The Debate:
Lightfield vs. Holographic

Presented by:

OSA Display Technology Technical Group

Display Technology (IT)

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  - Bio-Medical Optics
  - Fabrication, Design & Instrumentation
  - Information Acquisition, Processing & Display +
    - Applied Spectroscopy (IS)
    - Display Technology (IT)
    - Environmental Sensing (IE)
    - Image Sensing and Pattern Recognition (IR)
    - Optics in Digital Systems (ID)
  - Optical Interaction Science
  - Photonics and Opto-Electronics
  - Vision and Color Division
  - Technical Group Newsletter
  - Technical Group Webinars
- OSA CONNECT
- Minorities and Women in OSA (MWOSA)
- Diversity & Inclusion in OSA
- Young Professionals
- Corporate Members
- Optics & Photonics Regions
- Librarians
- Frequently Asked Questions

Display Technology (IT)

This group focuses on the various aspects of display technologies including the physical display media, algorithms needed to visualize data, systems and subsystems that present the display, and data formatting needed to interface with the physical display technologies used. New device technologies used for display incorporating OLEDs, holography, MEMS, etc. are within the scope of this group. The evolving field of 3-D display including 3-D data formation, lightfield processing, and 3-D television and electronic cinema are also within the scope of this group. Display holography has been a thrust of this group and expanded efforts on digital as well as analog processes and materials are expected. Techniques for improving visual quality of displays and reducing energy consumption are also of relevance to the group. The group will also investigate display and sensor technologies used for creating augmented reality and interactive environments including interactive control and display algorithms, opto-electronic interfaces, mechanical devices and optical sensors required for implementing interactivity.

GROUP LEADERSHIP | UPCOMING MEETINGS | RECENTLY PUBLISHED

Name	Affiliation	Title
Daniel Smalley	Brigham Young University	Chair
Ting-Chung Poon	Virginia Tech	Advisor
Edward Buckley	Qualcomm Inc	Member
Hongyue Gao	Shanghai University	Member
Josh Kvavle	Office of Naval Research	Member

Announcements

Join the OSA Display Technology Technical Group for a webinar debating the future of 3D displays on 29 September 2016 at 14:00 EDT. During the webinar, Dr. Levent Onural (Bilkent University) and Dr. Gordon Wetzstein (Standford University) will be engaging in a lighthearted debate on the relative merits of holographic video and lightfield displays.

Register today to participate in **The Debate: Lightfield vs. Holographic**! And join the discussion yourself by submitting a question to tgactivities@osa.org to be read during the debate.

The Display Technology Technical Group hosted the first ever Illumicon gathering at this year's Imaging and Applied Optics Congress in Hiedelberg, Germany. The event brought together over 30 individuals to discuss topics related to advanced displays.

You can read the notes from the first Illumicon online now!

The Display Technology Technical Group hosted an introductory webinar for the members of their community. You can now view the 'Introducing the OSA Display Technology Technical Group' webinar on-demand to learn more about this group and recent trends in the display technology field.

Work in Optics

ILLUMICON

3D Display and World Domination

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Display Technology (IT)

ILLUMICONCLAVE I

Description:
Meeting of experts convened to rule on topics related to advanced display.

Location:
Heidelberg, Germany 2016

Article I

DEFINITIONS

Ambiguous terms in display technology were given the following definitions:

1.1. ***Volumetric Display***—a volumetric display is defined as a display in which all image points are collocated with physical scattering surfaces. Consistent with this definition, volumetric displays have perfect accommodative cues as the viewer is able to focus on a material object in space. Also consistent with this definition and contrary to long-held popular opinion, it is *not* necessarily true that a volumetric display be incapable of self-occlusion as this may be possible by employing anisotropic scattering surfaces. However, at the time of this writing no volumetric display of which we are aware, meeting the above definition, has demonstrated self-occlusion.

1.1.1. *Examples* of volumetric displays include: helical and paddle swept volume displays, particle displays, plasma ball displays, active and passive grids, multilayer tensor displays.

1.1.2. Examples of displays which are *not volumetric* by this definition in their current configuration: Leia display Systems, iO2 technology (these would be light-field as ray bundles intersect in regions space not collocated with the modulated air). Volumetric display hardware may be used to create images which are not volumetric (i.e. abandon image point colocation with physical scatters) and lose the affordances of volumetric displays such as perfect accommodation (and, in so doing, may gain other affordances instead—such as greater control over view-angle content).

1.1.3. *Display advantages* include perfect accommodation and very low bandwidth requirements for sparse scenes.

1.1.4. *Display limitations* include the fundamental inability to display virtual images, display dependent bandwidth as well as challenging scanning requirements in most cases.

1.2. ***Holographic Display***—a holographic display is defined as a display for which the viewer can draw a straight line which intersects their eye, and image point and a region containing information encoded in spatial frequency such as in a Raman-Nath or volume (e.g. Bragg) grating. In volume holograms, including Denisyuk reflection holograms and Bragg gratings, volume reflection may also augment diffraction by providing color sensitivity (Denisyuk), angle sensitivity (Bragg) or diffraction efficiency (edge-lit). In order for a holographic display to be considered 'holographic video' or 'holovideo' it should be able to update its diffraction pattern quickly enough to make possible persistence of vision (e.g. greater than ten times a second).

1.2.1. Examples include displays based on diffraction from pixelated spatial light modulators. (Qinetiq, SeeReal) and scanned aperture acousto-optic displays (MIT Mar
as well as waveguide based diffractive displays.

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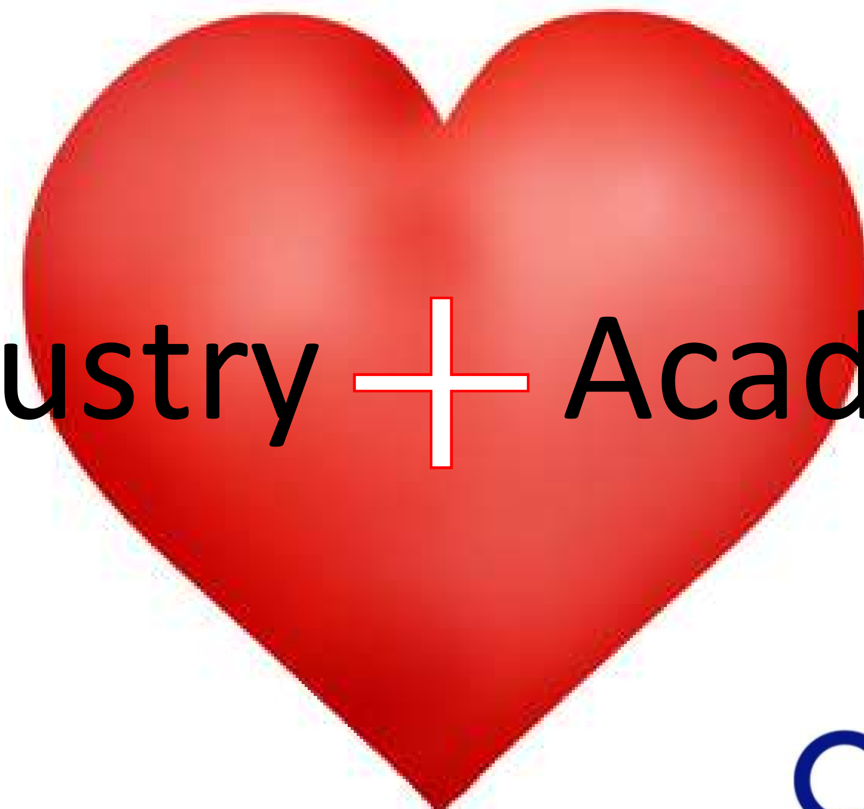
Next webinar, near valentines 2017…

Marriage Counseling for,



Industry + Academia

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Holographic vs. Lightfield Display Debate

Champions

Dr. Levent Onural

Dr. Gordon Wetzstein

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Display Technology (IT)

Holographic True-3D Displays: Basic Principles

Levent Onural

29 September 2016

Holographic True-3D Displays

True 3D:

- **Duplicates the physical volume-filling light**
- **Holography (Diffraction approach)**
- **Integral Imaging (Light field approach)**

Holographic True-3D Displays

- **We float in 3D (volume-filling) light - True**

•All optical receivers (human eye, cameras, animal eyes, insect eyes, etc.) float in time-varying volume-filling light.

•That volume-filling light originates from light sources, and then gets modulated by objects and scenery (carries their optical information)

Holographic True-3D Displays

- **We see objects and scenery around us - False**

  - We see only the light that enters through our pupils

  - Our visual system (including the brain) then processes and interprets that light

  - The same is true for any optical receiver

Holographic True-3D Displays

- **Holographic Goal:**

  -Capture the volume-filling time-varying light with all its “relevant” physical properties

  - Store or transmit it

  -Replay it at another place and maybe at another time

  - Thus a duplicate of the original volume-filling time-varying light distribution is obtained

  .

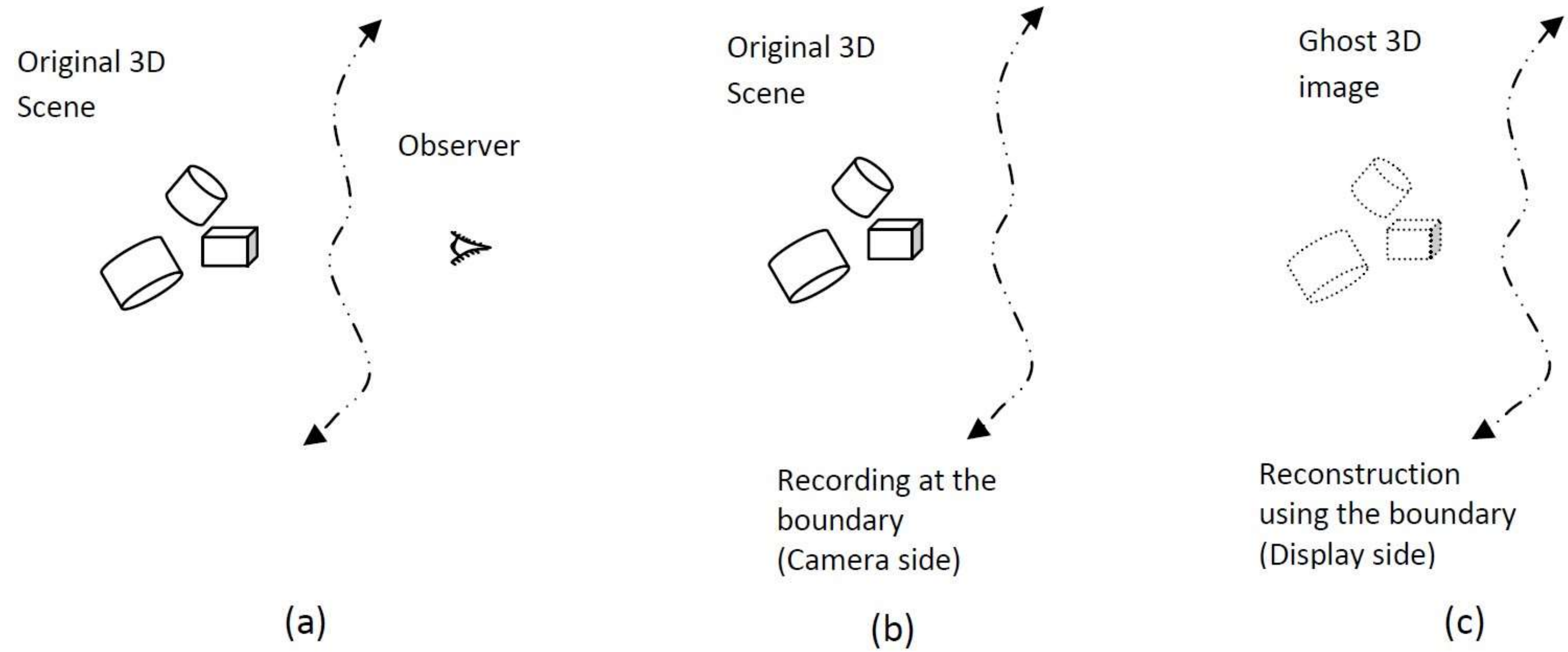
Holographic True-3D Displays

- **Holographic Goal:**

  -Any optical capture device (humans , for example) will get the exact duplicate of the original light as input

  -Since the input is the same as the original, any optical receiver floating in the duplicate field will see nothing but the indistinguishable duplicate of the original 3D time-varying scene.

Holographic True-3D Displays



Holographic True-3D Displays

- **What should be recorded?**
  - **Holography case:**

    -Propagating waves in 3D free space

    -A single 2D (over a surface) cross-section is sufficient for monochromatic case in free space

      -A complex-valued fringe pattern is needed to be captured

Holographic True-3D Displays

•Display side: write the complex-valued fringe pattern on the surface

- Illuminate it to diffract light by the fringe pattern to get the desired 3D field

Holographic True-3D Displays

- **“Light field” case - capture:**
  - Has the same goal to capture and reconstruct the time-varying volume filling light, as in holography : It is also a true 3D technique.
  - It is a valid mathematical model for true 3D:
    - -Represents the 3D field by rays
    - -If there is a collection of dense rays, their collection (superposition) forms the 3D field
    - -A capture of directional distribution of color and intensity at a 2D surface is sufficient for free space 3D light

Holographic True-3D Displays

- **“Light field” case - display:**
  - If the same directional distribution of color and intensity of rays is physically genenrated at the display side, the duplicate volume-filling time-varying field is recreated -> the goal is achieved
  - The problem is :
    - Light does not travel in the form of rays
      - This is a physical constraint

Holographic True-3D Displays

- **“Light field” case - display:**
  - Therefore, light-field representation of light is a good mathematical model, but such a physical display cannot be built
    - Uncertainty principle
    - Point source (small size) -> Spherical radiation
    - Directional radiation -> Large display patch
    - Extreme directional radiation (ray) -> Infinite display patch

Holographic True-3D Displays

- **“Light field" case - display:**

  - Only approximate physical devices are possible
  - For example, integral imaging -> Lenslet arrays
    - Requires perfect focused capture of “elementary images”

Holographic True-3D Displays

- **3D volume-filling light can have infinitely many different mathematical descriptions:**
  - 3D basis functions, their weighted superposition
    - (Terminology: psi(**x**) = 3D light field, **x** is the 3D position vector, psi() has complex values. Therefore, light field does not necessarily refer to ray decomposition, as in this discussion; rather it is a general term.)
    - One of the basis function sets is the set of line impulses in 3D space -> rays -> the "light field"

Holographic True-3D Displays

- **3D volume-filling light can have infinitely many different mathematical descriptions:**
  - Other common decompositions are:
    - Plane wave decomposition (idealization: assume infinite plane wave size)
    - Local Gaussian beam (a form of wavelet) decomposition
      - This is actually the physical counterpart of “light fields”: basis functions are directional physical beams (expanding as they propagate)

Holographic True-3D Displays

- **Local Gaussian beam decomposition:**
  - Local equivalent “patches” on a 2D surface
  - Local 2D frequency = local direction
  - Superpose using weights = local directional distribution NOT of idealized rays, but of physical beam shapes

Holographic True-3D Displays

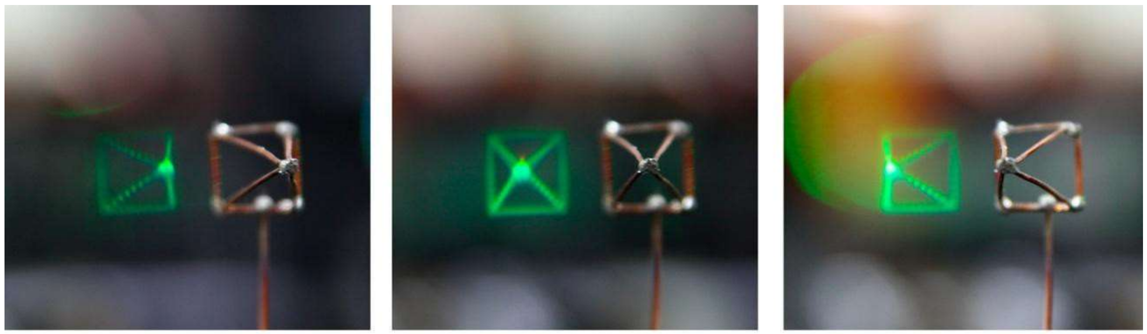
- **Holographic Displays:**
  - Easy to generate 2D diffracting grids for each 3D basis function
  - Easy to superpose 2D patterns, to get a superposition of 3D light components
  - No optics (lenses, mirrors, etc.) are needed for the basic principle
  - Many lab prototypes exist

Holographic True-3D Displays

- **Holographic Display problems are:**
  - •If ordinary pixels are utilized and a planar surface is utilized (currently the common case), too many pixels are needed -> A commercially acceptable quality maybe needs 64K by 64K pixels
  - •Complex valued pixels are not as easy to get as amplitude only or phase only cases

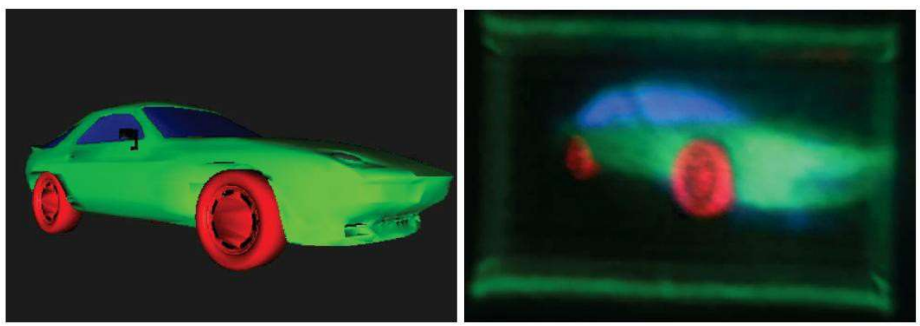
Real 3D

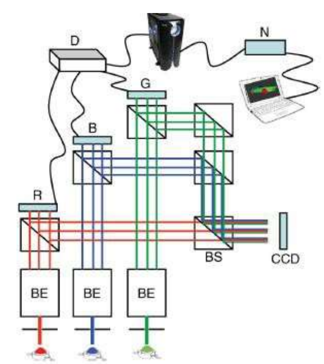
Some holographic display results from Bilkent Univ.



(a) (b) (c)

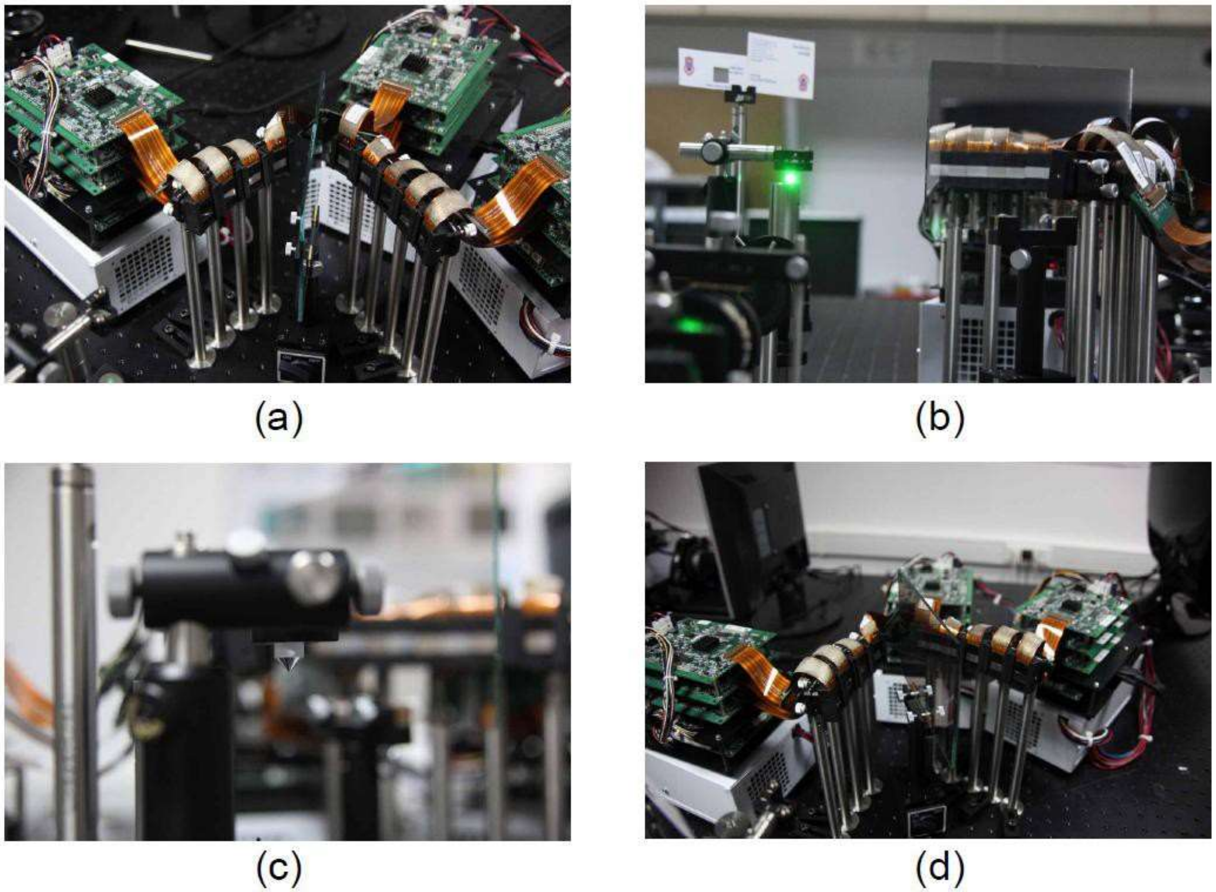
L. Onural, F. Yaraş and H. Kang, "Digital Holographic Three-Dimensional Video Displays", *Proc. of the IEEE*, vol 99, no 4, pp 576-589, Apr 2011.





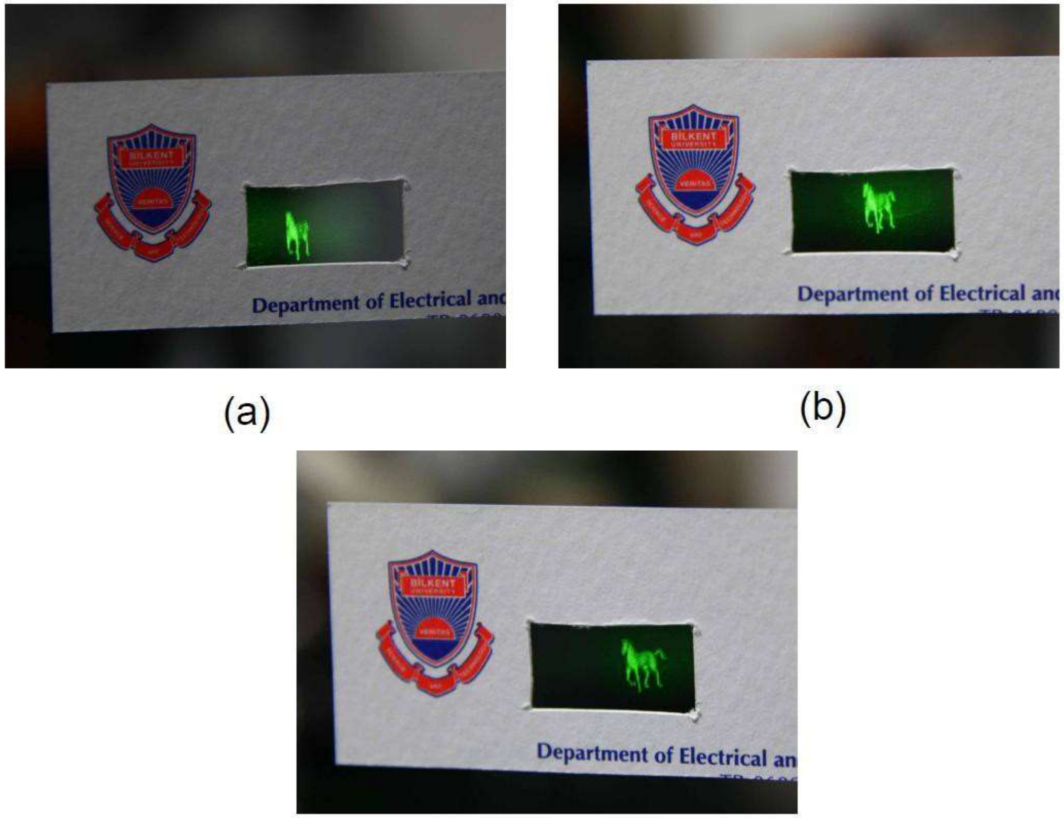
F. Yaraş, H. Kang and L. Onural, "Real-Time Phase-Only Color Holographic Display System Using LED Illumination", *Applied Optics*, vol 48, no 34, pp H48-H53, December 2009.

Real 3D Project



L. Onural, F. Yaraş and H. Kang, "Digital Holographic Three-Dimensional Video Displays",*Proc. of the IEEE*, vol 99, no 4, pp 576-589, Apr 2011.

Real 3D Project



(a) (b) (c)

L. Onural, F. Yaraş and H. Kang, "Digital Holographic Three-Dimensional Video Displays", *Proc. of the IEEE*, vol 99, no 4, pp 576-589, Apr 2011.

Holographic Input - Integral Imaging Display

Figure 11

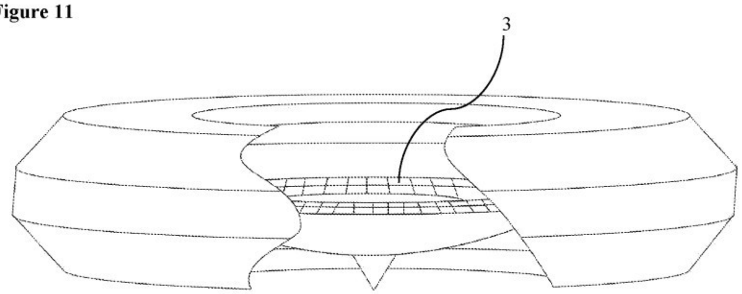


Figure 12

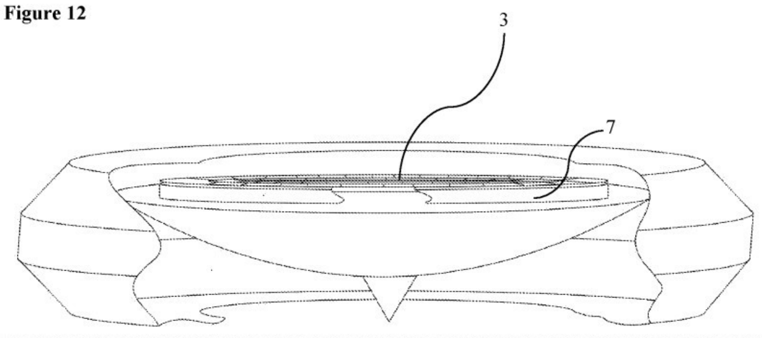
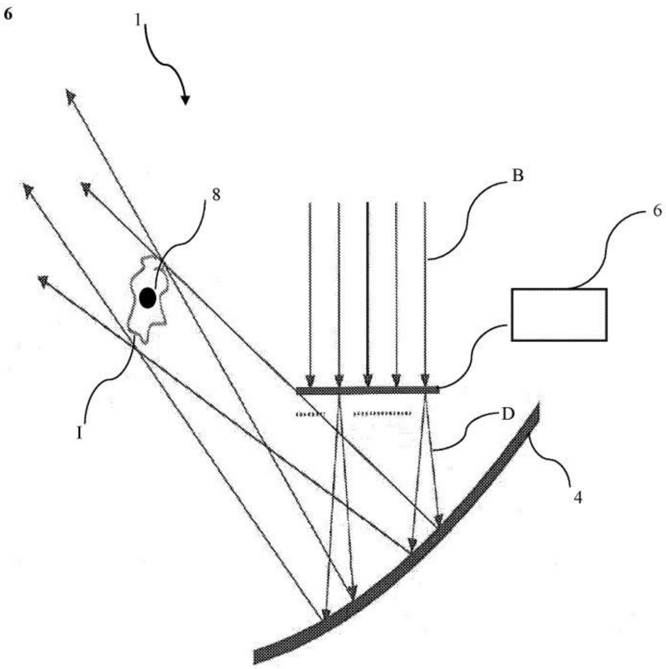


Figure 6



A recently filed patent application by Levent Onural
for a 360 degree view holographic display

Signal Processing Issues

Vol. 29, No. 7 / July 2012 / J. Opt. Soc. Am. A 1459

Scalar diffraction field calculation from curved surfaces via Gaussian beam decomposition

Erdem Şahin* and Levent Onural

Signal Processing Issues

2310 J. Opt. Soc. Am. A / Vol. 28, No. 11 / November 2011 Ulusoy *et al.*

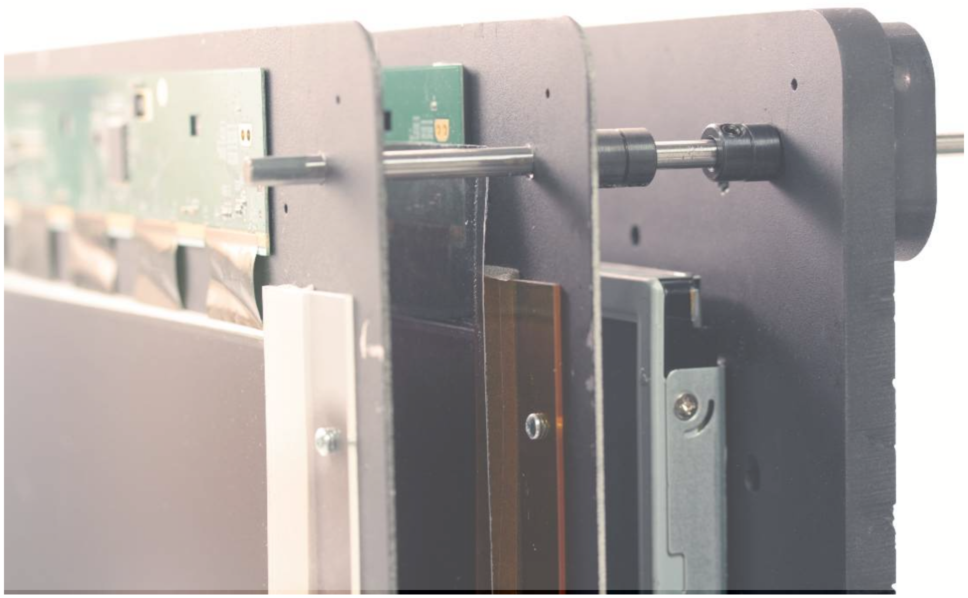
Full-complex amplitude modulation with binary spatial light modulators

Erdem Ulusoy,* Levent Onural, and Haldun M. Ozaktas

Department of Electrical and Electronics Engineering, Bilkent University, TR 06800 Bilkent, Ankara, Turkey
**Corresponding author: eulusoy@bilkent.edu.tr*

Light Fields

Cameras, Displays, and Applications



Gordon Wetzstein

Stanford University, EE & CS

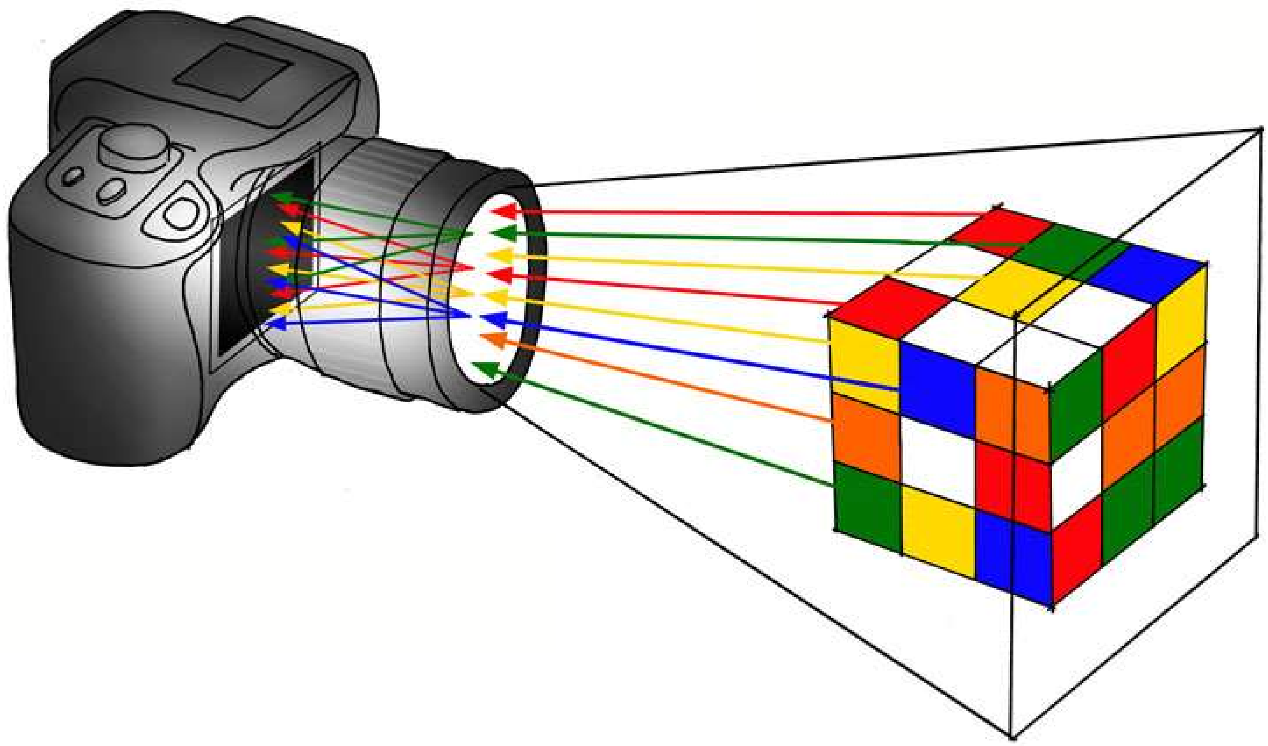
www.computationalimaging.org

September 29, 2016

OSA Light Field v Hologram Debate

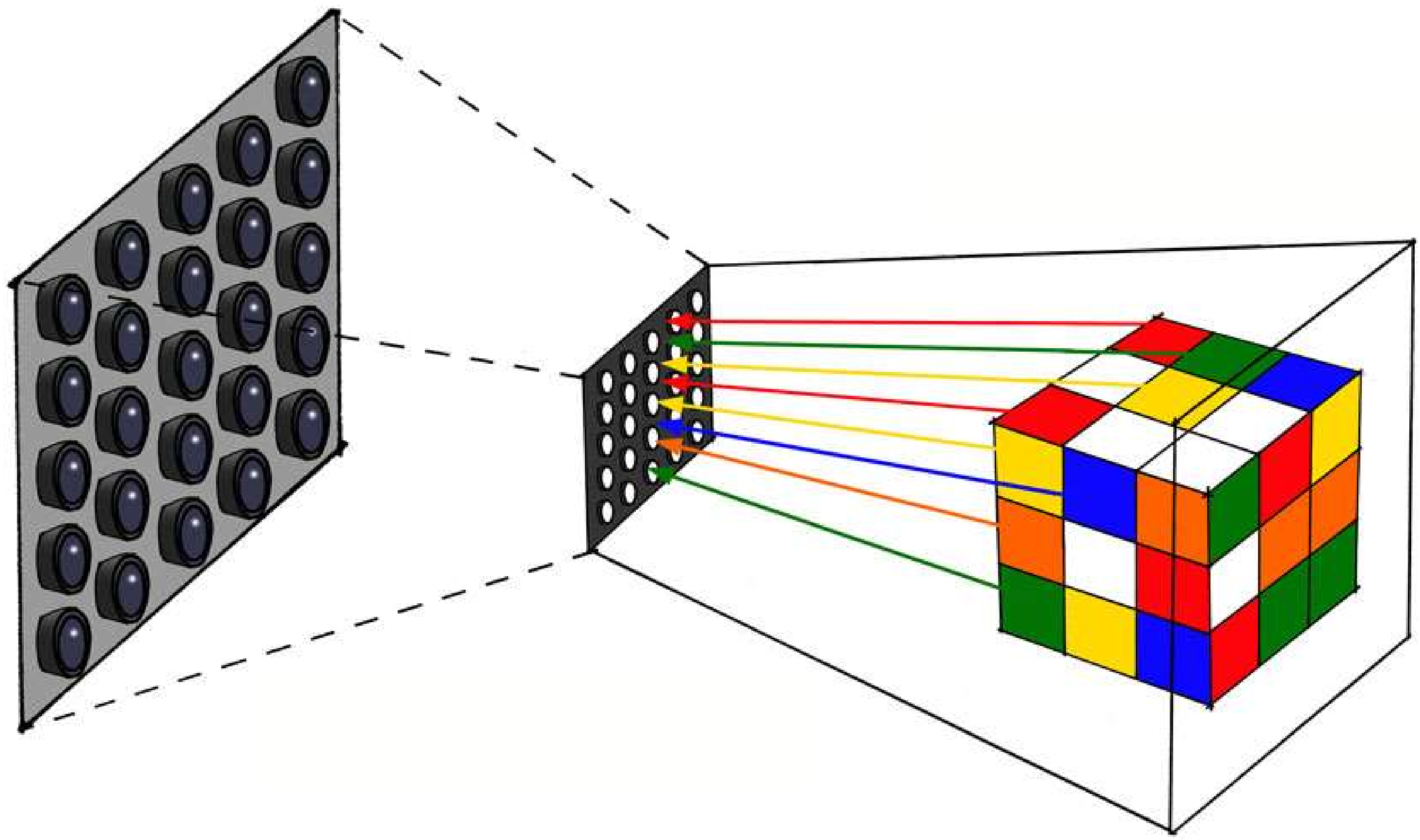
SCI STANFORD COMPUTATIONAL IMAGING

Light Field Camera



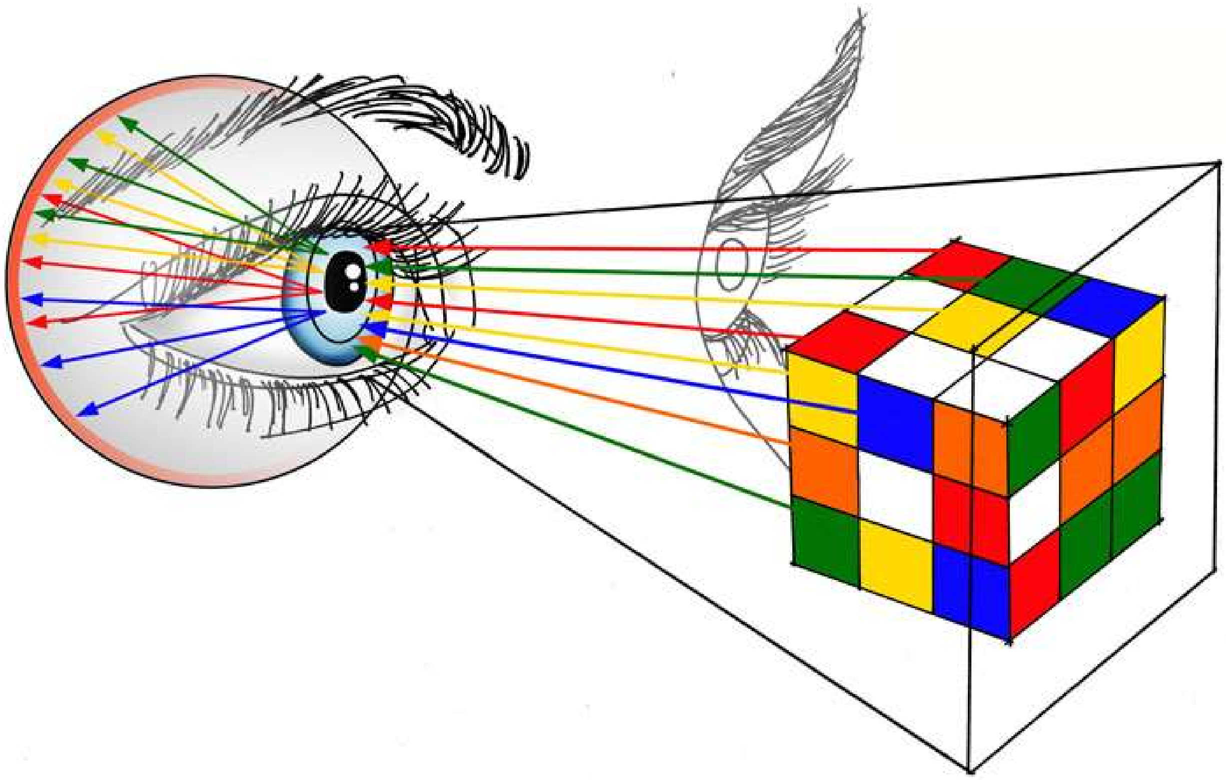
Primary applications: 3D imaging, refocus

Light Field Camera Array



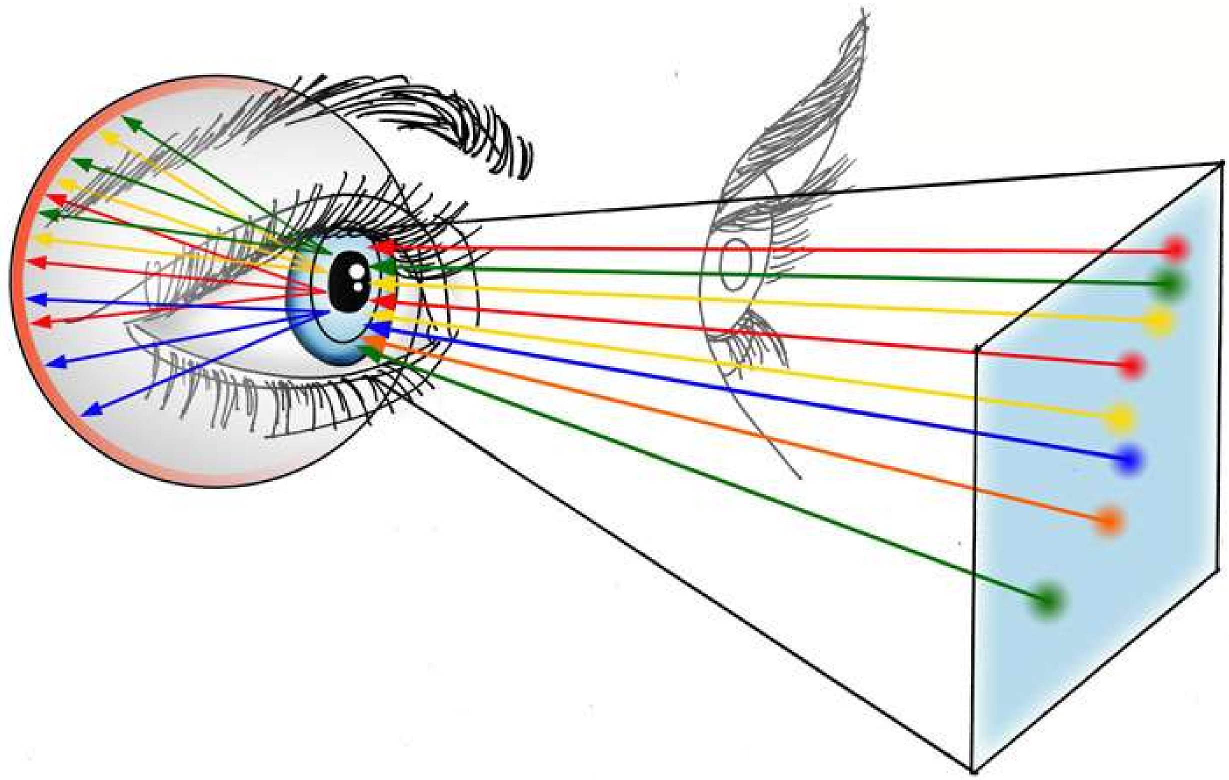
Primary applications: cinematic VR, 3D imaging, refocus

The Observed Light Field



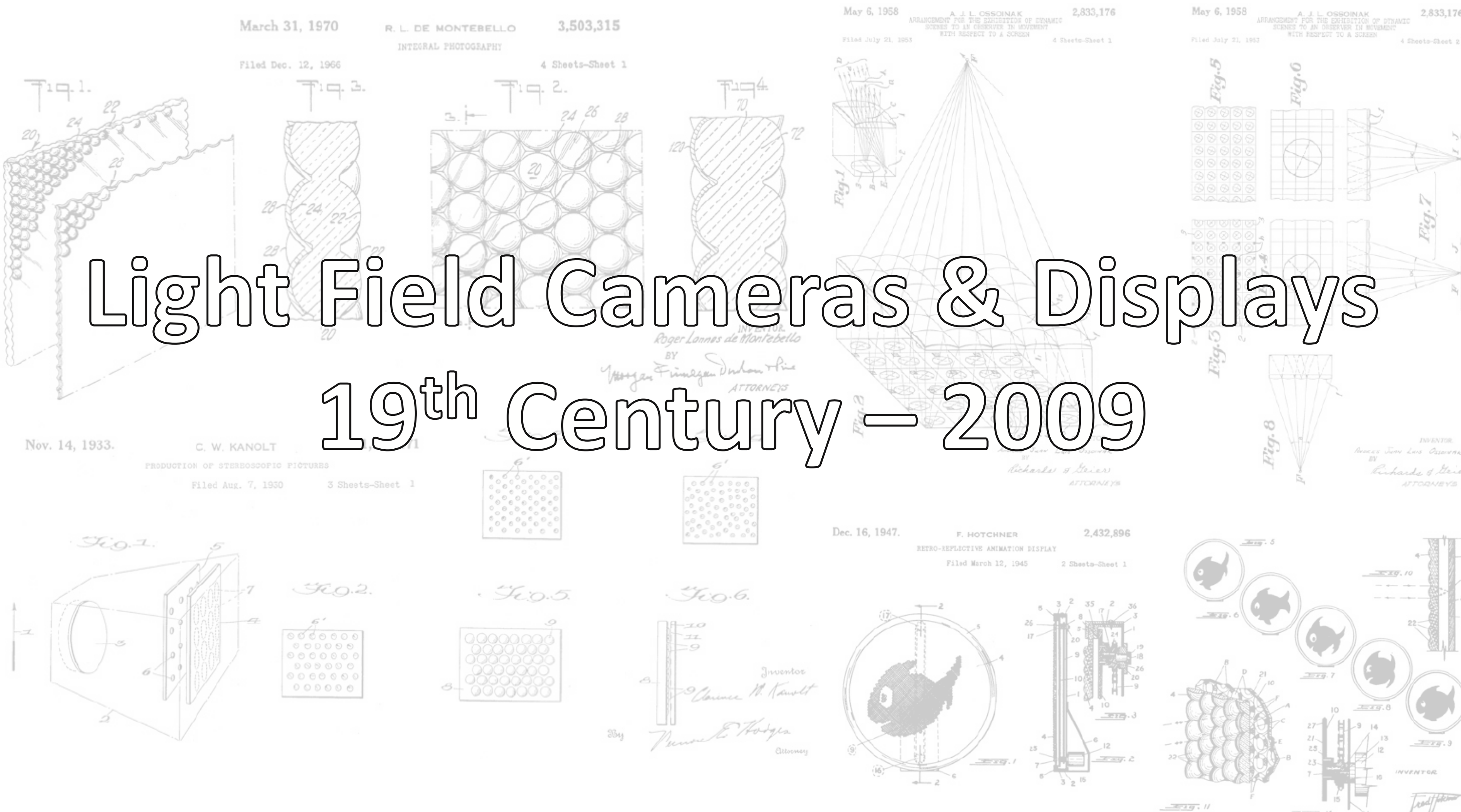
Primary applications: glasses-free 3D, focus cues for VR/AR, vision correction

The Observed Light Field

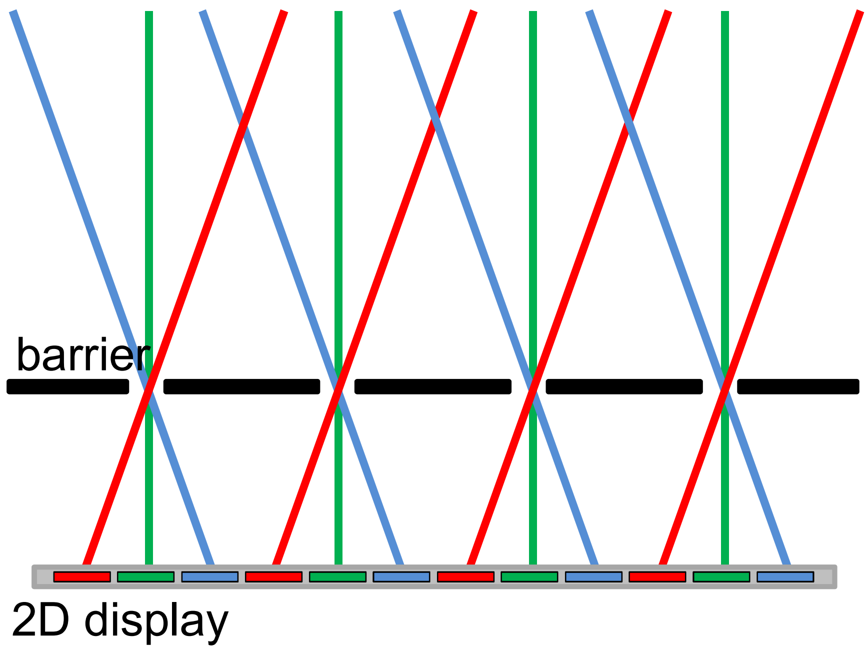


Primary applications: glasses-free 3D, focus cues for VR/AR, vision correction

Light Field Cameras & Displays
19th Century – 2009

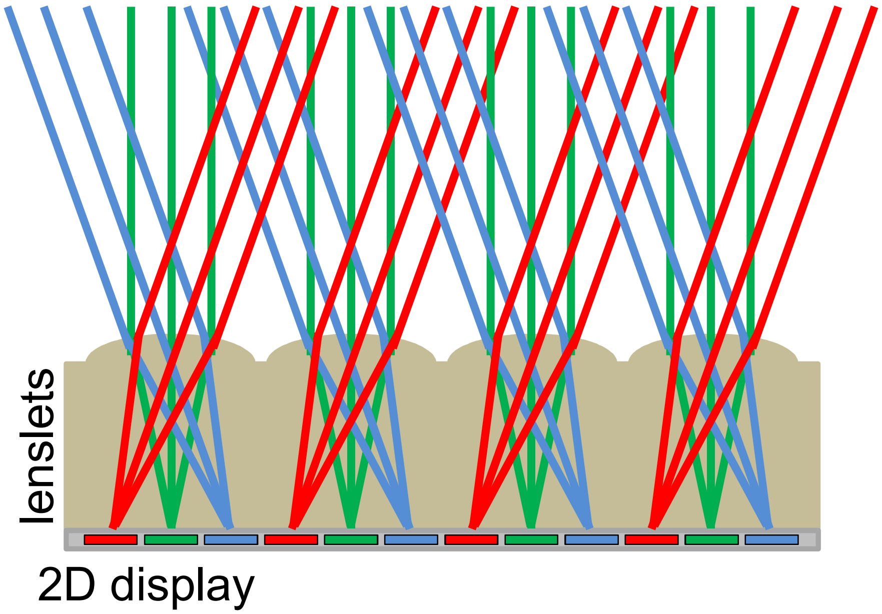


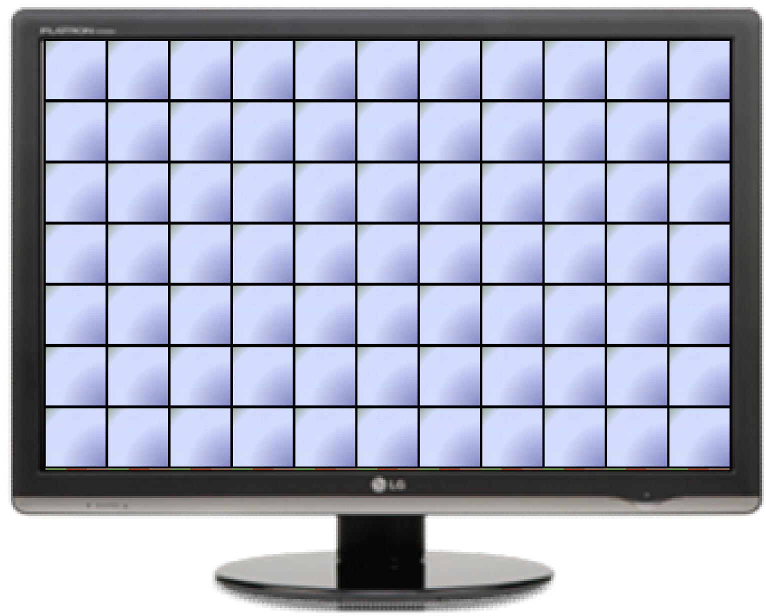
Parallax Barriers – Ives 1903



- low resolution & very dim

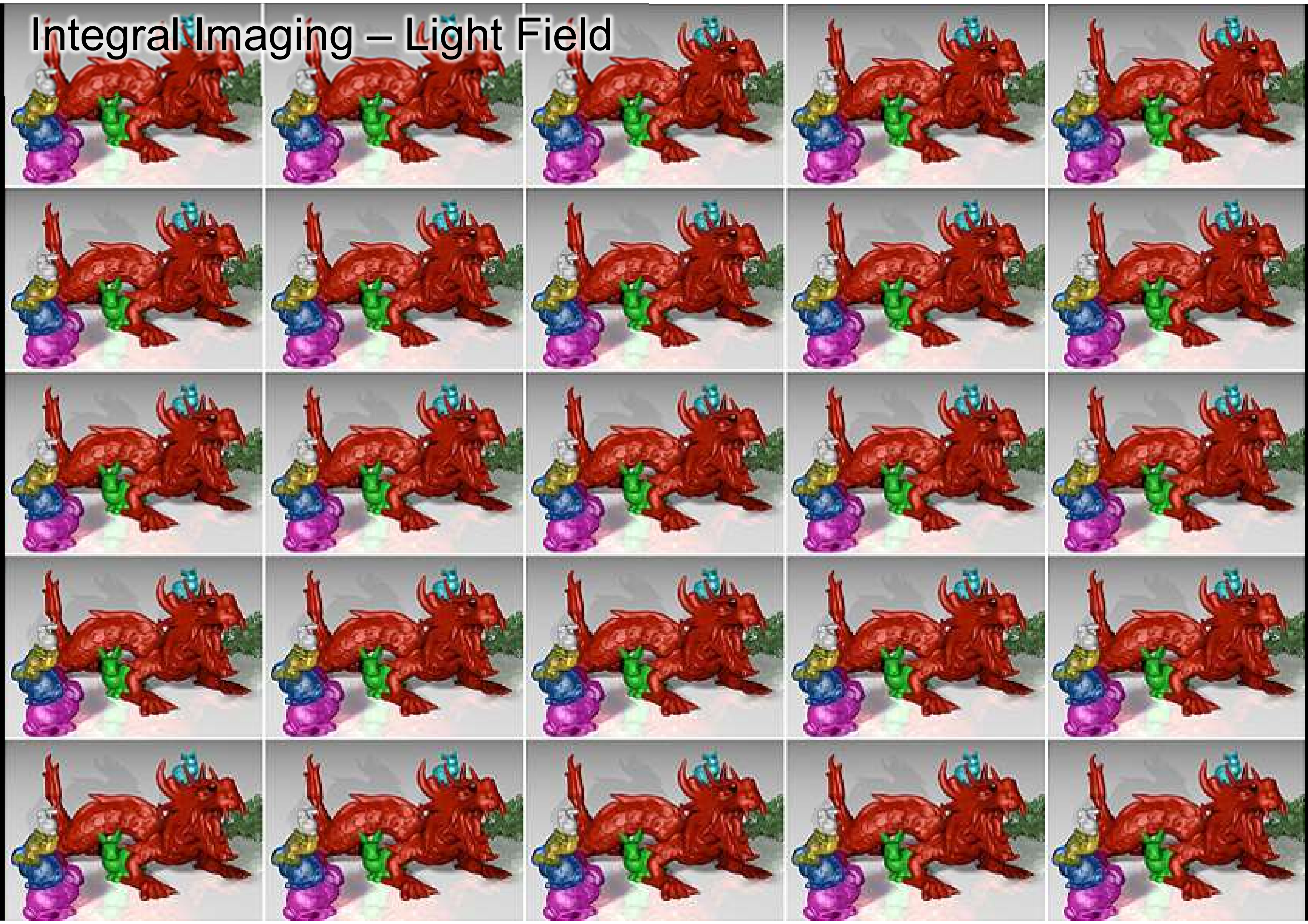
Integral Imaging – Lippmann 1908



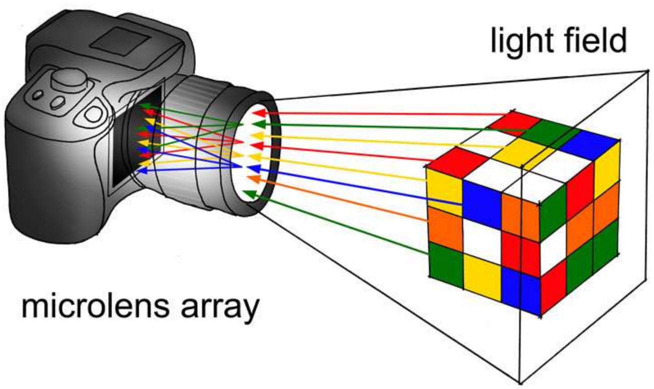


- low-res, but brighter than parallax barriers
- epreuves reversibles ≈ reversible photographs

Integral Imaging – Light Field

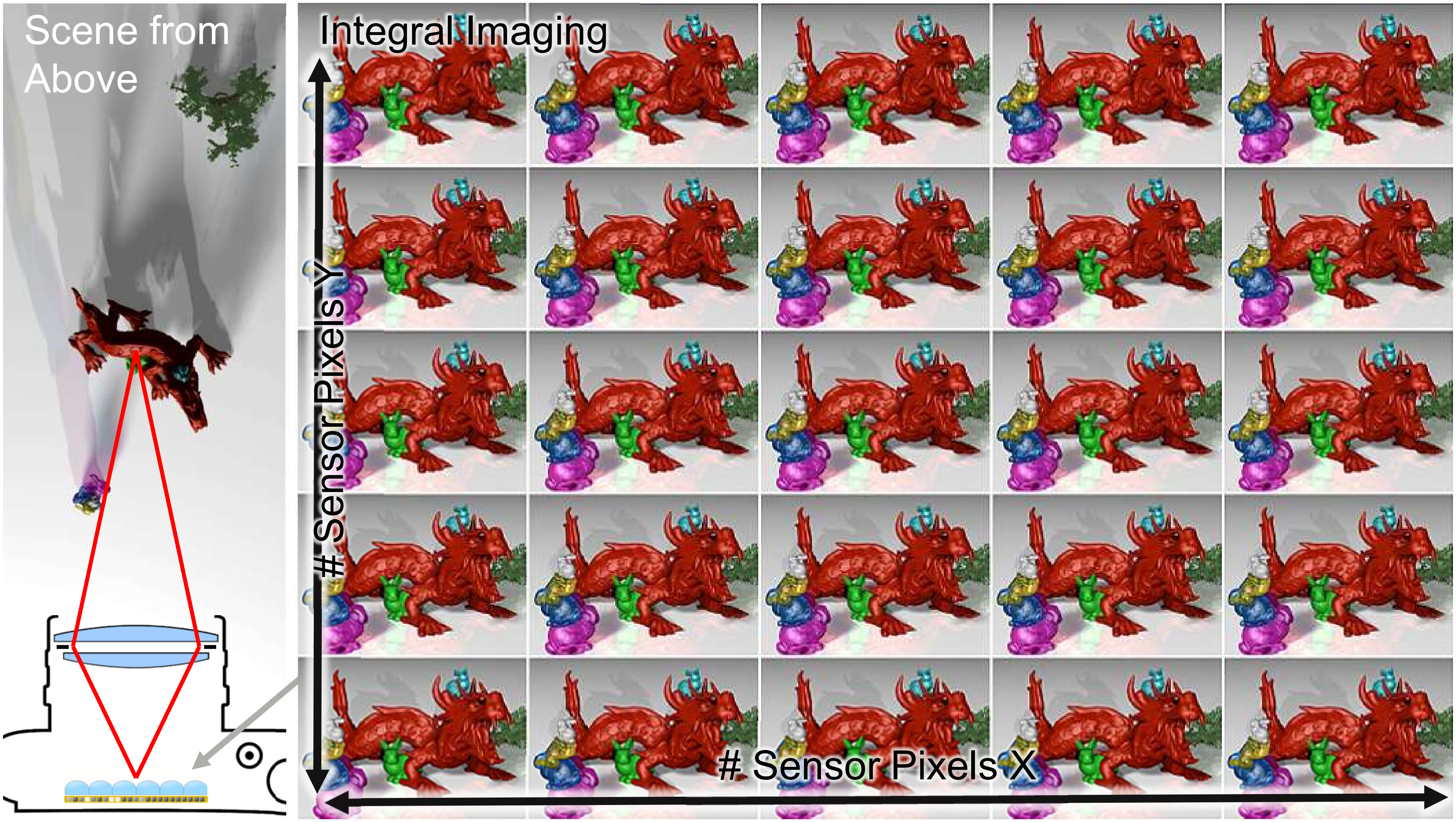


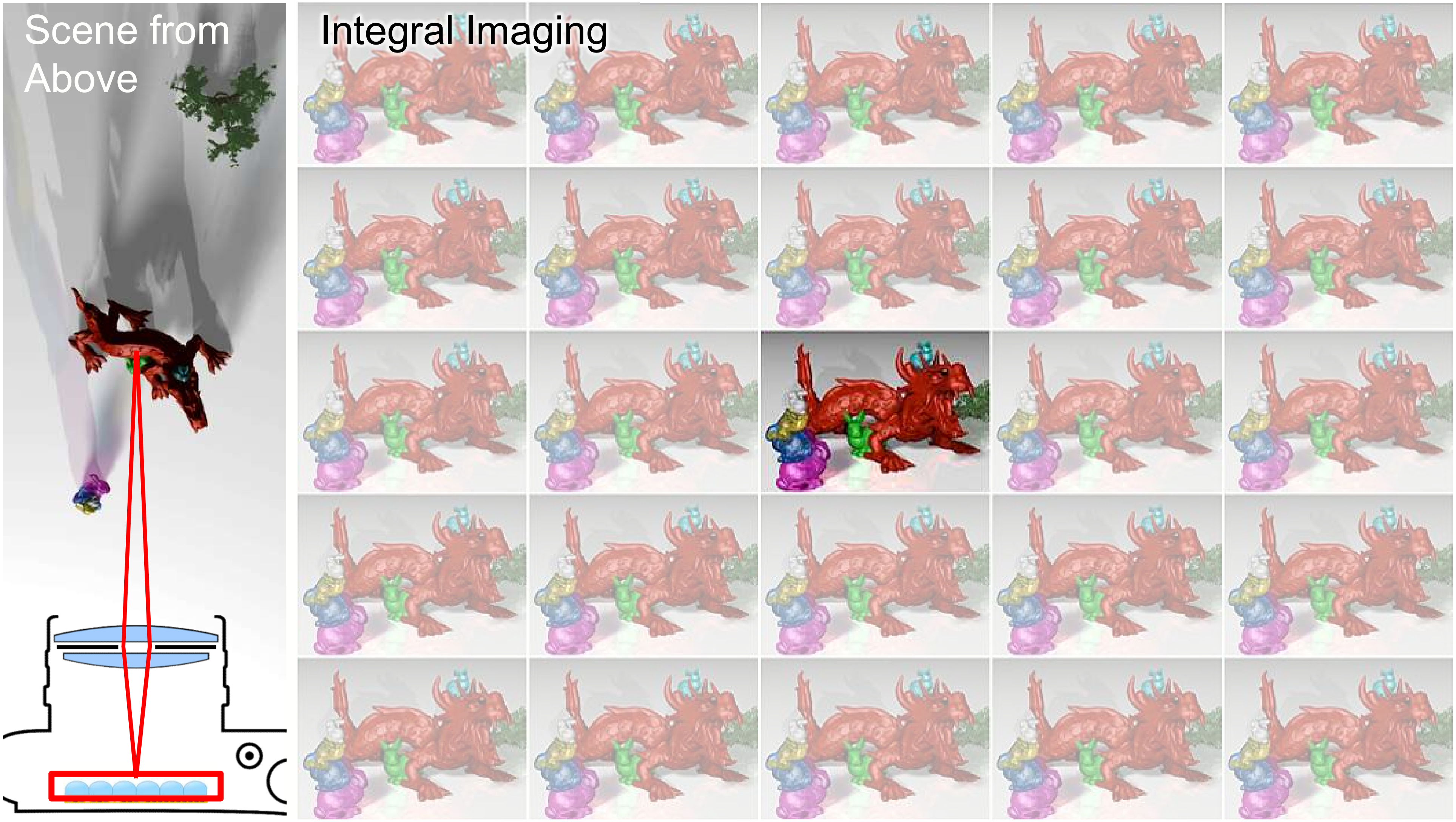

Integral Imaging – Microlens Image
Pixels Y / # Views Y
Pixels X / # Views X



Light Field Imaging


LYTRO

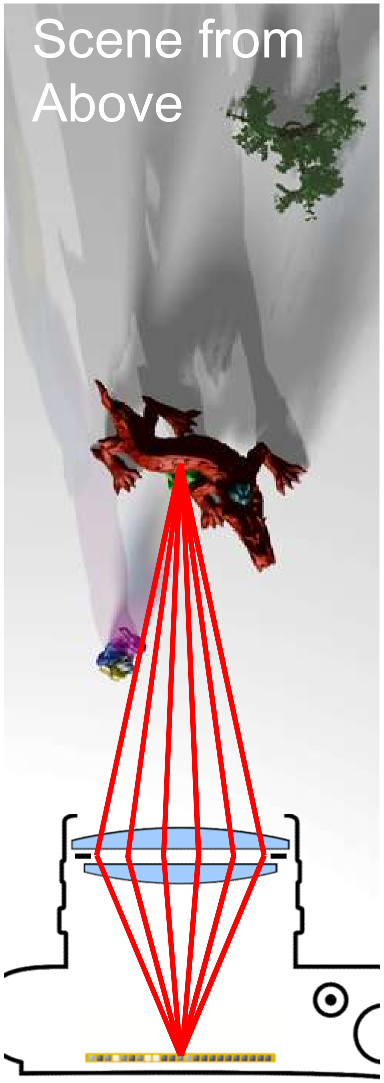

Scene from Above
Integral Imaging
Sensor Pixels Y
Sensor Pixels X



Scene from Above
Integral Imaging

Scene from Above
Integral Imaging: Spatio-Angular Resolution Tradeoff!
Sensor Pixels Y / # Views Y
Sensor Pixels X / # Views X
How to overcome resolution tradeoff?

Key Insight: Light Field is Redundant!



Compressive Light Field Photography

ACM SIGGRAPH 2013

Exploit Redundancy Computationally

Sparse Reconstruction

Sparse Representation

Overcomplete Dictionaries
Light Field Atoms

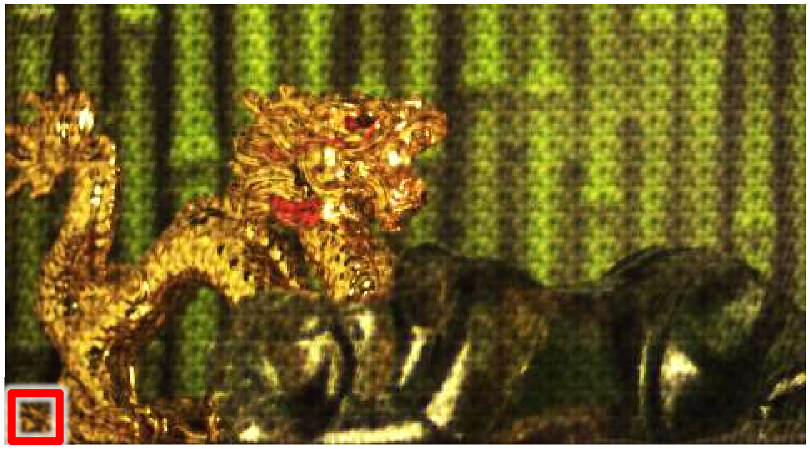
Optimal Optical Setup

Mask-based
Light Field Coding

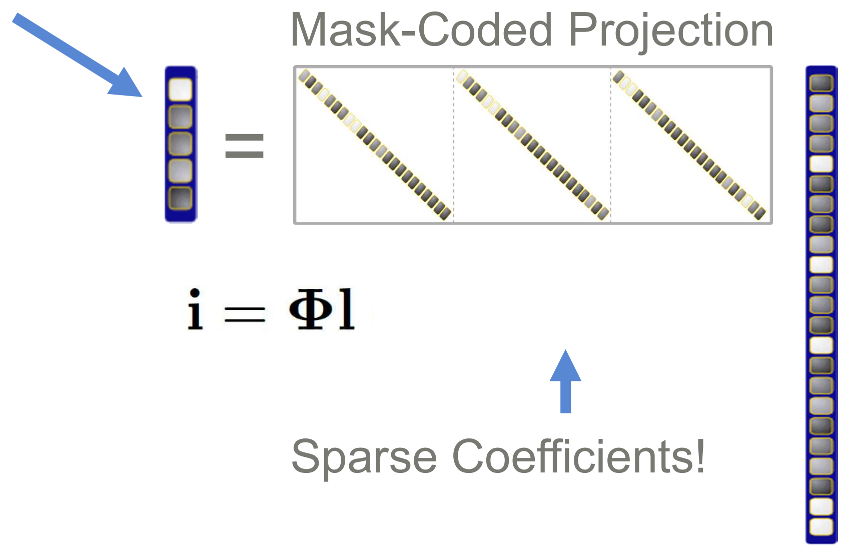
Compressive Light Field Photography

ACM SIGGRAPH 2013

Captured 2D Image



4D Reconstruction



$$\mathbf{i} = \mathbf{\Phi}\mathbf{l}$$

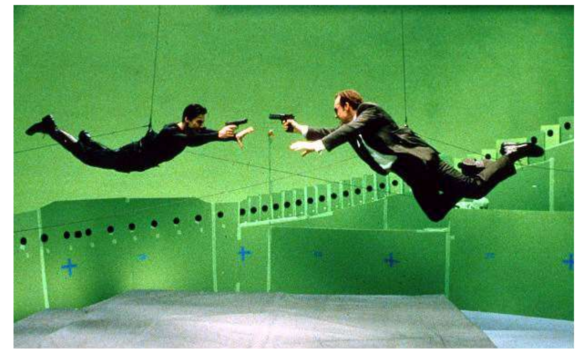
Basis Pursuit Denoise:

$$\begin{aligned} \underset{\{\alpha\}}{\text{minimize}} \quad & \|\boldsymbol{\alpha}\|_1 \\ \text{subject to} \quad & \|\mathbf{i} - \mathbf{\Phi}\boldsymbol{\mathcal{D}}\boldsymbol{\alpha}\|_2 \leq \epsilon \end{aligned}$$

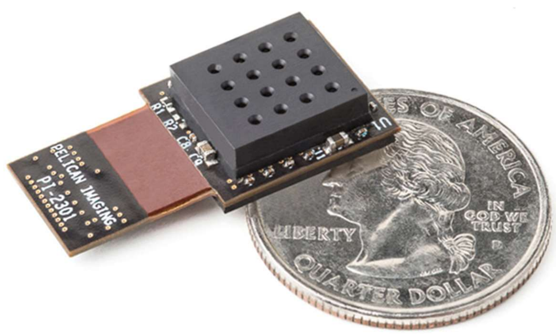
Multi-camera Light Field Imaging

light.co

stanford camera array



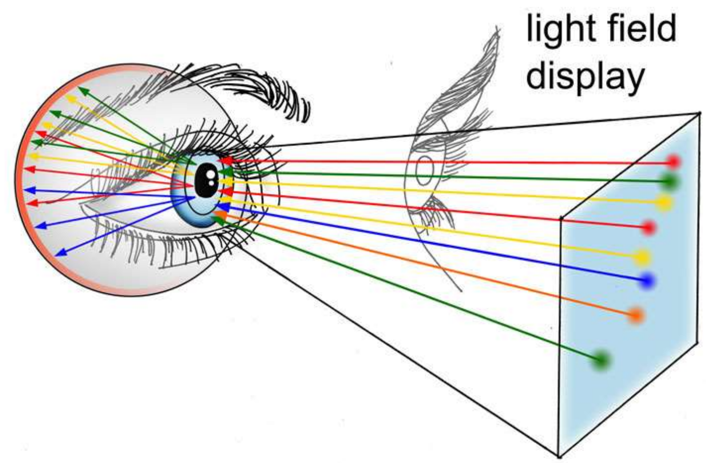
the matrix



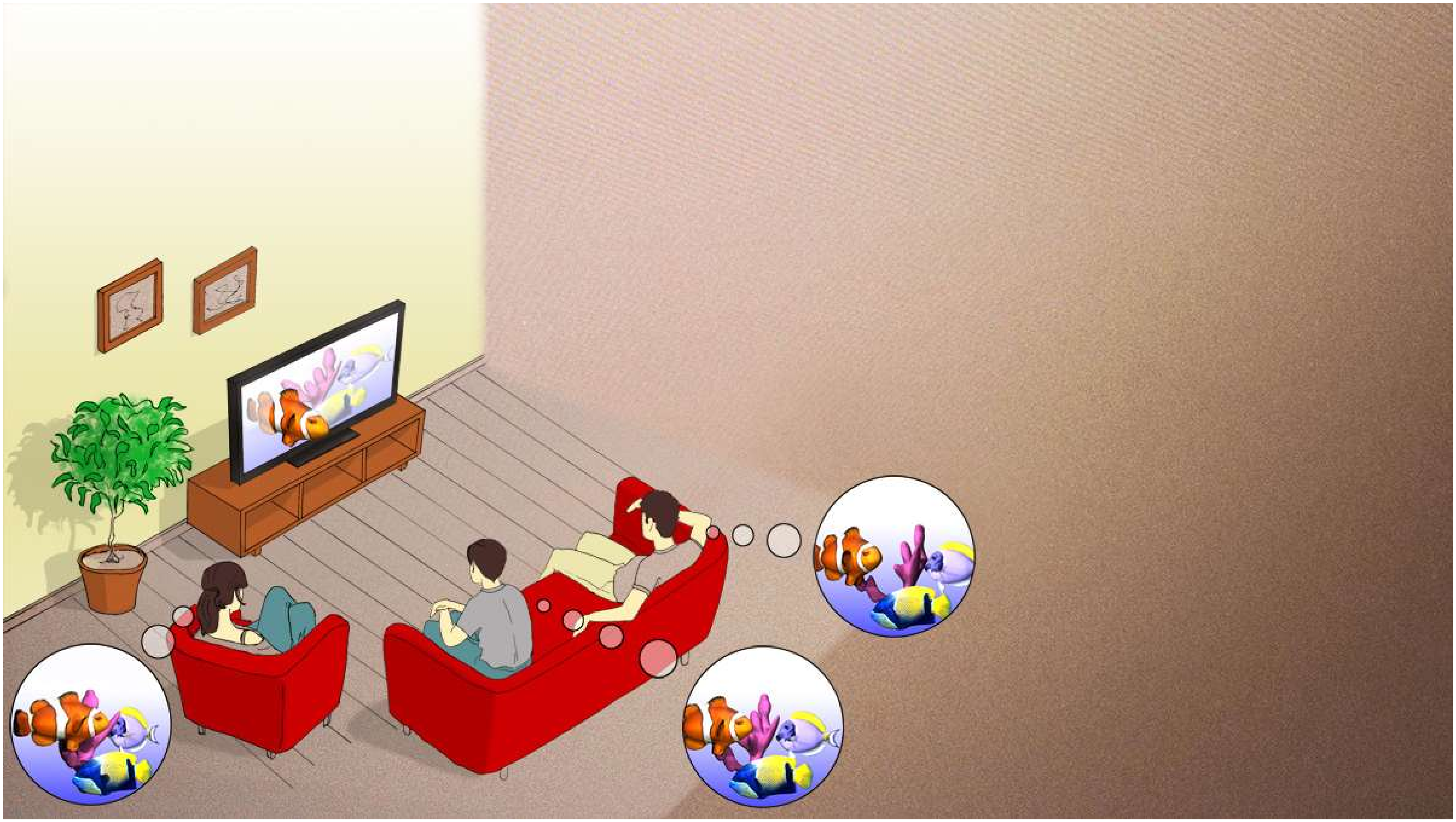
pelican imaging

facebook 360

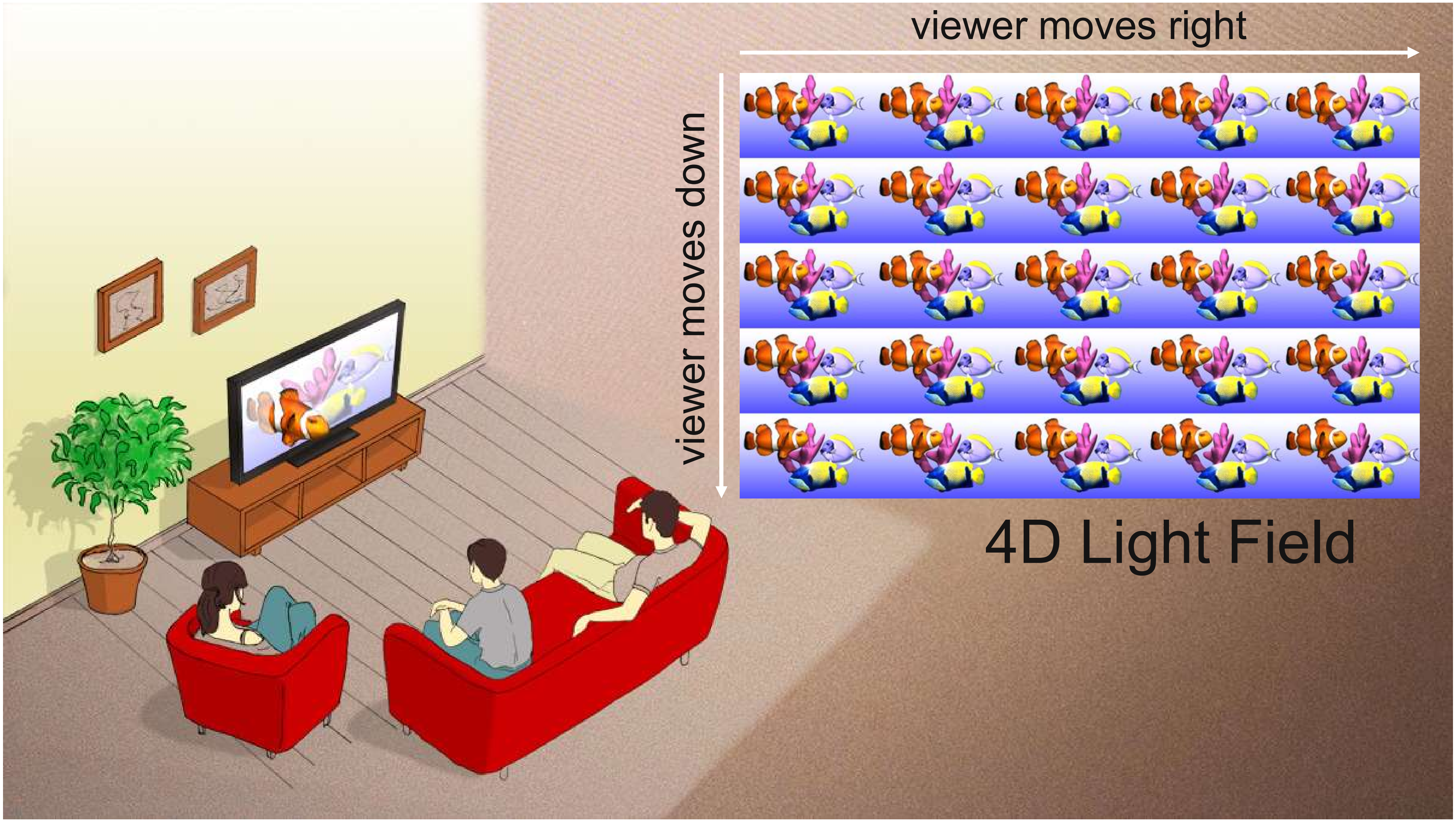
google jump



Light Field Displays



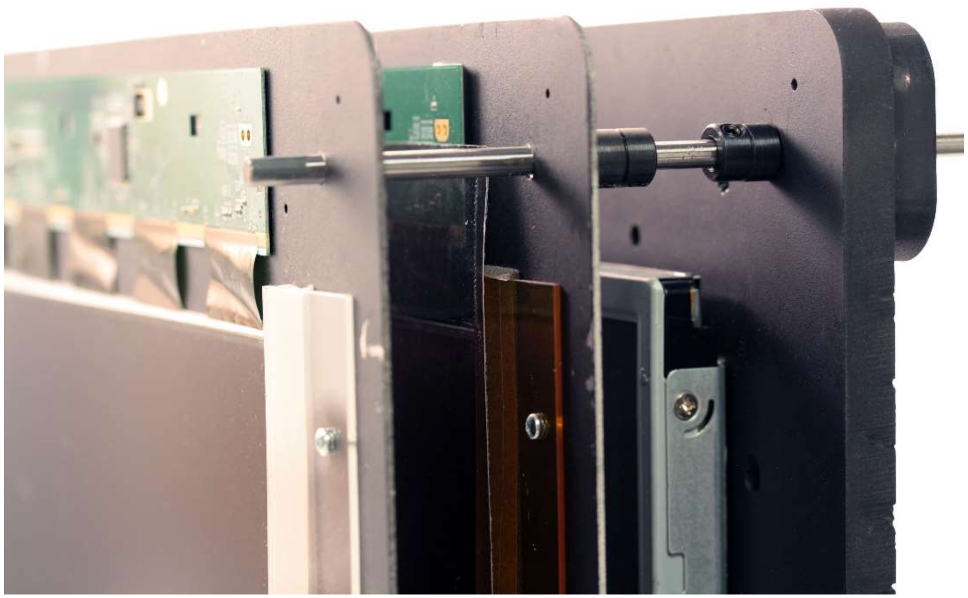
4D Light Field



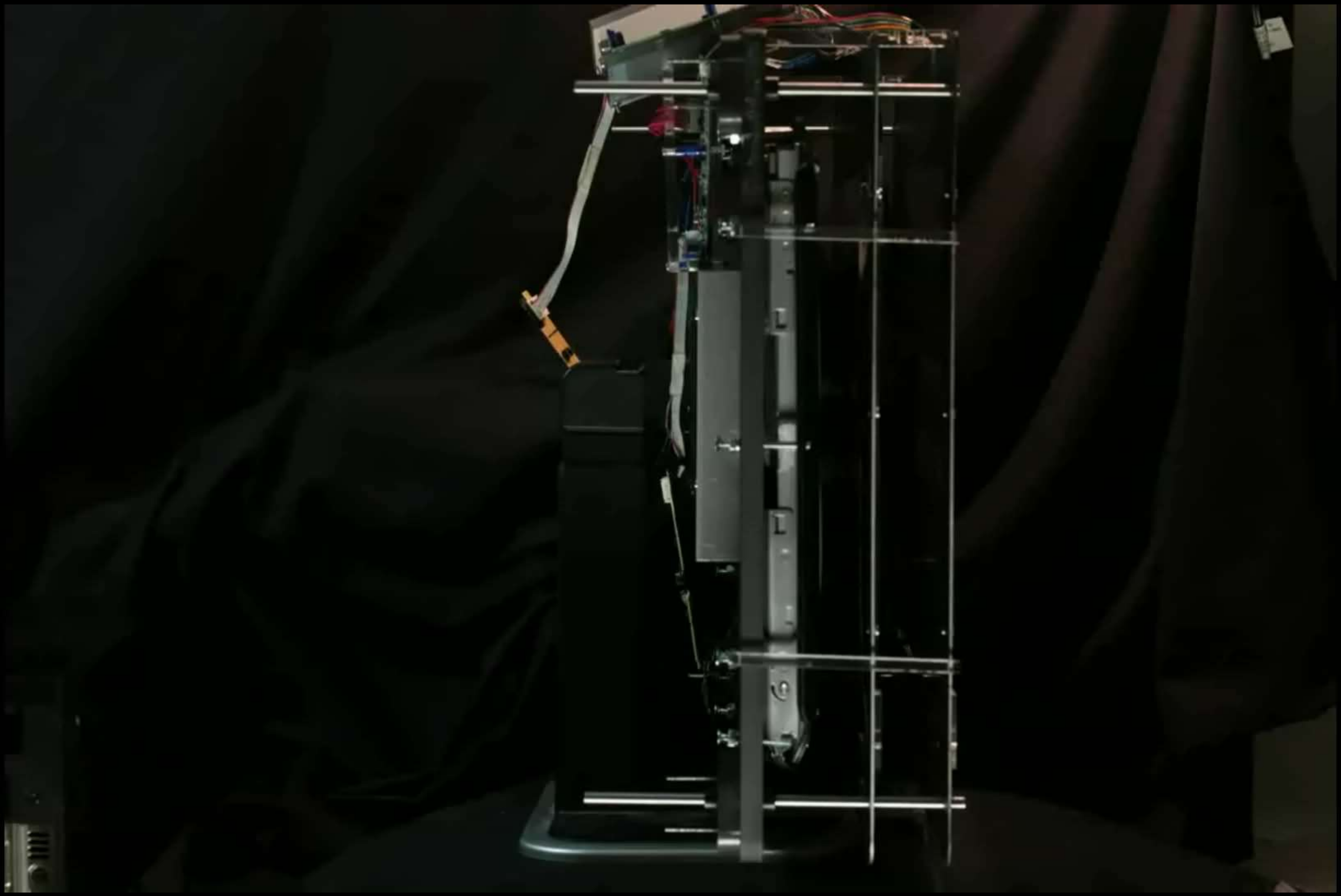
viewer moves right
viewer moves down
4D Light Field

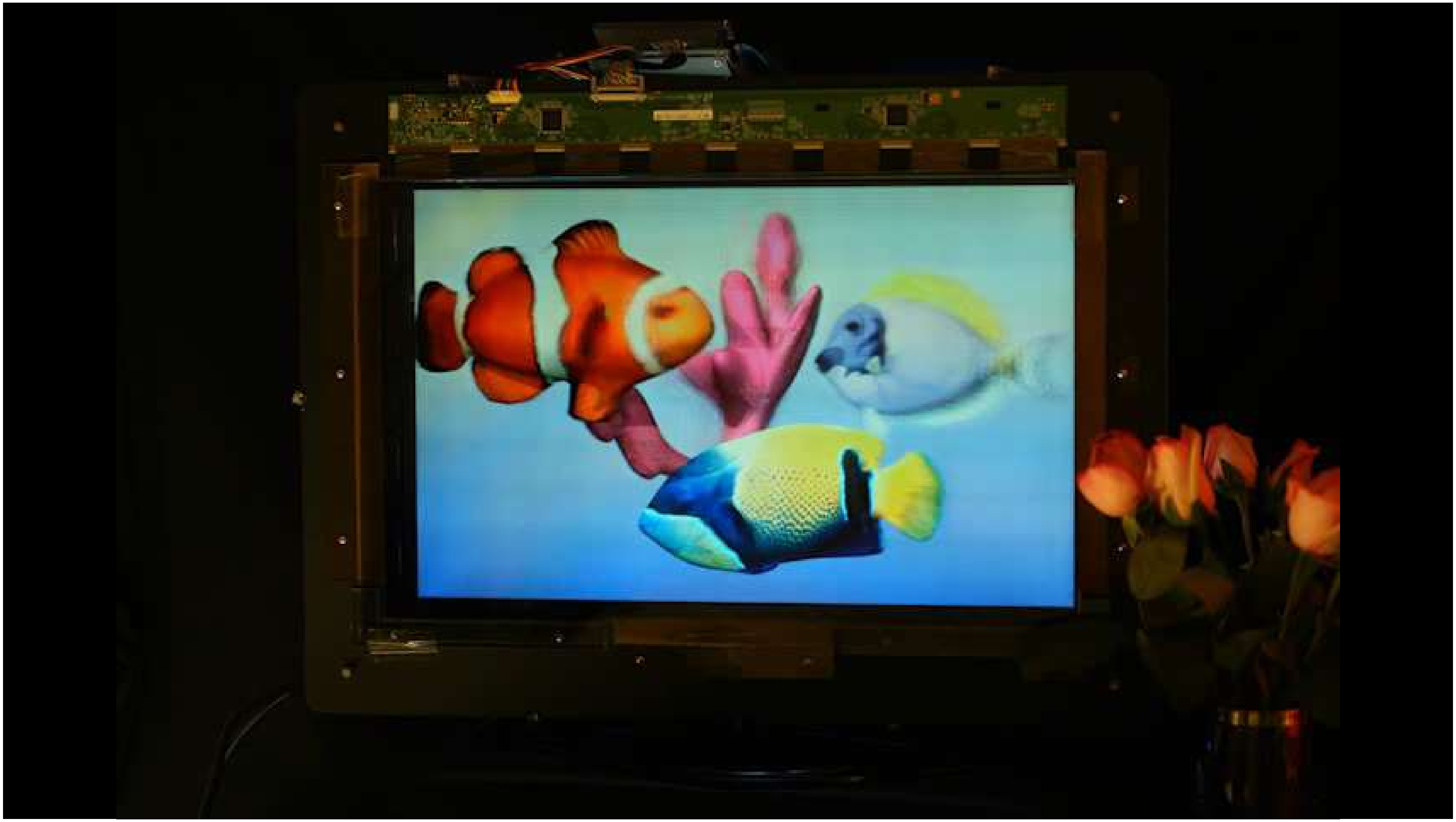
Three-layer Tensor Display

SIGGRAPH 2012, with D. Lanman, M. Hirsch, R. Raskar



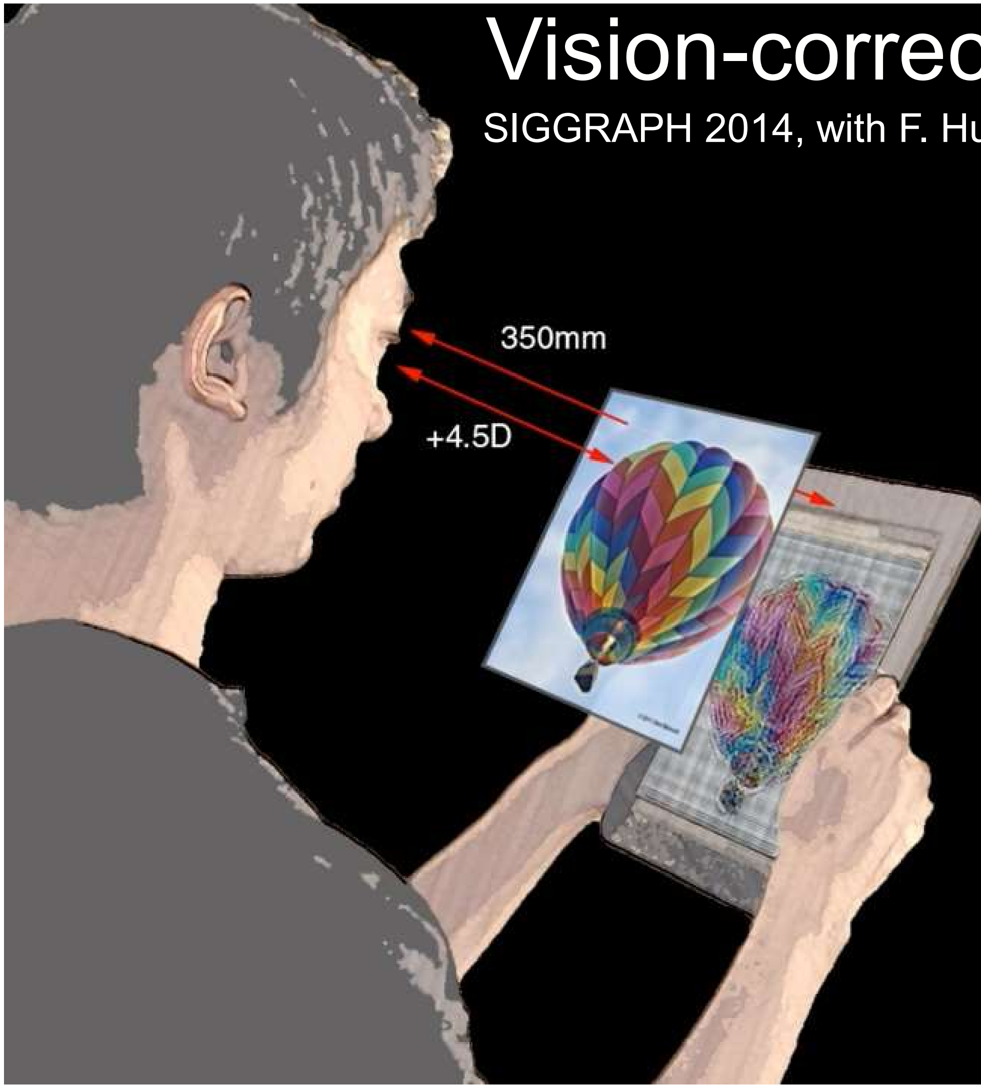
Three Layer Prototype





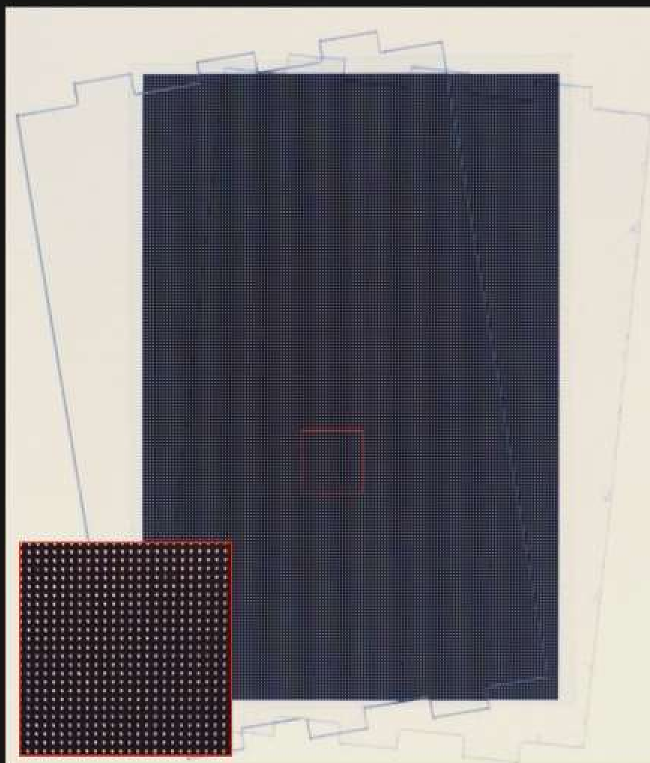
Vision-correcting Display

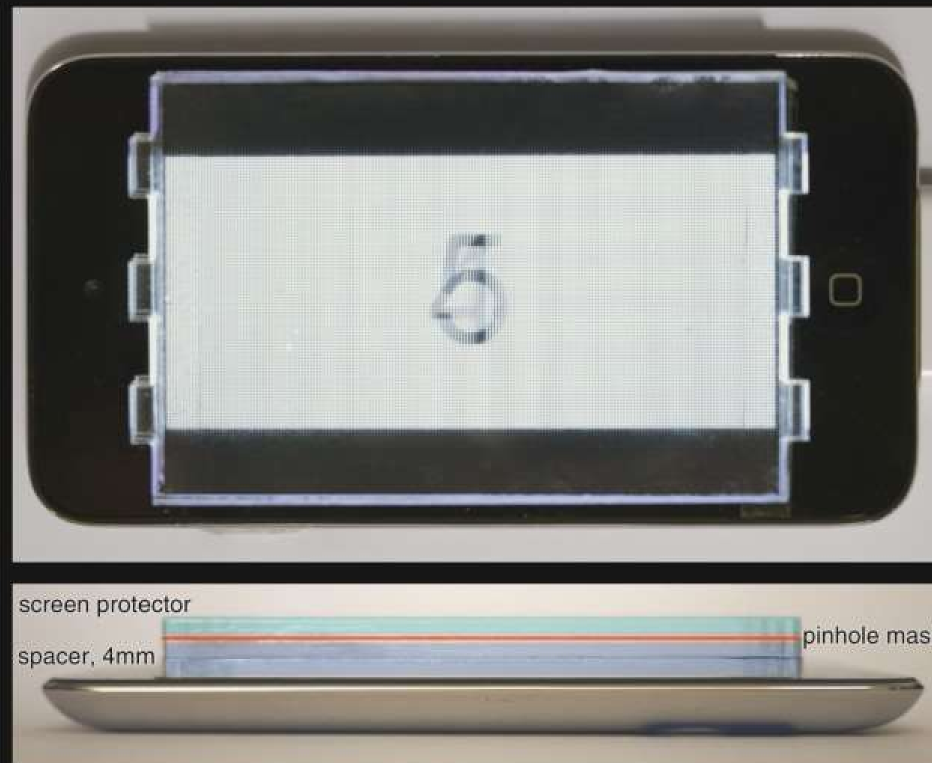
SIGGRAPH 2014, with F. Huang, B. Barsky (UC Berkeley)



Vision-correcting Display

SIGGRAPH 2014, with F. Huang, B. Barsky (UC Berkeley)





printed

iPod Touch

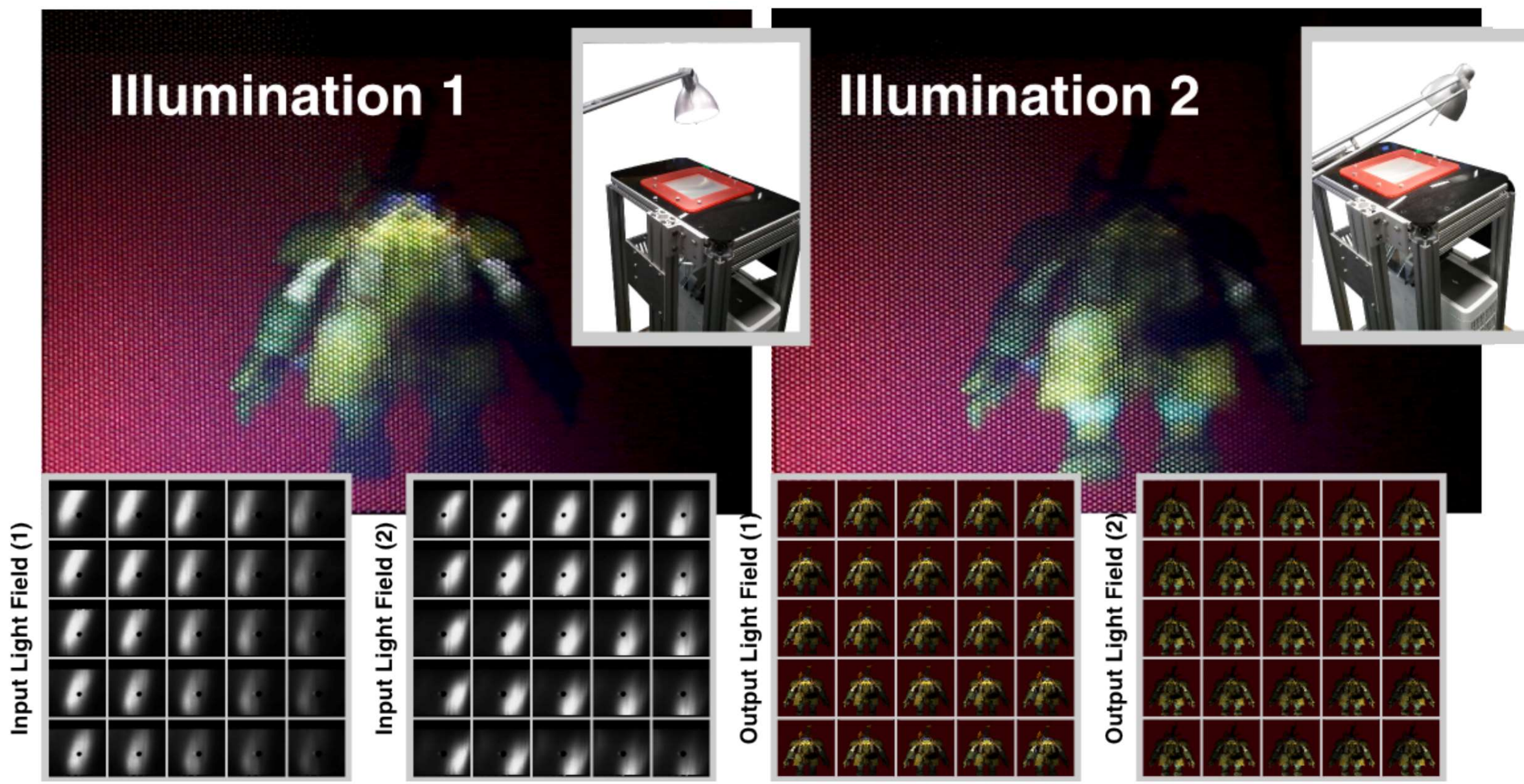
prototype construction

300 dpi or higher

conventional vision-correcting

8D Display

Hirsch et al., SIGCHI 2013

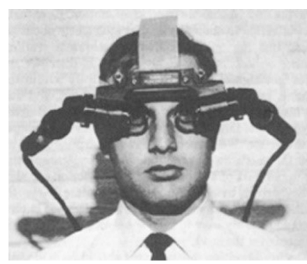



Virtual Reality
image courtesy: vpl research

A Brief History of Virtual Reality

Stereoscopes
Wheatstone, Brewster, …

VR, AR,
Ivan Sutherland

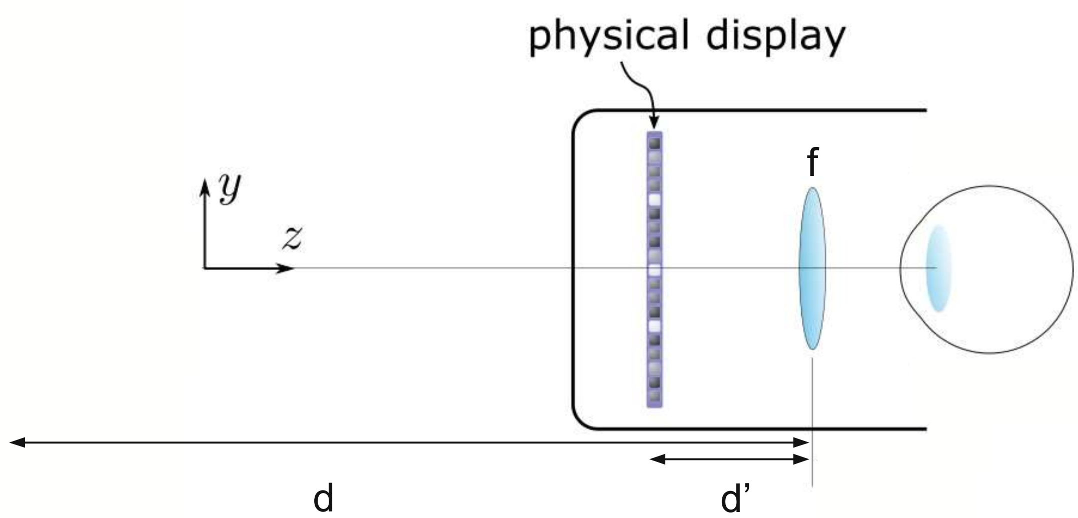


Nintendo Virtual Boy

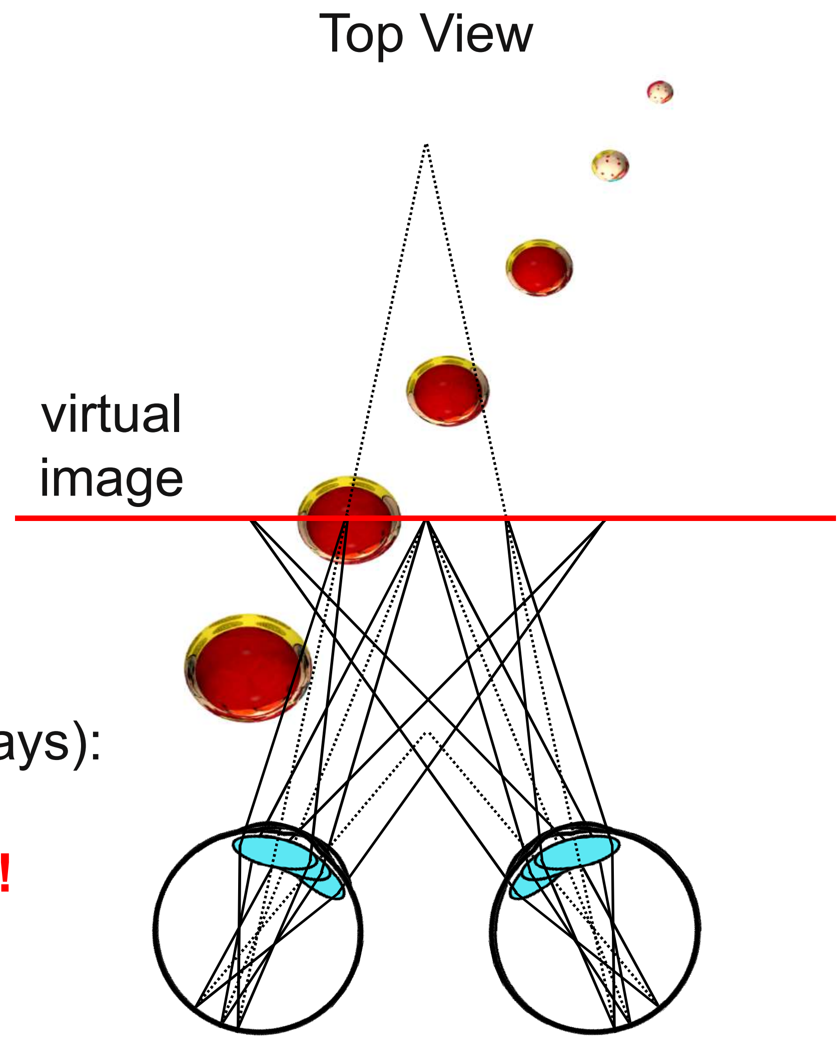
VR explosion
Oculus, Sony, HTC, MS, …

1838 — 1968 — 1995 — 2012-2016

VR Display Optics = Simple Magnifier



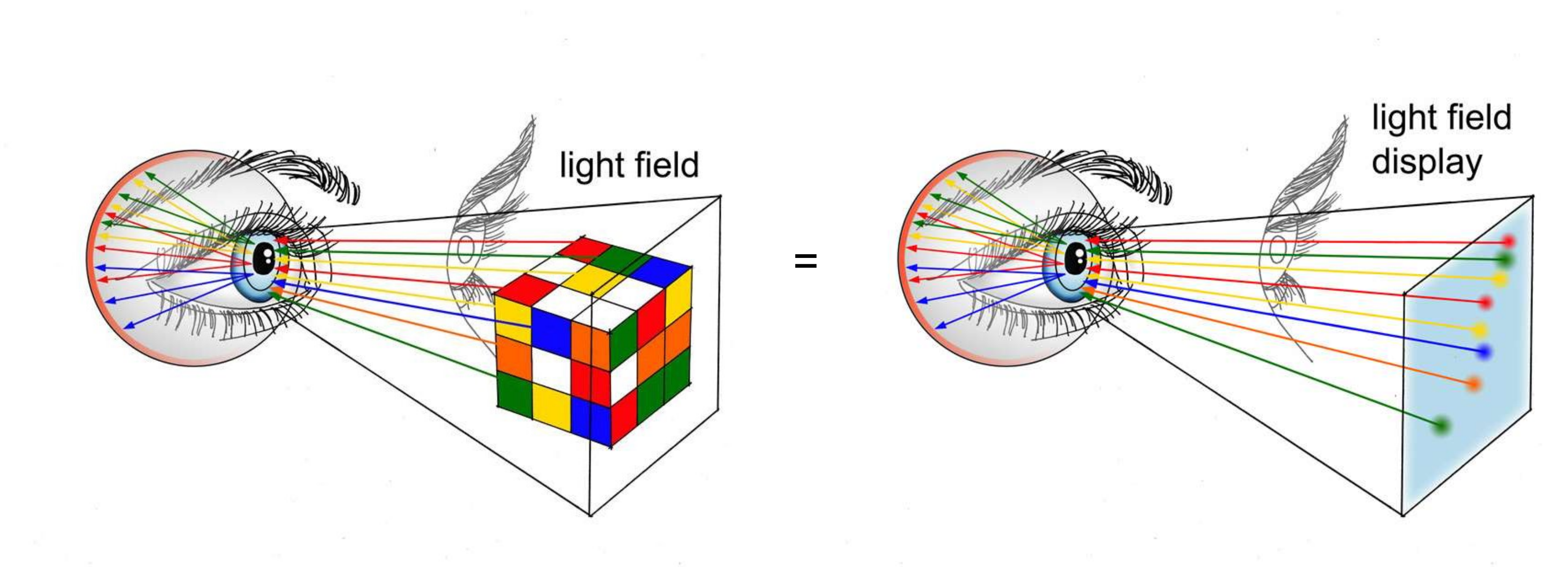
Gaussian thin lens formula: $\frac{1}{d} + \frac{1}{d'} = \frac{1}{f}$



Near-eye Displays Today (all stereo displays):

Vergence-Accommodation **Mismatch!**

Near-eye Light Field Displays

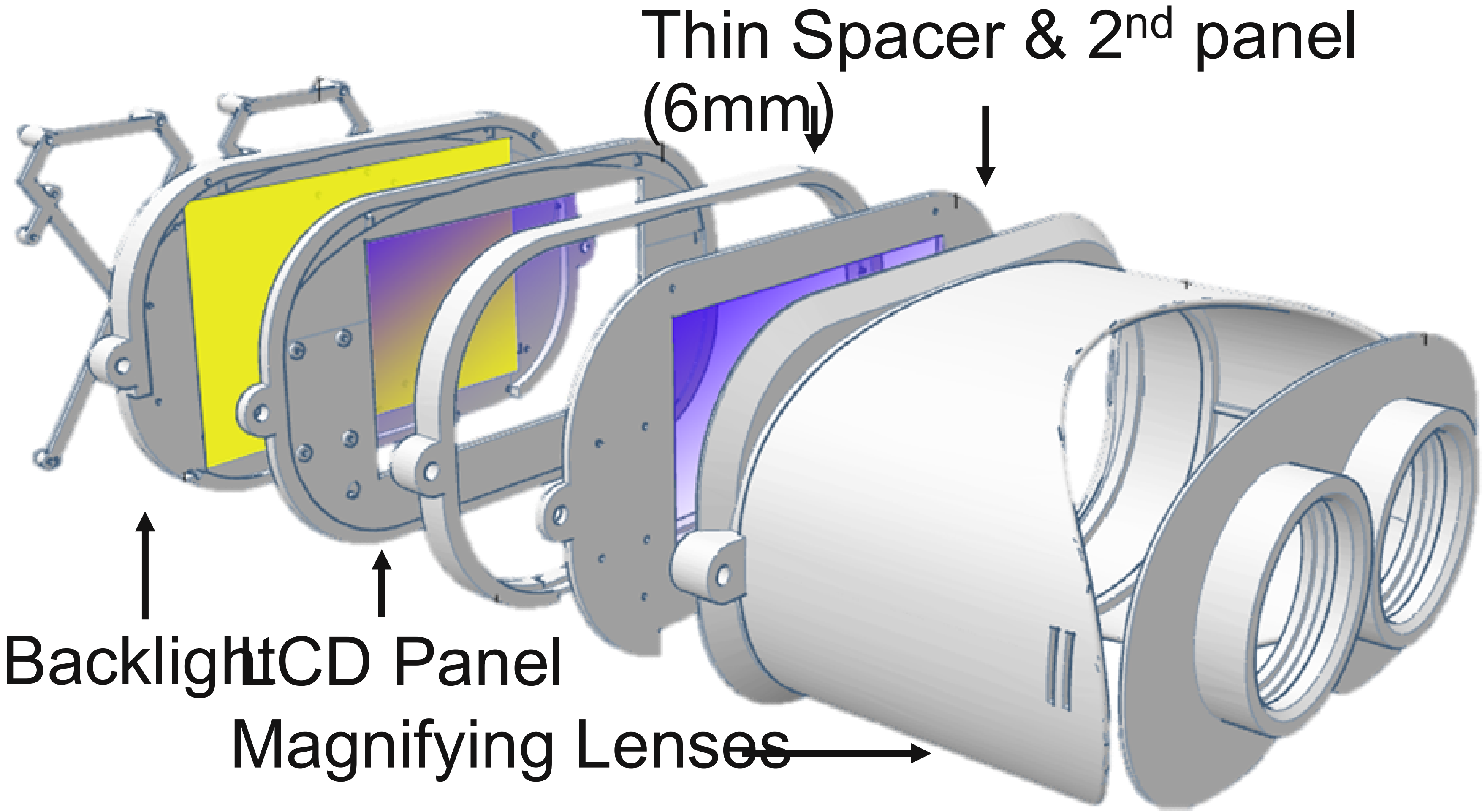


Primary applications: focus cues for VR/AR
Light field approach: project multiple different views into pupil!

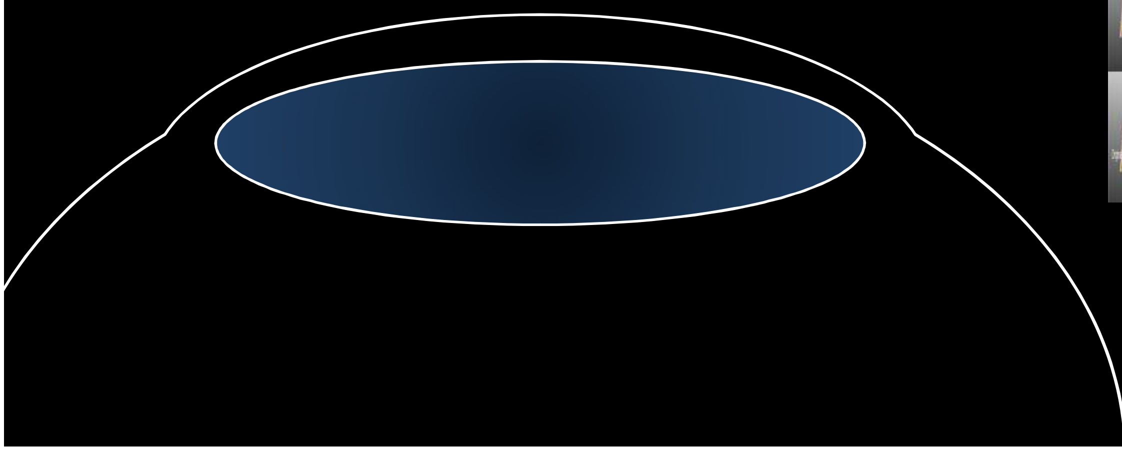

Light Field Stereoscope
ACM SIGGRAPH 2015

Light Field Stereoscope

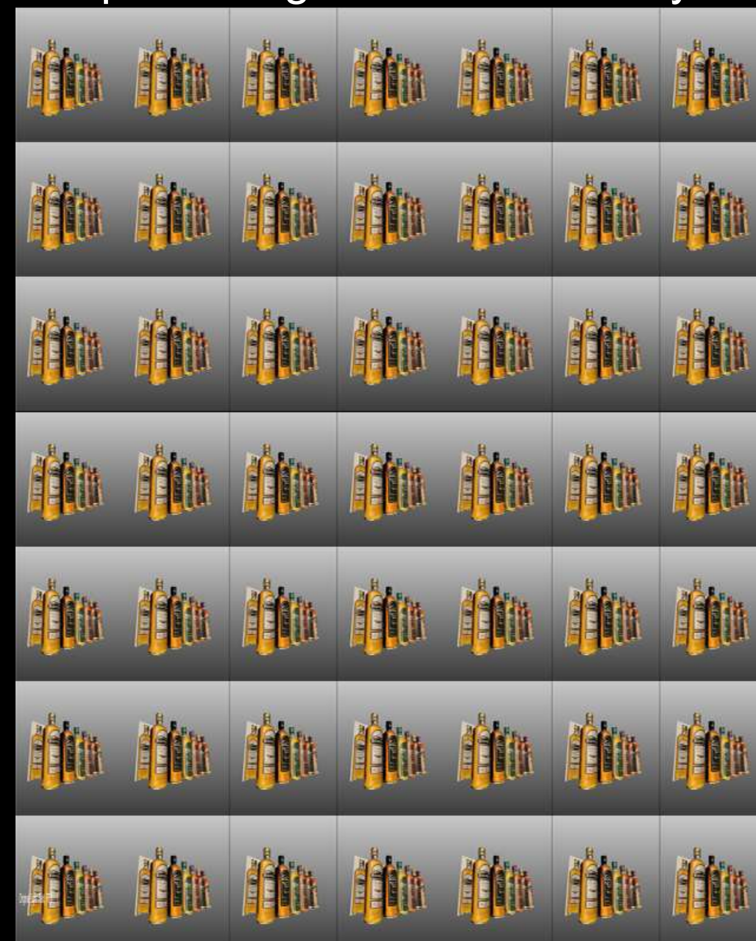
ACM SIGGRAPH 2015



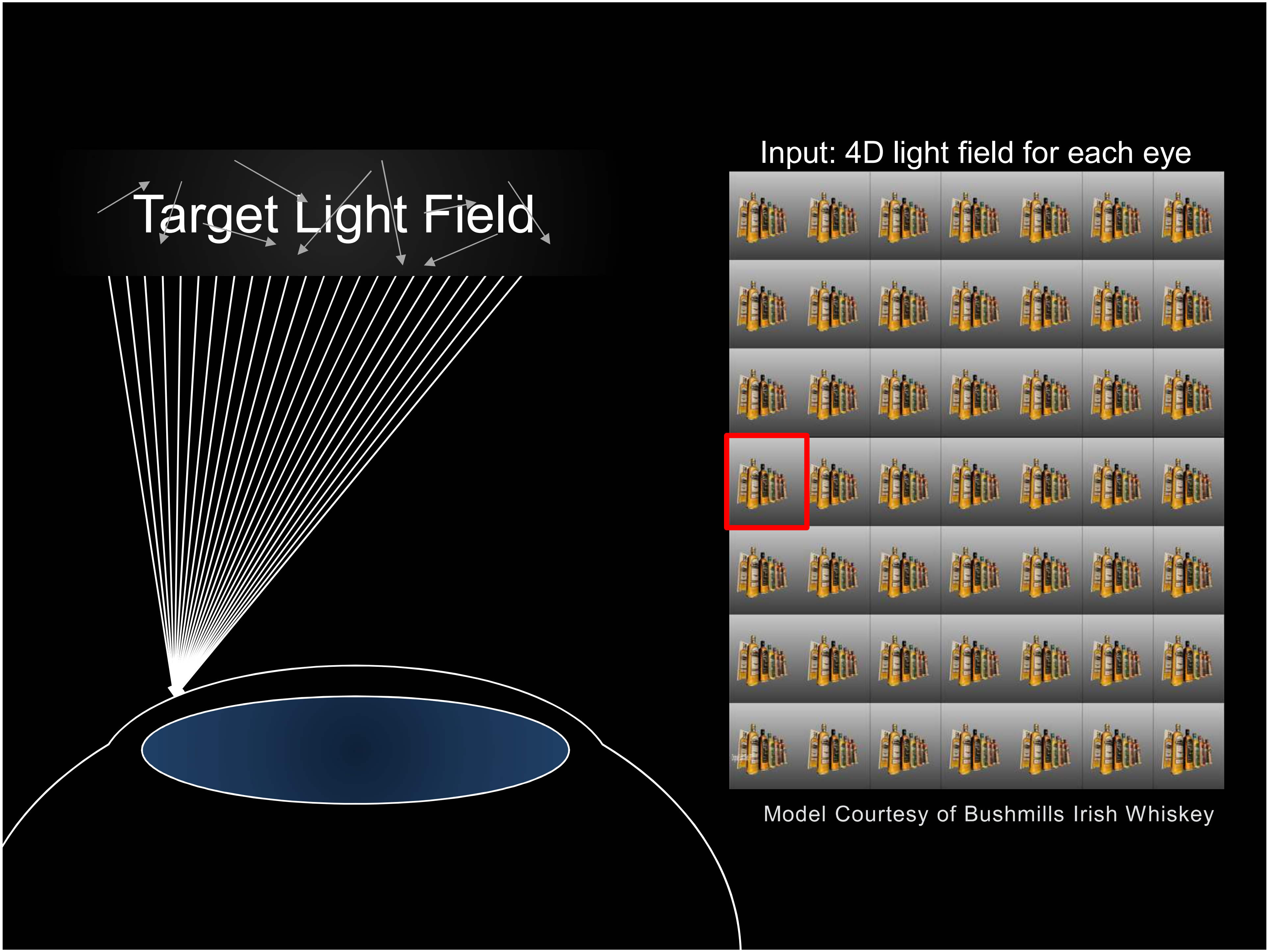
Target Light Field

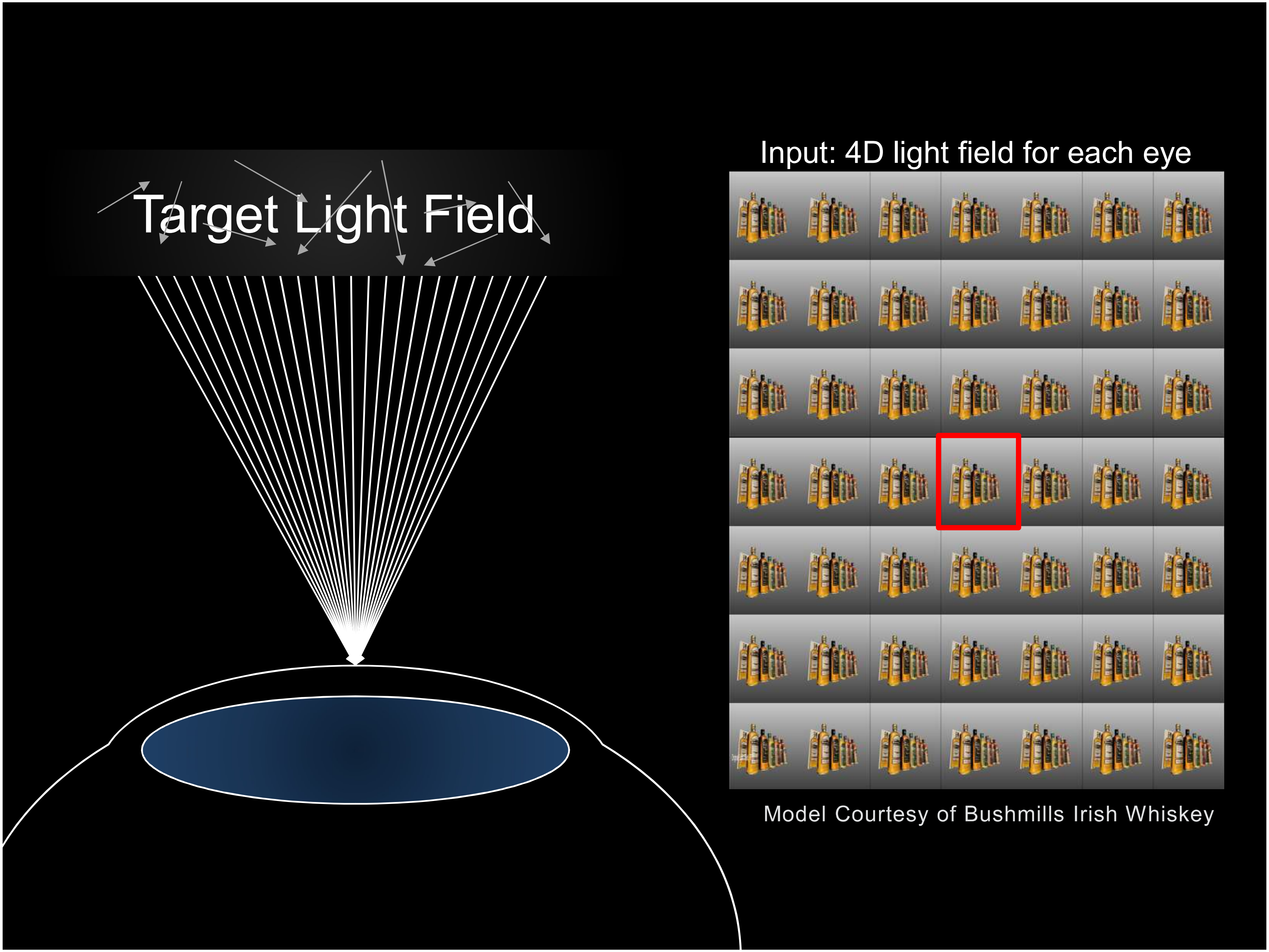


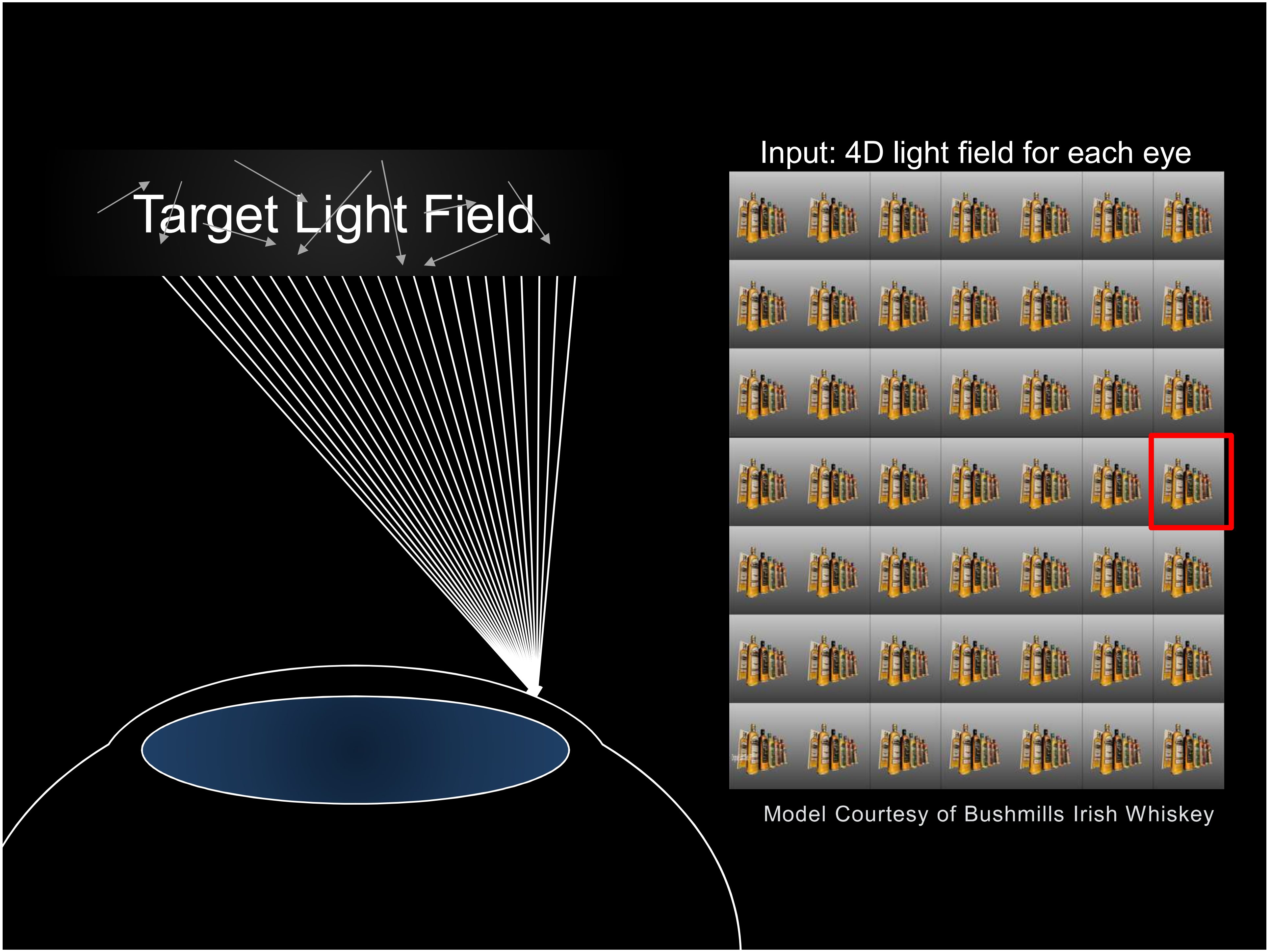
Input: 4D light field for each eye

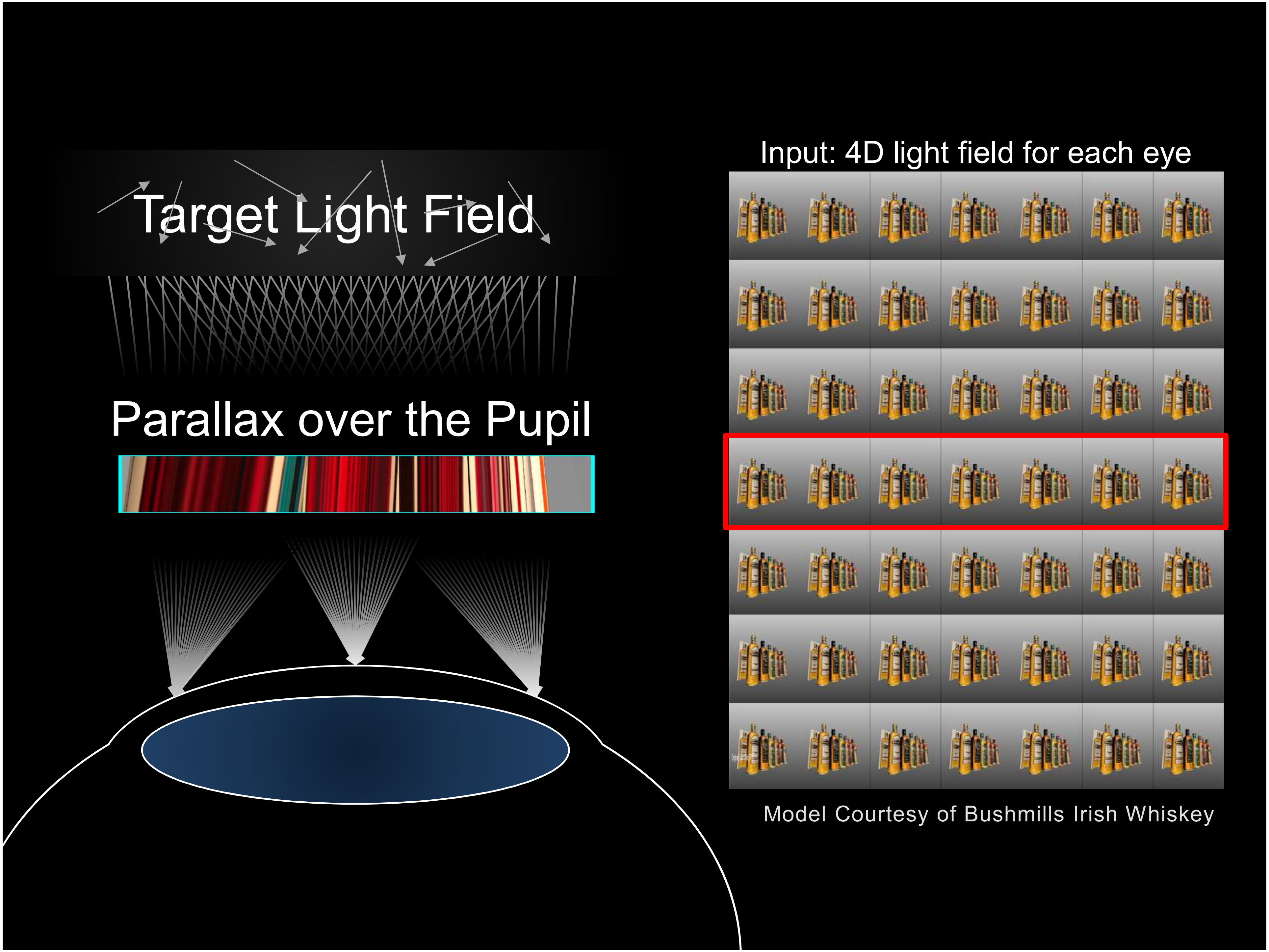


Model Courtesy of Bushmills Irish Whiskey

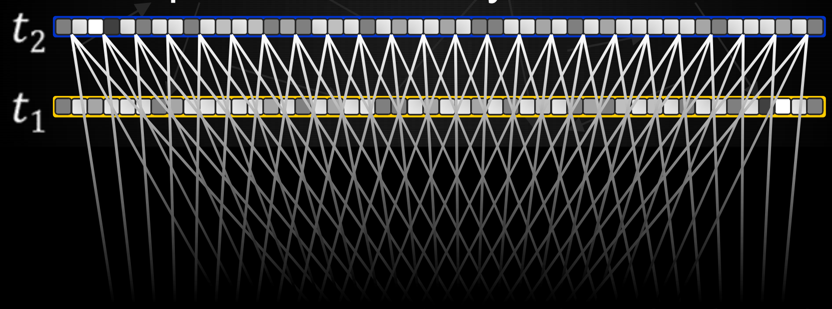

Target Light Field
Input: 4D light field for each eye
Model Courtesy of Bushmills Irish Whiskey


Target Light Field
Input: 4D light field for each eye
Model Courtesy of Bushmills Irish Whiskey


Target Light Field
Input: 4D light field for each eye
Model Courtesy of Bushmills Irish Whiskey


Target Light Field
Parallax over the Pupil
Input: 4D light field for each eye
Model Courtesy of Bushmills Irish Whiskey

Multiplicative Two-layer Modulation



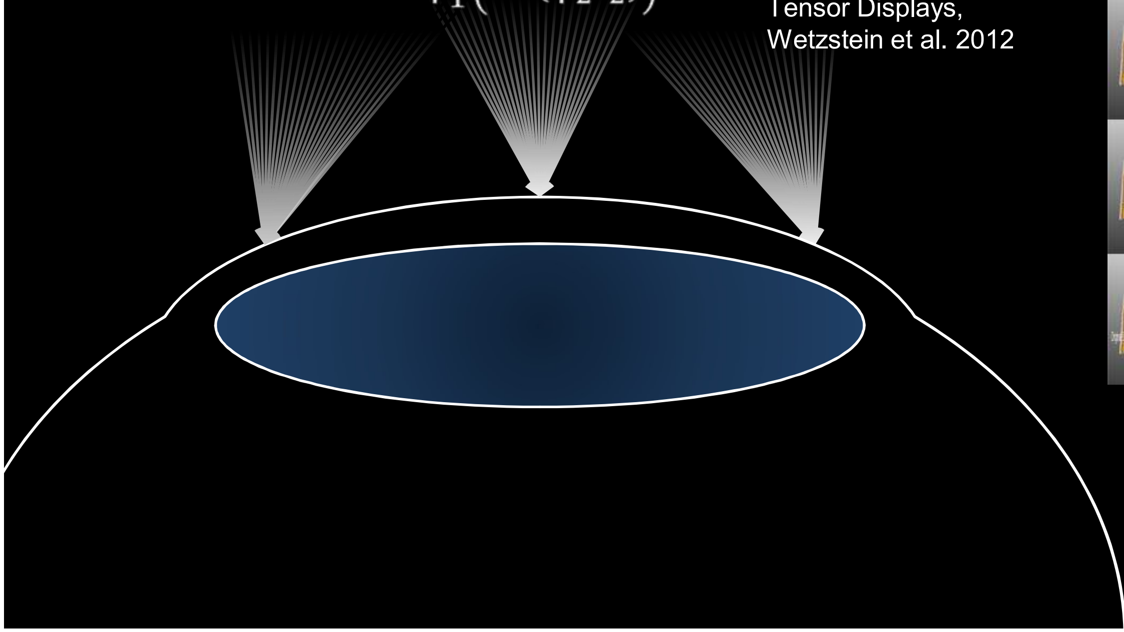
$$\underset{\{t_1,t_2\}}{minimize} \; \|\beta \mathrm{l} - (\phi_1 t_1) \circ (\phi_2 t_2)\|^2 \quad s.t.\; 0 \leq t_1, t_2 \leq 1$$

Reconstruction:

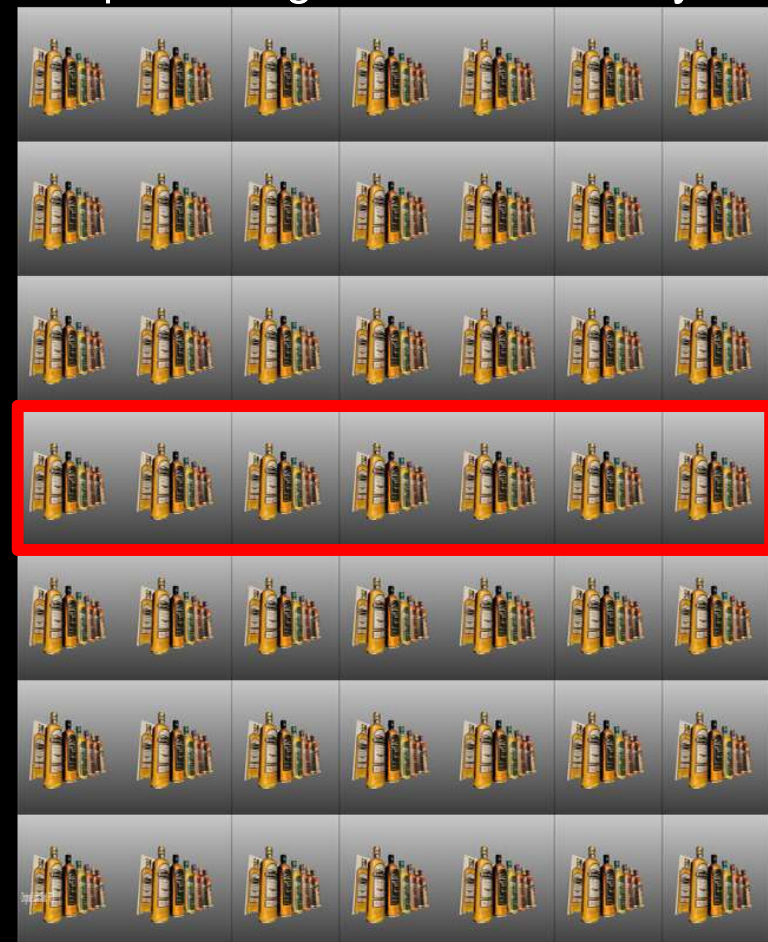
$$t_1 \leftarrow t_1 \circ \frac{\phi_1^T(\beta \mathrm{l} \circ (\phi_2 t_2))}{\phi_1^T\left(\tilde{\mathrm{l}} \circ (\phi_2 t_2)\right) + \epsilon}$$

for layer t_1

Tensor Displays, Wetzstein et al. 2012



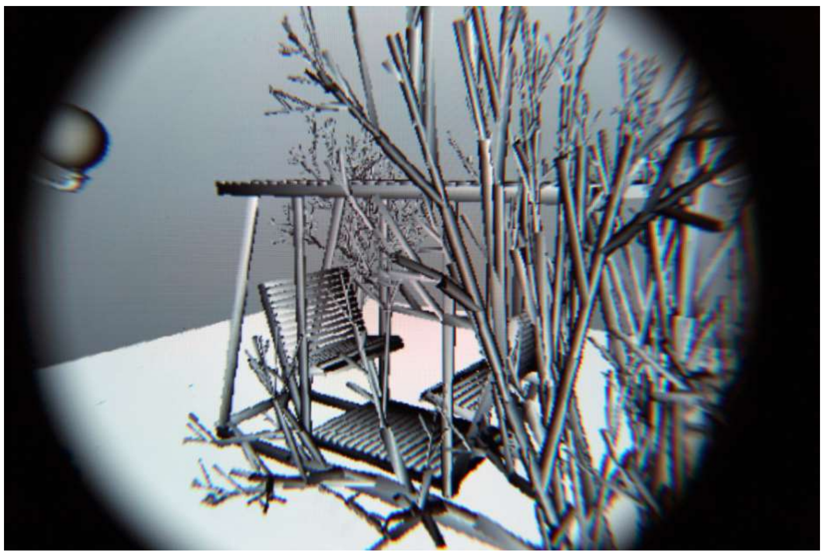
Input: 4D light field for each eye



Model Courtesy of Bushmills Irish Whiskey

Light Field Stereoscope

ACM SIGGRAPH 2015



Traditional HMDs
- No Focus Cues

The Light Field HMD
Stereoscope

Light Field Stereoscope

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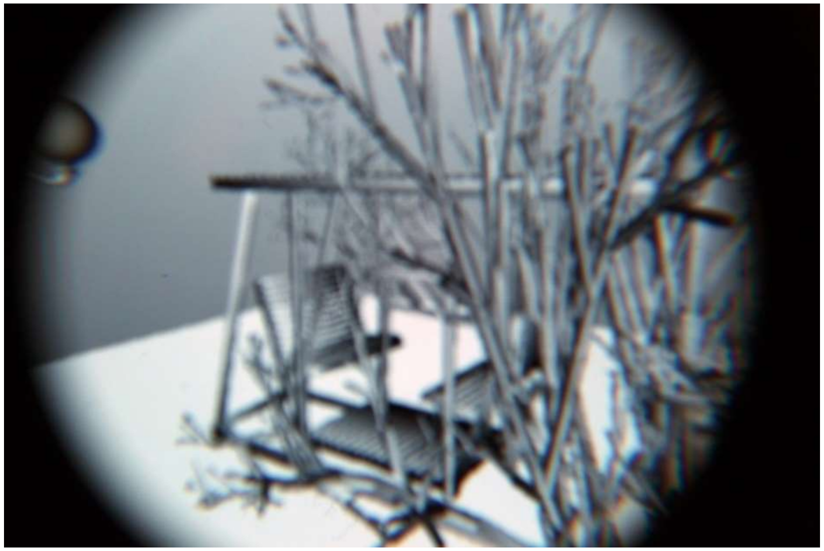
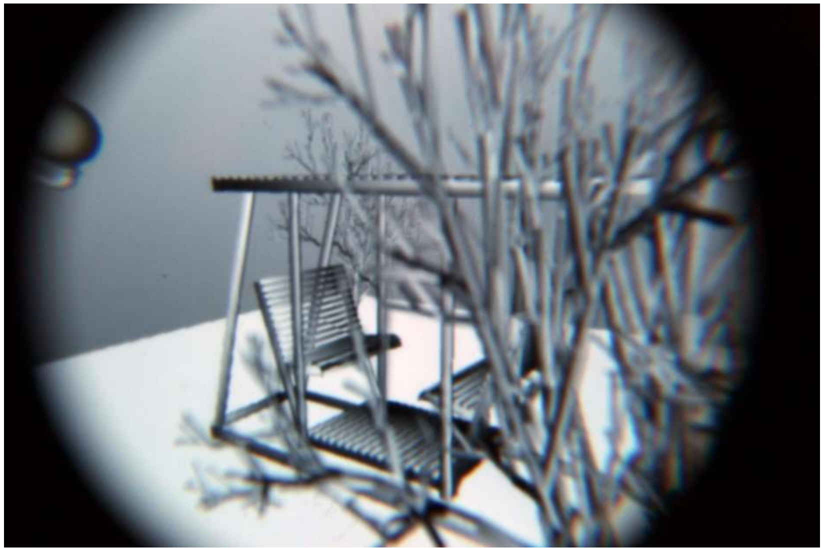


Traditional HMDs
- No Focus Cues



The Light Field HMD
Stereoscope

Light Field Stereoscope

ACM SIGGRAPH 2015

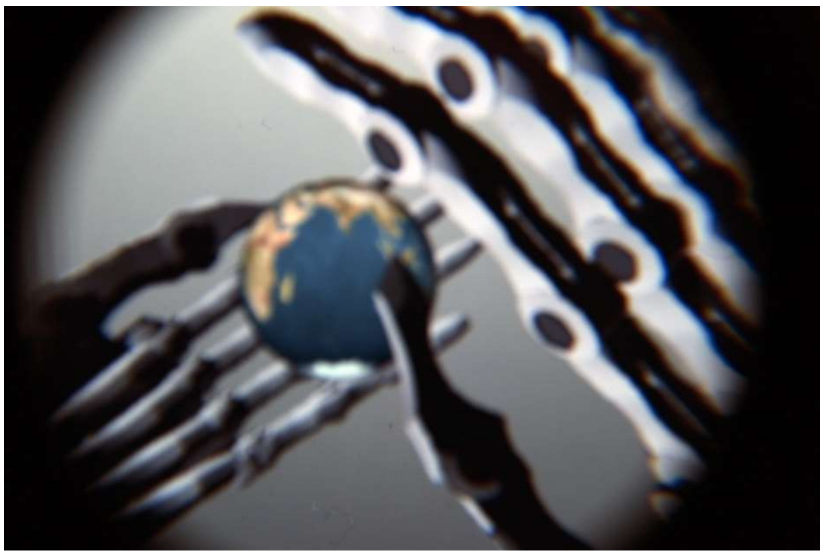
Traditional HMDs
- No Focus Cues

The Light Field HMD
Stereoscope

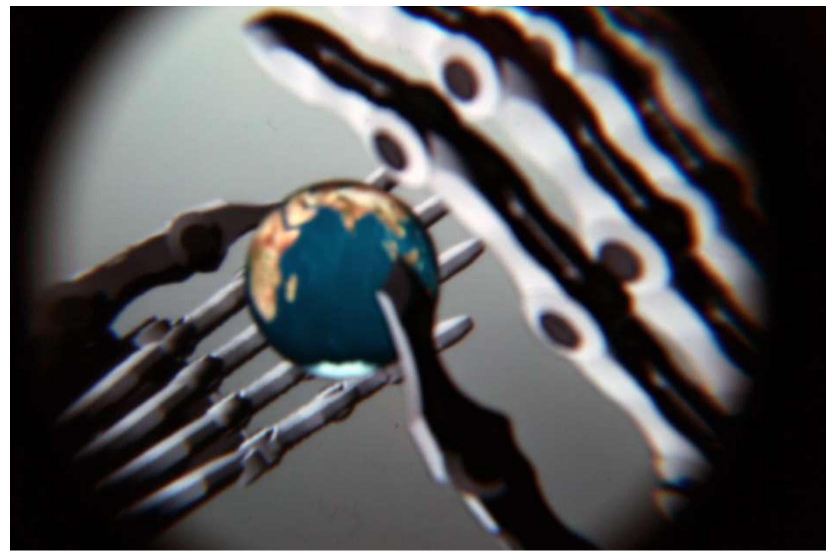
Model Courtesy of Paul H. Manning

Light Field Stereoscope

ACM SIGGRAPH 2015



Traditional HMDs
- No Focus Cues



The Light Field HMD
Stereoscope

Model Courtesy of Paul H. Manning

Light Field Summary

- light field = great tool to model light transport in cameras and displays
- ray-space model is intuitive & easy to connect to modern signal processing and optimization
- lacks interference / diffraction
- light field is similar to phase space models (e.g. Wigner distribution function), except for interference & diffraction – models joint distribution of space & spatial frequency

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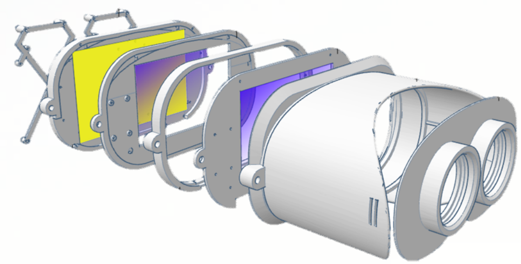
www.computationalimaging.org



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