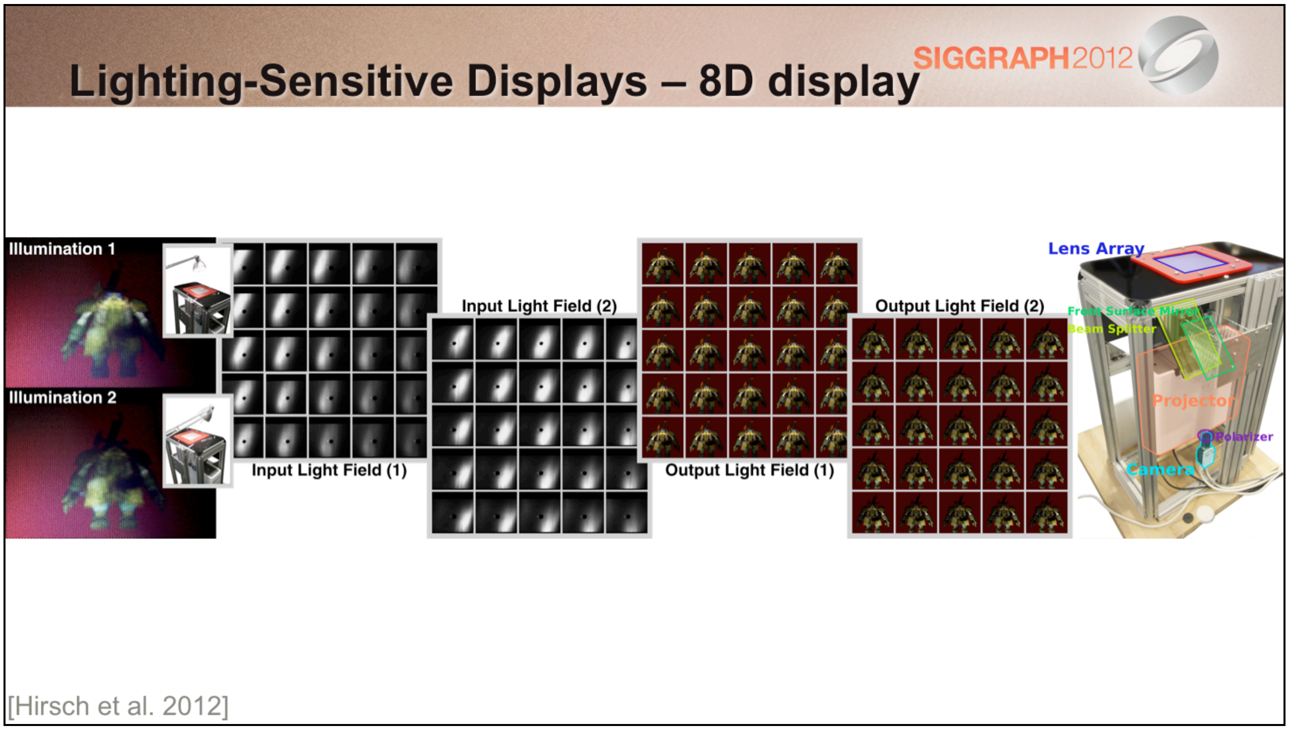
time lapse

Light field display

Reflectance field display

[Fuchs et al. 2008]

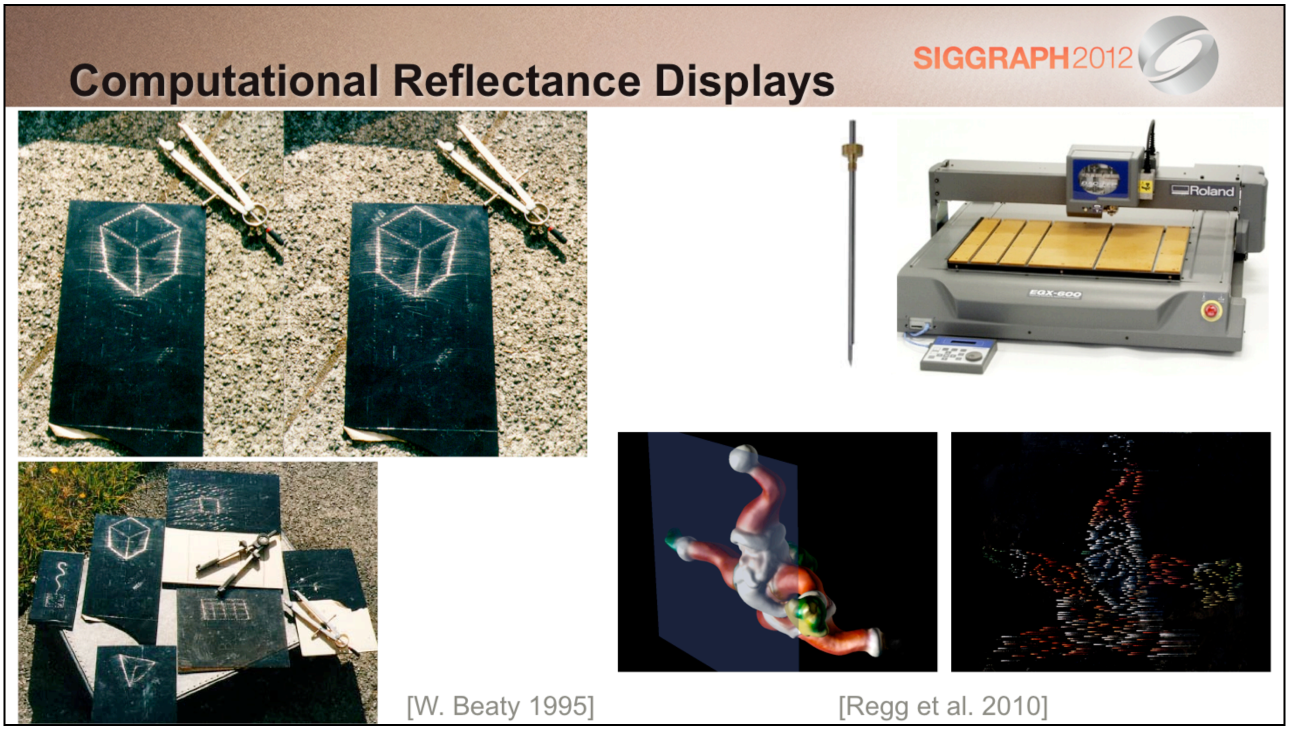
Another light sensitive display is the 6D display. This is a passive display which shows objects that are rear-illuminated by the real world. It uses a lenslet array that is flipped around and converts the incident 4D illumination light field into an interlaced 2D pattern on a transparency; the latter encodes images showing a scene under exactly these lighting conditions.



Lighting-Sensitive Displays – 8D display

[Hirsch et al. 2012]

Combining the ideas of capturing and displaying 4D light fields with a single display surface results in the 8D display, which was recently built by Matthew Hirsch. Here, the viewer looks sees 3D objects without having to wear glasses. By capturing the incident light field, these objects can also be lit by physical illumination. Shadows are cast from the real world onto virtual objects in the most natural manner.



Computational Reflectance Displays

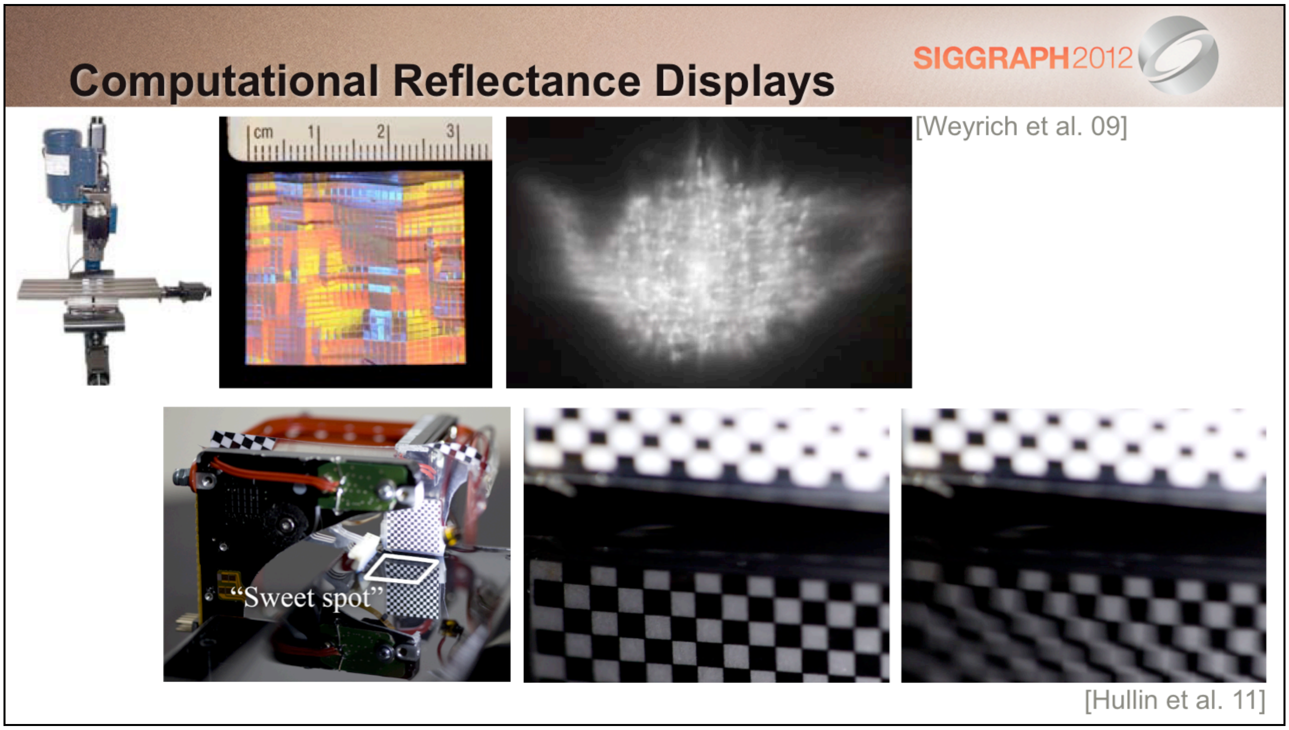
SIGGRAPH2012

[W. Beaty 1995]

[Regg et al. 2010]

While we will discuss glasses-free 3D displays in more detail in the second part of our course, I would just like to highlight an unconventional example of fabricating 3D displays. Scratch holography was explored in online tutorials by William Beaty in the 90s and what he basically did was using a compass to scratch many circles into the surface of a surface. When illuminated by a distant light source, such as the sun, the surface then creates specular highlights that create a most convincing impression of a 3D object floating around the screen. You can move around the screen – it supports motion parallax and binocular disparity.

A computational approach to scratch holography was proposed by Regg et al. in 2010. The authors decomposed a given 3D object into “scratches” and then automatically fabricated the surface with an engraving machine. While the results have a relatively low-resolution, this is a perfect example of a computational display that combines fabrication and computational pre-processing.



Computational Reflectance Displays

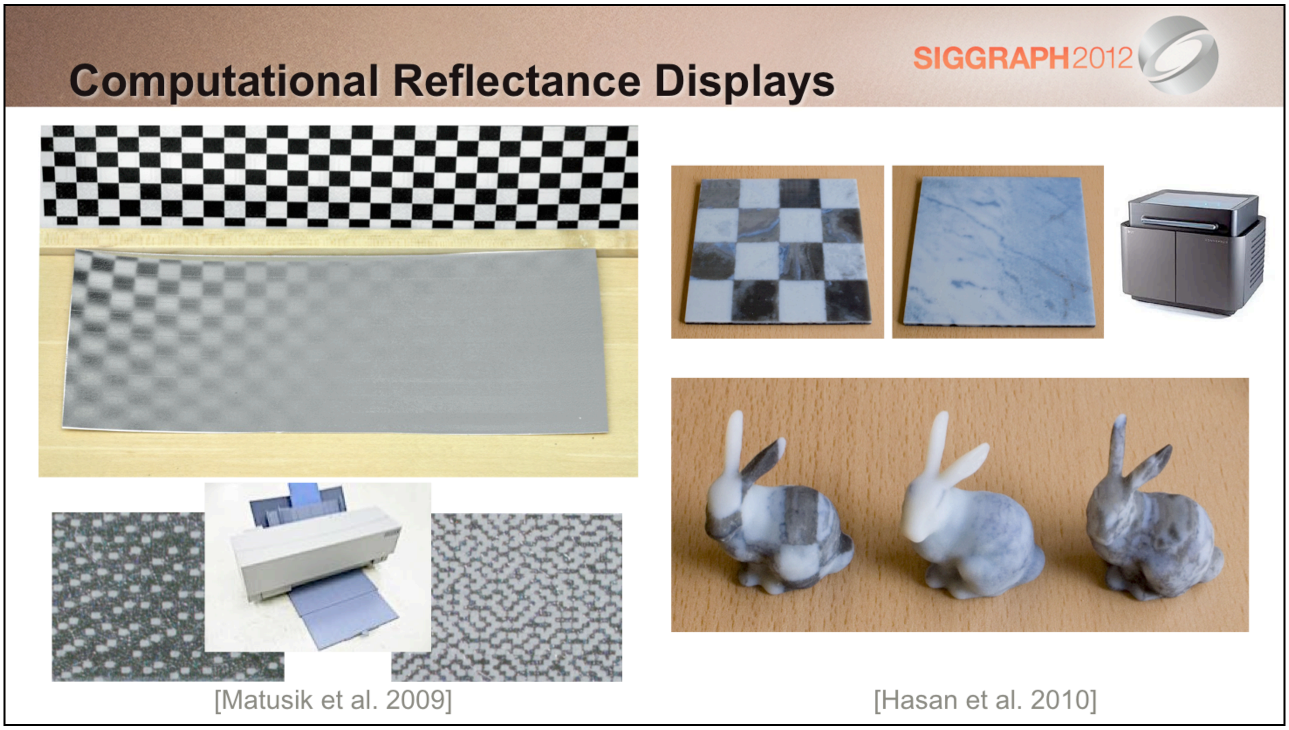
SIGGRAPH2012

[Weyrich et al. 09]

[Hullin et al. 11]

The idea of computational materials has been rather popular in the last few years. Weyrich and colleagues proposed a computational approach to fabricating micro-geometry so as to achieve a predefined reflectance behavior of the material. Custom reflections can, for instance, be teapots as seen in the top row here.

A dynamic BRDF display was proposed by Matthias Hullin and presented at Siggraph emerging technologies last year in Vancouver. In case you did not have a chance to see it there, it’s basically a small water tank with programmable actuators on the side. These are moved in a way to create wave-patterns that overlay and create a desired BRDF. In the bottom center, you see a checkerboard reflected in the water tank without any waves, whereas the bottom shows the same scene with wave patterns that create a custom reflectance of the surface.



Computational Reflectance Displays

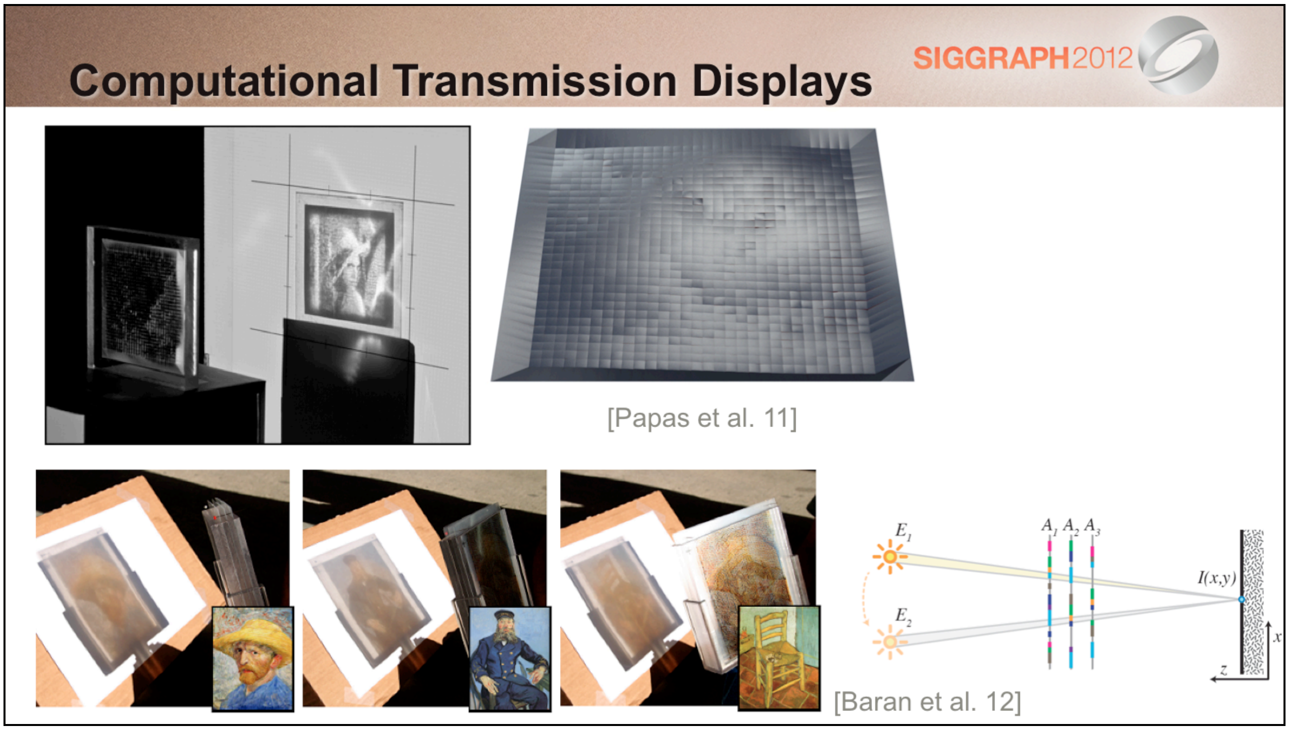
[Matusik et al. 2009]

[Hasan et al. 2010]

Spatially-varying reflectance can also be “printed”, as proposed by Wojciech Matusik in 2009. Here, a 2D multi-material desktop printer mixes different materials to achieve a custom reflectance of the printed patterns. Printed reflectance properties range from purely reflective to diffuse and anything in between.

But not only 2D materials can be mixed to create a spatially varying reflectance, also 3D printers can facilitate new display capabilities by mixing different materials. Objet’s Connex 500, a rather expensive 3D printer, actually has the capability mix two different print materials in addition to the support material. By combining those in clever ways, an approximation to arbitrary, spatially-varying subsurface scattering can be created on printed 3D objects, such as the bunnies and printed marble slabs on the right.

On this note, I would like to point you to Neri Oxman's work at the MIT Media Lab. She has been exploring computational materials for design, art, and architecture for a number of years. So please see the website of her mediated matter group for more information, if you are interested in this topic: http://www.media.mit.edu/research/groups/mediated-matter



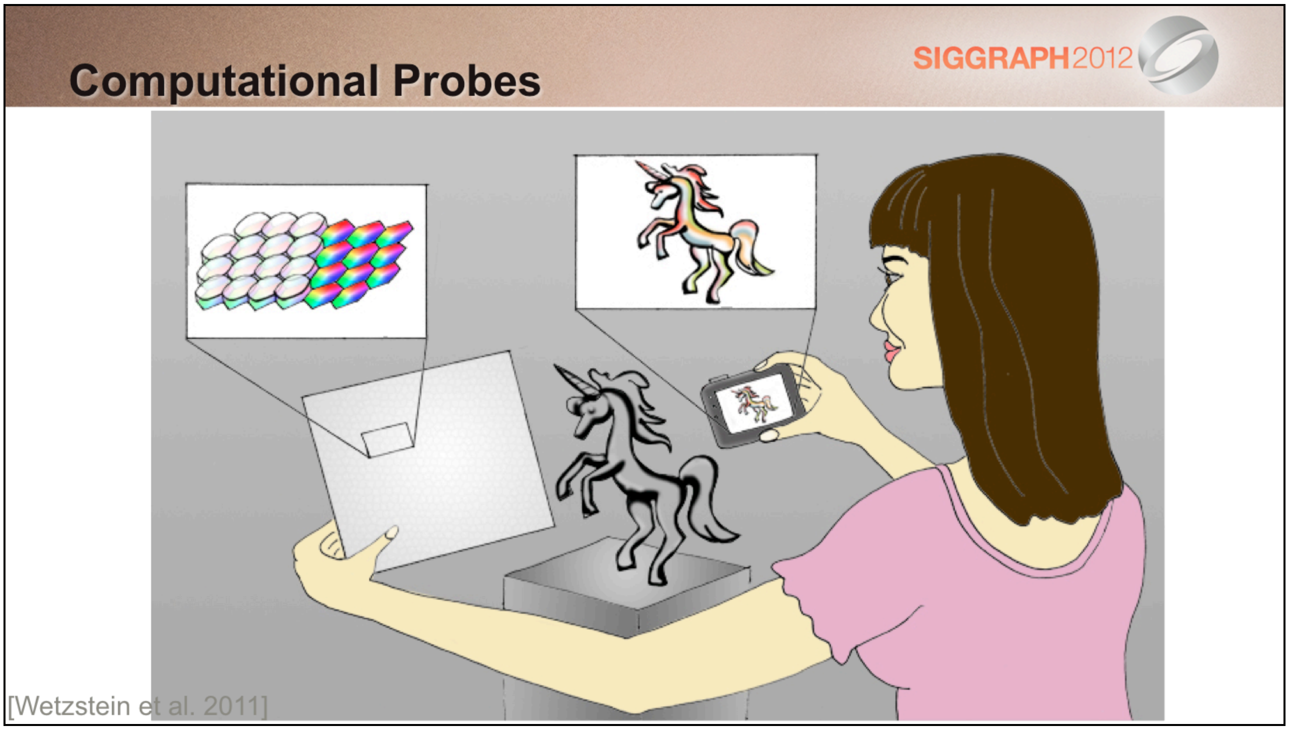
Computational Transmission Displays

[Papas et al. 11]

[Baran et al. 12]

Not only can materials with custom reflection properties be fabricated, similar concepts also apply to transmissive displays. The folks at Disney Research in Zurich have been actively working on that topic and proposed an approach to milling the surface of a refractive piece of plexiglas so that it creates caustics that form an image, such as Lena seen in the top.

Rather than using a refractive surface, multiple stacked layers of light attenuators can also be used. Spaced by clear acrylic sheets, multiple inkjet-printed transparences contain pre-computed patterns that create different shadow images depending on the incident angle of a distant light source.

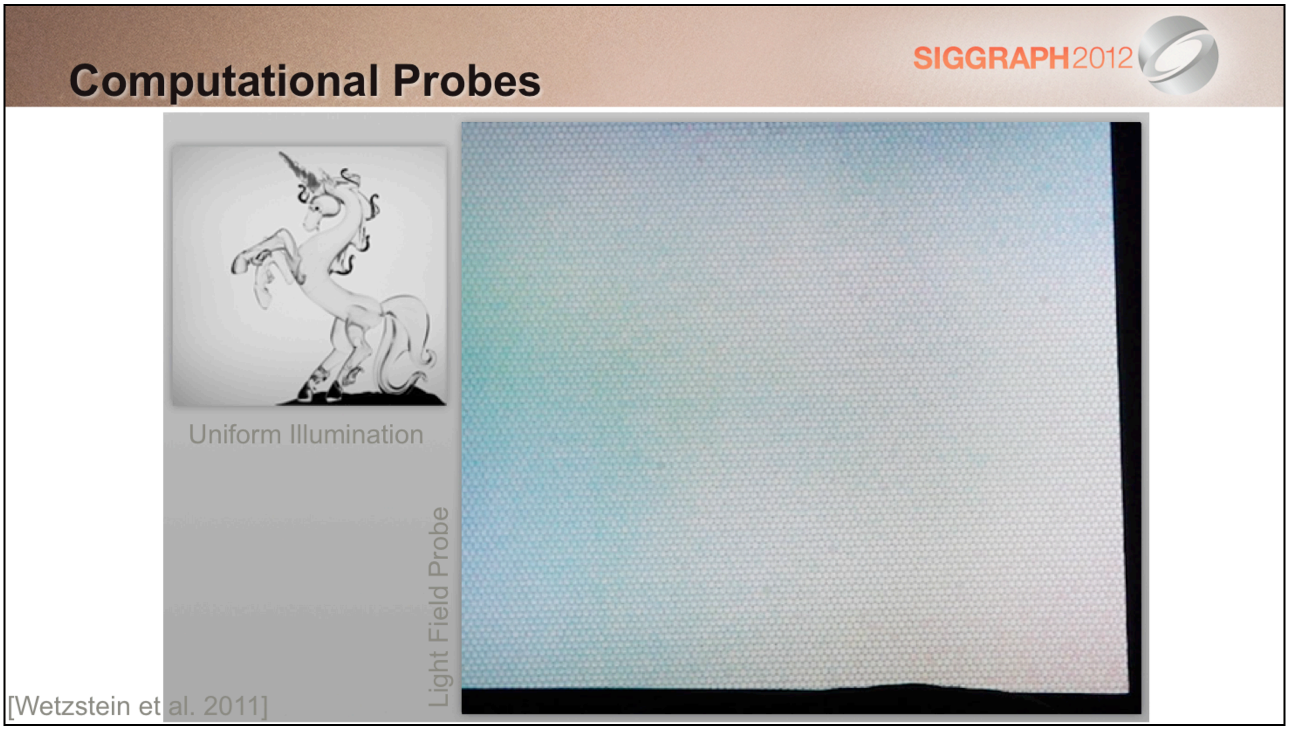


Computational Probes

SIGGRAPH2012

[Wetzstein et al. 2011]

Displays can also be used as probes that encode visual information for computer vision applications rather than for a human observer. Last year, we introduced light field probes for visualizing and reconstructing transparent refractive objects. For this purpose, a light field display consisting of a lenslet array with a high-frequency pattern is placed behind the transparent object of interest. When observed without the object from the central position, the probe just looks white. As the object refracts light, the incident angle of observed light rays on the background probe change and different ray angles on the background are color coded.



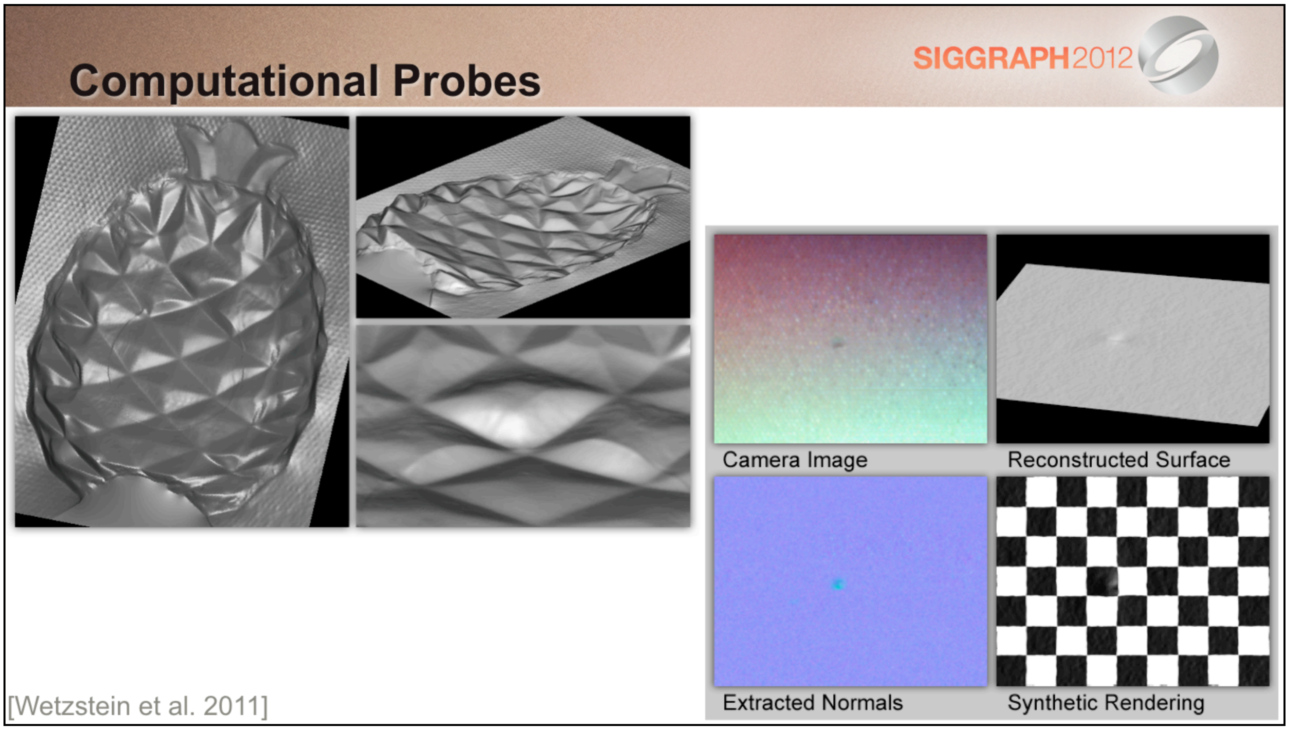
Computational Probes

Uniform Illumination

Light Field Probe

[Wetzstein et al. 2011]

Here’s an example. The glass unicorn is almost transparent when observed in front of a uniform light source. On the right, we see the probe without an object. But when placing the object in front of the probe, the angles and magnitudes of refracted light rays are optically coded in color and saturation.



Computational Probes

SIGGRAPH2012

Camera Image

Reconstructed Surface

Extracted Normals

Synthetic Rendering

[Wetzstein et al. 2011]

This information can directly be used to reconstruct the surface of refractive objects. As only a single image is required, even dynamic surfaces such as wavy water can be acquired and reconstructed.

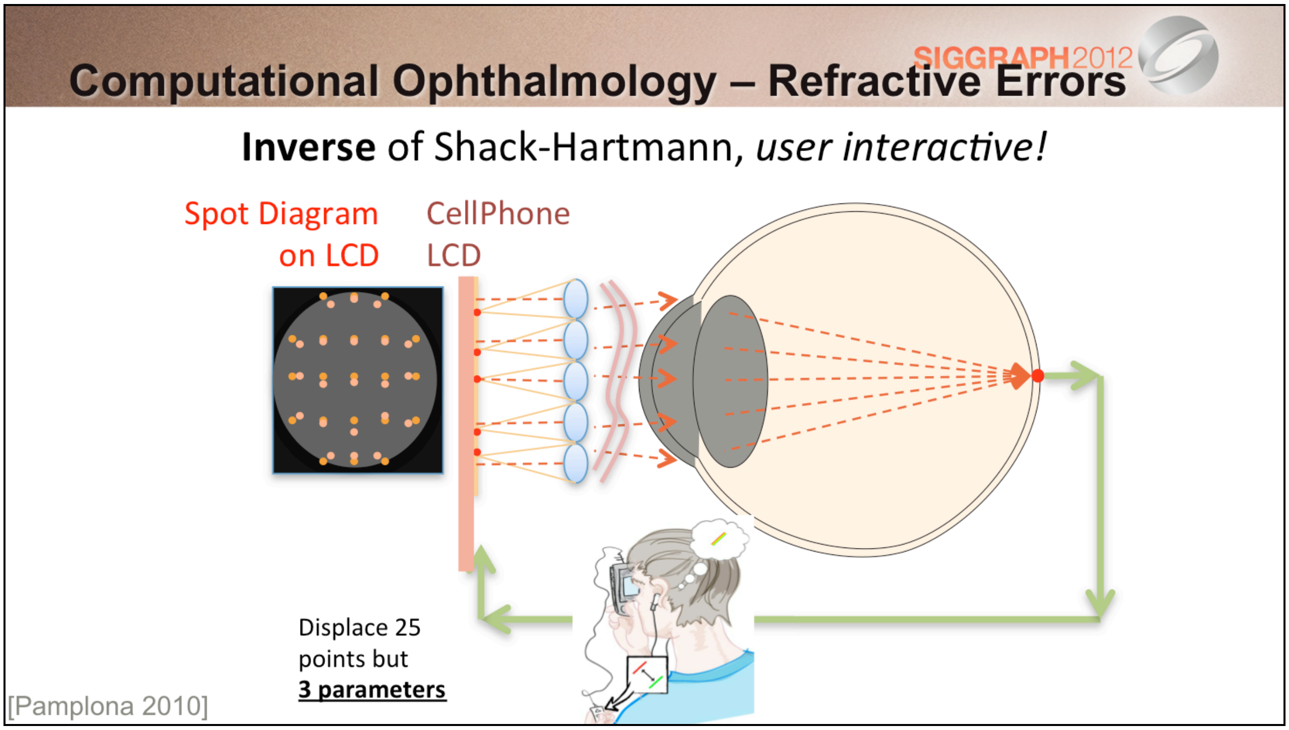
Computational Ophthalmology

SIGGRAPH2012

[Pamplona 2010]

Computational displays are nor only fun but also have important applications in global health. A final family of computational displays for ophthalmological applications has been proposed over the last few years.

In this example, we see how a smart phone display can be converted into a 4D light field display using an inexpensive clip on. By asking the user to interactively align a few patterns, this device has the capability of measuring the refractive errors of the observer.



Computational Ophthalmology – Refractive Errors

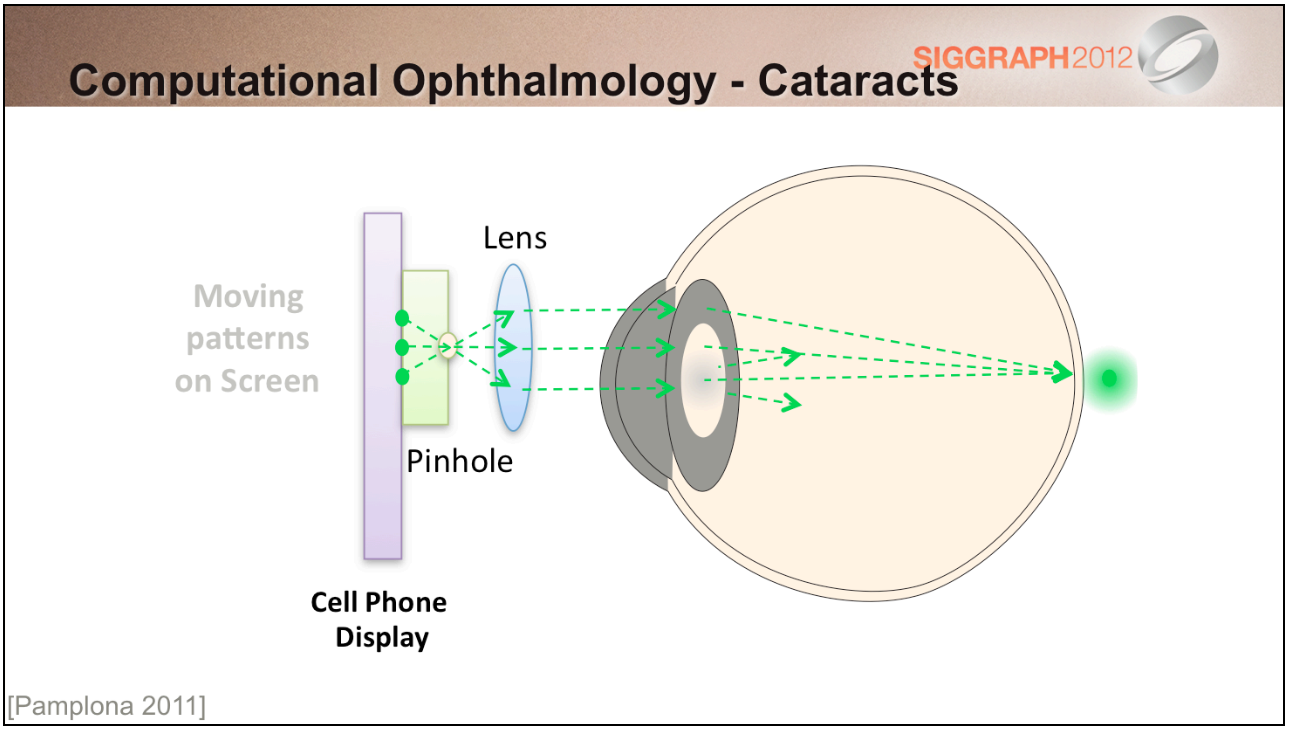
SIGGRAPH2012

Inverse of Shack-Hartmann, *user interactive!*

Displace 25 points but **3 parameters**

[Pamplona 2010]

The display acts as the inverse of a Shack-Hartmann sensor that is often used in astronomical imaging to capture an incident wavefront. In this application, the user basically changes the patterns to align in some form in the perceived image, but the displayed pattern itself is predistorted so as to compensate for the refractive errors of the eye.



Computational Ophthalmology - Cataracts

SIGGRAPH2012

[Pamplona 2011]

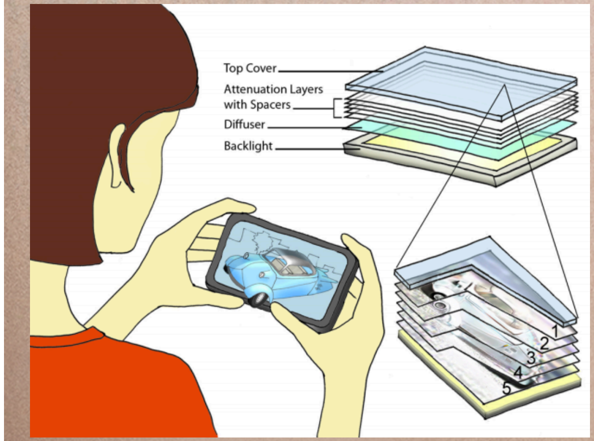
A very similarly-looking smart-phone clip-on has presented last year at Siggraph with a different purpose: measuring cataracts. In this case, the display basically acts as a radar scanning a pattern over he viewers pupil. The observer simply clicks a few buttons and gets back a detailed map of cataracts on his lens.

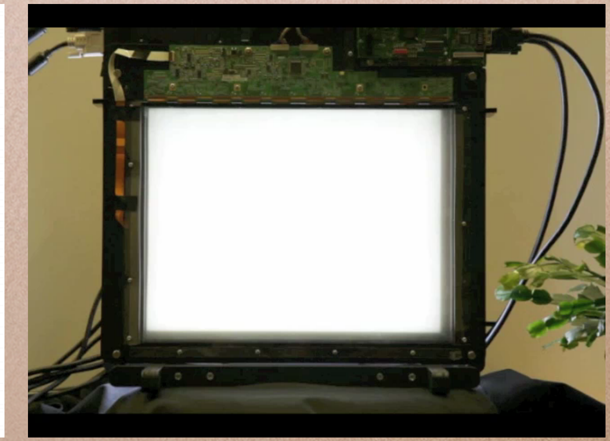
Computational Ophthalmology – Tailored Displays

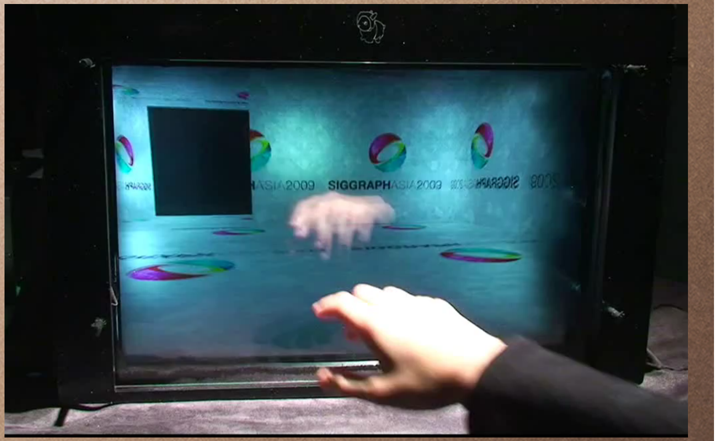
[Pamplona 2012]

Finally, a new tailored display is presented at this year's Siggraph by the same authors. This is a special light field display that has the capability to show a sharp image for an observer that doesn't need his glasses. It displays the light field corresponding to a 2D image that is moved within the focus range of the observer.

Computational Light Field Displays







Douglas Lanman
MIT Media Lab

Matthew Hirsch
MIT Media Lab

Is “glasses-free 3D” ready?

SIGGRAPH2012

Nintendo 3DS
E3 2010

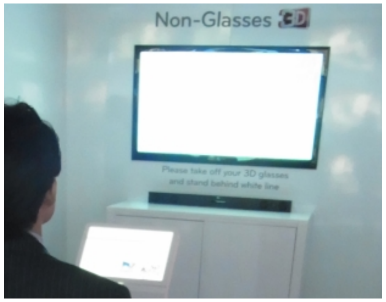
MasterImage 3D
Computex 2011

Asus Eee Pad MeMO 3D
Computex 2011

LG Optimus 3D
Mobile World Congress 2011

Toshiba 3DTV Prototype
CES 2011

Sony 3DTV Prototype
CES 2011



LG 3DTV Prototype
CES 2011

Taxonomy of 3D Displays:

Glasses-bound vs. Unencumbered Designs

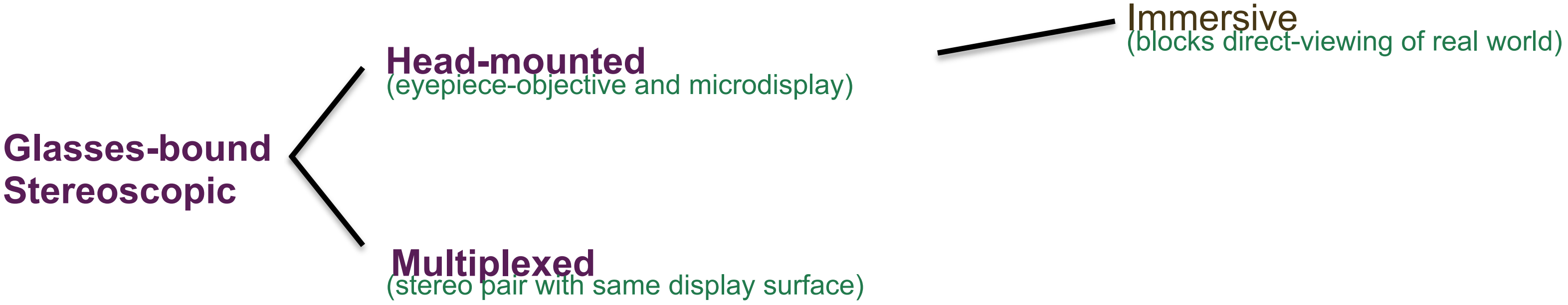
SIGGRAPH2012

- **Glasses-bound Stereoscopic**
  - **Head-mounted** (eyepiece-objective and microdisplay)
    - Immersive (blocks direct-viewing of real world)
    - See-through (superimposes synthetic images onto real world)
  - **Multiplexed** (stereo pair with same display surface)
    - Spatially-multiplexed (field-concurrent) (color filters, polarizers, autostereograms, etc.)
    - Temporally-multiplexed (field-sequential) (LCD shutter glasses)
- **Unencumbered Automultiscopic**
  - **Parallax-based** (2D display with light-directing elements)
    - Parallax Barriers (uniform array of 1D slits or 2D pinhole arrays)
    - Integral Imaging (lenticular sheets or fly's eye lenslet arrays)
  - **Volumetric** (directly illuminate points within a volume)
    - Multi-planar (time-sequential projection onto swept surfaces)
    - Transparent Substrates (intersecting laser beams, fog layers, etc.)
  - **Holographic** (reconstructs wavefront using 2D element)
    - Static (holographic films)
    - Dynamic (holovideo)

Taxonomy adapted from Hong Hua

Taxonomy of 3D Displays:

Immersive Head-mounted Displays (HMDs)



Glasses-bound Stereoscopic

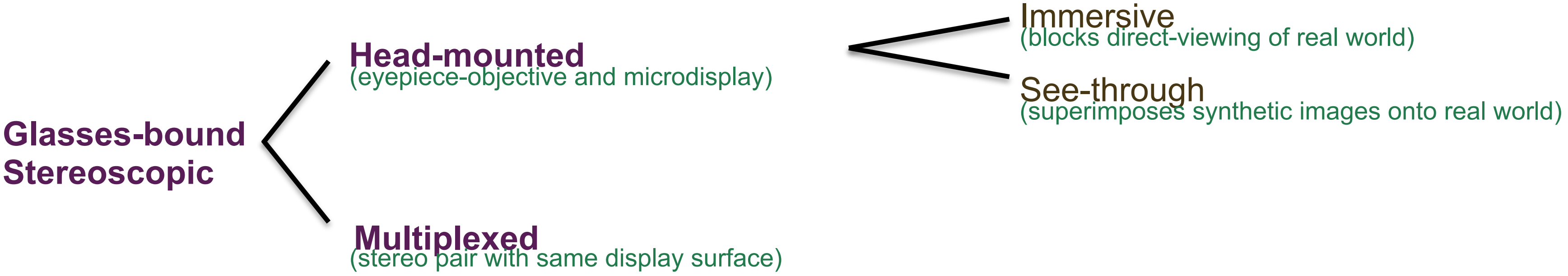
Head-mounted
(eyepiece-objective and microdisplay)

Immersive
(blocks direct-viewing of real world)

Multiplexed
(stereo pair with same display surface)

Taxonomy of 3D Displays:

See-through Head-mounted Displays (HMDs)



Glasses-bound Stereoscopic

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(eyepiece-objective and microdisplay)

Immersive
(blocks direct-viewing of real world)

See-through
(superimposes synthetic images onto real world)

Multiplexed
(stereo pair with same display surface)

Taxonomy of 3D Displays:

Spatial Multiplexing (e.g., Anaglyphs)

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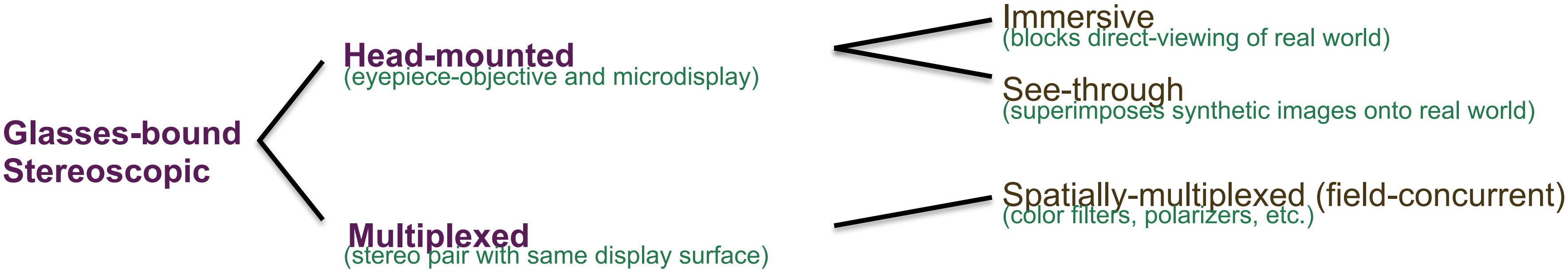

Glasses-bound Stereoscopic

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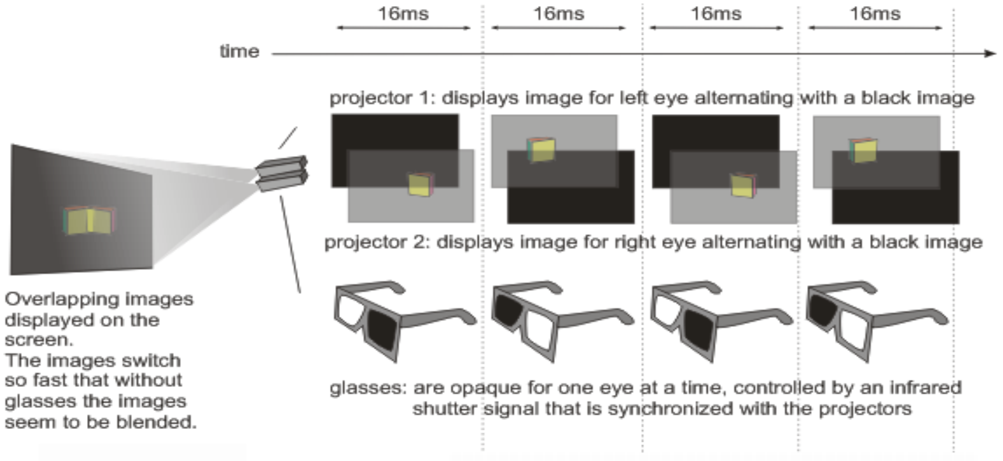
  - Immersive (blocks direct-viewing of real world)
  - See-through (superimposes synthetic images onto real world)
- **Multiplexed** (stereo pair with same display surface)
  - Spatially-multiplexed (field-concurrent) (color filters, polarizers, etc.)

Taxonomy of 3D Displays:

Temporal Multiplexing (e.g., Shutter Glasses)



projector 1: displays image for left eye alternating with a black image

projector 2: displays image for right eye alternating with a black image

Overlapping images displayed on the screen. The images switch so fast that without glasses the images seem to be blended.

glasses: are opaque for one eye at a time, controlled by an infrared shutter signal that is synchronized with the projectors

- **Glasses-bound Stereoscopic**
  - **Head-mounted** (eyepiece-objective and microdisplay)
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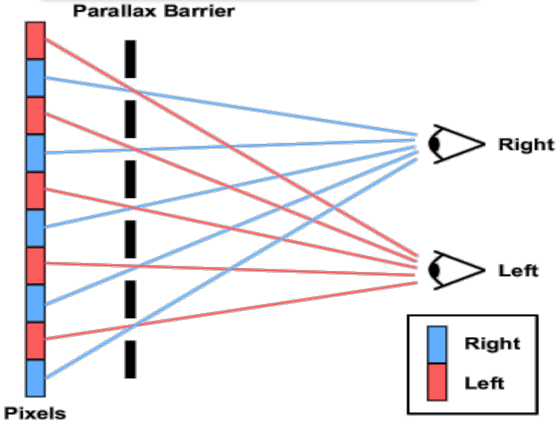
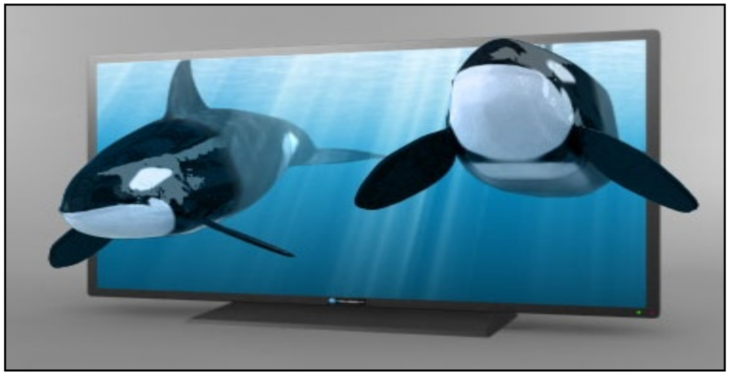
Taxonomy of 3D Displays:

Parallax Barriers





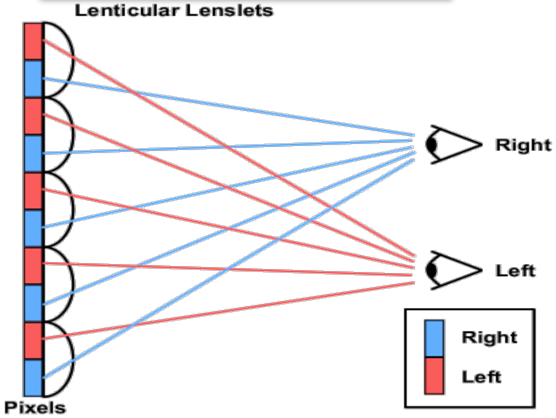
NewSight MV-42AD3 42''
(1920x1080, 1x8 views)

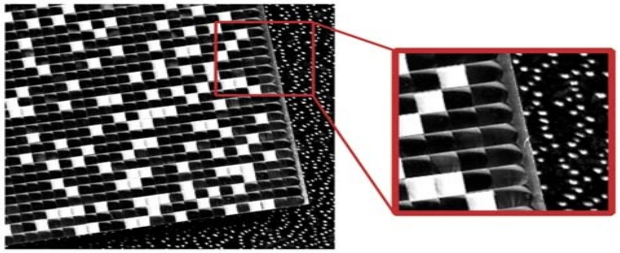
Unencumbered Automultiscopic

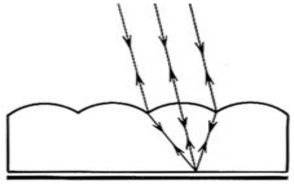
- **Parallax-based**
  (2D display with light-directing elements)
  - Parallax Barriers
    (uniform array of 1D slits or 2D pinhole arrays)
- **Volumetric**
  (directly illuminate points within a volume)
- **Holographic**
  (reconstructs wavefront using 2D element)

Taxonomy of 3D Displays:

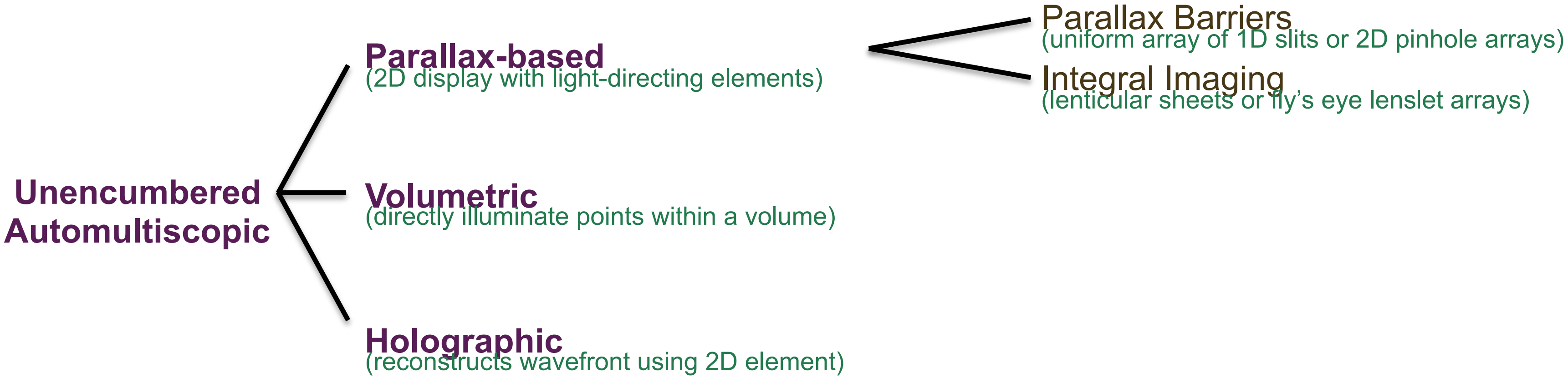
Integral Imaging







Alioscopy 3DHD 42''
(1920x1200, 1x8 views)



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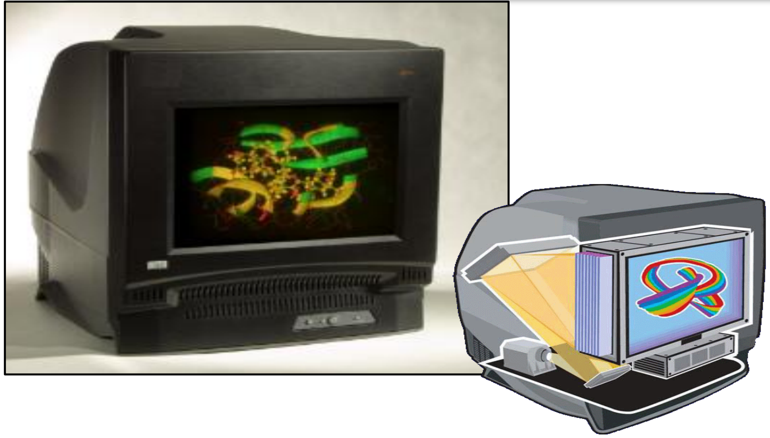
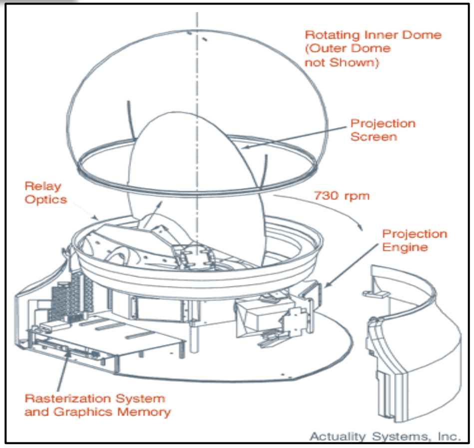
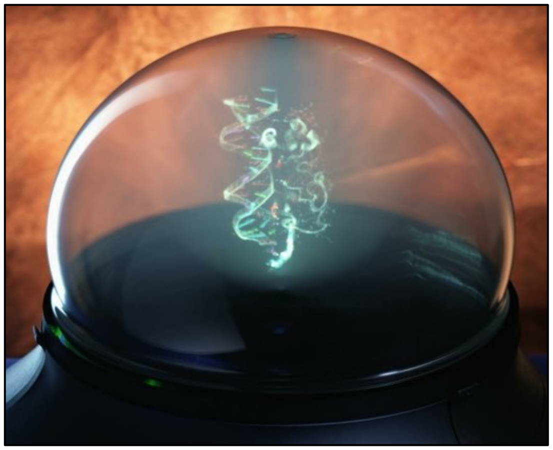
Taxonomy of 3D Displays:

Multi-planar Volumetric Displays







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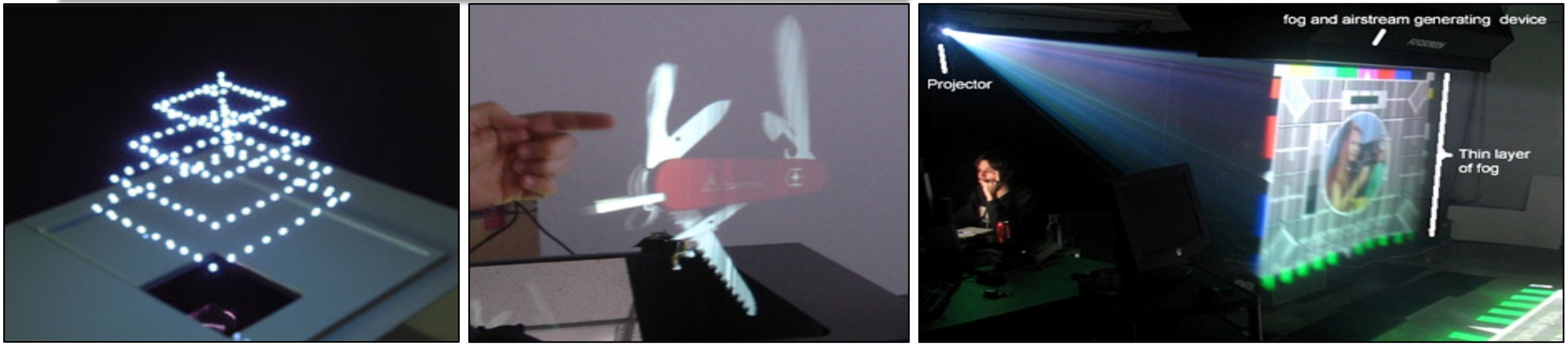
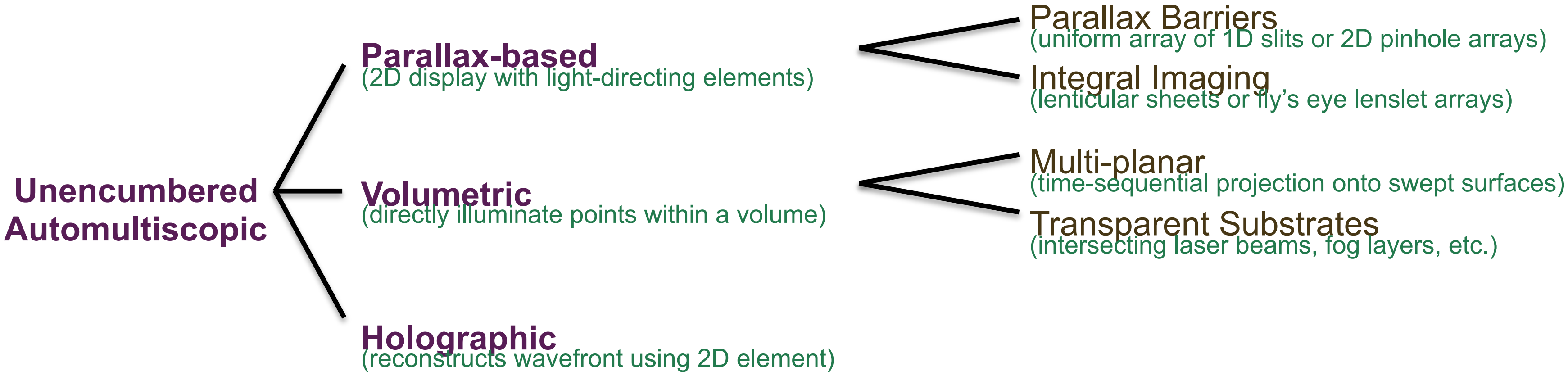
Taxonomy of 3D Displays:

Transparent-substrate Volumetric Displays





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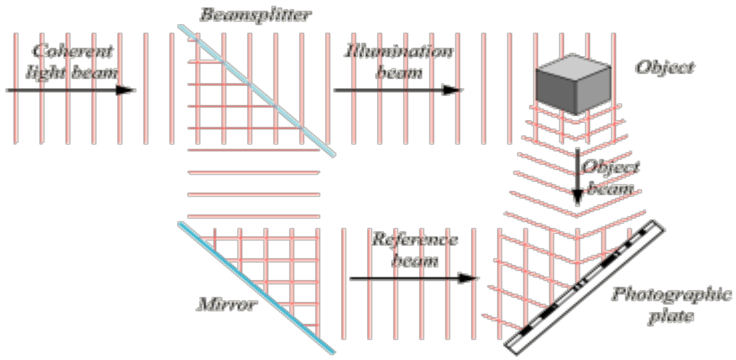
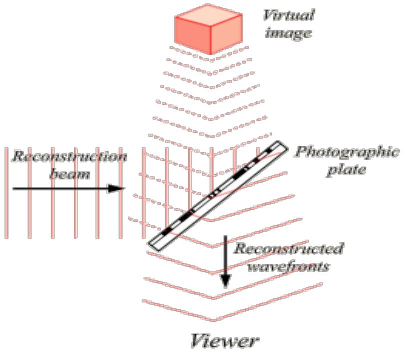
Taxonomy of 3D Displays:

Static Holograms

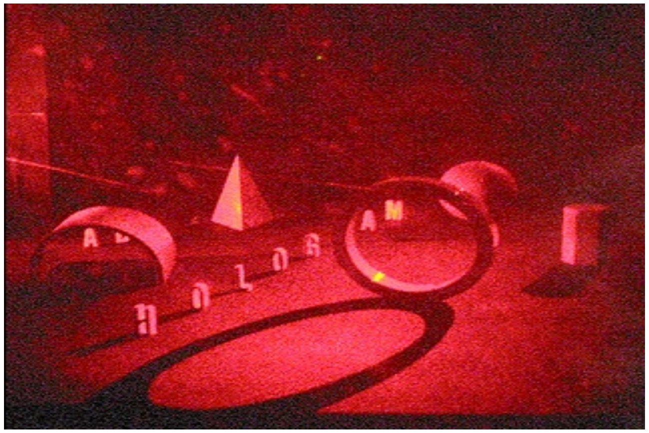
SIGGRAPH2012



capture



reconstruction



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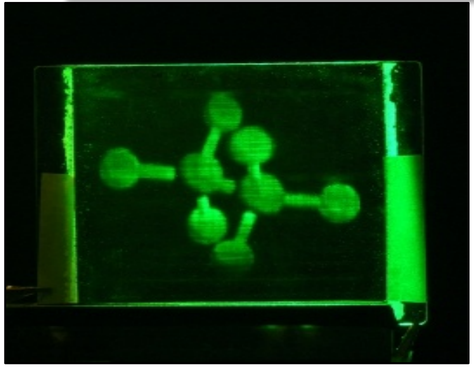
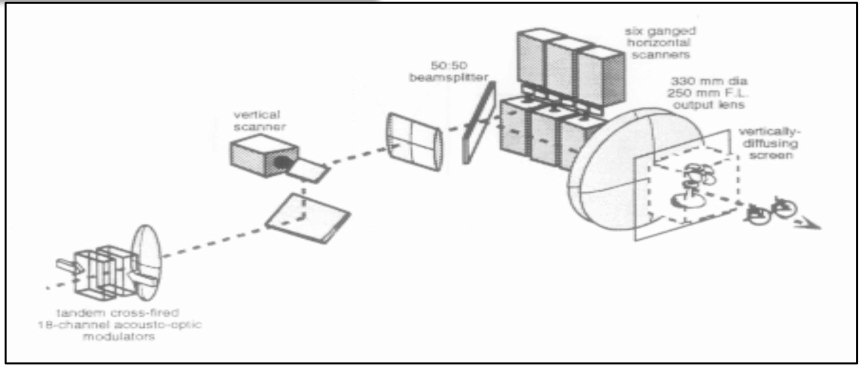
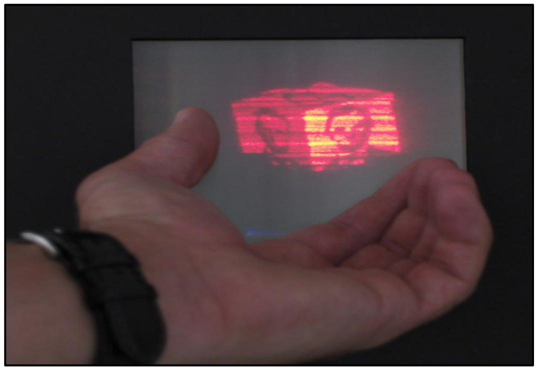
Taxonomy of 3D Displays:

Dynamic Holograms (Holovideo)



Tay et al.
[Nature, 2008]





MIT Media Lab Spatial Imaging Group
[Holovideo, 1989 – present]

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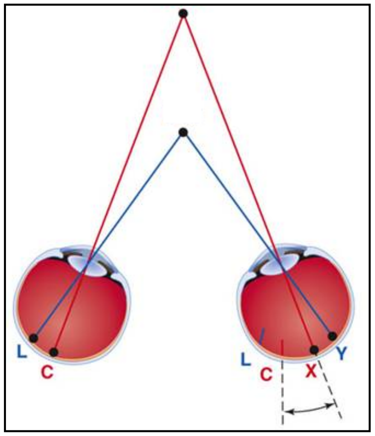
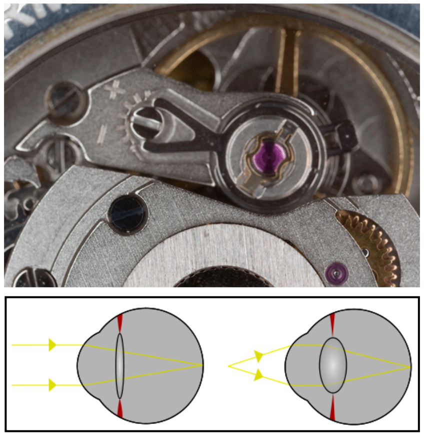
What is meant by “glasses-free 3D”?

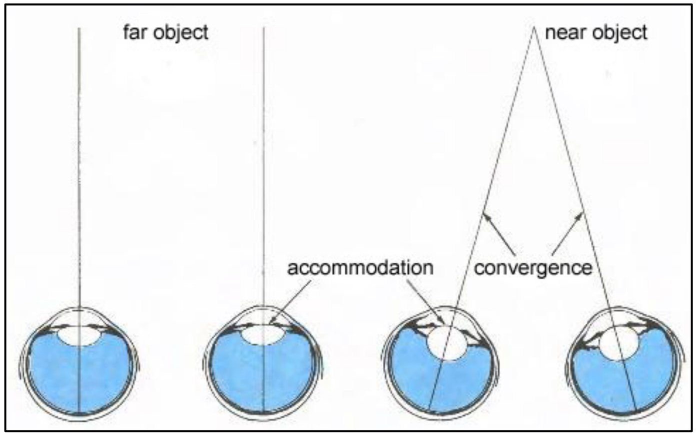


binocular disparity

motion parallax



accommodation



convergence

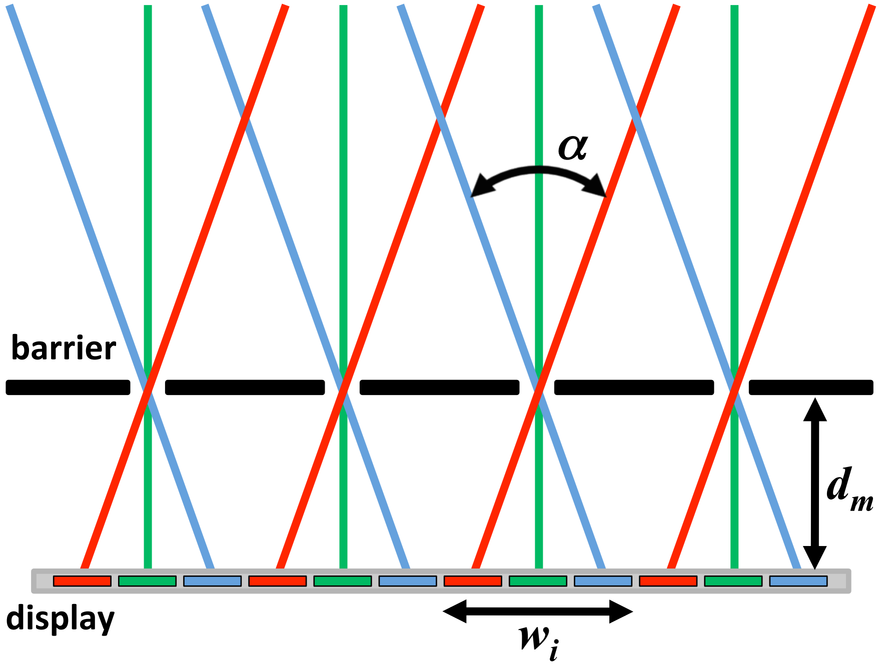
current glasses-based (stereoscopic) displays

near-term glasses-free (automultiscopic) displays

longer-term volumetric and holographic displays

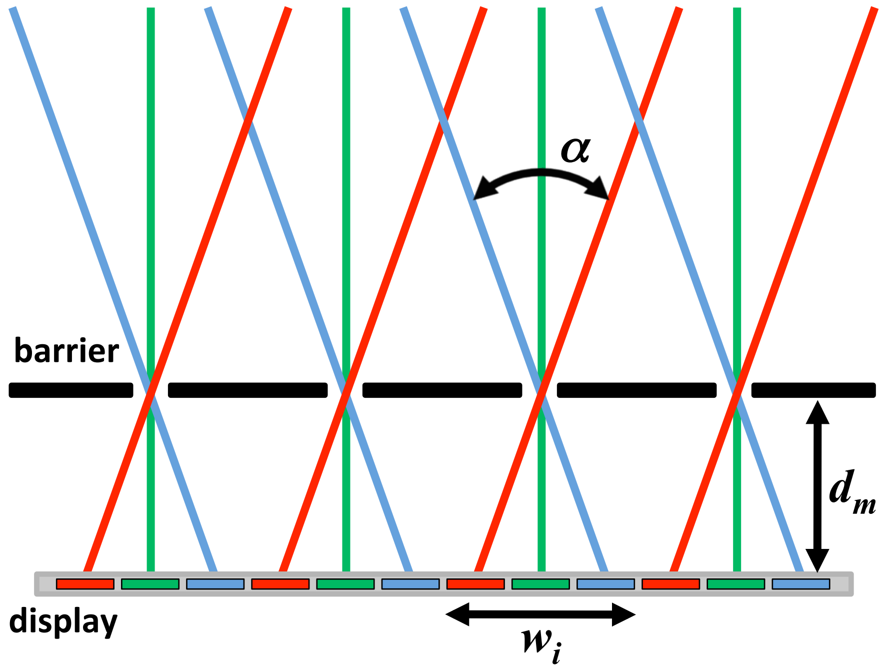
Parallax Barriers

SIGGRAPH2012

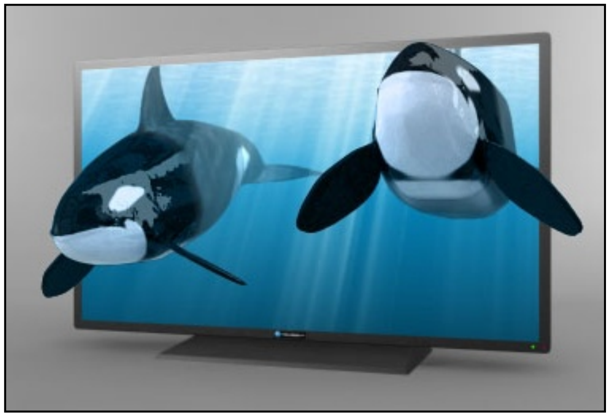


- Introduced by Frederic E. Ives in 1903
- Requires two light-attenuating layers (i.e., masks)
- Allows multi-view display, but results in dim images due to attenuation

Parallax Barriers



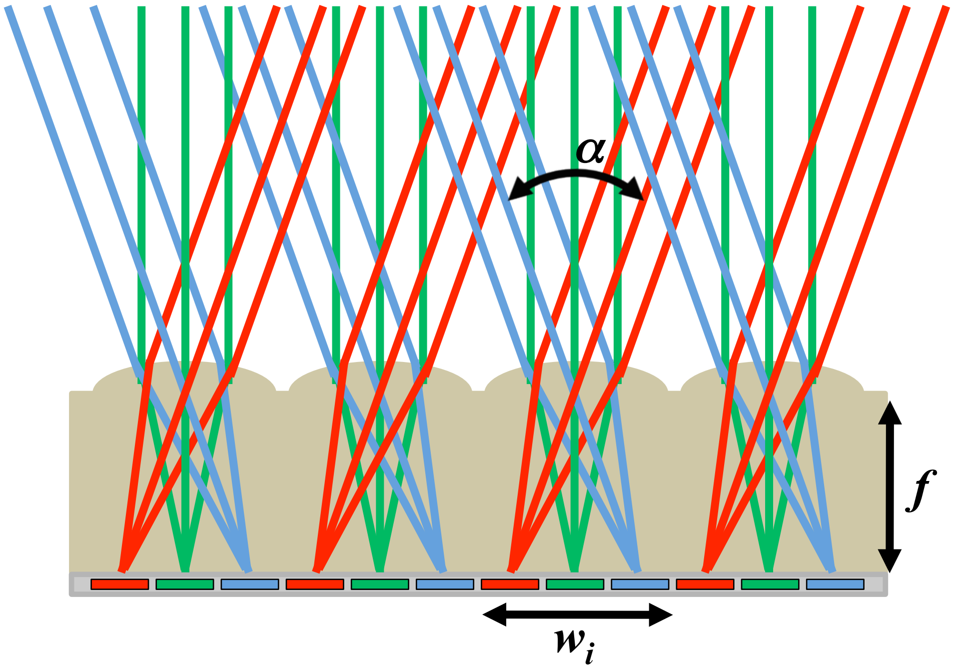
Range Rover 2010
Dual-View Navigation

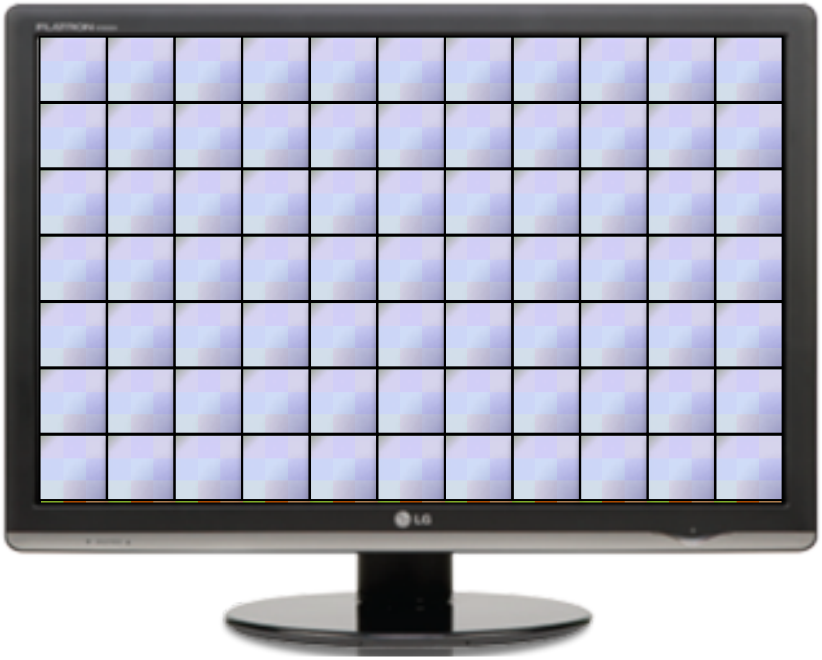


NewSight MV-42AD3 42''
(1920x1080, 1x8 views)

- Introduced by Frederic E. Ives in 1903
- Requires two light-attenuating layers (i.e., masks)
- Allows multi-view display, but results in dim images due to attenuation

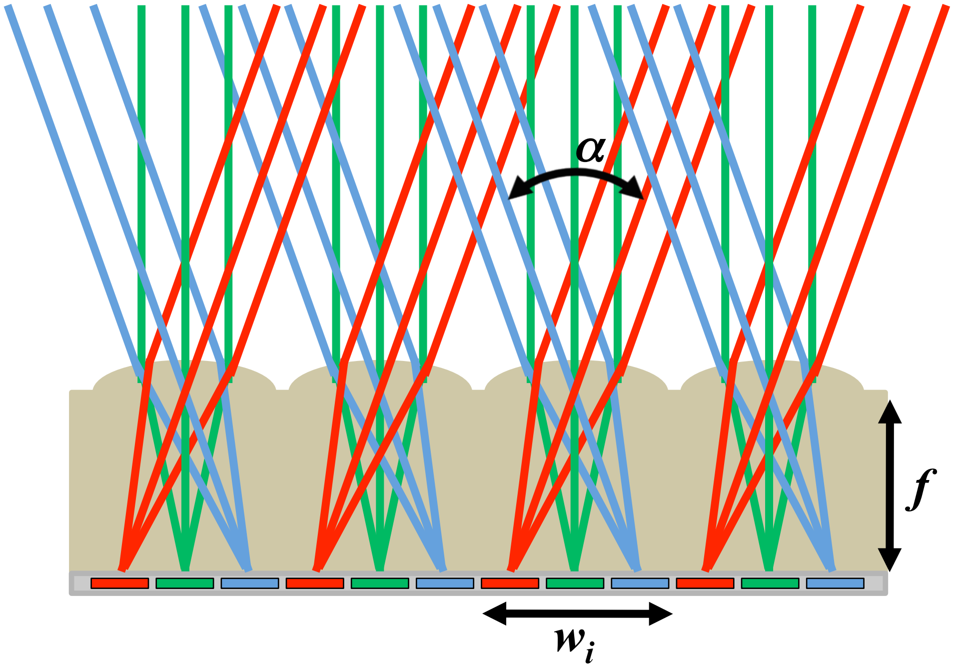
Integral Imaging





- Introduced by Gabriel Lippmann in 1908
- Requires a refractive lenslet array to be affixed to a conventional display
- Allows multi-view display, but imposes fixed trade-off between spatial and angular resolution

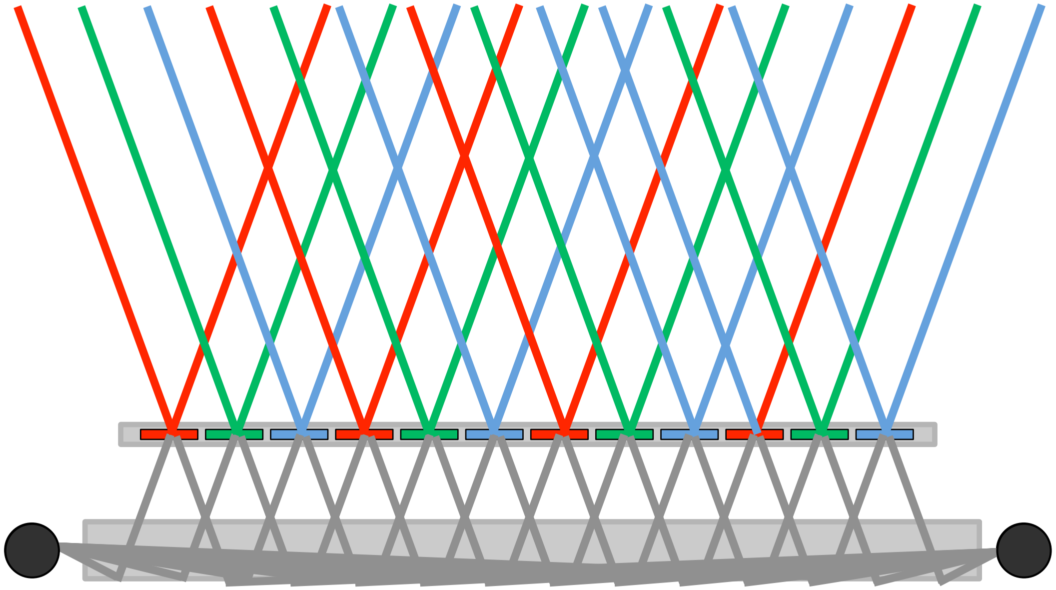
Integral Imaging

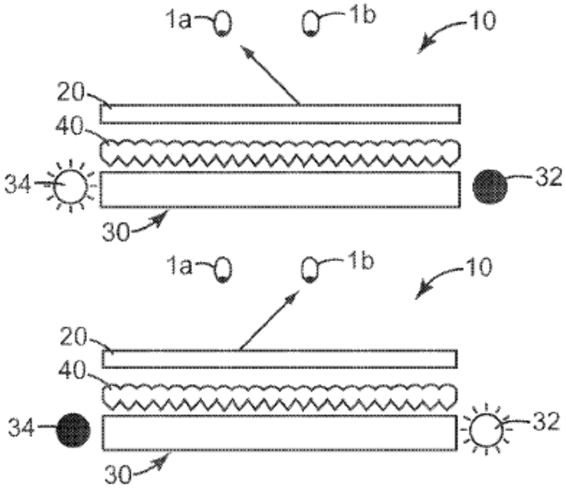


Alioscopy 3DHD 42''
(1920x1200, 1x8 views)

- Introduced by Gabriel Lippmann in 1908
- Requires a refractive lenslet array to be affixed to a conventional display
- Allows multi-view display, but imposes fixed trade-off between spatial and angular resolution

Directional Backlighting

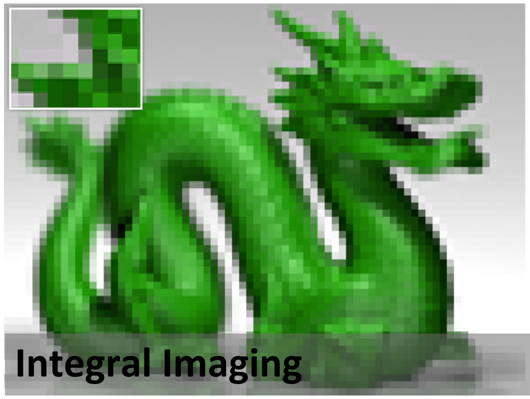




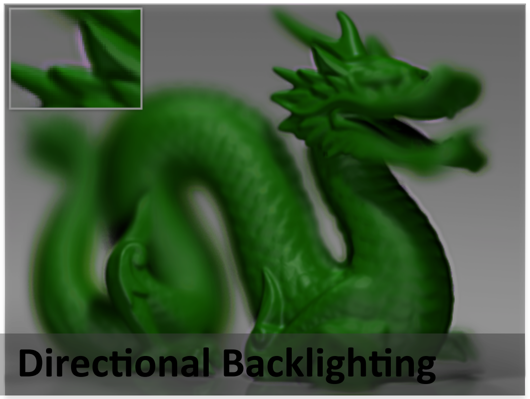
Nelson and Brott, 2010
US Patent 7,847,869

- Currently promoted by 3M
- Requires a high-speed (120 Hz) LCD panel, an additional double-sided prism film, and a pair of LEDs
- Allows multi-view display, but requires higher-speed LCD and additional light sources for each view

Design Trade-offs

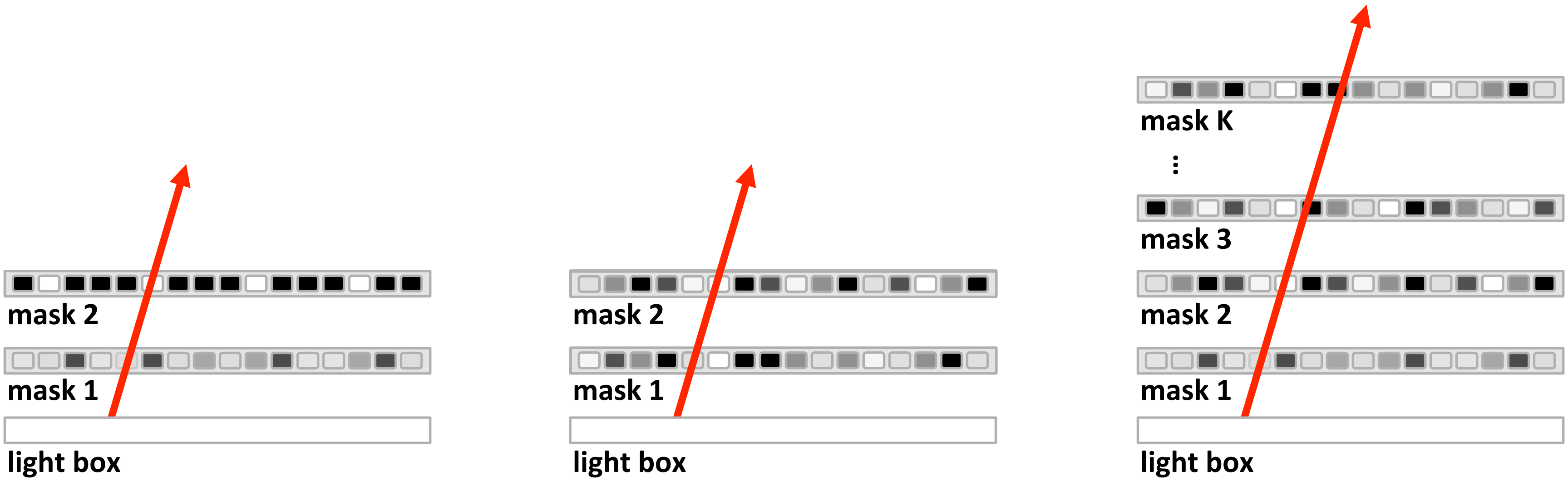

Integral Imaging


Parallax Barriers


Directional Backlighting

	Integral Imaging	Parallax Barriers	Directional Backlighting
Spatial Resolution	low	low	high
Brightness	high	low	moderate
Cost	low	low – moderate	moderate – high
Full-resolution 2D	no	yes (dual-layer LCD)	yes
Motion Parallax	yes	yes	no

Generalizing Parallax Barriers



Conventional Parallax Barrier ***High-Rank 3D*** **(*HR3D*)** ***Layered 3D*** **and** ***Polarization Fields***

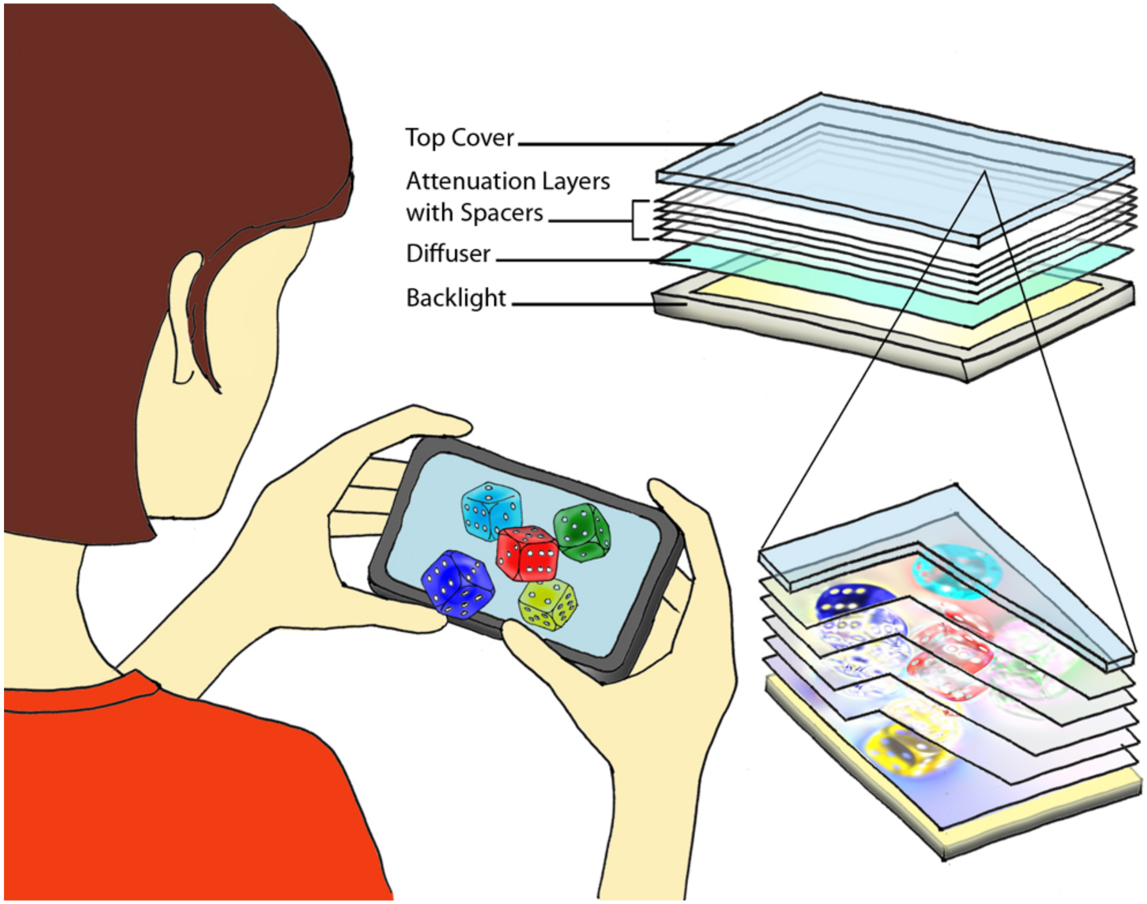
- Parallax barriers use *heuristic* design: front mask with slits/pinholes, rear mask with interlaced views
- *High-Rank 3D* (*HR3D*) considers **dual-layer design with arbitrary opacity and temporal multiplexing**
- *Layered 3D and Polarization Fields* considers **multi-layer design without temporal multiplexing**

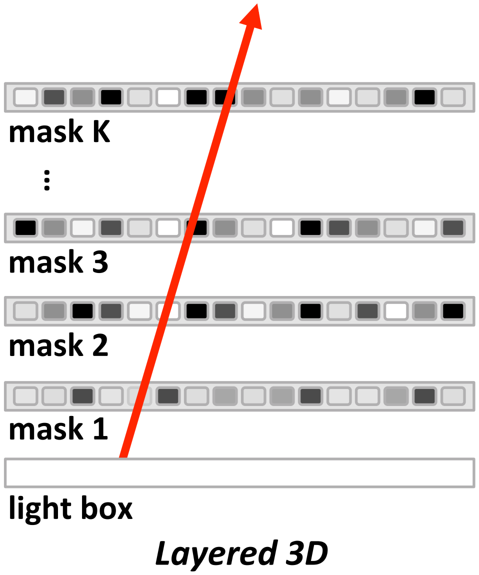
Outline

- *Automultiscopic Displays*
  - ***Multi-Layer Displays***
    - **Layered 3D**
    - Polarization Fields
  - Dual-Layer Displays
    - High-Rank 3D (HR3D)

Layered 3D: Multi-Layer Displays

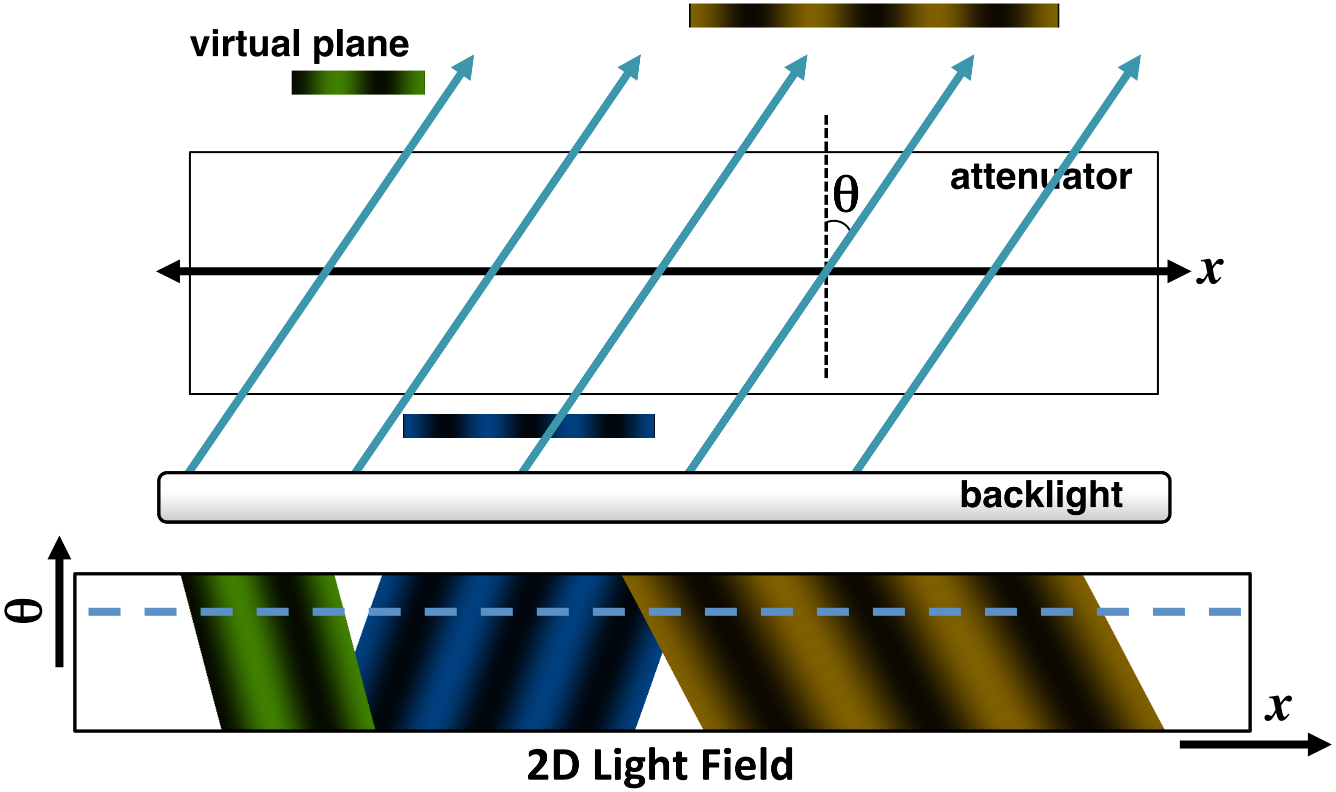
SIGGRAPH2012





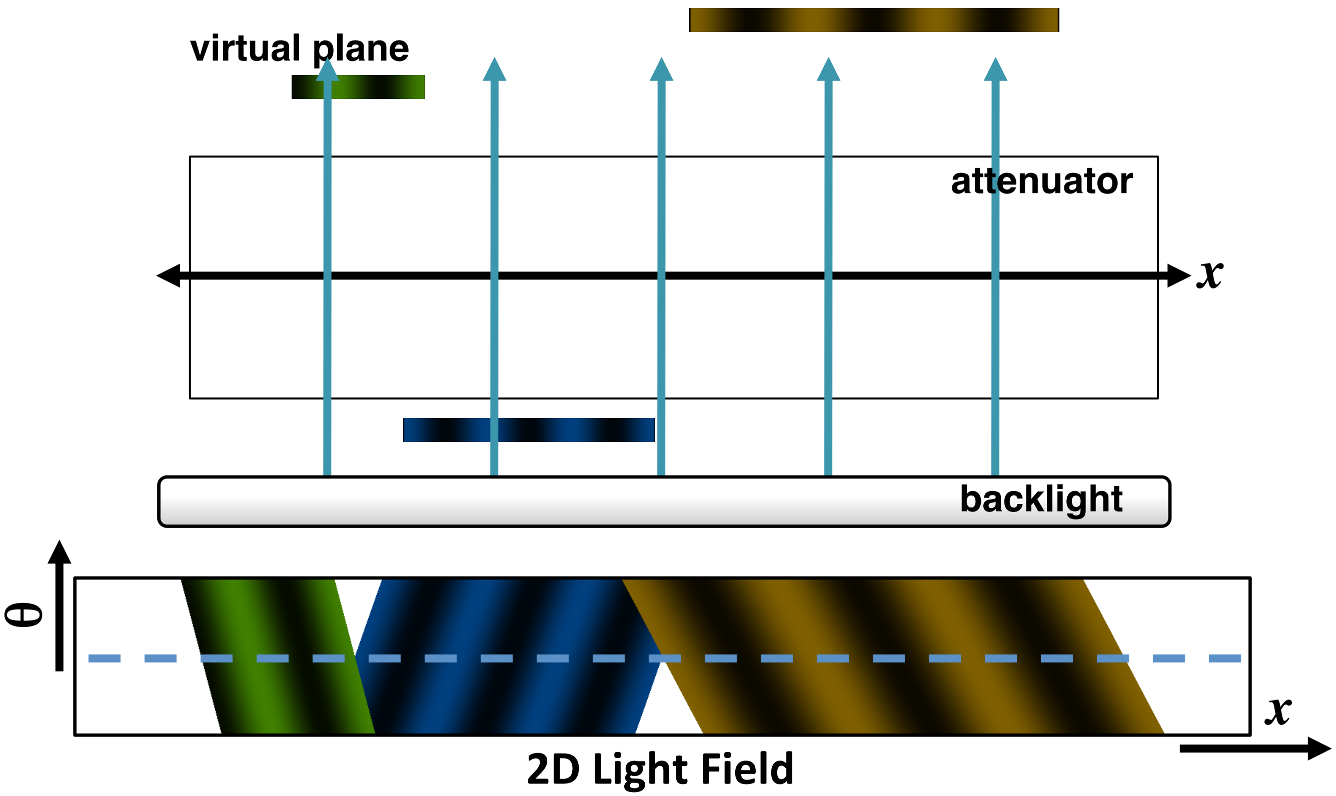
Tomographic Light Field Synthesis

SIGGRAPH2012

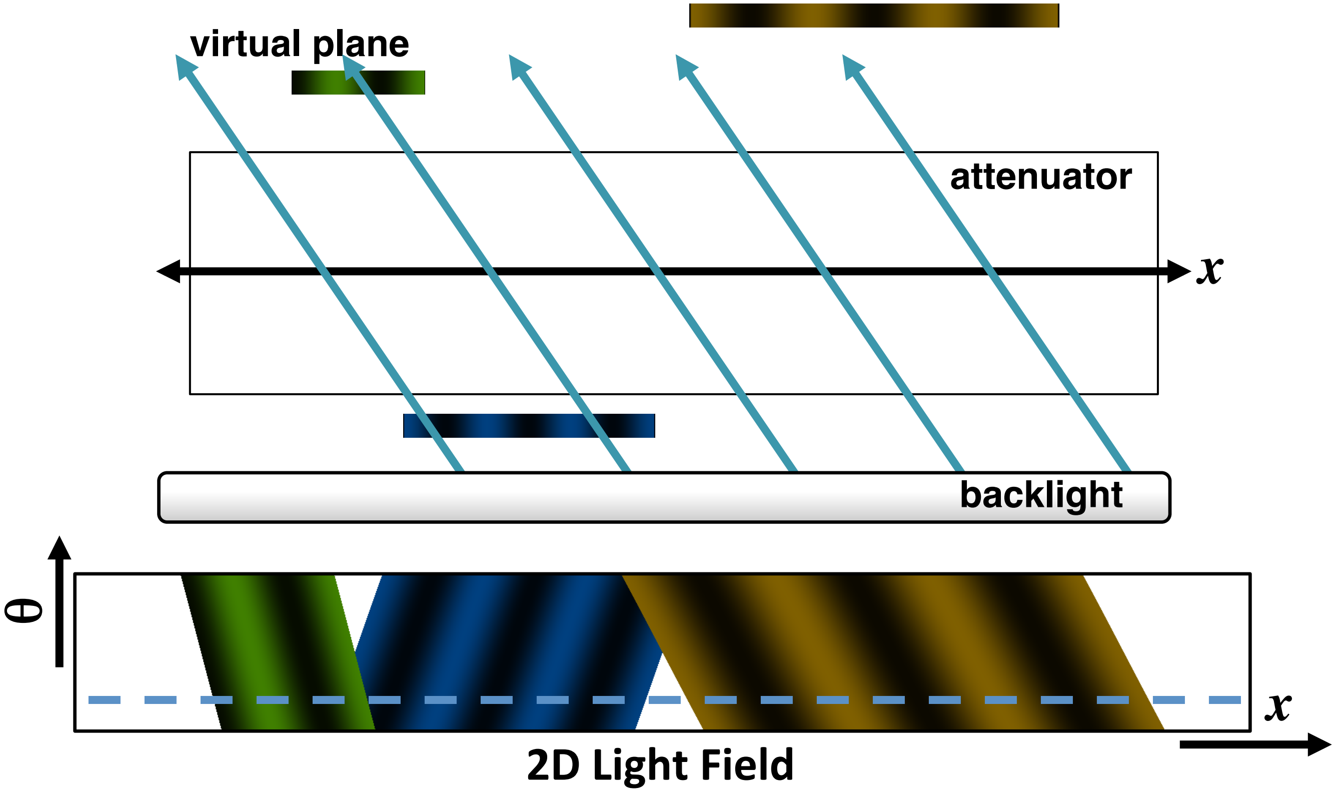


Tomographic Light Field Synthesis

SIGGRAPH2012



Tomographic Light Field Synthesis



Tomographic Light Field Synthesis

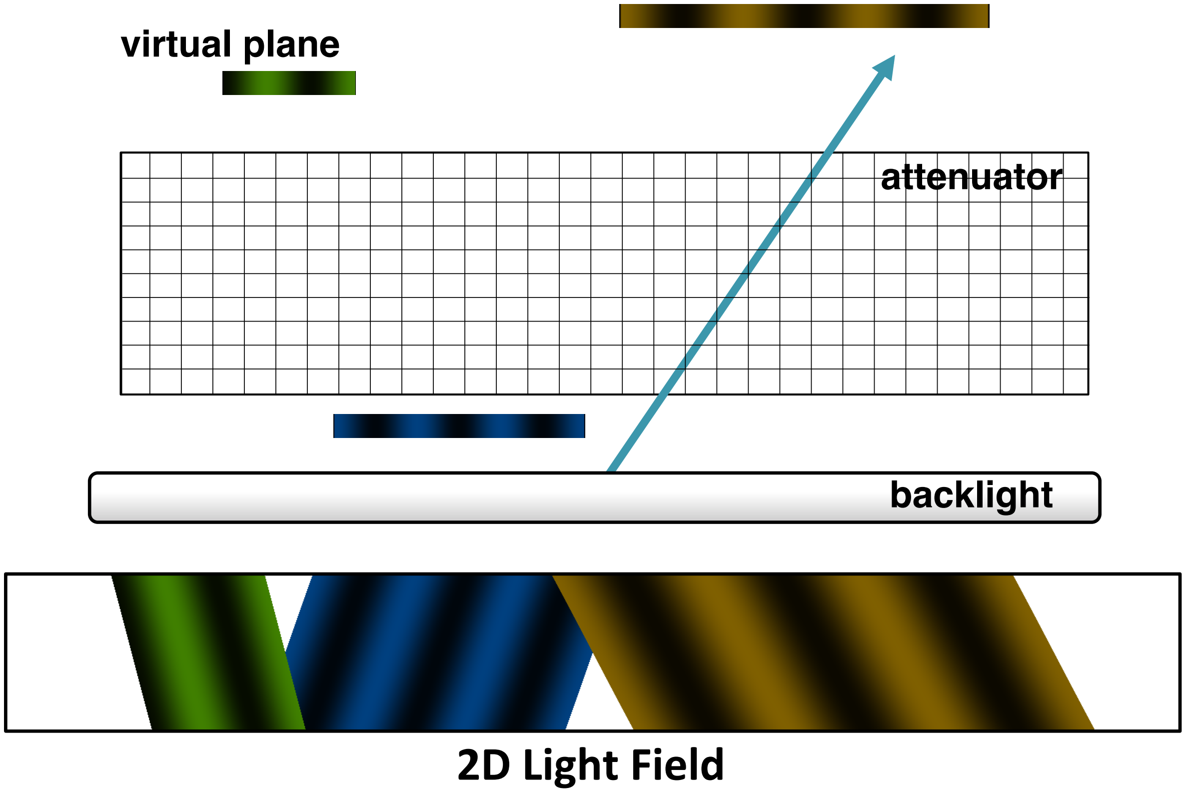


Image formation model:

$$L(x,\theta) = I_0 e^{-\int_C \mu(r)dr}$$

$$\bar{L}(x,\theta) = \ln\left(\frac{L(x,\theta)}{I_0}\right) = -\int_C \mu(r)\,dr$$

$$\bar{\mathbf{l}} = -\mathbf{Pa}$$

Tomographic synthesis:

$$\underset{\mathbf{a}}{\arg\min} \left\| \bar{\mathbf{l}} + \mathbf{Pa} \right\|^2, \text{ for } \mathbf{a} \geq 0$$

Tomographic Light Field Synthesis

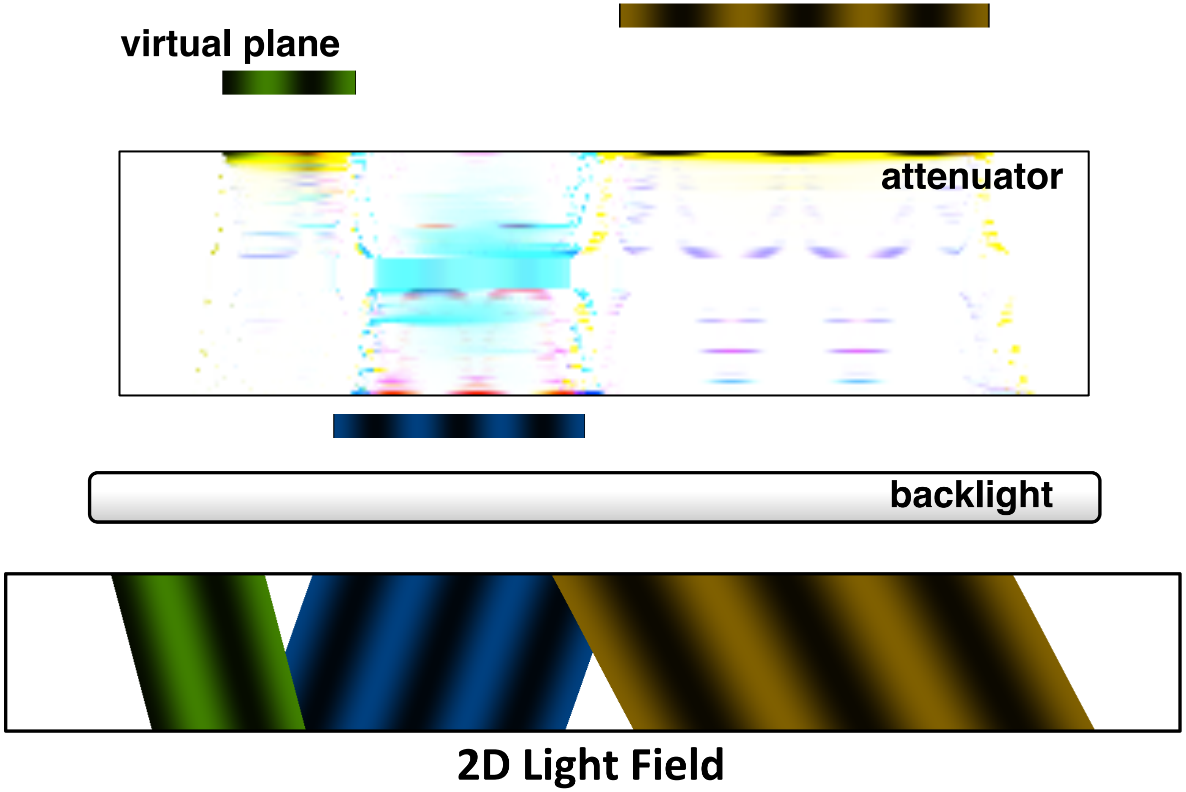


Image formation model:

$$L(x,\theta) = I_0 e^{-\int_C \mu(r)dr}$$

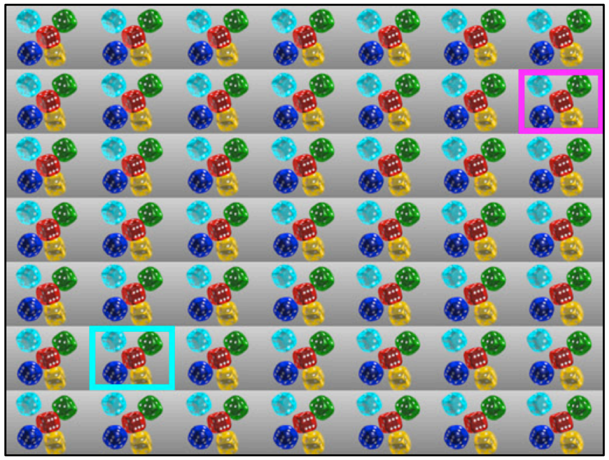
$$\bar{L}(x,\theta) = \ln\left(\frac{L(x,\theta)}{I_0}\right) = -\int_C \mu(r)\,dr$$

$$\bar{\mathbf{l}} = -\mathbf{Pa}$$

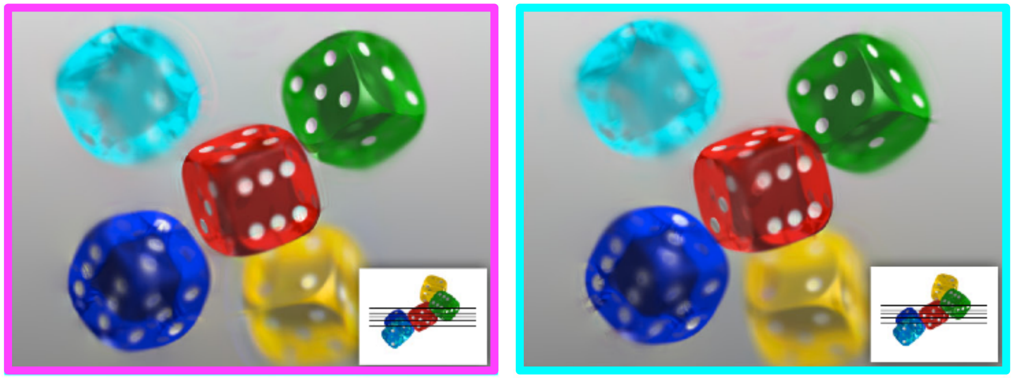
Tomographic synthesis:

$$\arg\min_{\mathbf{a}} \left\| \bar{\mathbf{l}} + \mathbf{Pa} \right\|^2, \text{ for } \mathbf{a} \geq 0$$

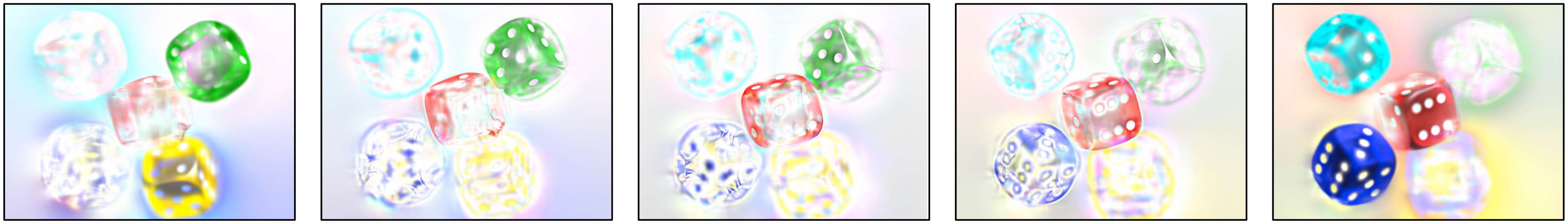
Multi-Layer Light Field Decomposition



Target 4D Light Field

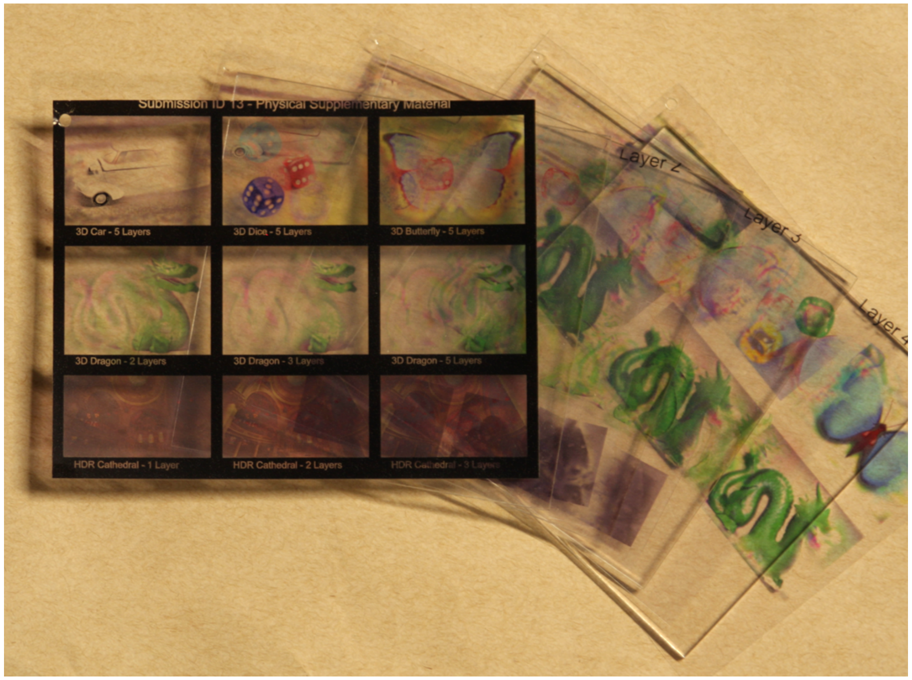


Reconstructed Views

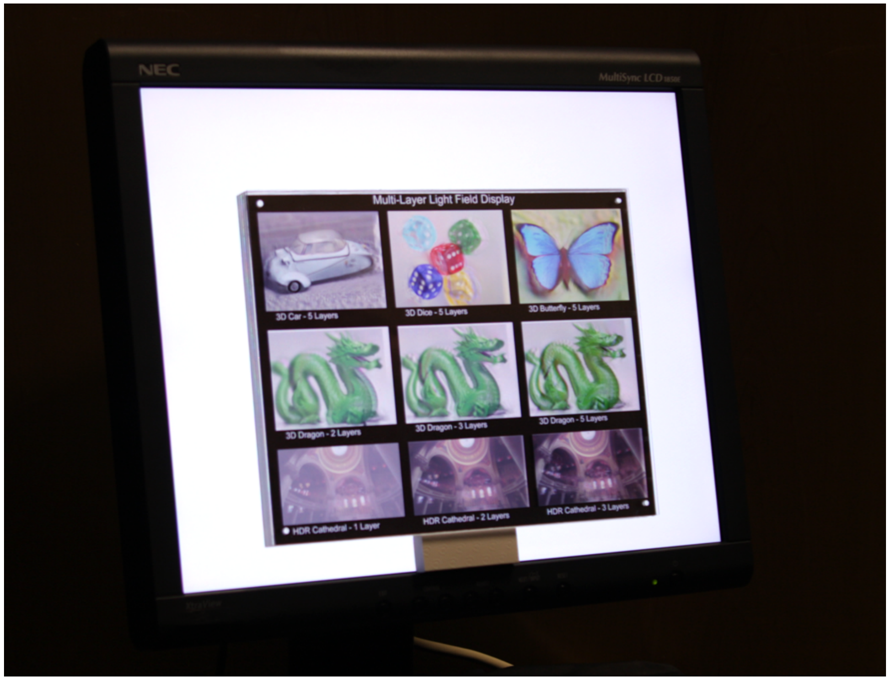


Multi-Layer Decomposition

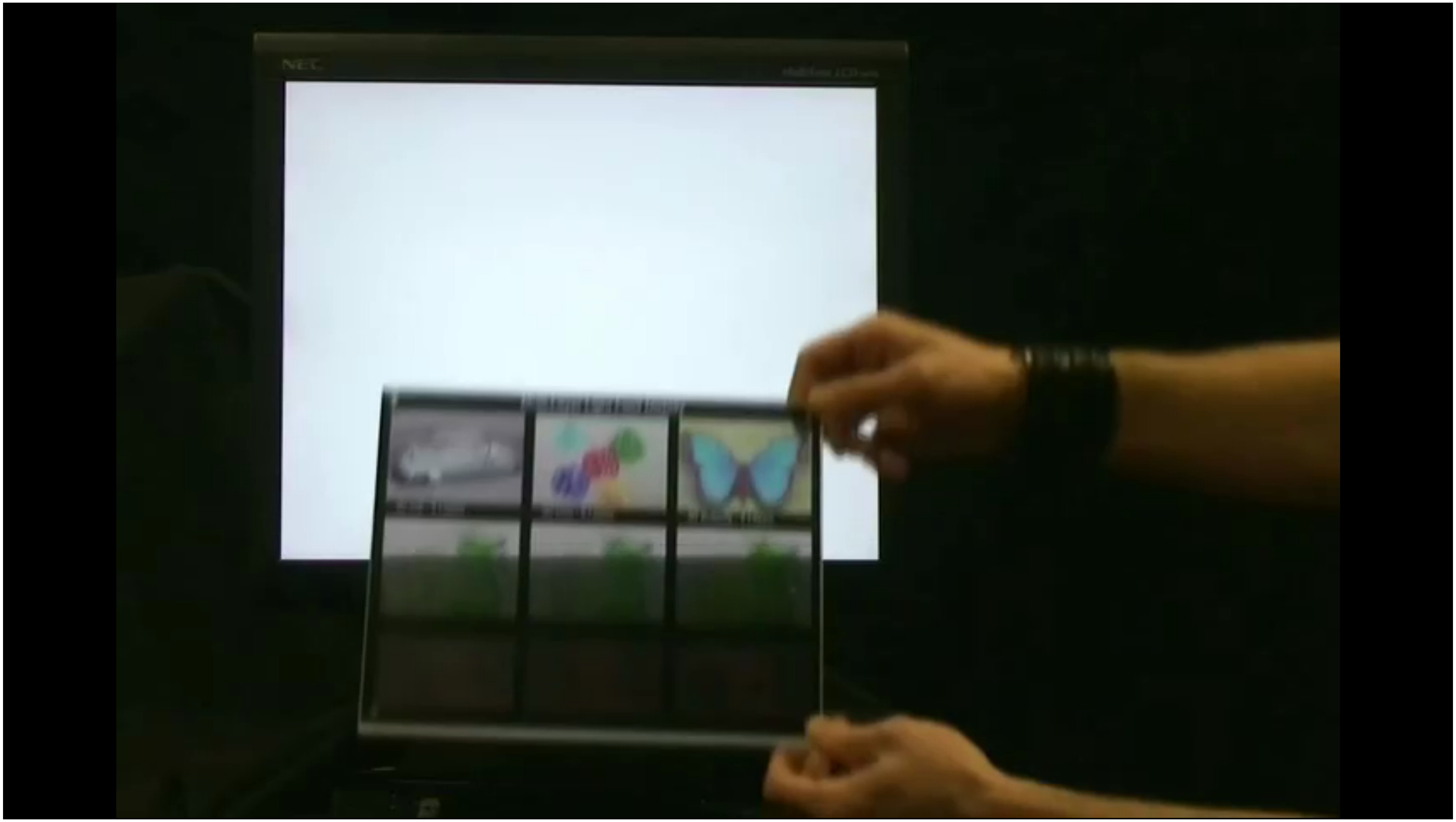
Prototype *Layered 3D* Display



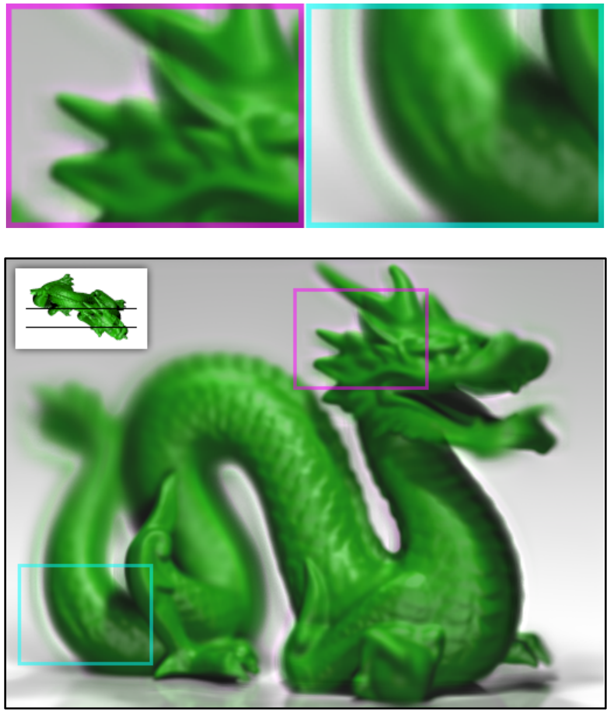
Transparency stack with acrylic spacers



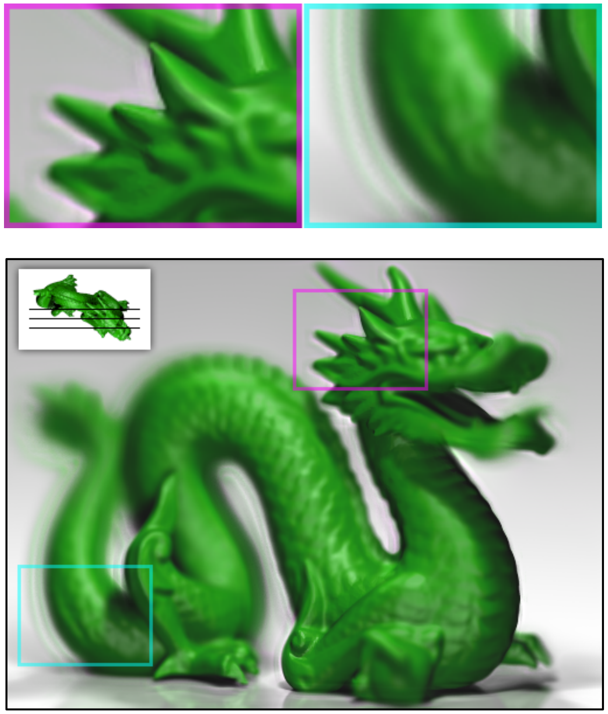
Prototype in front of LCD (backlight source)


NEC

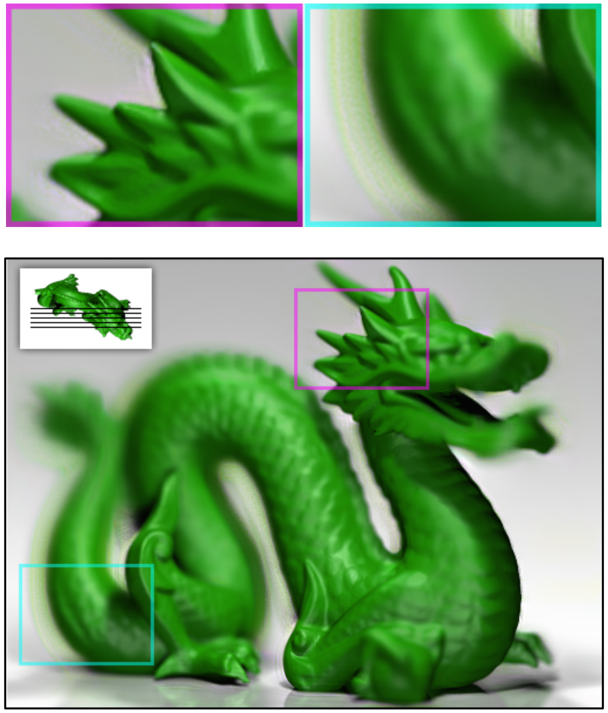
Depth of Field



Two Layers



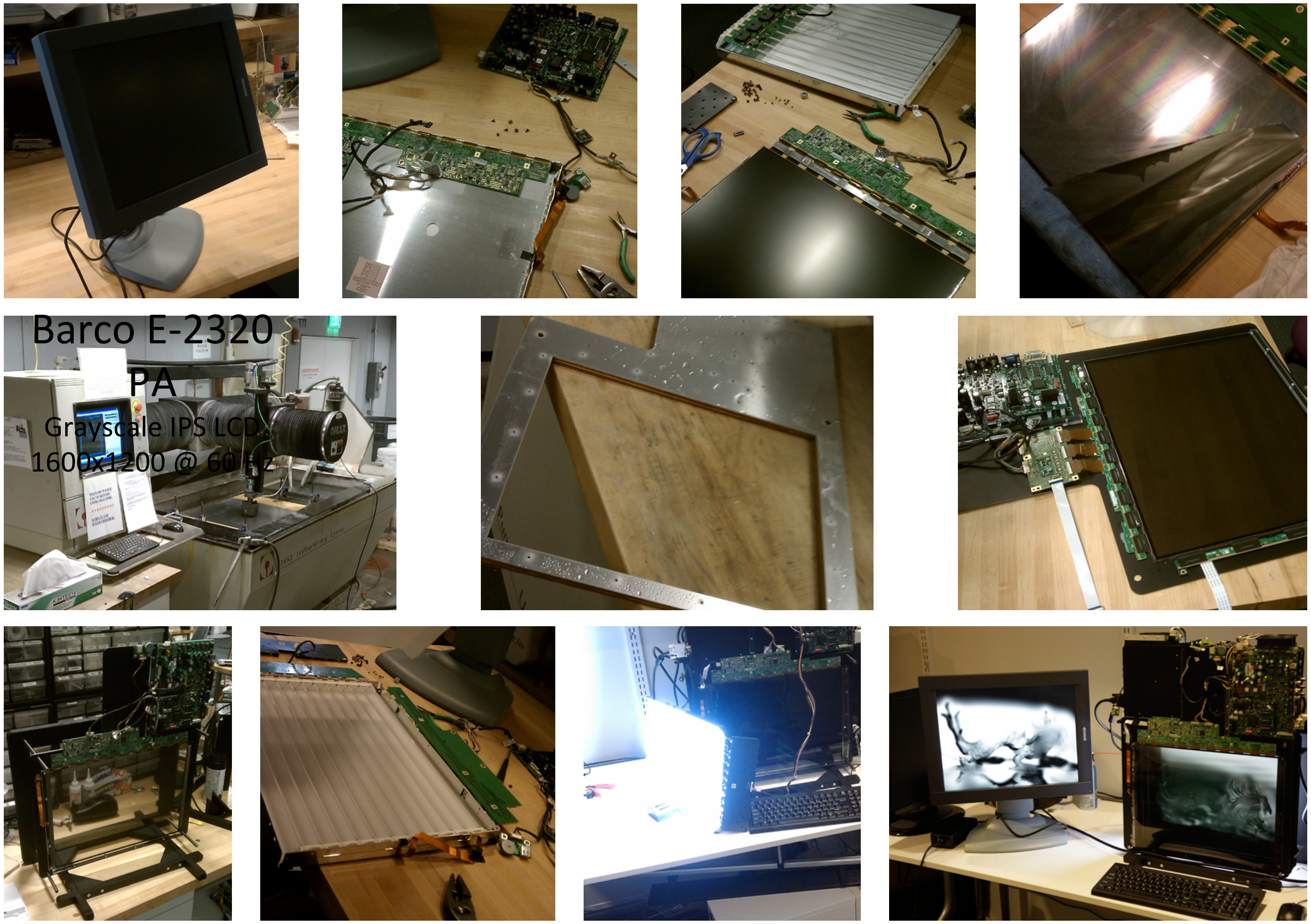
Three Layers



Five Layers

Outline

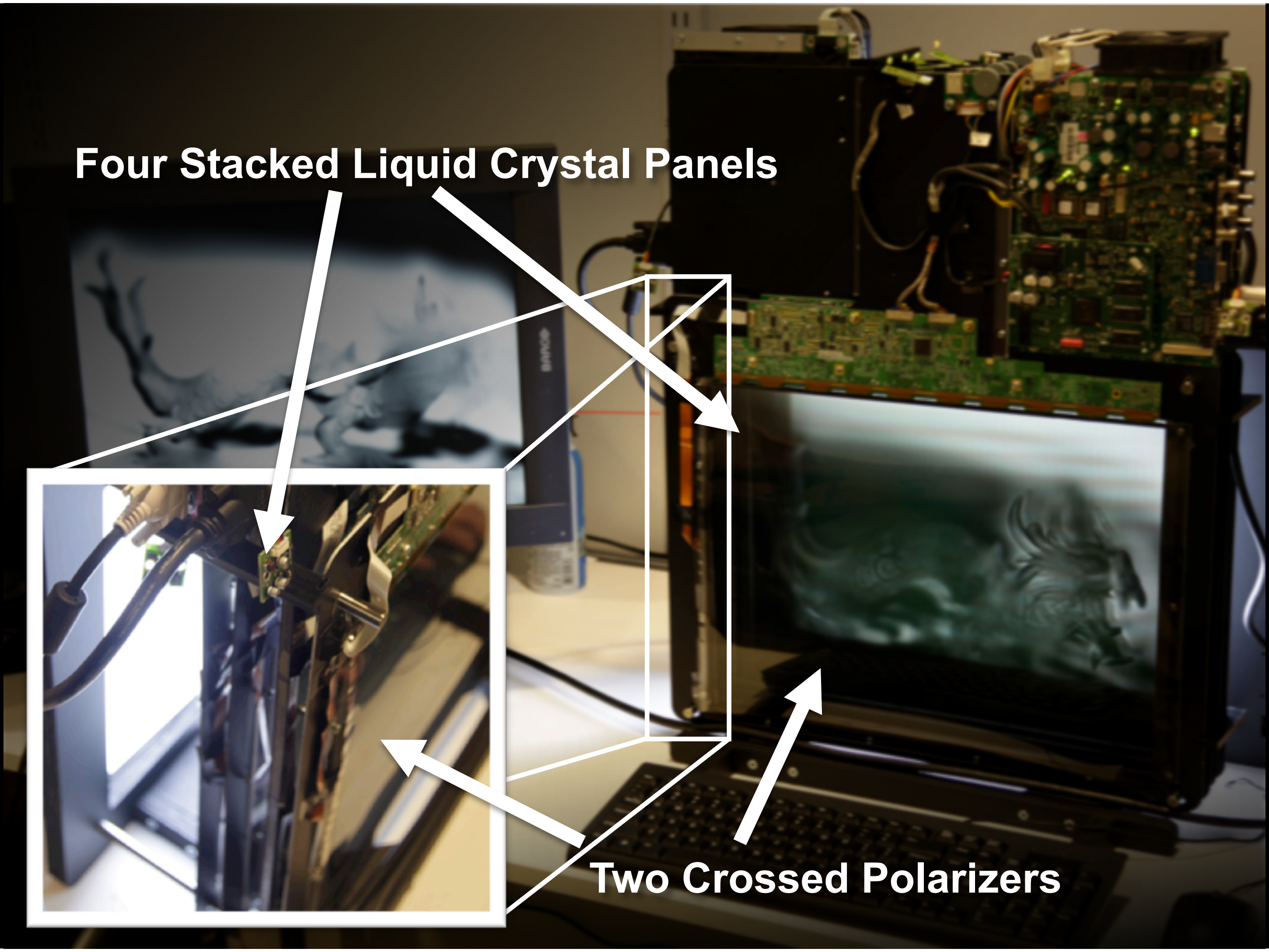
- *Automultiscopic Displays*
  - ***Multi-Layer Displays***
    - Layered 3D
    - ➢ **Polarization Fields**
  - Dual-Layer Displays
    - High-Rank 3D (HR3D)



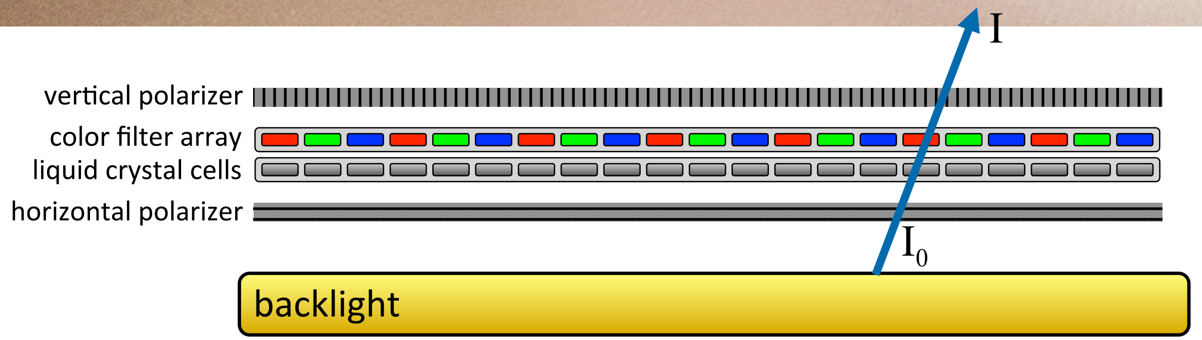
Barco E-2320 PA

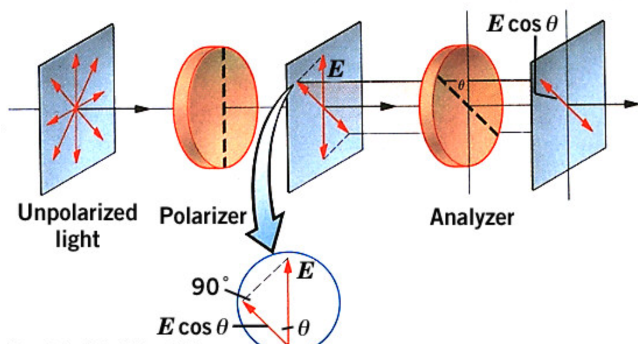
Grayscale IPS LCD

1600x1200 @ 60 Hz


Four Stacked Liquid Crystal Panels
Two Crossed Polarizers

Overview of LCDs





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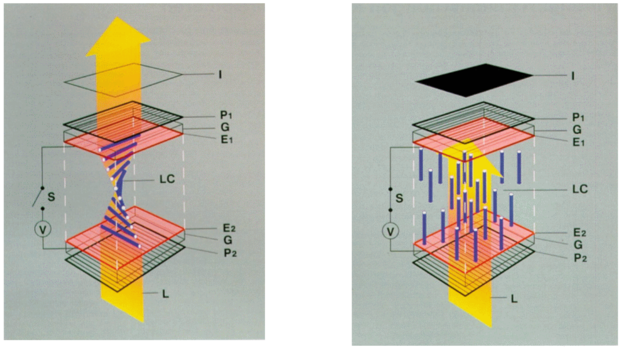
Malus' Law

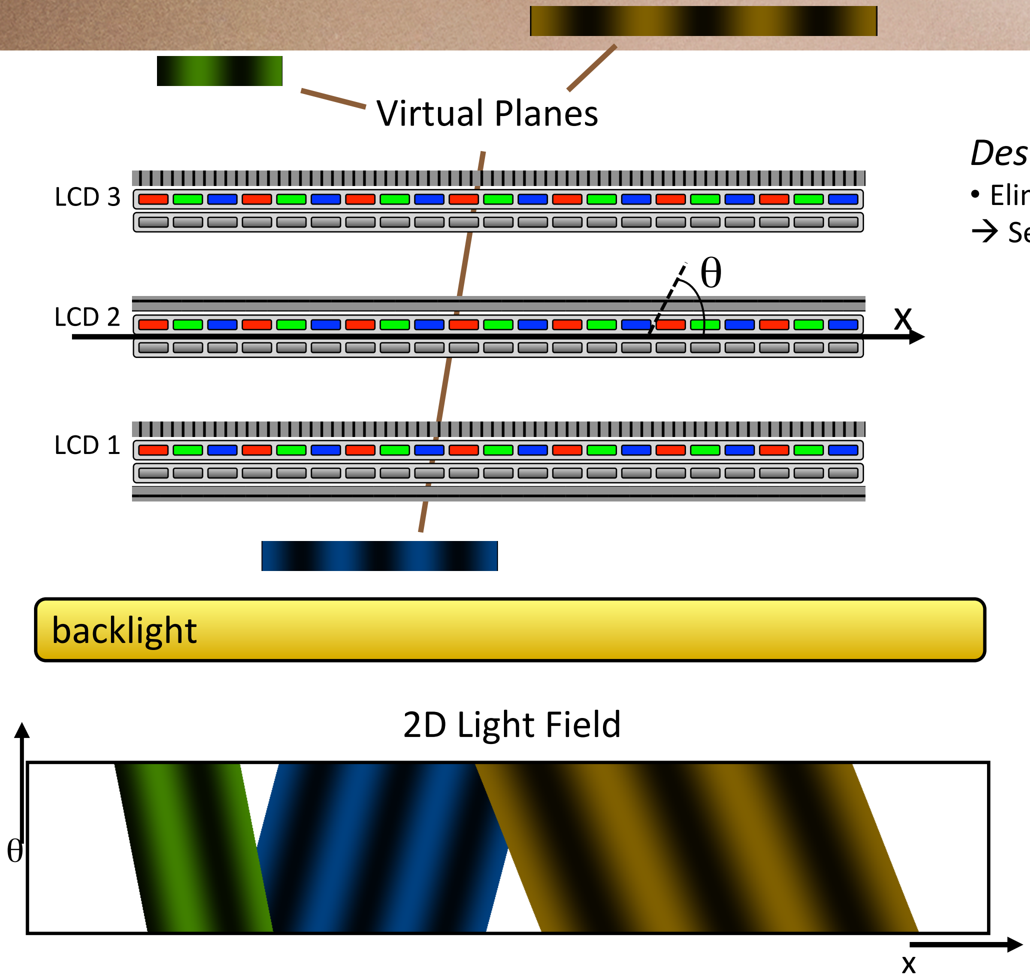


Intensity Modulation with Liquid Crystal Cells

$$I = I_0 \sin^2(\theta)$$

Extending *Layered 3D* to Multi-Layer LCDs

SIGGRAPH2012



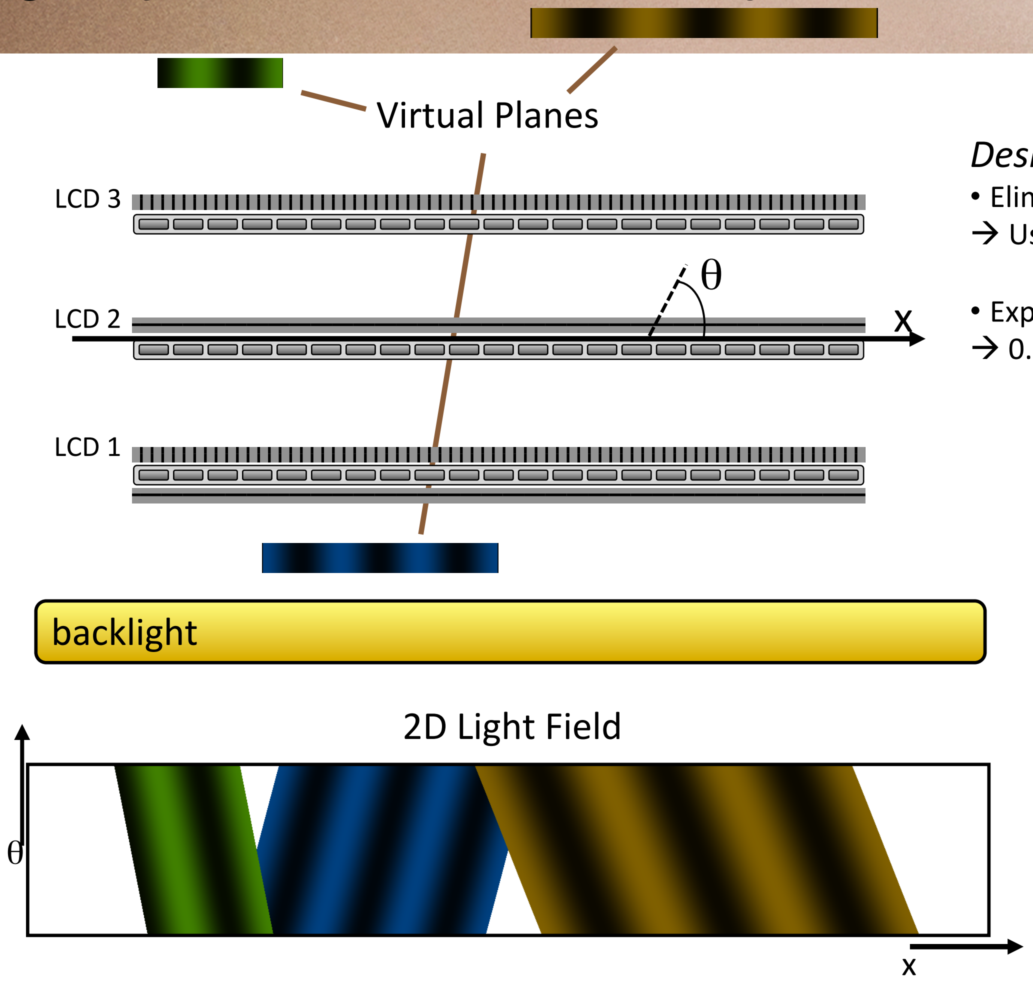
Design Optimization

- Eliminate redundant polarizers

→ Sequentially-crossed design

Extending *Layered 3D* to Multi-Layer LCDs

SIGGRAPH2012



Design Optimization

- Eliminate redundant polarizers

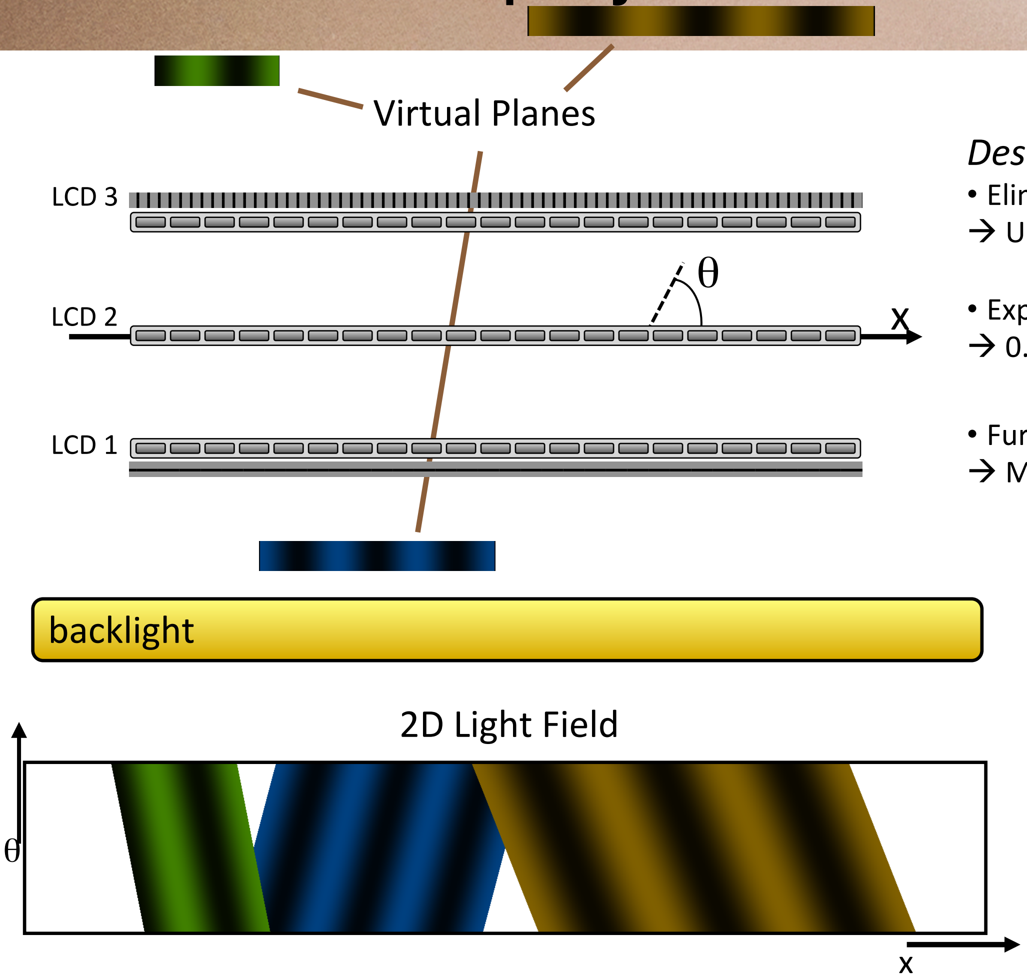
→ Use sequentially-crossed

- Exploit field-sequential color

→ 0.3^3 = 2.7% brightness

Polarization Field Displays

SIGGRAPH2012



Design Optimization

- Eliminate redundant polarizers

→ Use sequentially-crossed

- Exploit field-sequential color

→ $0.3^3 = 2.7\%$ brightness

- Further optimize polarizers

→ Minimum is a crossed pair

Polarization Field Displays

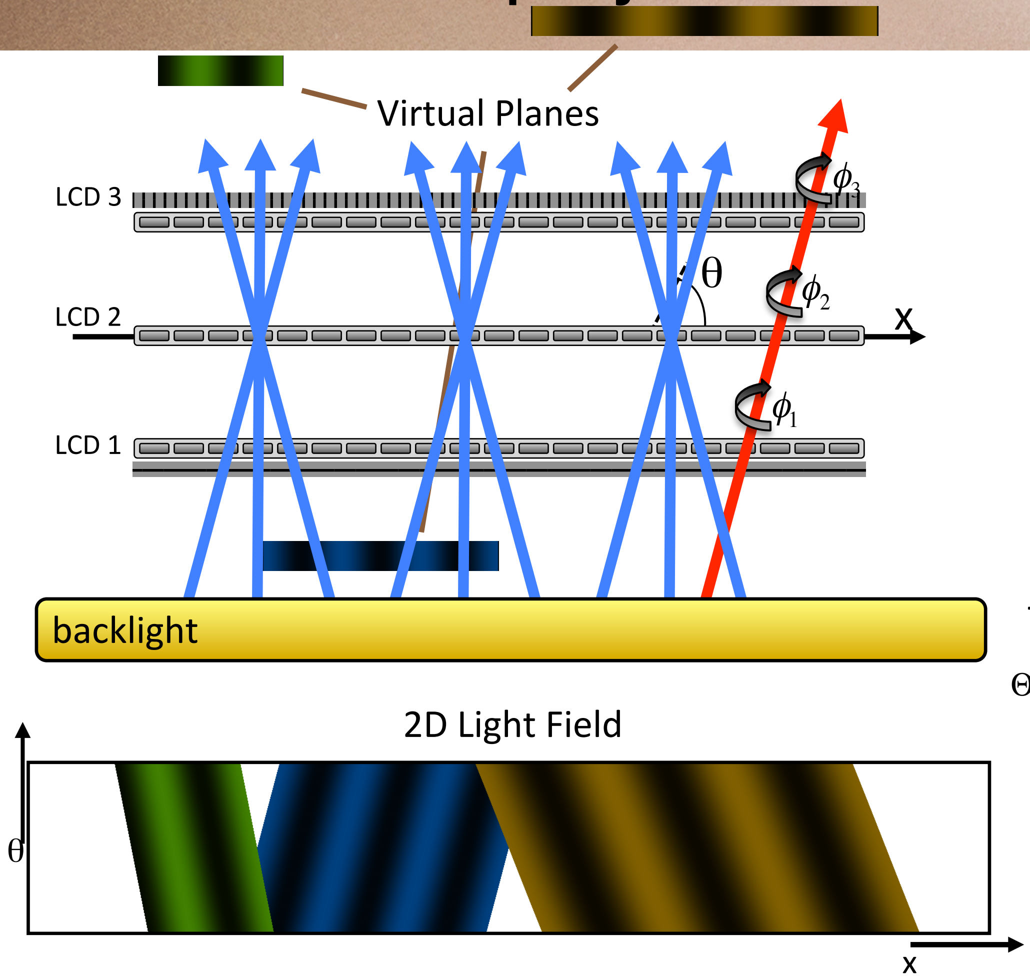


Image Formation

$$\Theta(x,\theta)=\sum_{k=1}^{K}\phi_k(x,\theta)$$

$$L(x,\theta)=\sin^2\left(\Theta(x,\theta)\right)$$

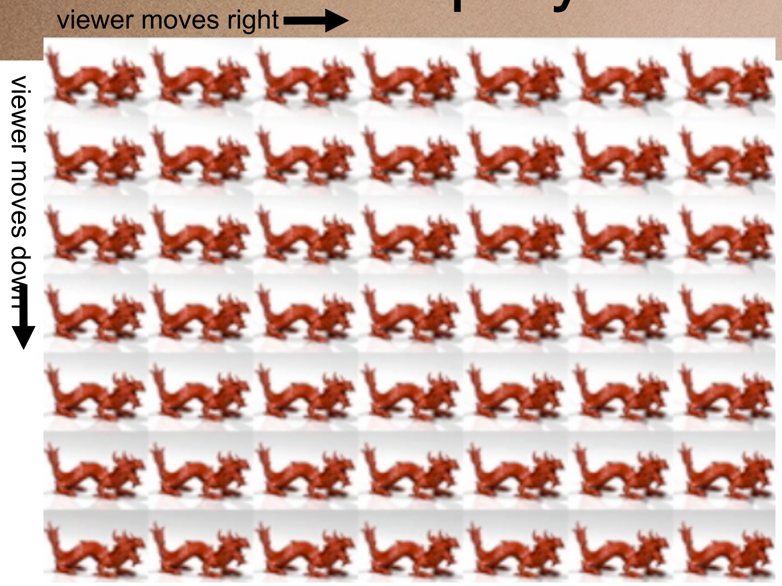
Tomographic Synthesis

$$\Theta(x,\theta)=\pm\sin^{-1}\left(\sqrt{L(x,\theta)}\right)\bmod\pi$$

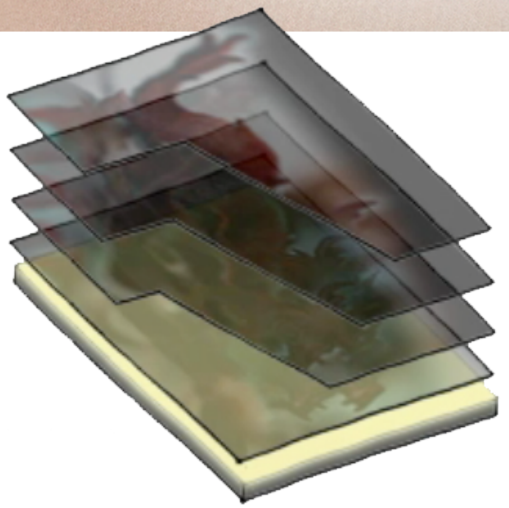
$$\Theta=\mathrm{P}\phi$$

$$\boxed{\underset{\phi_{\min}\le\phi\le\phi_{\max}}{\operatorname{argmin}}\left\|\Theta-\mathrm{P}\phi\right\|_2^2}$$

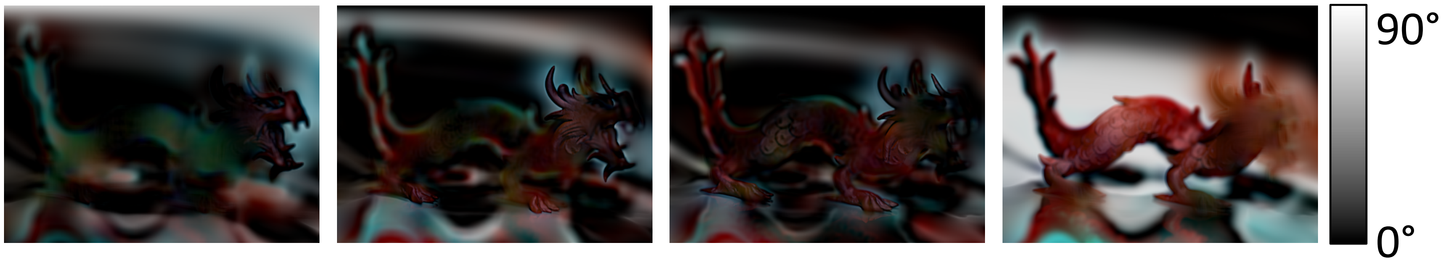
Polarization Field Displays



Input 4D Light Field

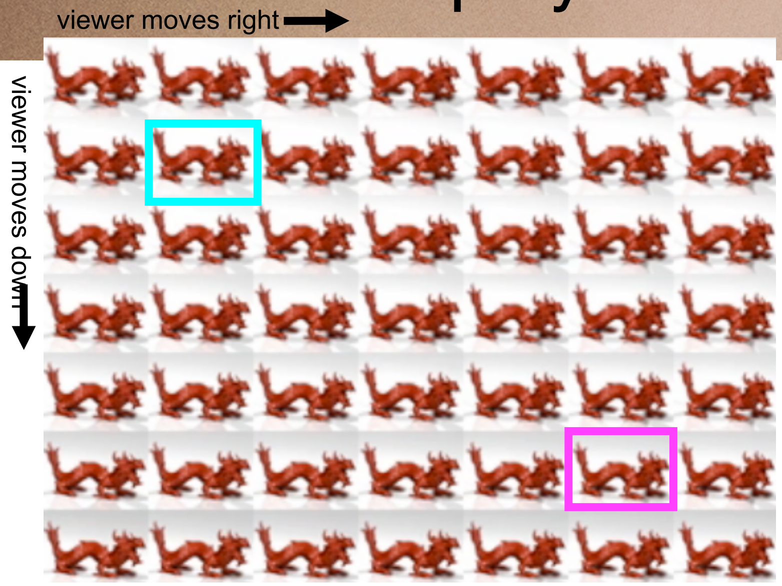


Stacked Polarization Rotating Layers

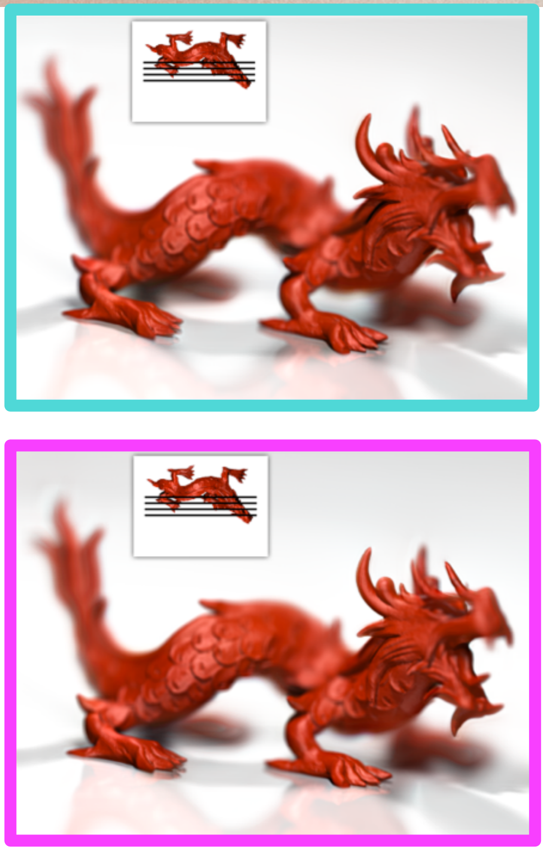


Optimized Rotation Angles for Each Layer

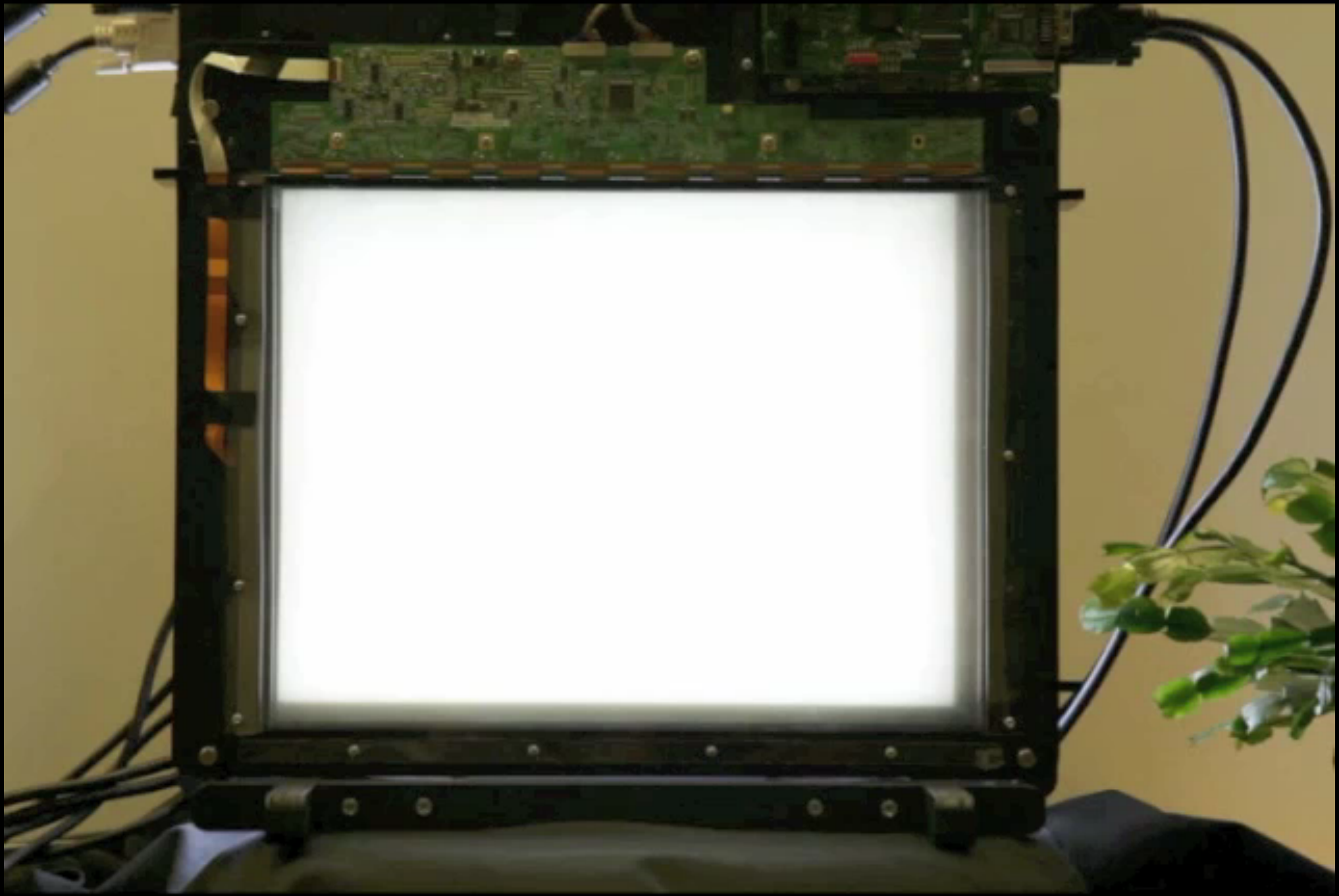
Polarization Field Displays



Input 4D Light Field



Reconstruction Results



Outline

- *Automultiscopic Displays*
  - Multi-Layer Displays
    - Layered 3D
    - Polarization Fields
  - ***Dual-Layer Displays***
    - ➢ **High-Rank 3D (HR3D)**

Input 4D Light Field

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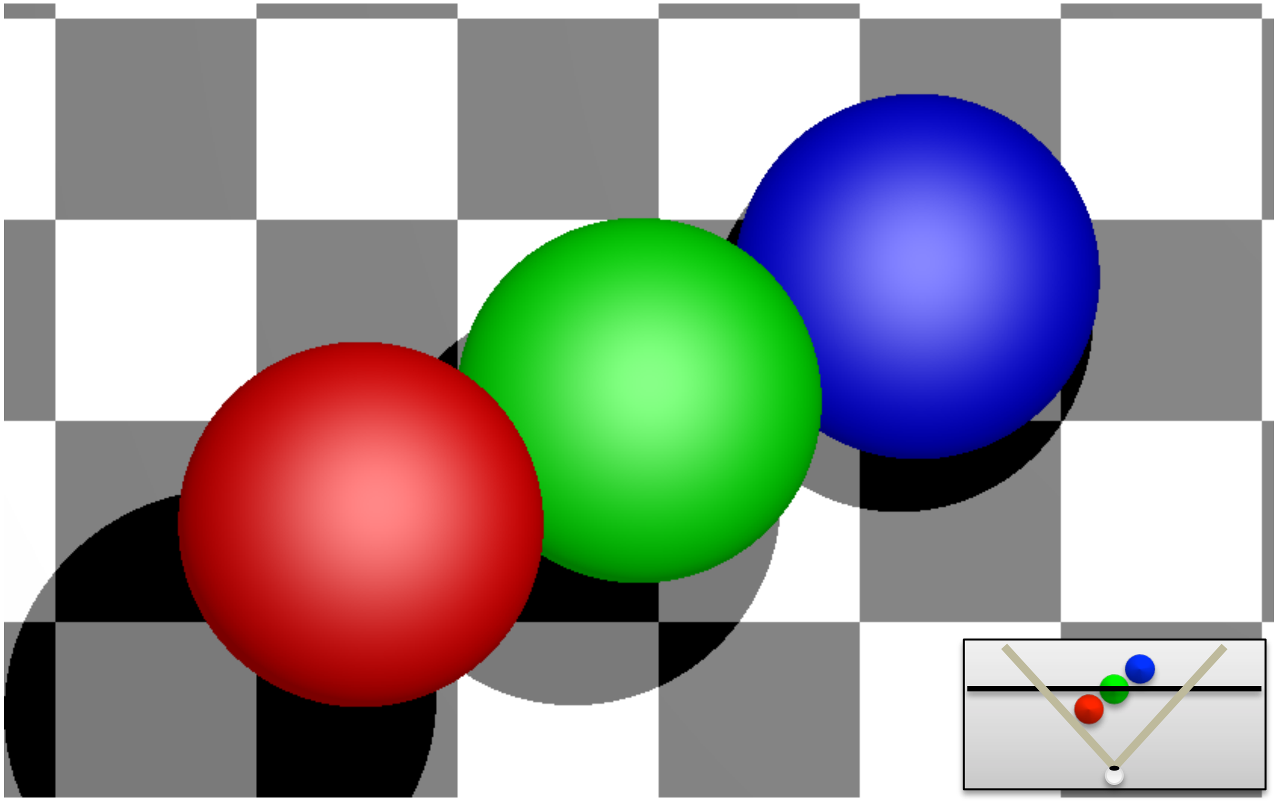
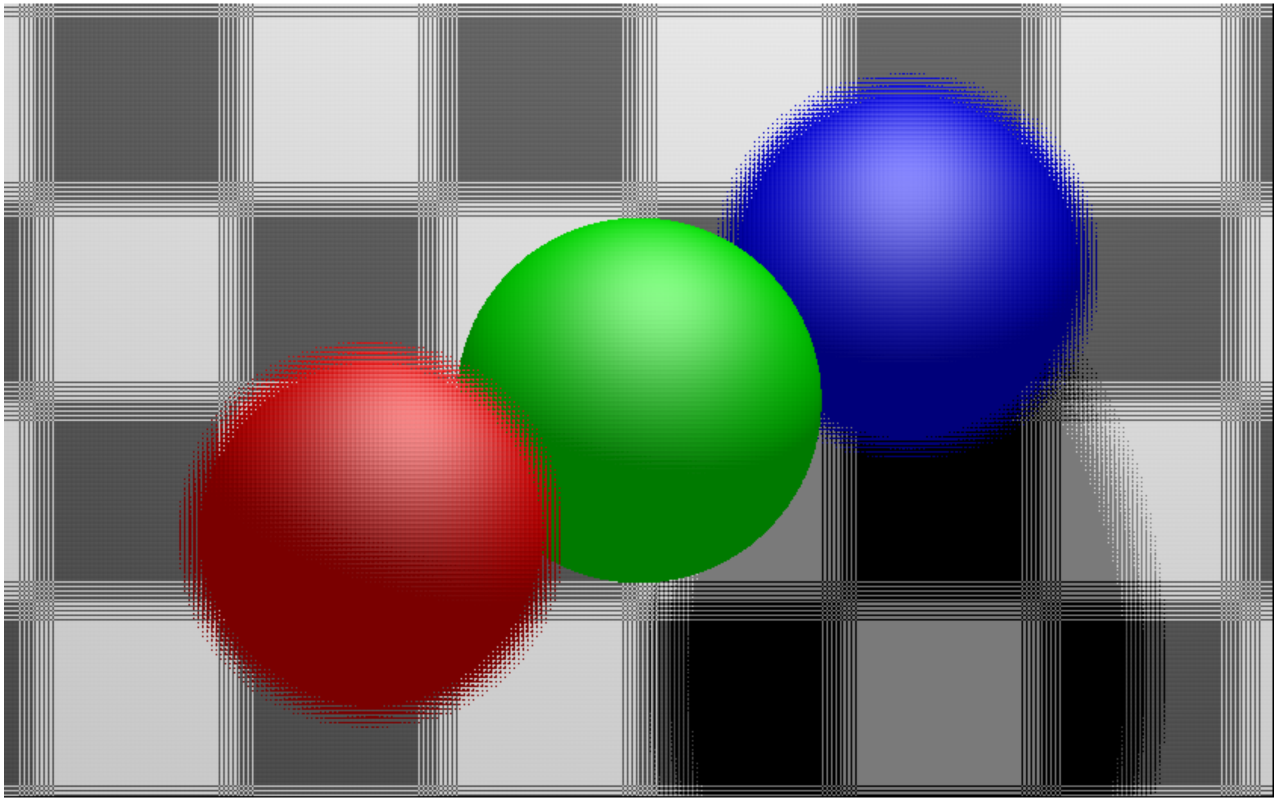
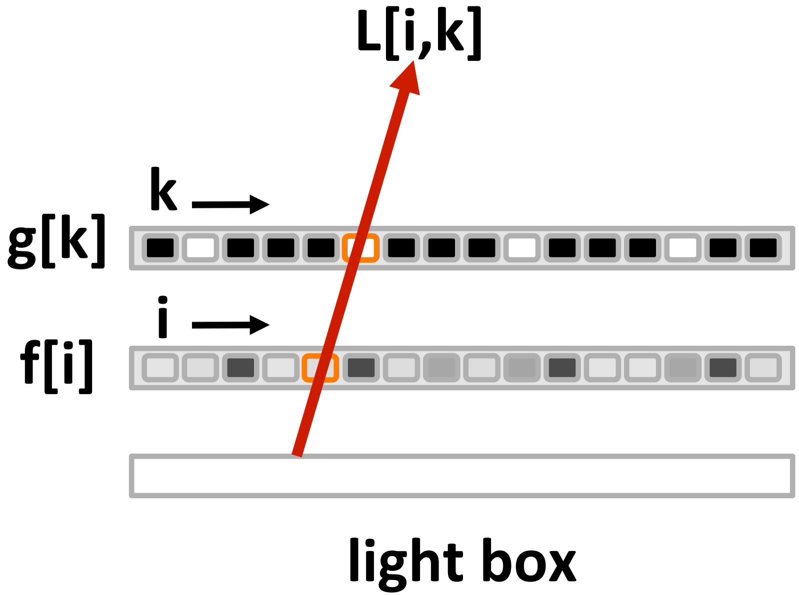


Parallax Barrier: Front Layer

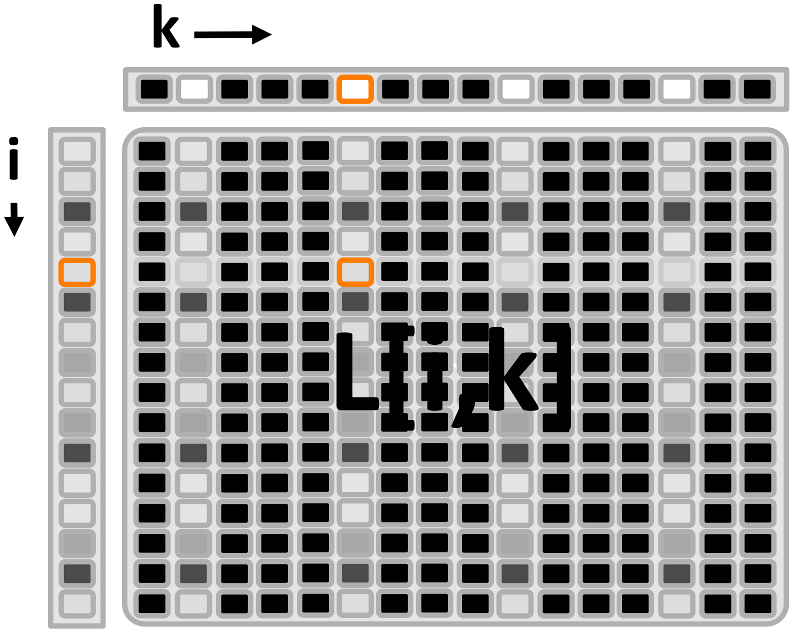
Parallax Barrier: Rear Layer



Analysis of Parallax Barriers

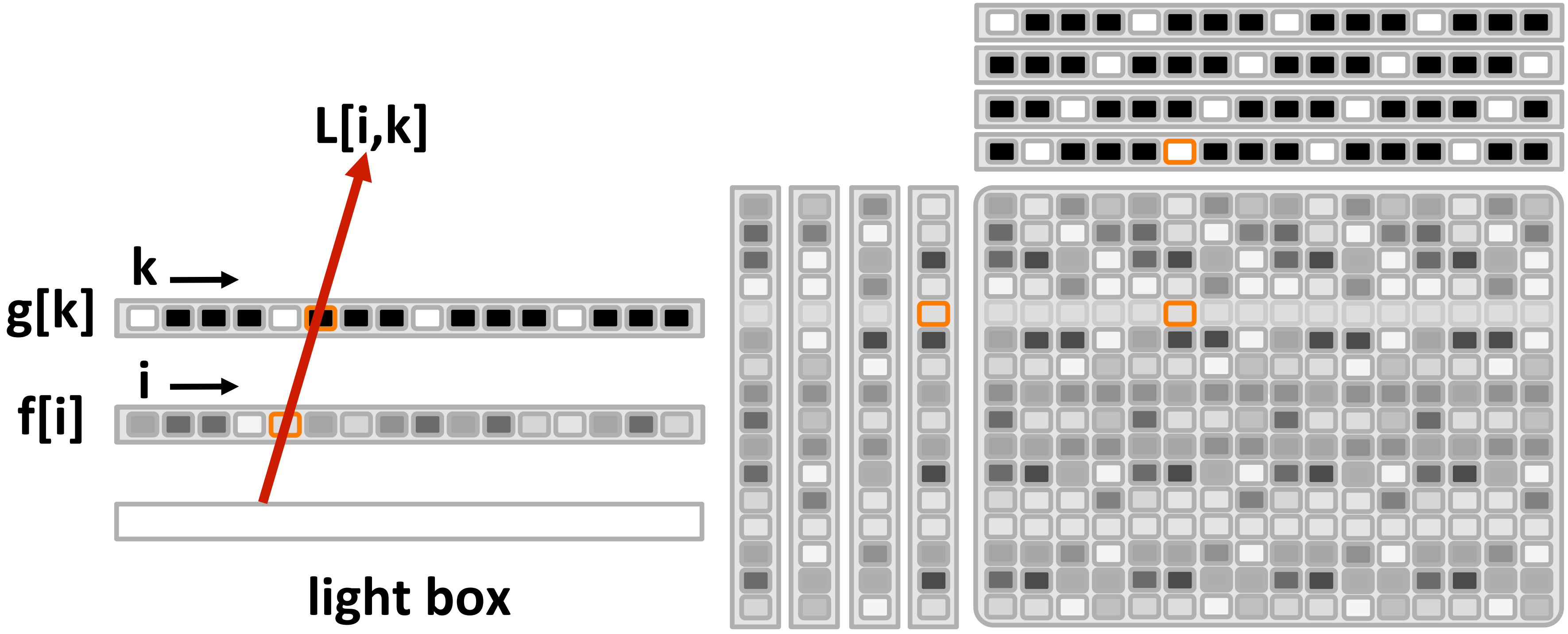


$$L[i,k] = f[i] \cdot g[k]$$



$$L[i,k] = f[i] \otimes g[k]$$

Analysis of Parallax Barriers

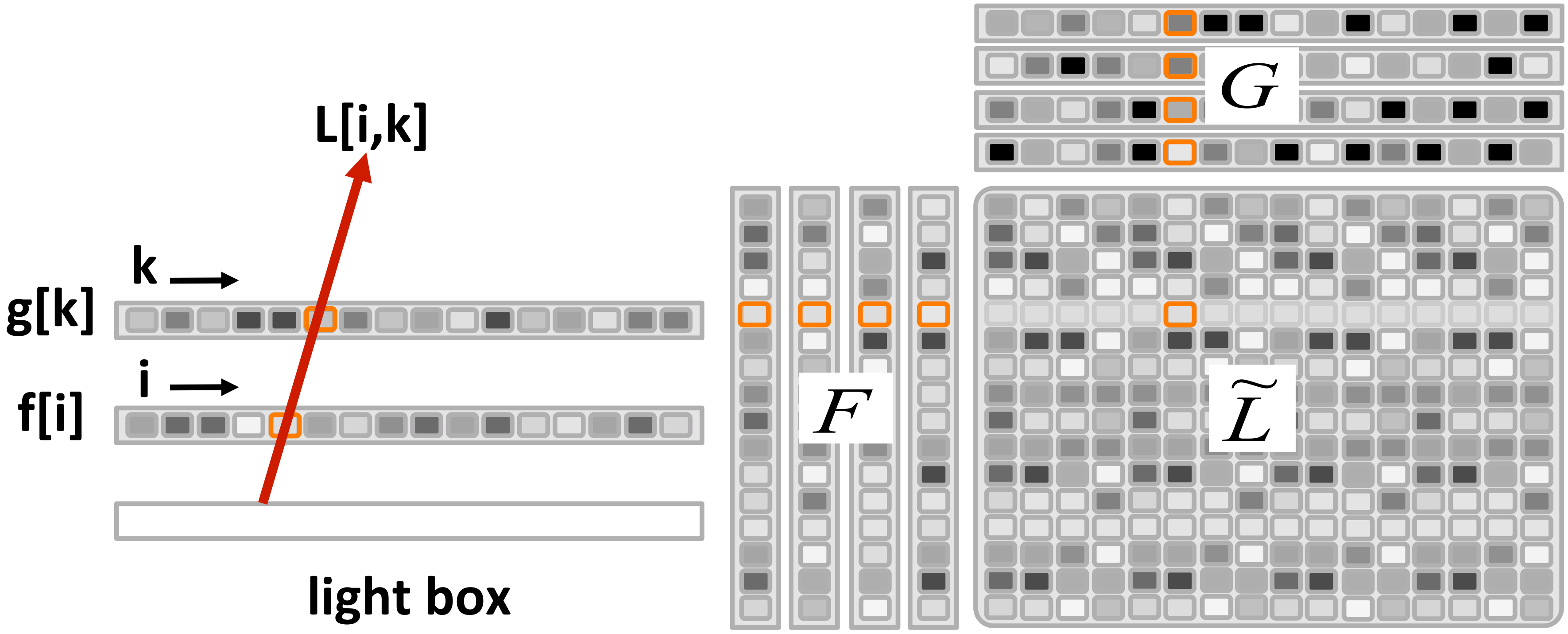


$$L[i,k] = \sum_{t=1}^{T} f_t[i] \otimes g_t[k]$$

Ken Perlin *et al*. An Autostereoscopic Display. 2000.
Yunhee Kim *et al*. Electrically Movable Pinhole Arrays. 2007.

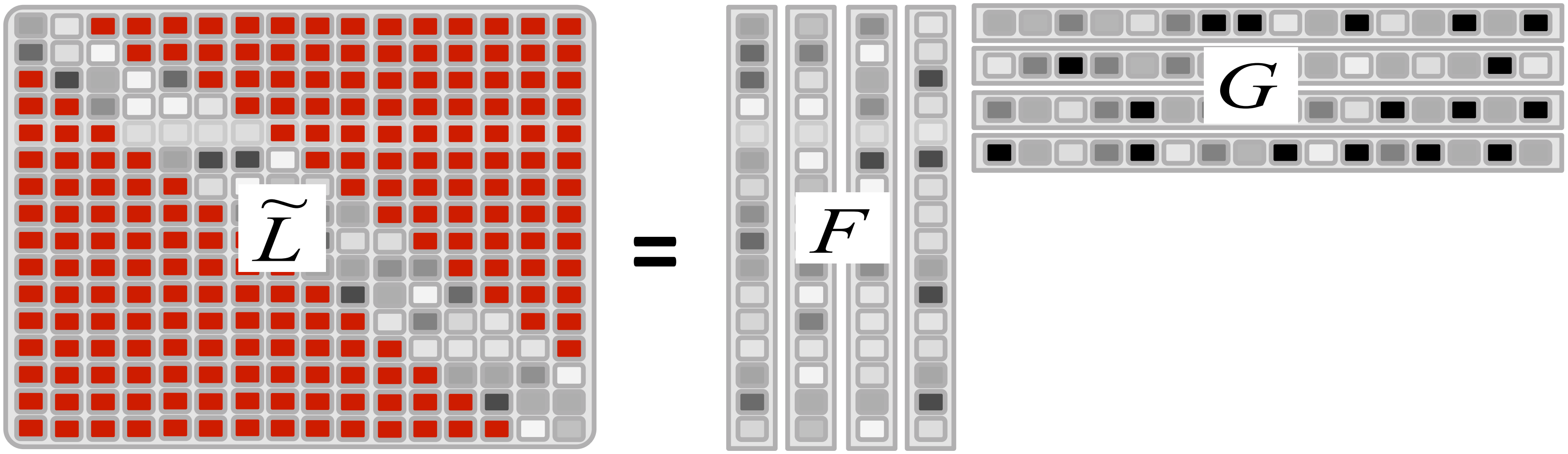
Content-Adaptive Parallax Barriers

SIGGRAPH2012



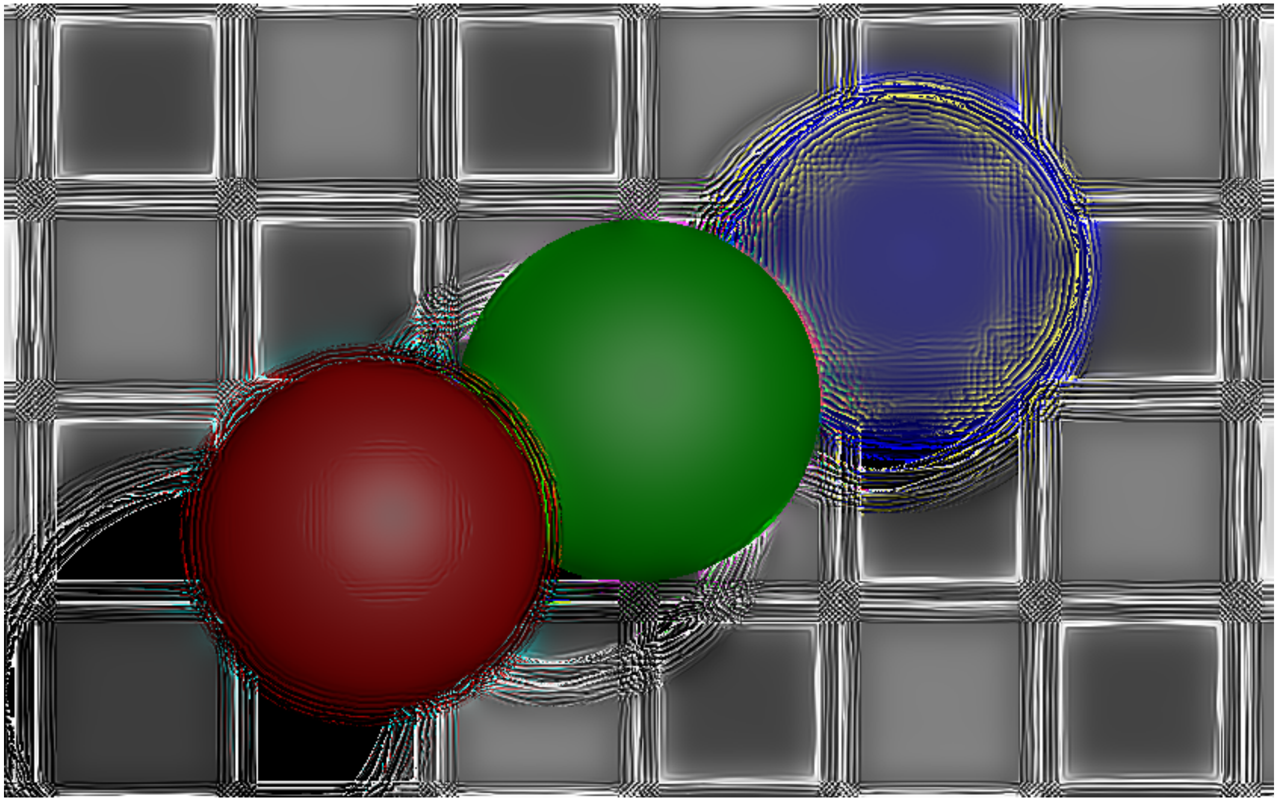
$$\widetilde{L} = FG$$

Content-Adaptive Parallax Barriers



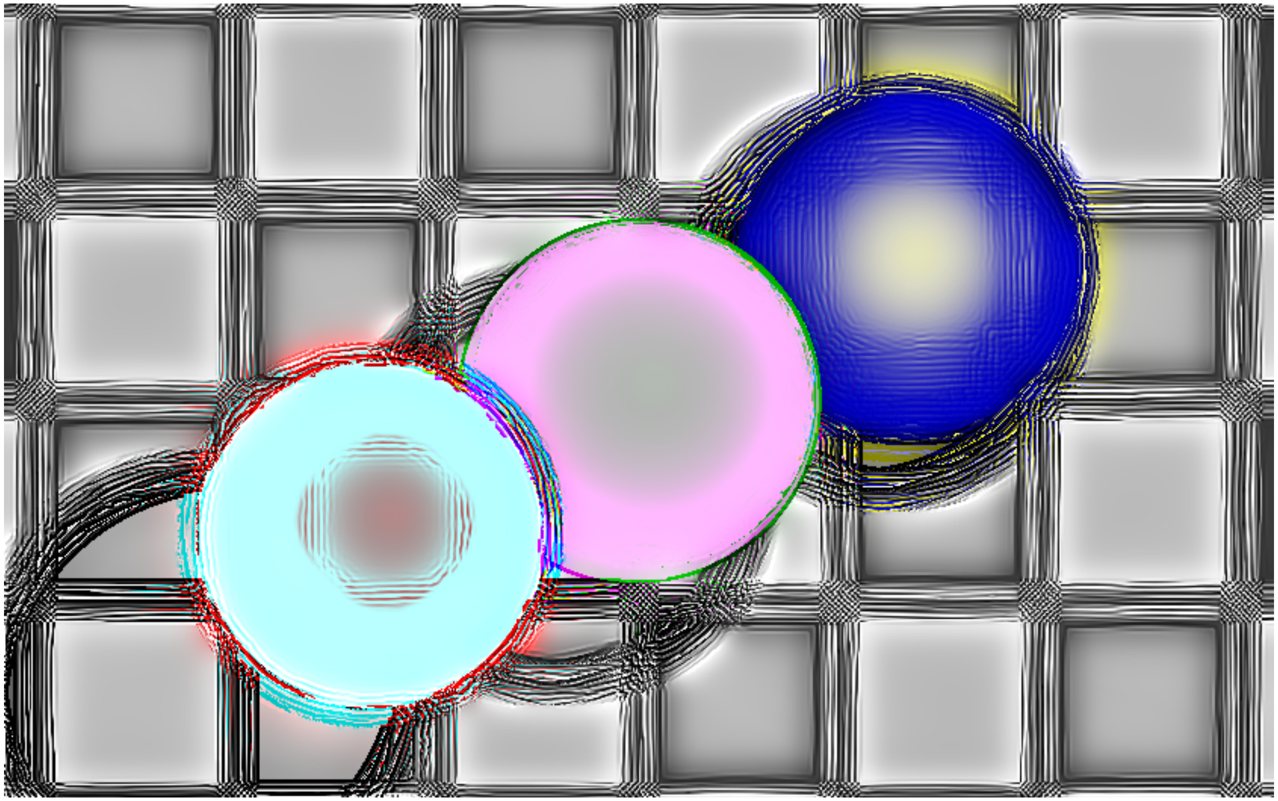
$$\underset{F,G}{\arg\min} \; \| L - FG \|_W^2 , \text{ for } F, G \geq 0$$

Content-Adaptive Parallax Barrier: Front Layer

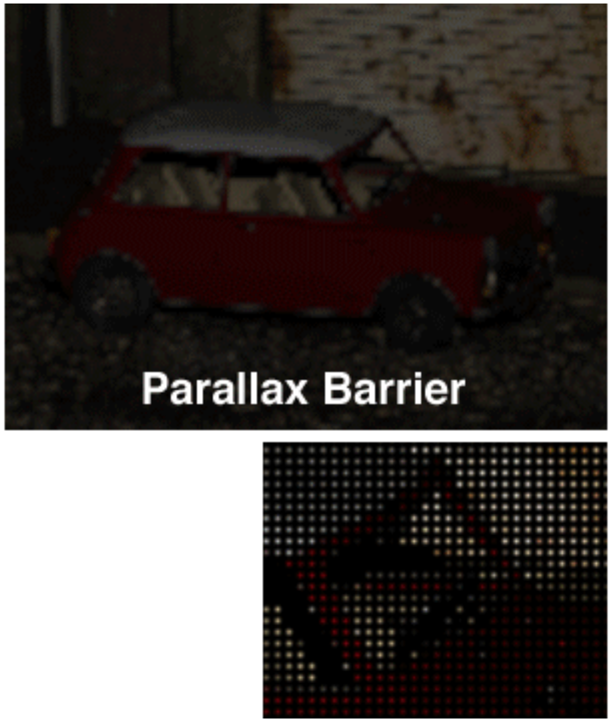


Content-Adaptive Parallax Barrier: Rear Layer

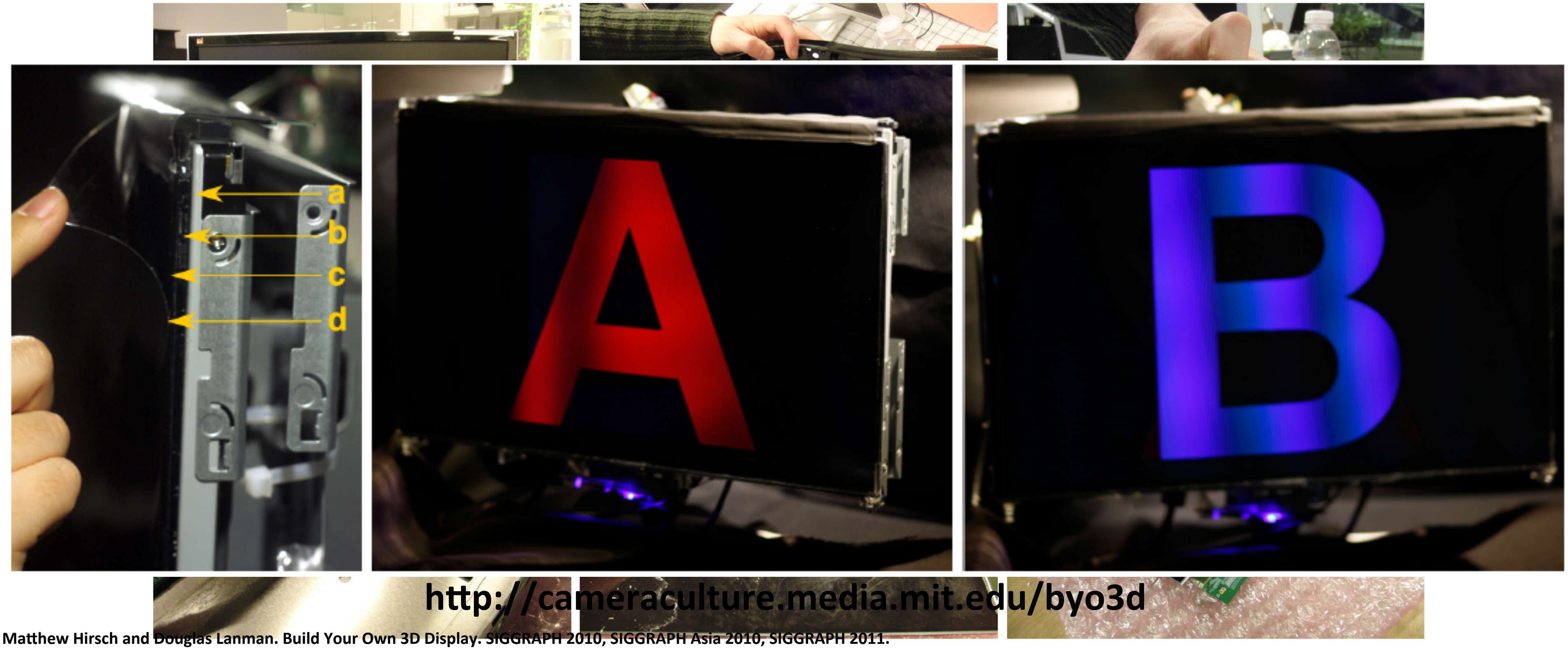
SIGGRAPH2012



Simulation Results



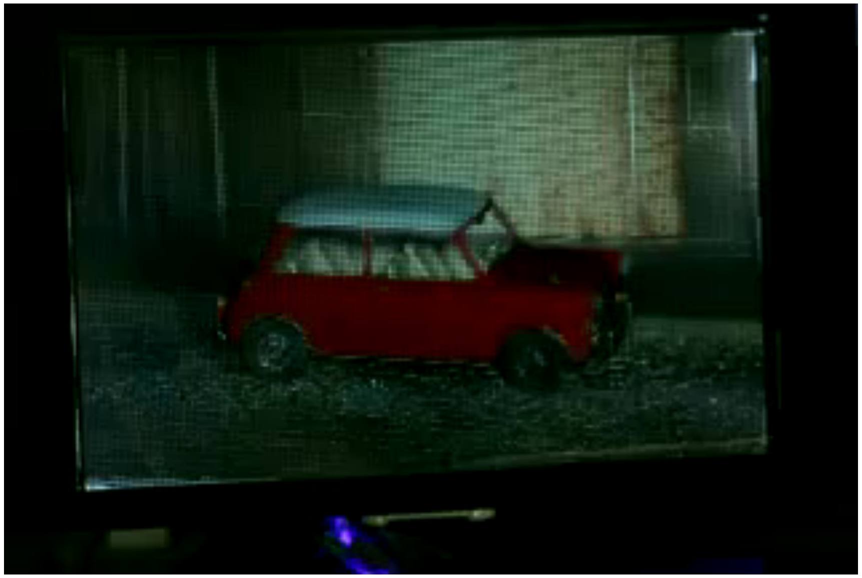
Prototype *High-Rank 3D (HR3D)* Display



http://cameraculture.media.mit.edu/byo3d

Matthew Hirsch and Douglas Lanman. Build Your Own 3D Display. SIGGRAPH 2010, SIGGRAPH Asia 2010, SIGGRAPH 2011.

Experimental Results



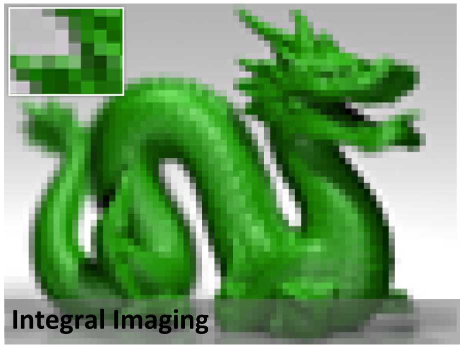
Time-Multiplexed Parallax Barrier

***High-Rank 3D* (*HR3D*)**

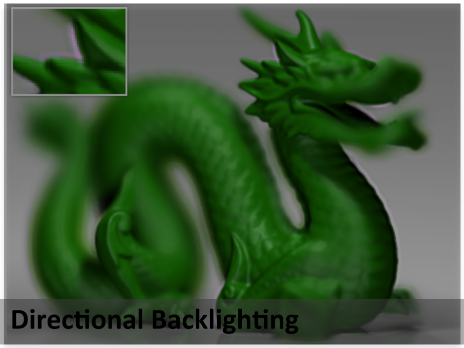
Outline

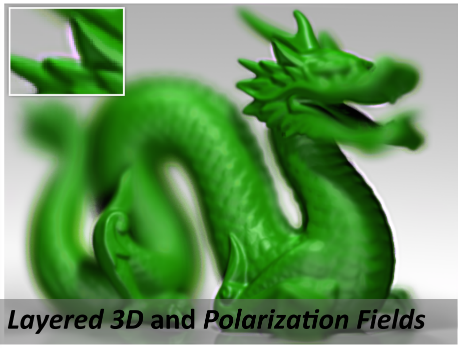
- *Automultiscopic Displays*
    - Multi-Layer Displays
        - Layered 3D
        - Polarization Fields
    - Dual-Layer Displays
        - High-Rank 3D (HR3D)

Design Trade-offs

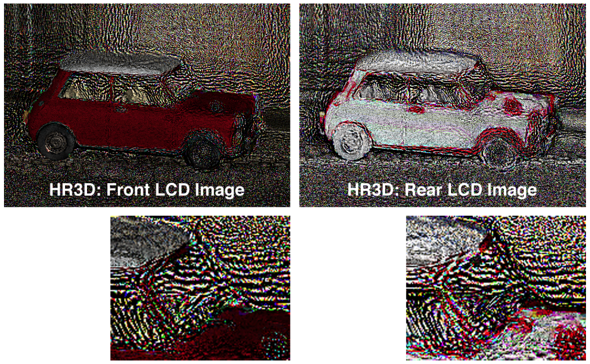

Integral Imaging


Parallax Barriers

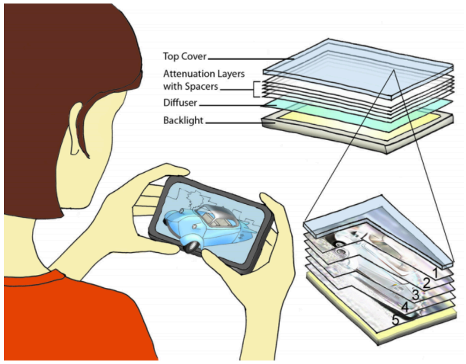

Directional Backlighting


Layered 3D and *Polarization Fields*

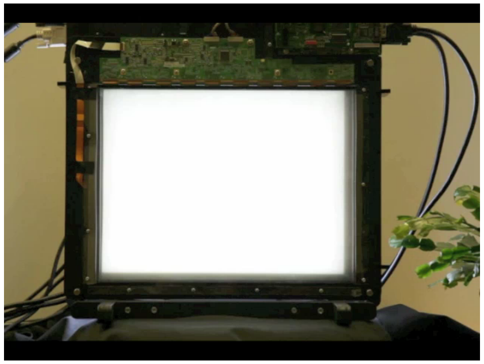
	Integral Imaging	**Parallax Barriers**	**Directional Backlighting**	***HR3D***	***Layered 3D* and *Polarization Fields***
Spatial Resolution	low	low	high	high	high
Brightness	high	low	moderate	moderate	high
Cost	low	low – moderate	moderate – high	moderate – high	low – high
Full-resolution 2D	no	yes	yes	yes	yes
Motion Parallax	yes	yes	no	yes	yes



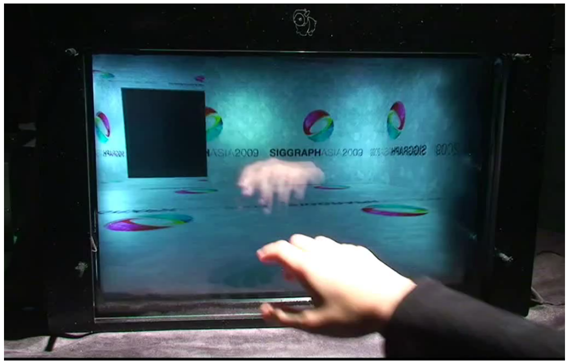
High-Rank 3D (HR3D)
www.hr3d.info



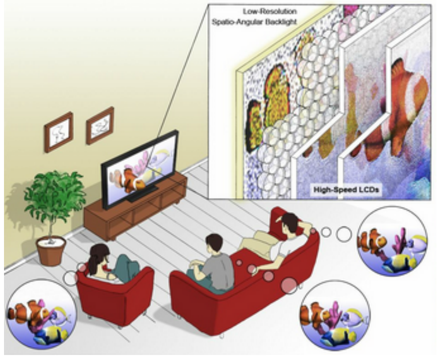
Layered 3D
www.layered3d.info



Polarization Fields
tinyurl.com/polarization-fields



BiDi Screen
www.bidiscreen.com



Tensor Displays
tinyurl.com/tensordisplays

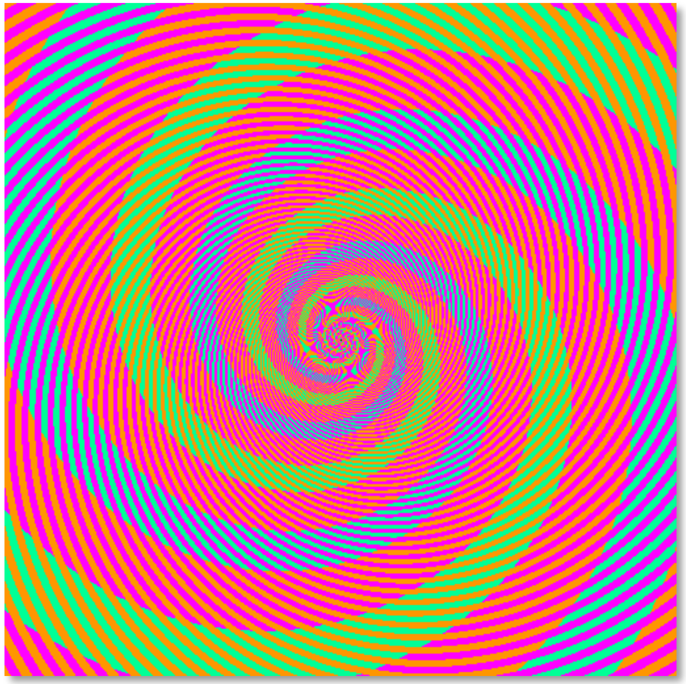
Perceptually-driven Computational Displays

Diego Gutierrez
Universidad de Zaragoza

SIGGRAPH2012

- For the latest version of the slides, please go to:
  - http://giga.cps.unizar.es/~diegog/pub.html

The HVS is not perfect…



http://blogs.discovermagazine.com/badastronomy/2009/06/24/the-blue-and-the-green/

The HVS is not perfect…

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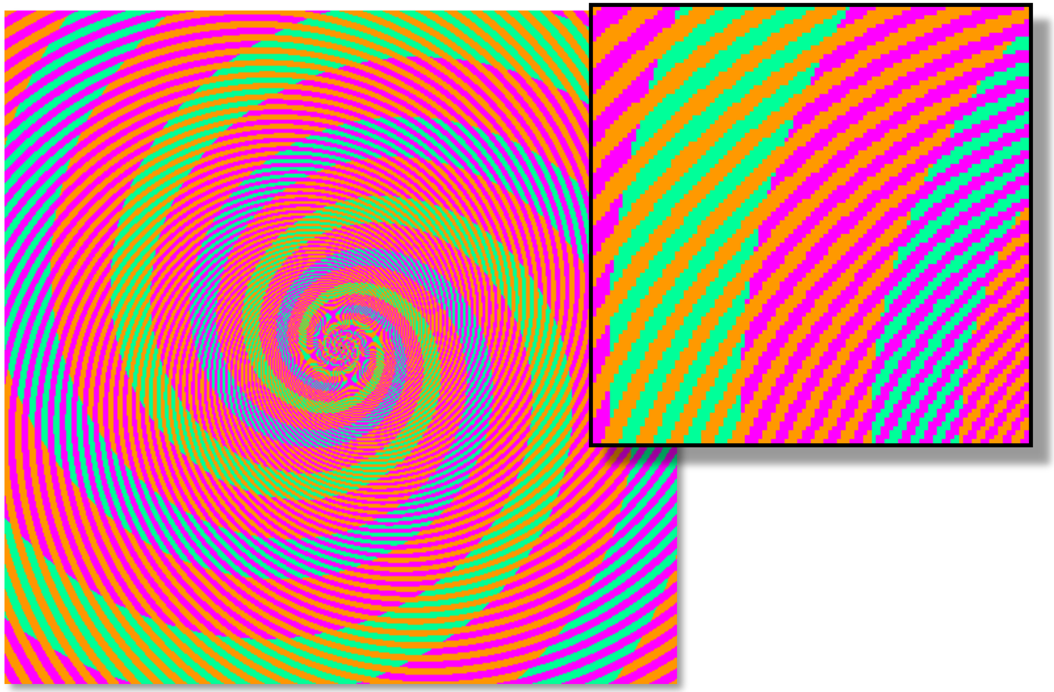
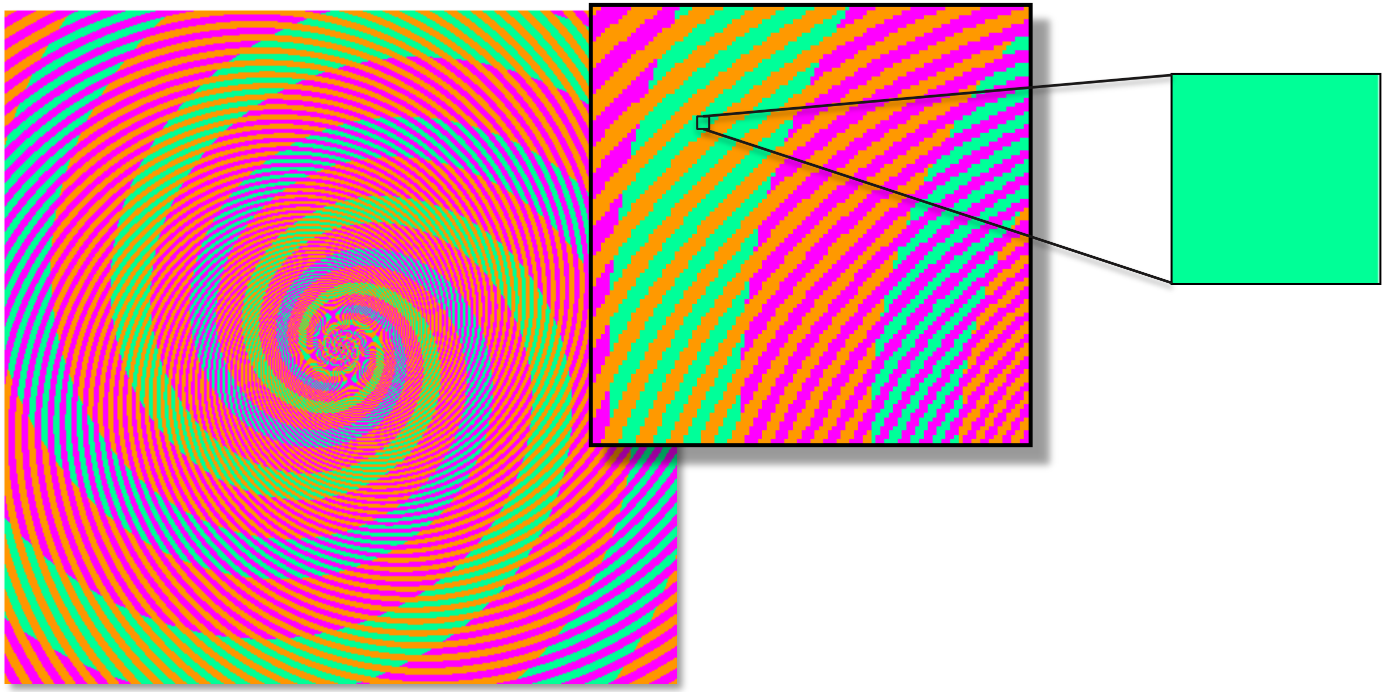


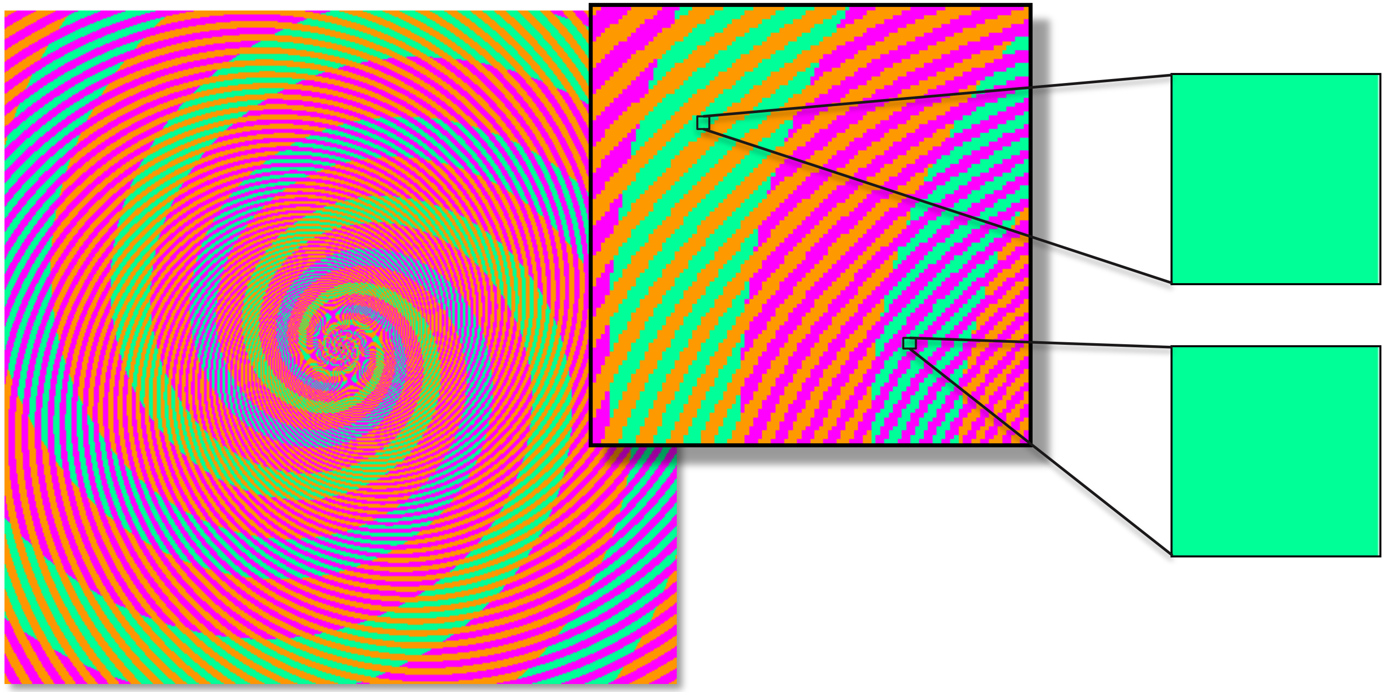
http://blogs.discovermagazine.com/badastronomy/2009/06/24/the-blue-and-the-green/

The HVS is not perfect…



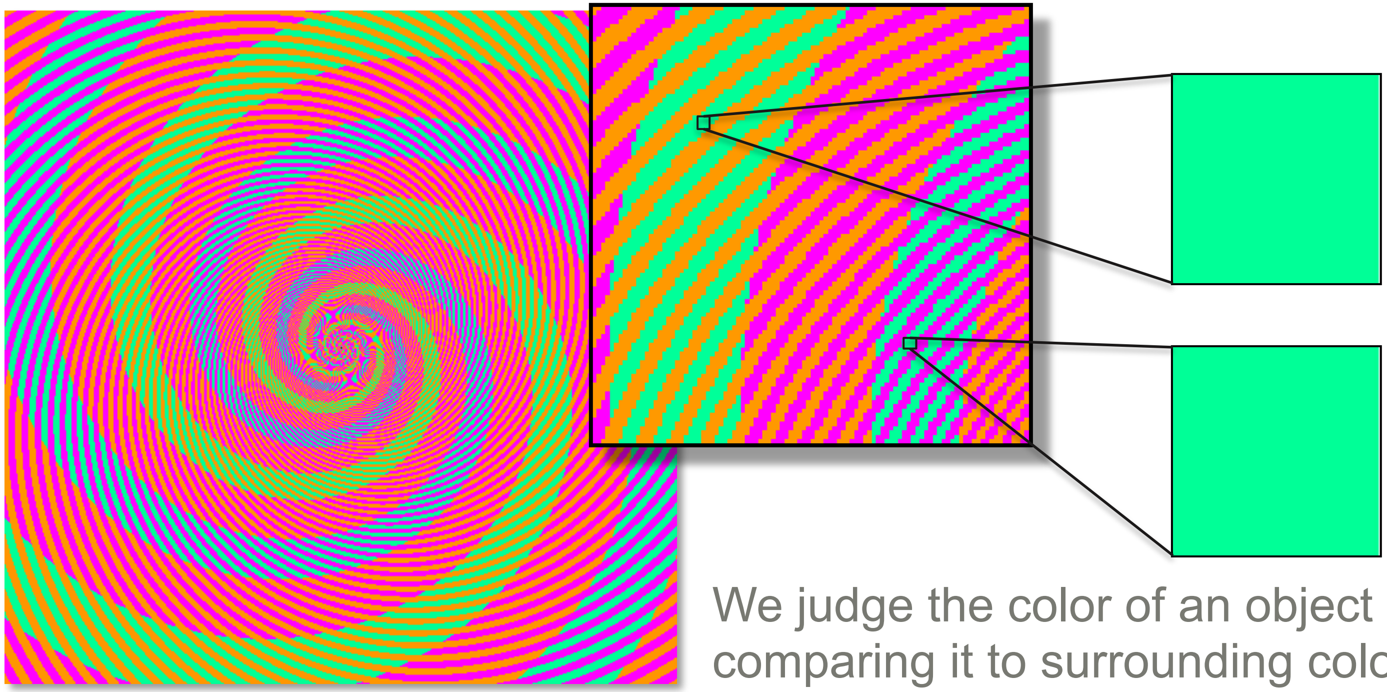
http://blogs.discovermagazine.com/badastronomy/2009/06/24/the-blue-and-the-green/

The HVS is not perfect…



http://blogs.discovermagazine.com/badastronomy/2009/06/24/the-blue-and-the-green/

The HVS is not perfect…



We judge the color of an object by comparing it to surrounding colors!

http://blogs.discovermagazine.com/badastronomy/2009/06/24/the-blue-and-the-green/

Displays are limited too

- Dynamic range
- Depth
- Spatial frequencies
- Temporal frequencies
- …

Computational displays

- Dynamic range
- Depth
- Spatial frequencies
- Temporal frequencies
- …

- Can we exploit the limitations of the HVS to enhance their **perceived** capabilities?

Color and tone mapping

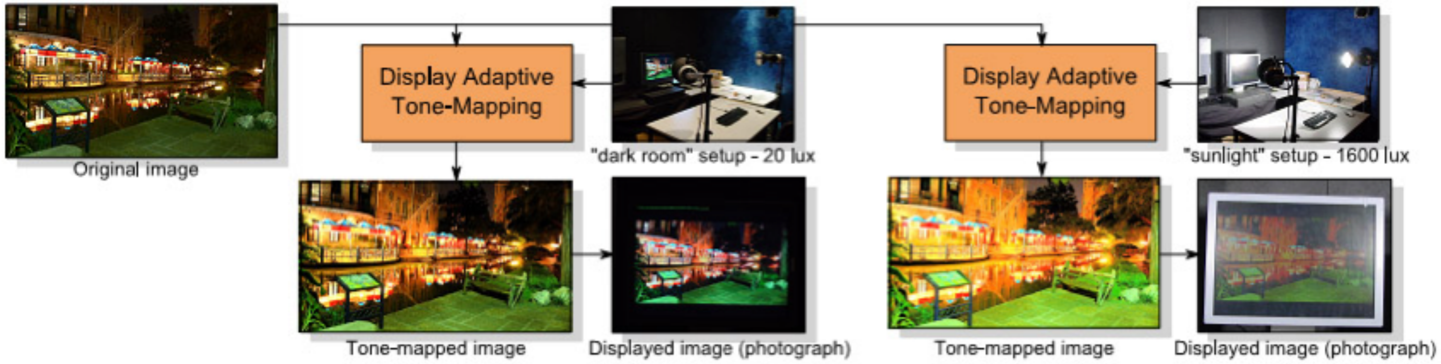
Real-world

Display

Goal: map colors to a restricted color space

Multidimensional image retargeting, SIGGRAPH Asia 2011 (slide by Rafal Mantiuk)

Color and tone mapping

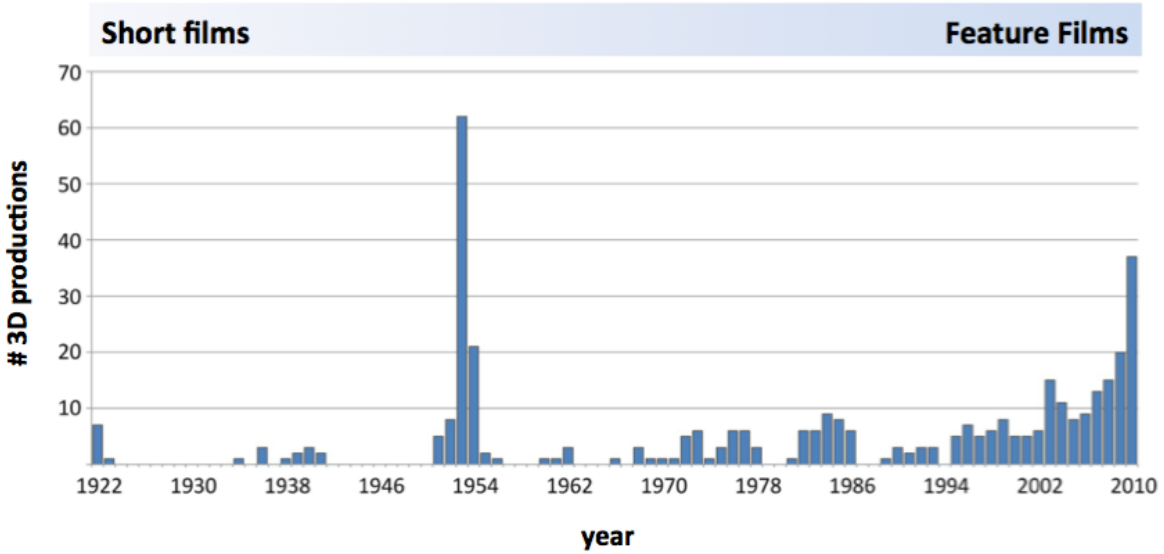


A model of the HVS predicts the visibility of contrast distortions, which are minimized

Display adaptive tone mapping, SIGGRAPH 2008 [Mantiuk et al.]

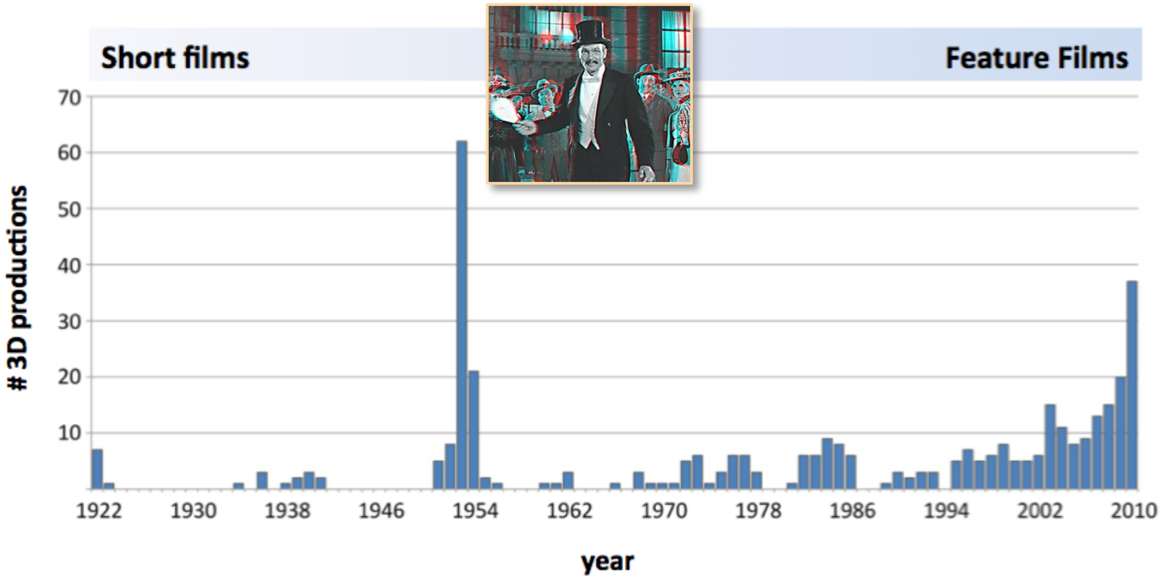
Stereo

Stereo retargeting



Multidimensional image retargeting, SIGGRAPH Asia 2011 (slide by Piotr Didyk)

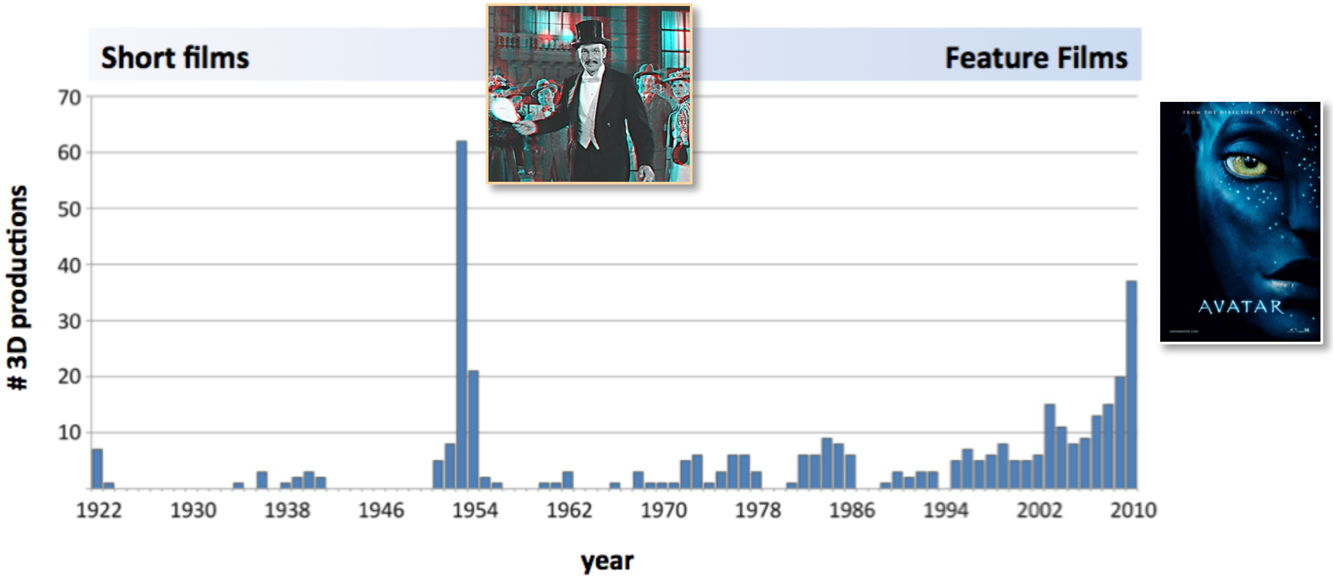
Stereo retargeting



Multidimensional image retargeting, SIGGRAPH Asia 2011 (slide by Piotr Didyk)

Stereo retargeting

SIGGRAPH2012

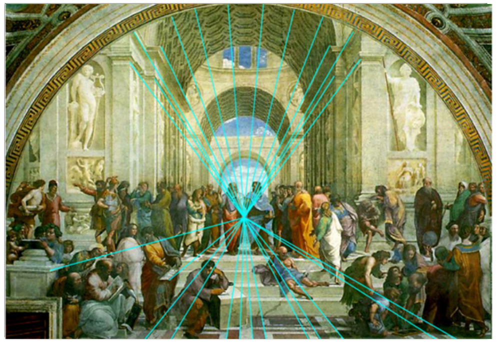


Multidimensional image retargeting, SIGGRAPH Asia 2011 (slide by Piotr Didyk)

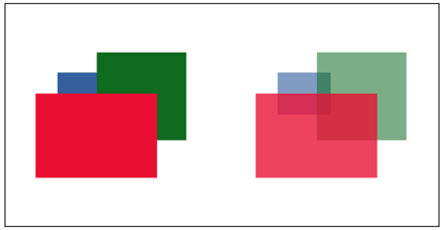
Stereo Retargeting

How do we perceive depth?

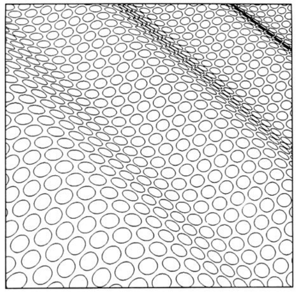
- 2D can convey sensation of depth



Perspective



Occlusions



Texture

How do we perceive depth?

- Perspective

How do we perceive depth?

- Perspective
- Occlusions

How do we perceive depth?

- Perspective
- Occlusions
- Texture

How do we perceive depth?

- **Monocular**
  - Perspective
  - Occlusions
  - Texture
  - Relative size
  - Familiar size
  - Aerial perspective
  - Motion parallax
  - Accomodation
  - Shading
  - Defocus blur
  - …
- **Binocular**
  - Binocular disparity
  - Convergence

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How do we perceive depth?

SIGGRAPH2012

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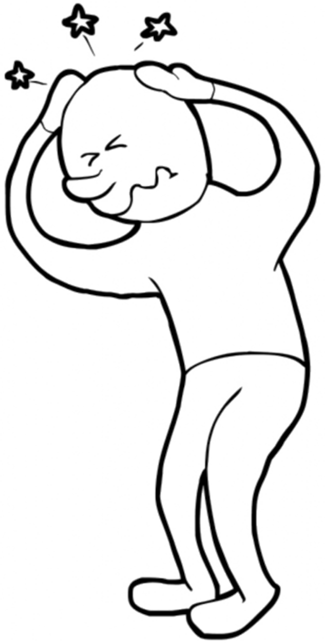
  - Defocus blur
  - …
- **Binocular**
  - **Binocular disparity**
  - **Convergence**

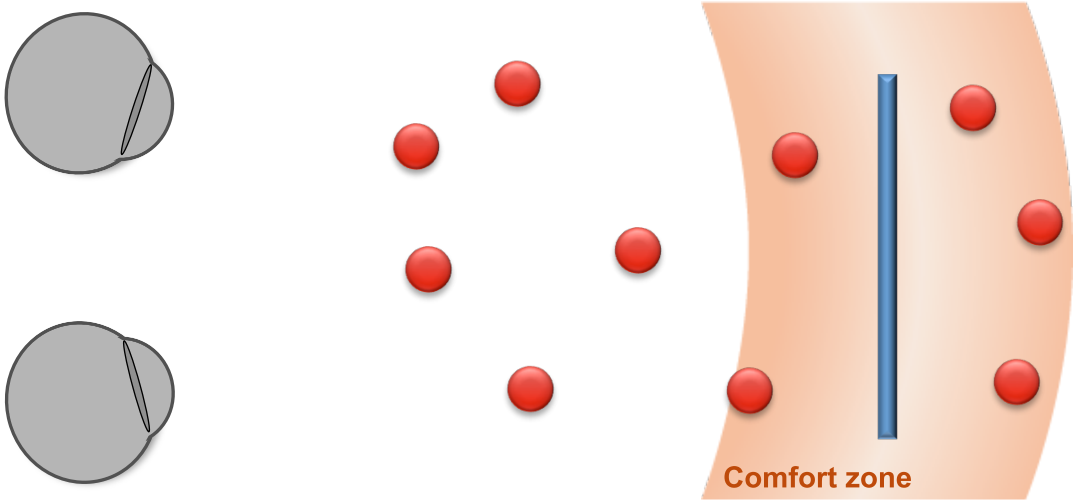
In 3D
Our screens are 2D…

Stereo Retargeting

SIGGRAPH2012



Visual Discomfort

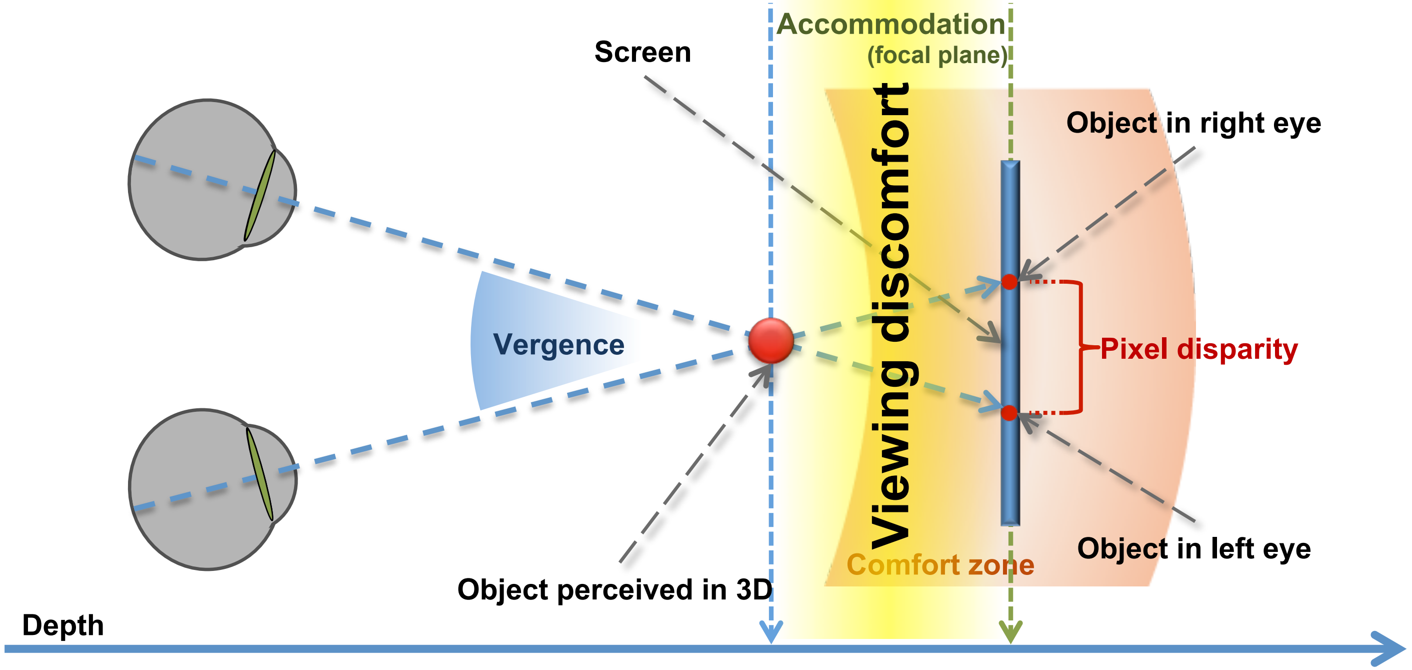


Viewing discomfort → Scene manipulation → Viewing comfort

(slide by Piotr Didyk)

Visual Discomfort

SIGGRAPH2012

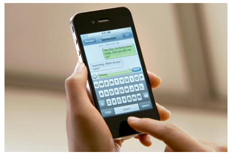


(slide by Piotr Didyk)

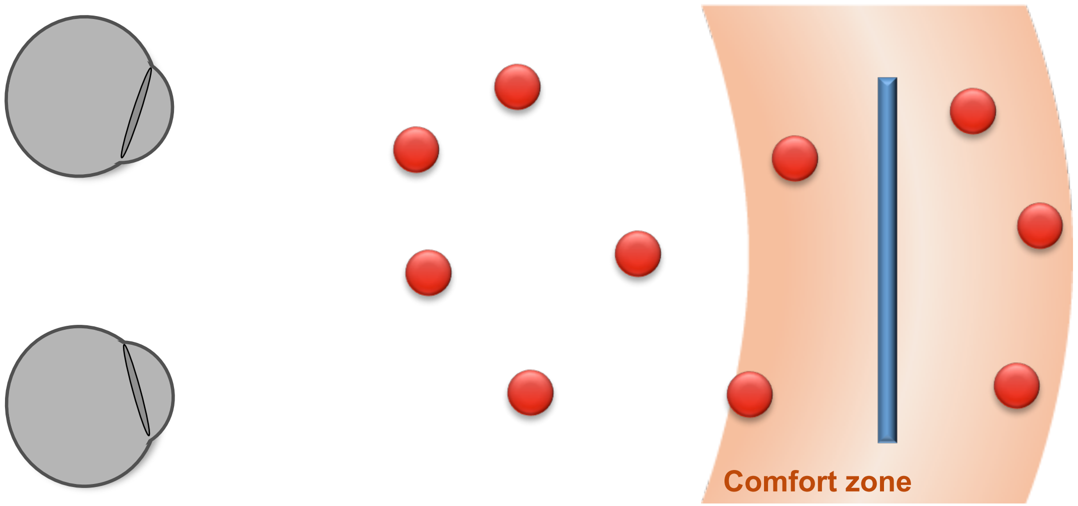
Disparity Remapping






Visual Discomfort



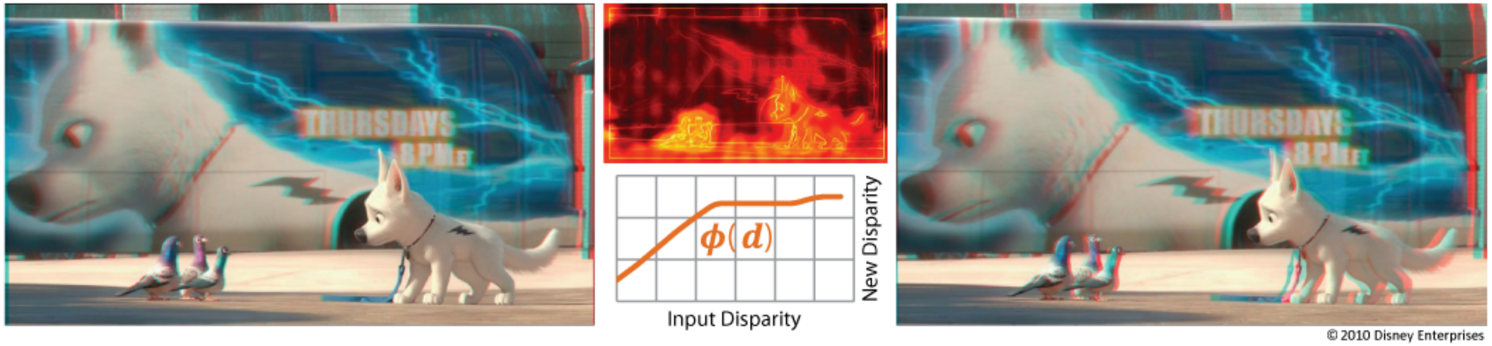
Viewing discomfort

Scene manipulation →

Viewing comfort

(slide by Piotr Didyk)

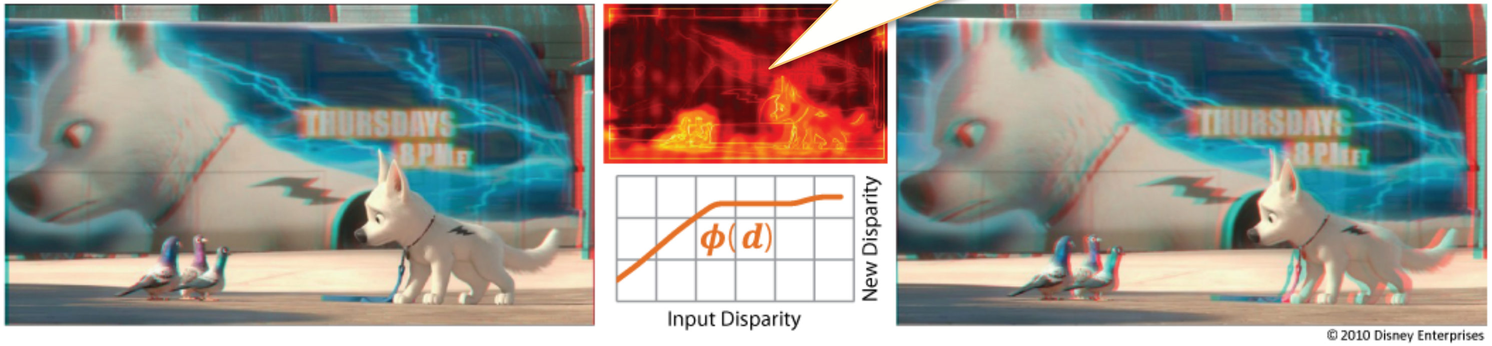
Disparity Remapping



“Nonlinear Disparity Mapping for Stereoscopic 3D” by Lang et al. 2010

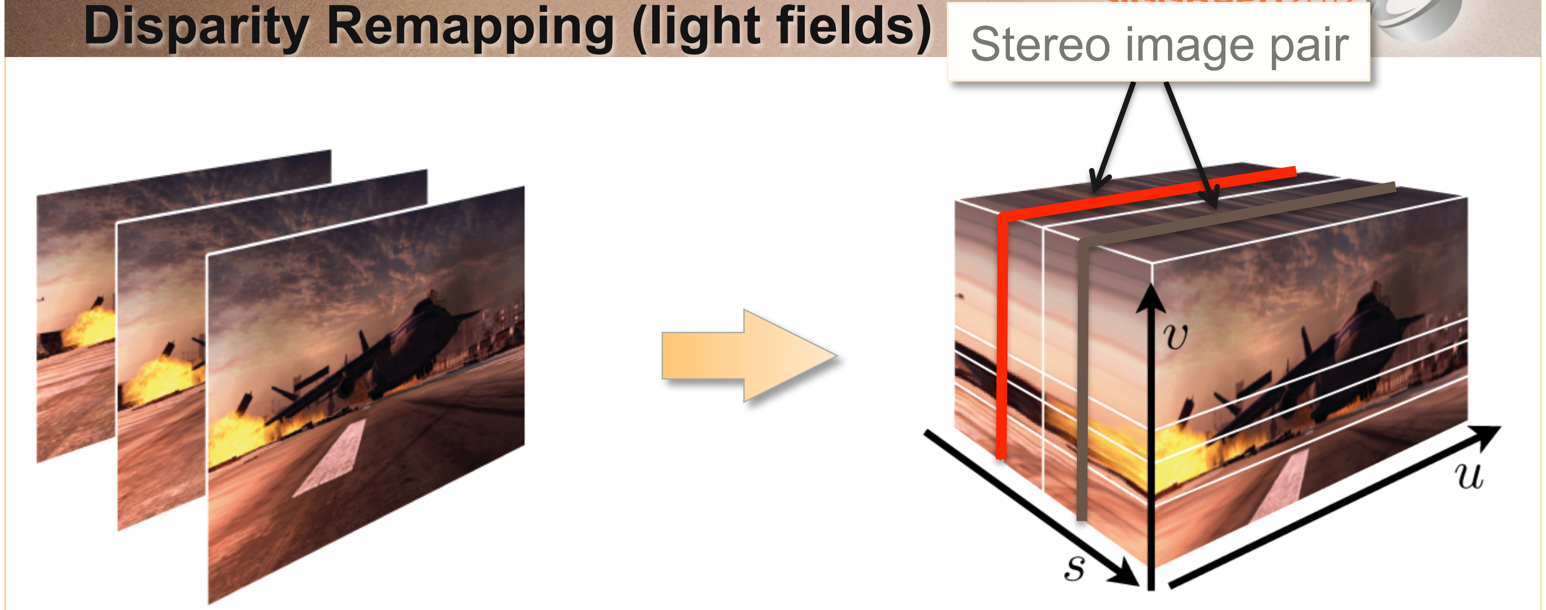
Disparity Remapping

Visual Importance
based on saliency



"Nonlinear Disparity Mapping for Stereoscopic 3D" by Lang et al. 2010

Disparity Remapping (light fields)

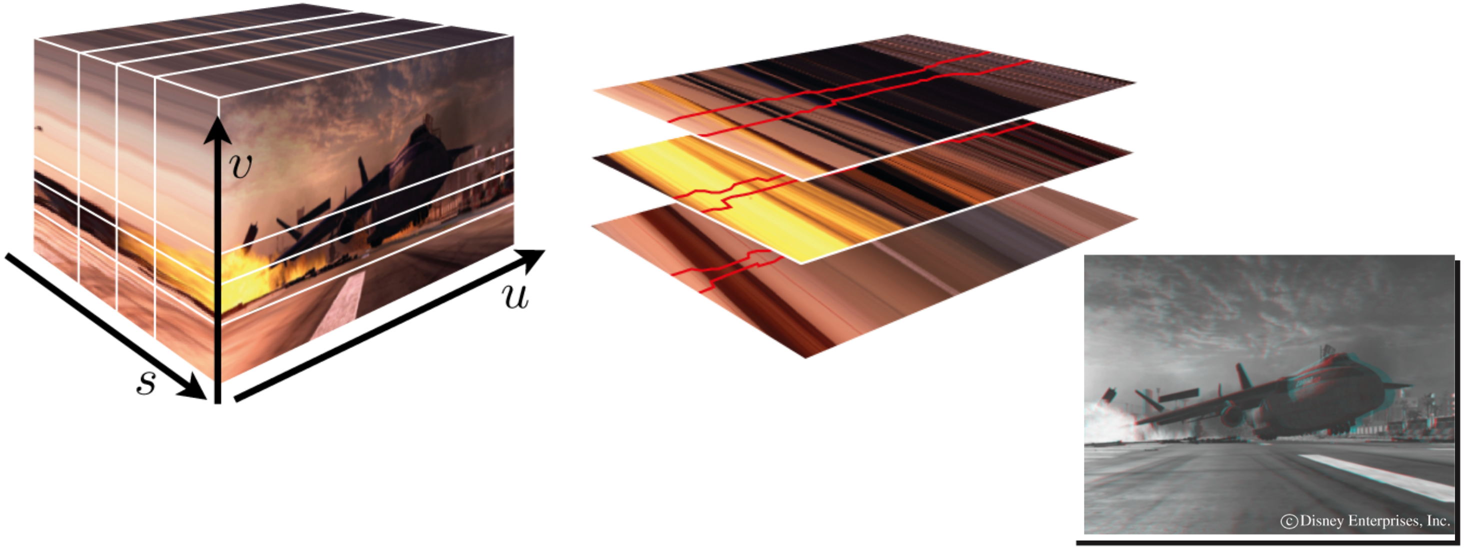


Stereo image pair

Light Field

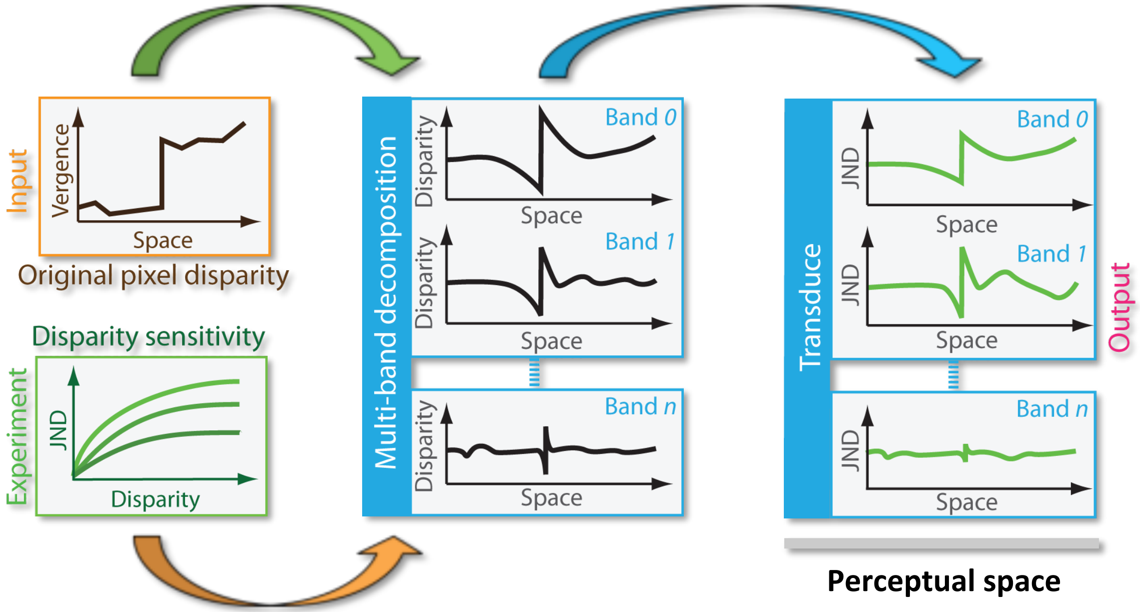
"Multi-Perspective Stereoscopy from Light Fields" by Kim et al. 2011

Disparity Remapping (light fields)



"Multi-Perspective Stereoscopy from Light Fields" by Kim et al. 2011

A perceptual model



Perceptual space

"A perceptual model for disparity" by Didyk et al. 2011

A perceptual model

- Drawing inspiration from more traditional spaces:
  - Luminance – Vergence
  - Contrast – Disparity
  -

“A perceptual model for disparity” by Didyk et al. 2011

A perceptual model

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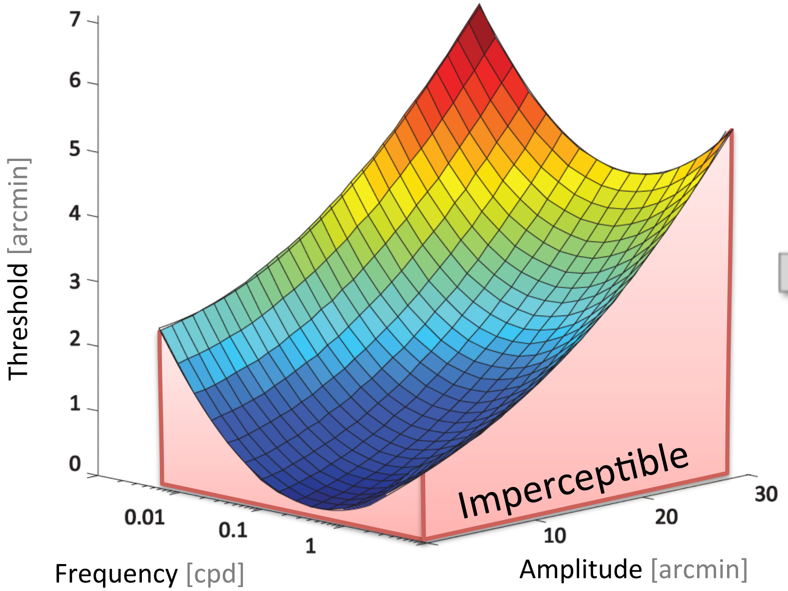
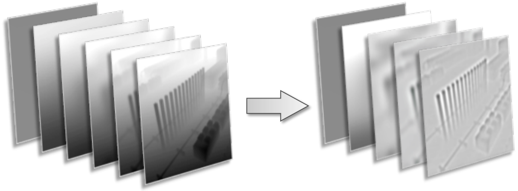




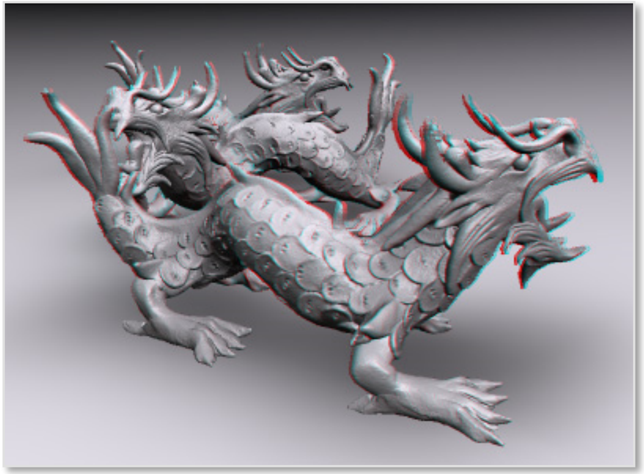
Can be removed

Without reducing quality

“A perceptual model for disparity” by Didyk et al. 2011

A perceptual model

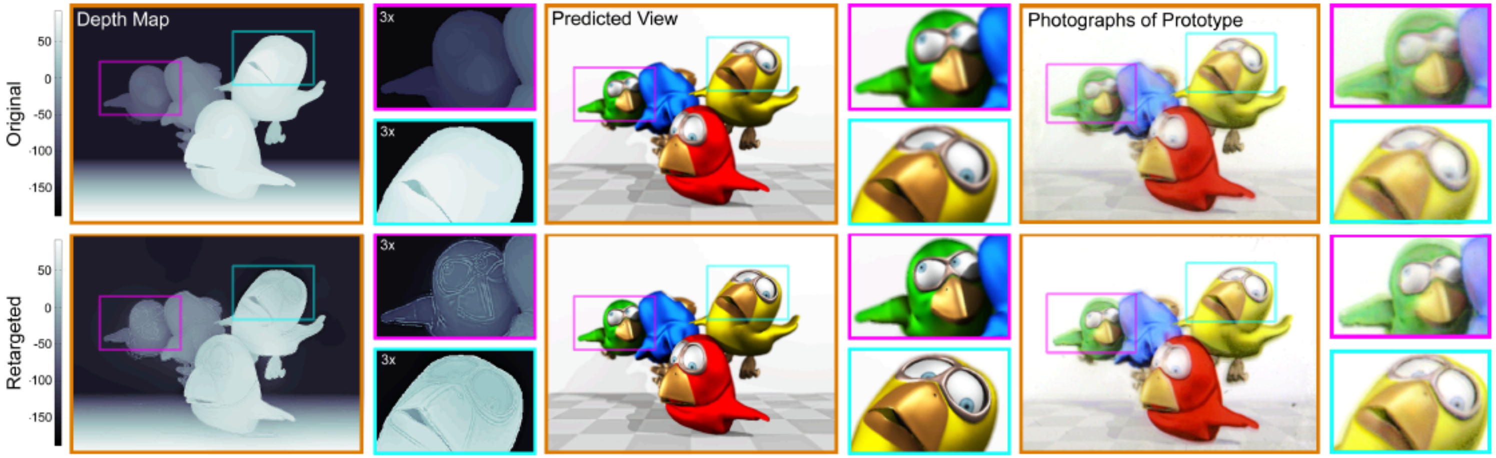
Standard stereo



Backward-compatible stereo

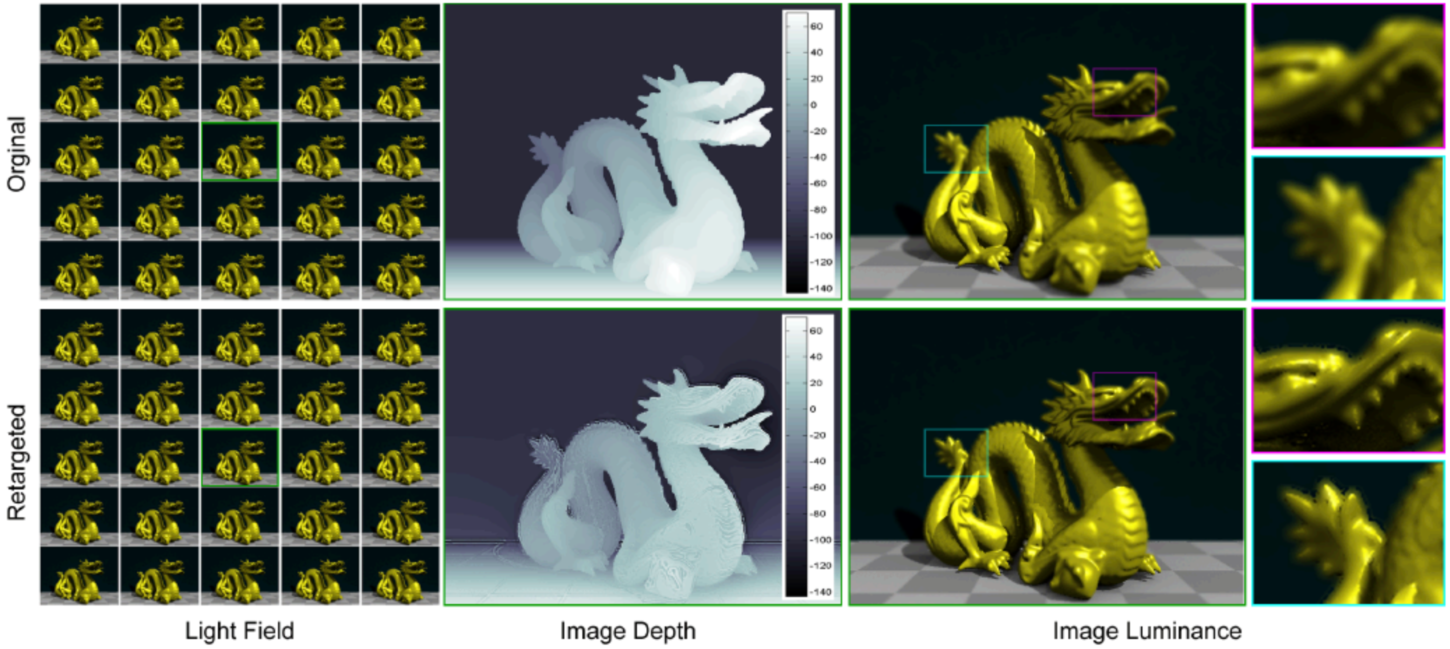
"A perceptual model for disparity" by Didyk et al. 2011

Automultiscopic displays



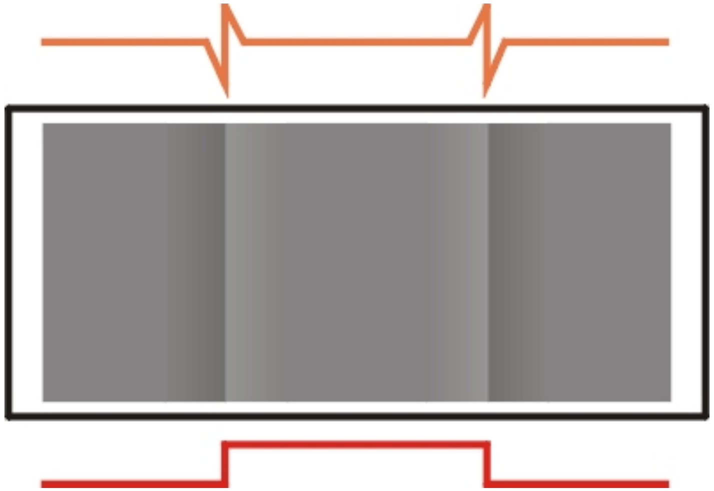
"Perceptually-optimized content remapping for automultiscopic displays" by Masia et al. 2012

Automultiscopic displays



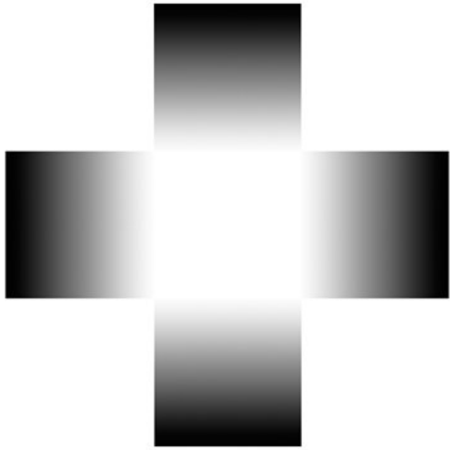
“Perceptually-optimized content remapping for automultiscopic displays” by Masia et al. 2012

Cornsweet



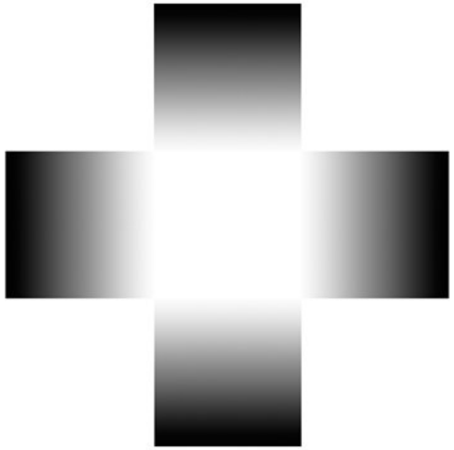
http://www.pc.rhul.ac.uk/staff/J.Zanker/PS1061/L3/PS1061_3.htm

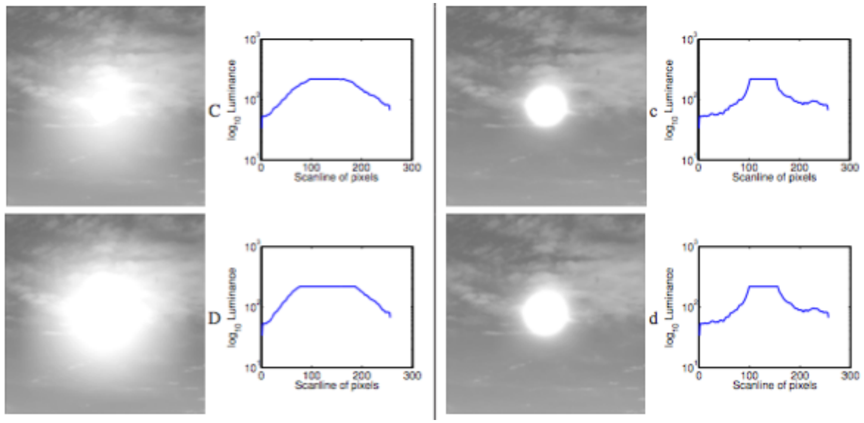
Apparent brightness



http://www.opticalillusion.net/optical-illusions/grey-glow-illusion-the-glare-effect/

Apparent brightness





http://www.opticalillusion.net/optical-illusions/grey-glow-illusion-the-glare-effect/

“Brightness of the glare illusion” by Yoshida et al. 2008

Apparent brightness

SIGGRAPH2012

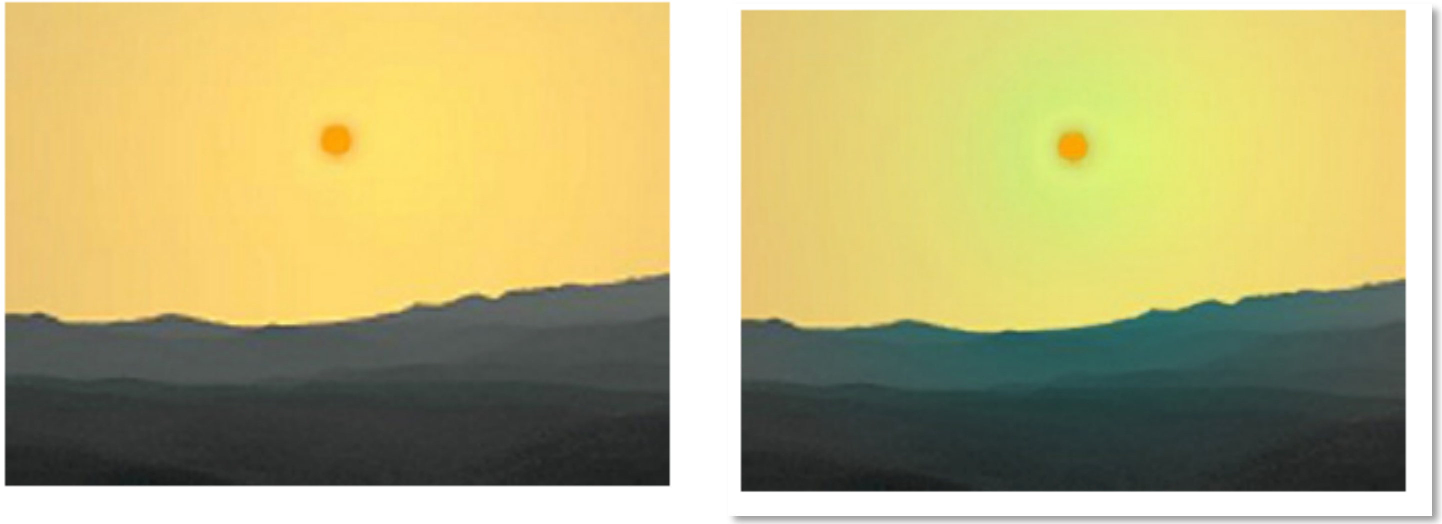

keep staring at the black dot.

"Perception-based rendering: eyes wide bleached" by Anson et al. 2005

Apparent brightness

"Perception-based rendering: eyes wide bleached" by Anson et al. 2005

Apparent brightness



"Perception-based rendering: eyes wide bleached" by Anson et al. 2005

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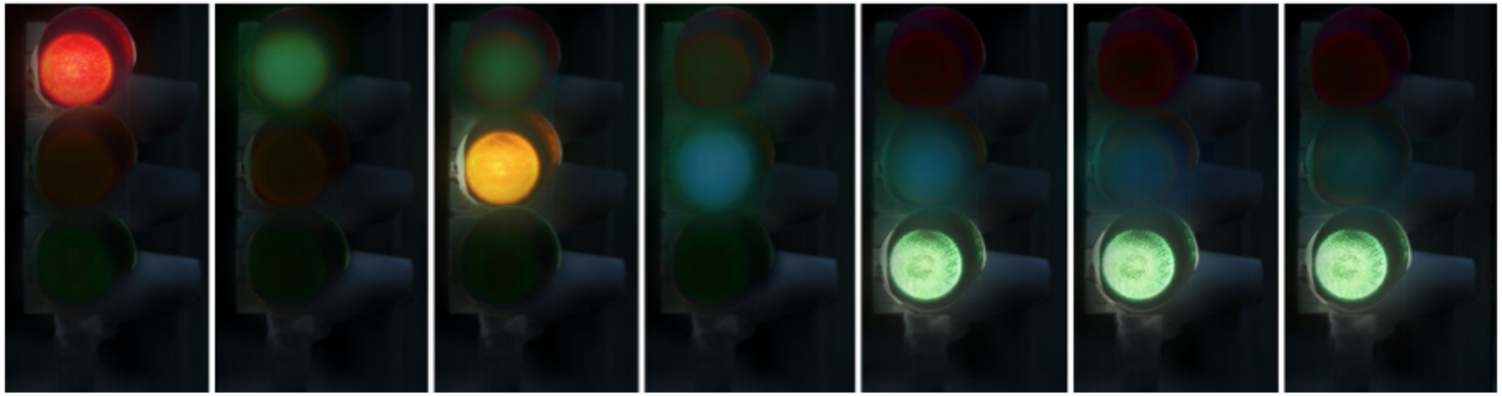
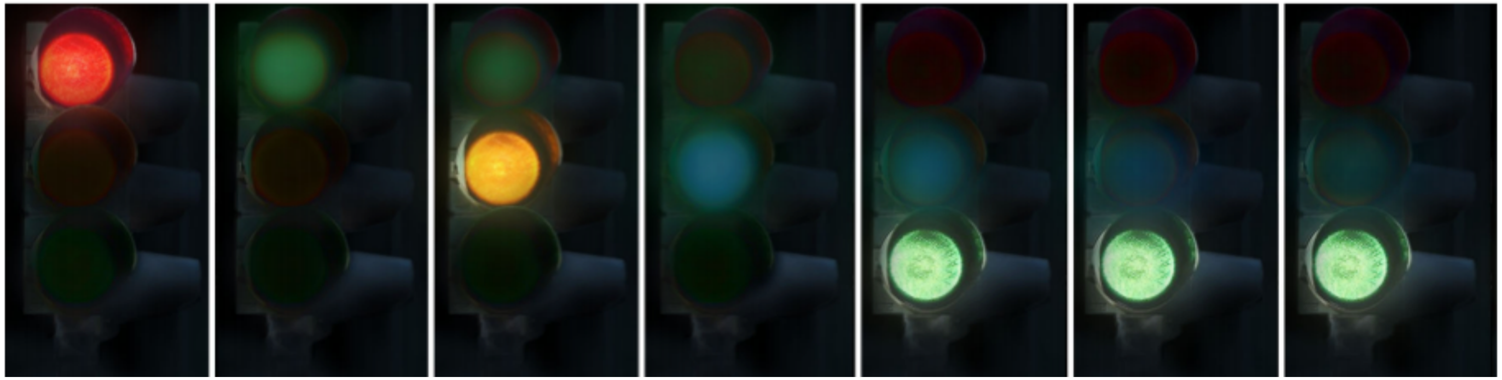
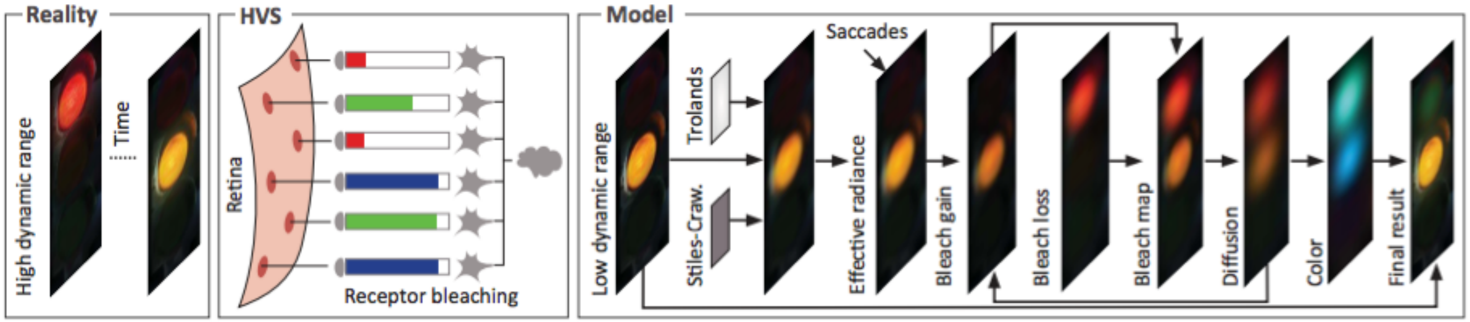


"A computational model of afterimages" by Ritschel and Eisemann 2012

Apparent brightness

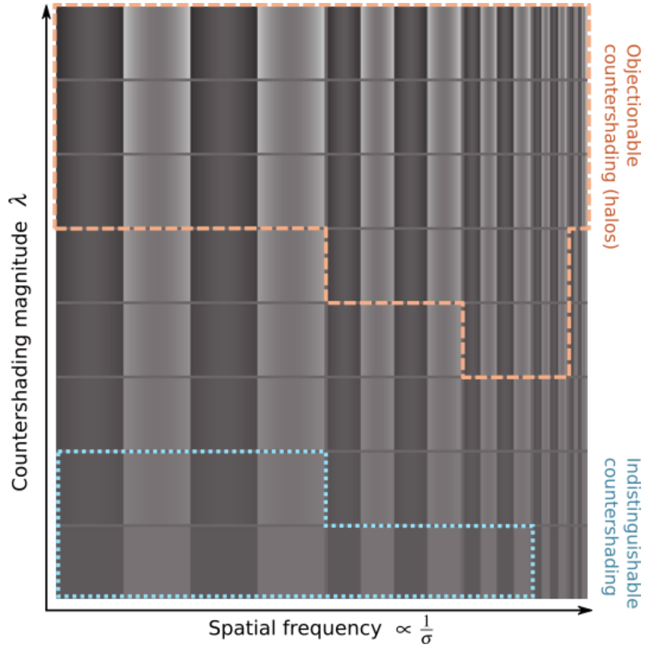




Apparent brightness

“Unsharp masking, countershading and halos: enhancements or artifacts?” by Trentacoste et al. 2012

Apparent brightness



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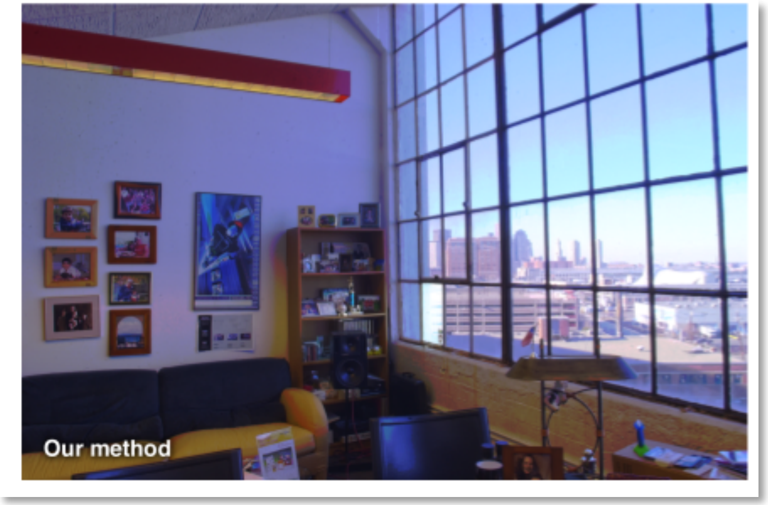
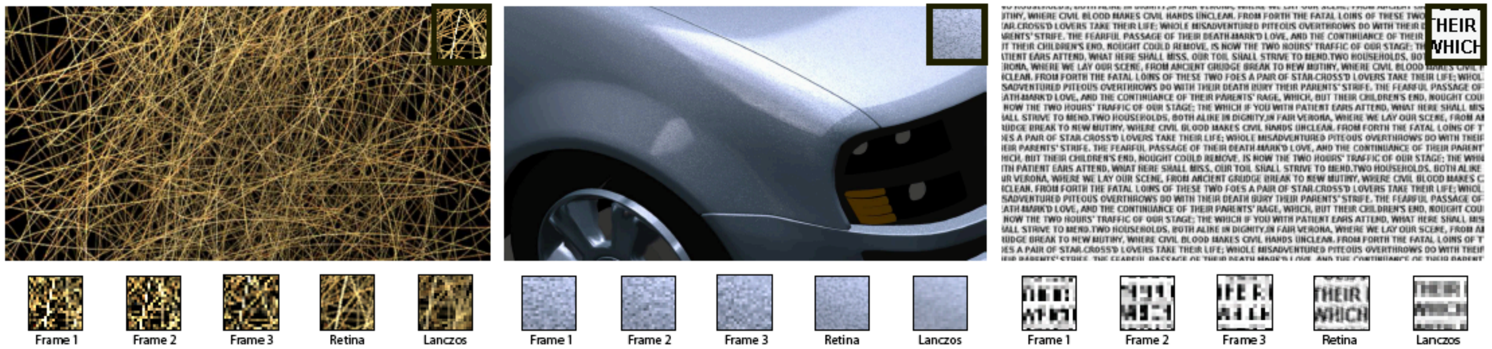


“Unsharp masking, countershading and halos: enhancements or artifacts?” by Trentacoste et al. 2012

Resolution enhacement



“Apparent display resolution enhancement for moving images” by Didyk et al. 2010

Resolution enhacement

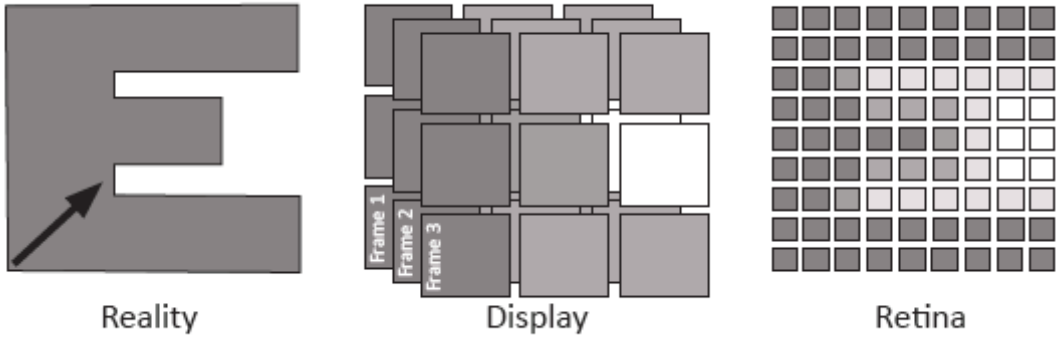
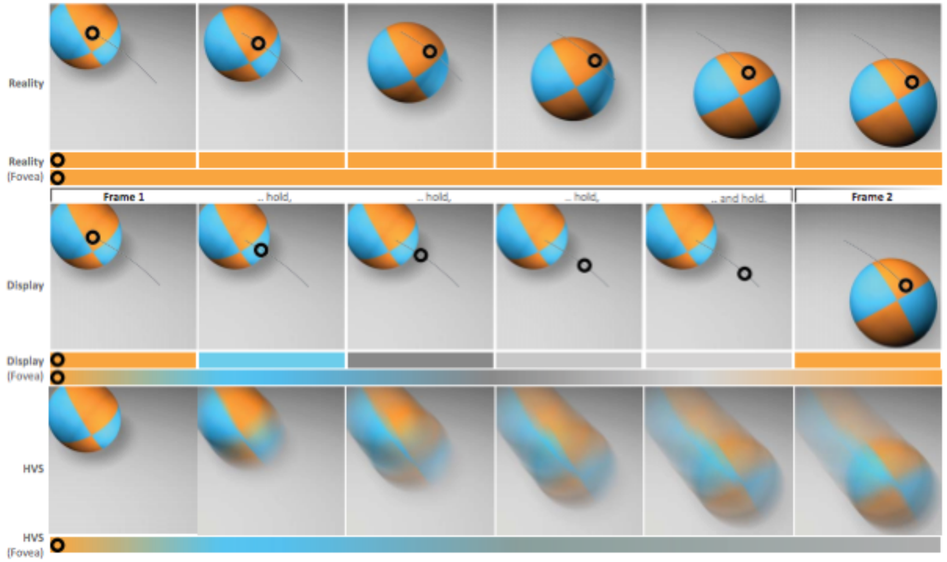


Figure 2: *Fixational eye tracking over an region of interest in combination with a low-resolution image sequence leads to an apparent high-resolution image via integration in the retina.*

“Apparent display resolution enhancement for moving images” by Didyk et al. 2010

Temporal upsampling



“Perceptually-motivated real-time temporal upsampling of 3D content for high-refresh-rate displays” by Didyk et al. 2010
“Perceptual considerations for motion blur rendering” by Navarro et al. 2011

Aknowledgements

- Belen Masia
- Piotr Didyk
- Rafal Mantiuk
- Karol Myszkowski
- Elmar Eisemann

Stereo retargeting

- To know more:
    - Multidimensional image retargeting. *SIGGRAPH Asia 2011 Course*