

# Display Tech. for VR/AR

- Computational  
Light Field and  
Holography



GAMES 204

2022-11

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*Evan Y. Peng*



香港大學

THE UNIVERSITY OF HONG KONG



# Facebook parent company Meta 11,000 employees

By Catherine Thorbecke, CNN Business

Updated 4:11 PM EST, Wed November 9, 2022



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# Future Display and Visualization Scenarios

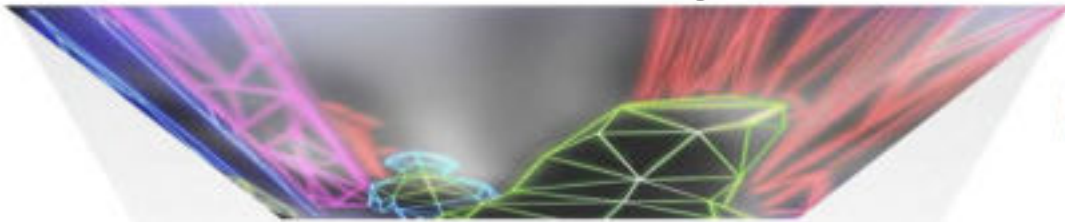


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# Accelerating Progress of Near-eye Displays

## Virtual Image



- fixed focal plane, lacking focus cues
- VAC: vergence-accommodation conflict, and other side effects



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# Computational Near-eye Displays with Focus Cues

Gaze-contingent  
Varifocal Displays



**Mechanical actuation  
or focus-tunable lens**

Multiplane Displays



**High-speed SLMs or  
high system complexity**

Near-eye Light Field  
Displays



**Resolution is limited  
by diffraction**

Shiwa et al. 1996; Liu et al. 2008;

Konrad et al. 2016; Padmanaban et al. 2016, 2017; ...

Roland et al. 2000; Alexey et al. 2004;

Liu et al. 2008; Love et al. 2009; ...

Lanman and Luebke 2013;

Hua and Javidi 2014; Huang et al. 2015;

# Evolution of Holography

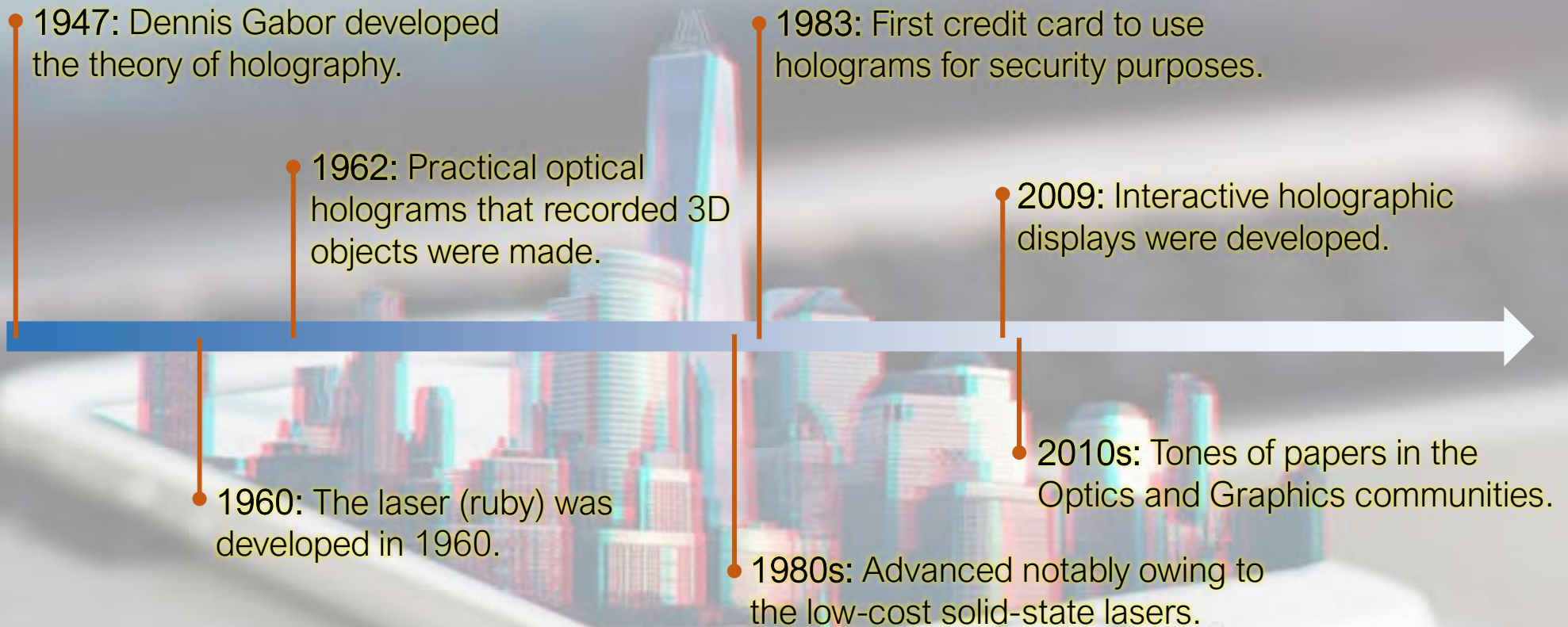
- 
- A horizontal timeline arrow pointing to the right, with a blue segment at the beginning and a white segment for the rest. Seven vertical orange lines connect specific years to text descriptions of milestones in holography. The background features a blurred 3D cityscape with red and blue color fringing, and a white object, possibly a smartphone, is visible in the lower foreground.
- 1947: Dennis Gabor developed the theory of holography.
  - 1960: The laser (ruby) was developed in 1960.
  - 1962: Practical optical holograms that recorded 3D objects were made.
  - 1980s: Advanced notably owing to the low-cost solid-state lasers.
  - 1983: First credit card to use holograms for security purposes.
  - 2009: Interactive holographic displays were developed.
  - 2010s: Tones of papers in the Optics and Graphics communities.

Image credit @ bbvaopenmind

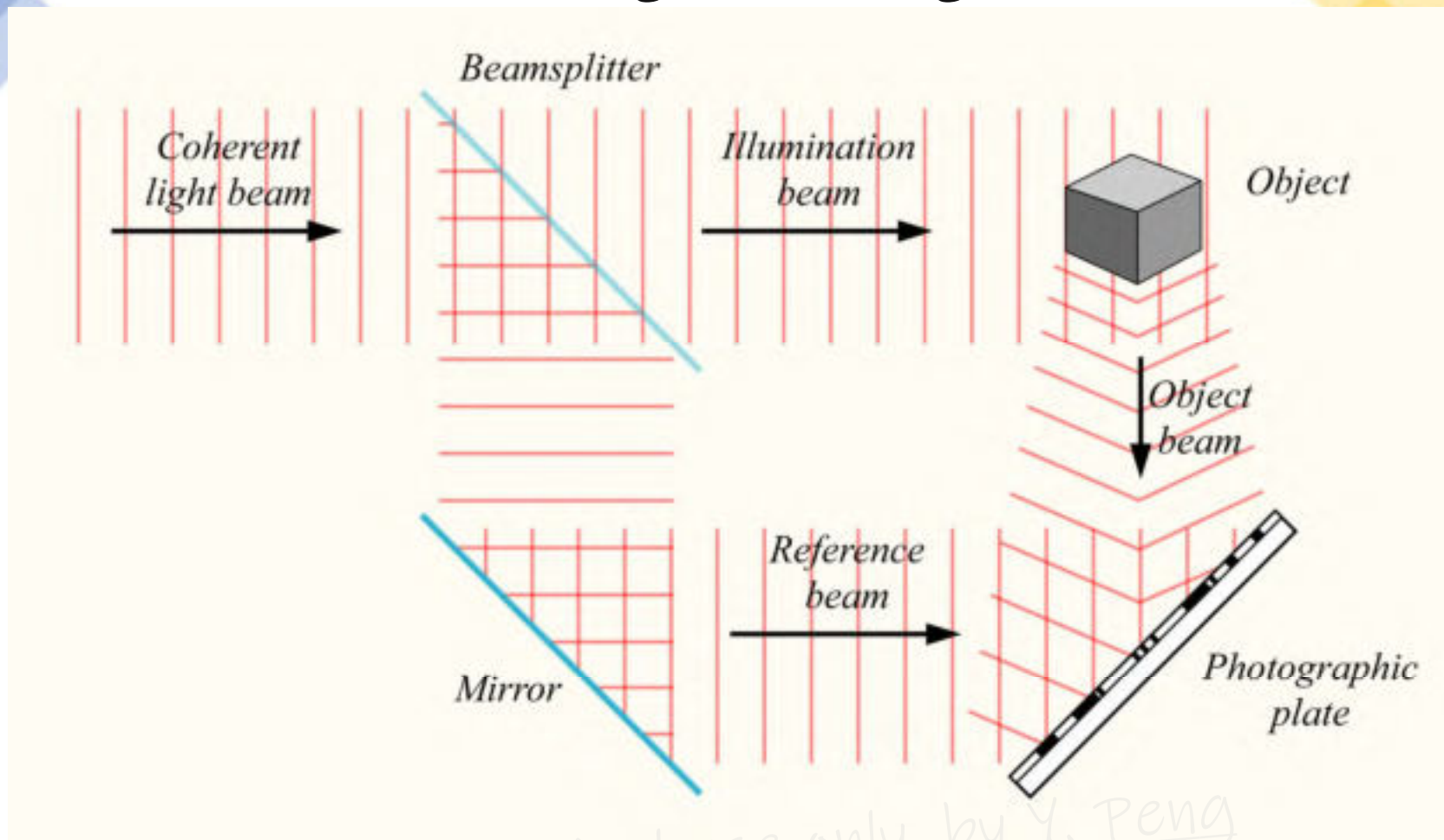
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# Holographic Displays (Holograms)





# Recording the Hologram

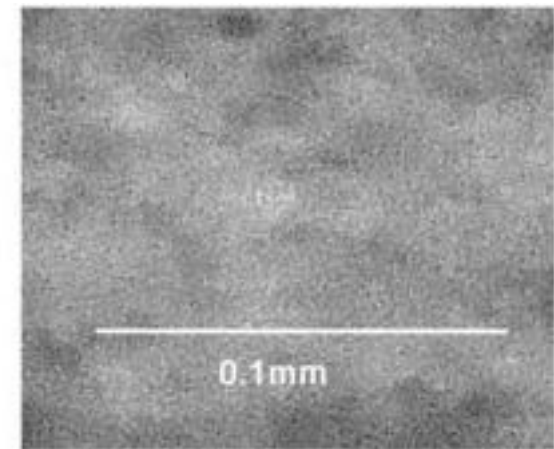
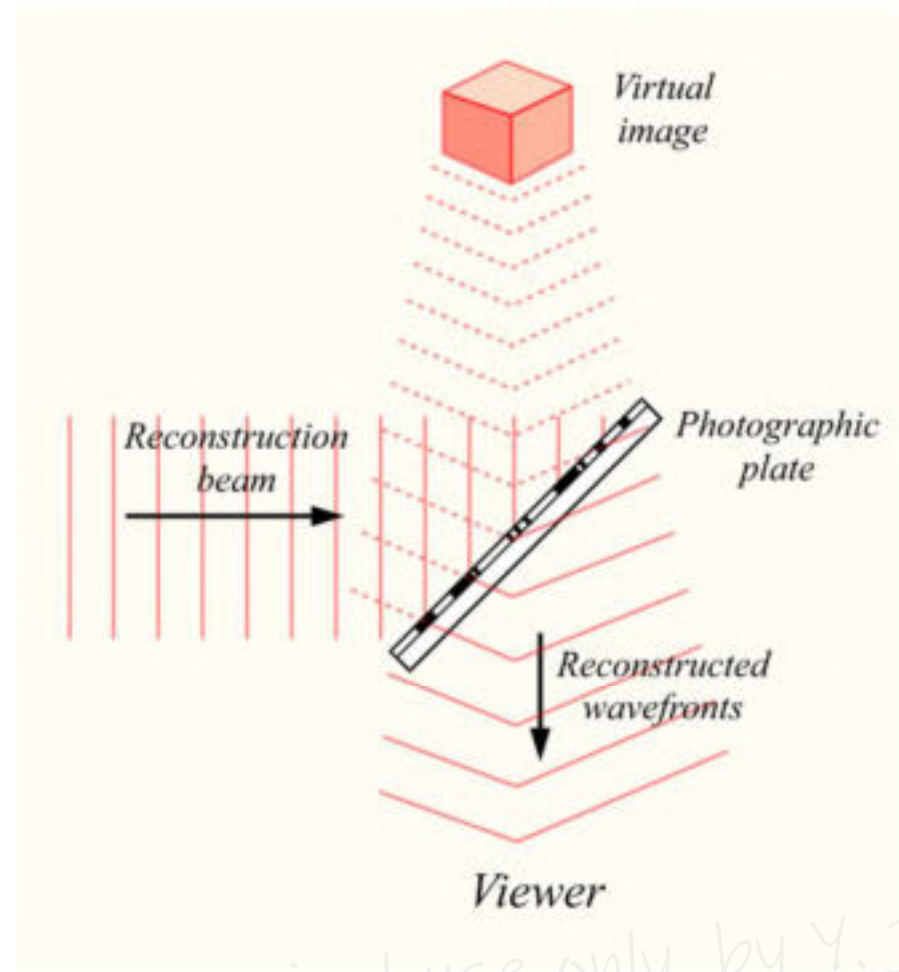
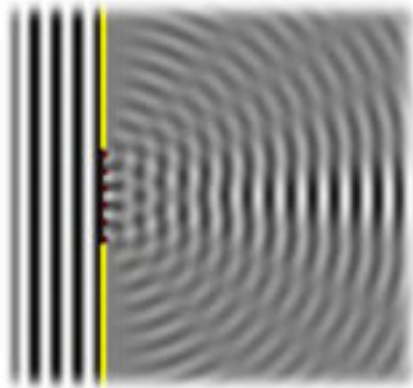


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[Figure Credit: Wikipedia]



# Reconstructing the Hologram



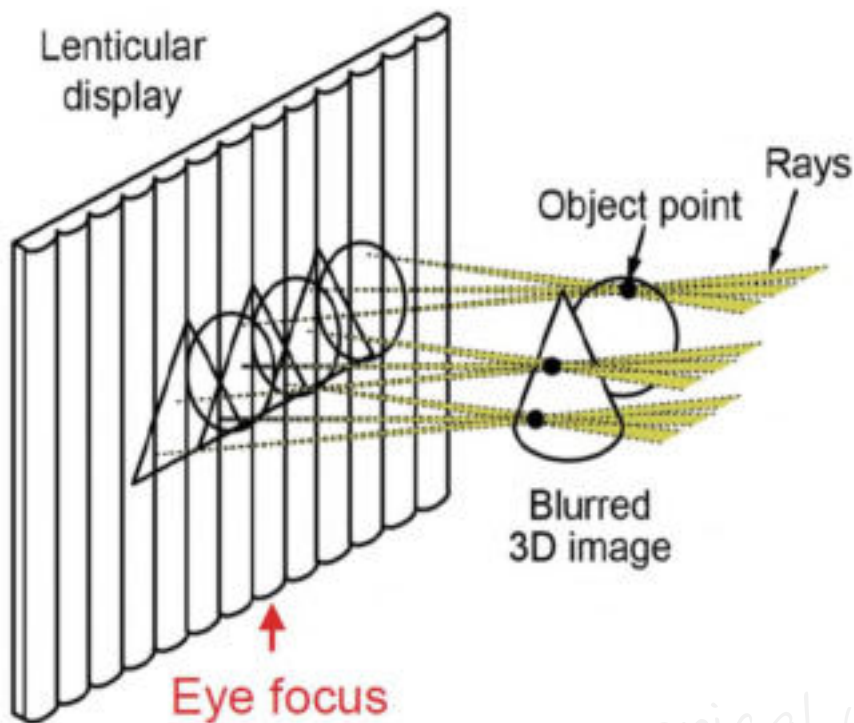
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[Figure Credit: Wikipedia]

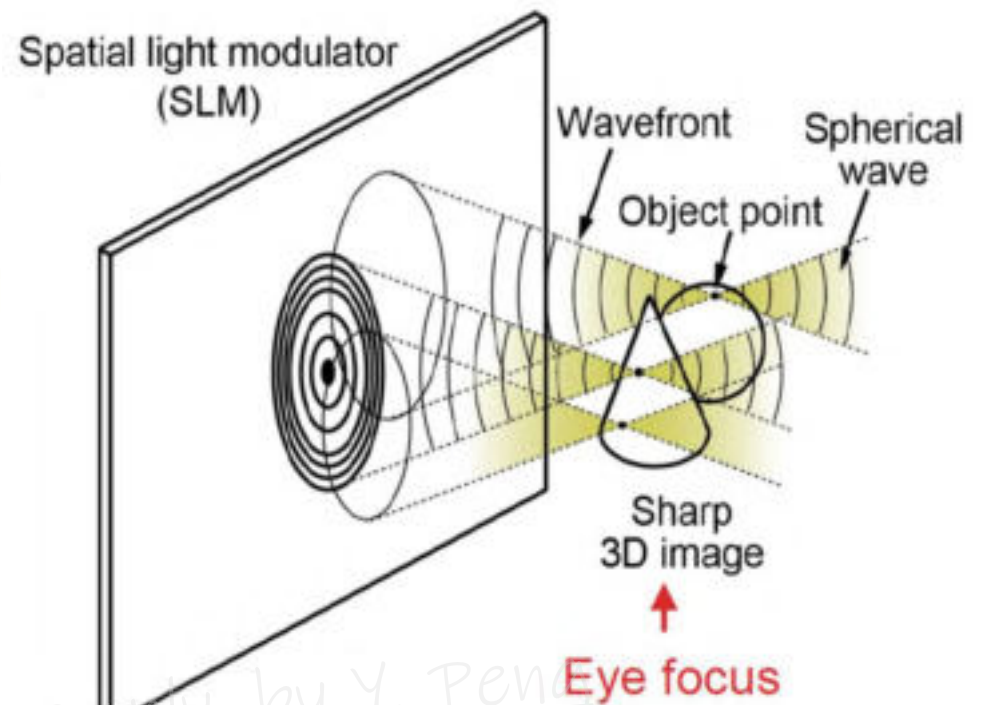
# Multi-view or Light Field or Holography

*From Ray Reconstruction to Wavefront Reconstruction*

multi-view, integral imaging



holography

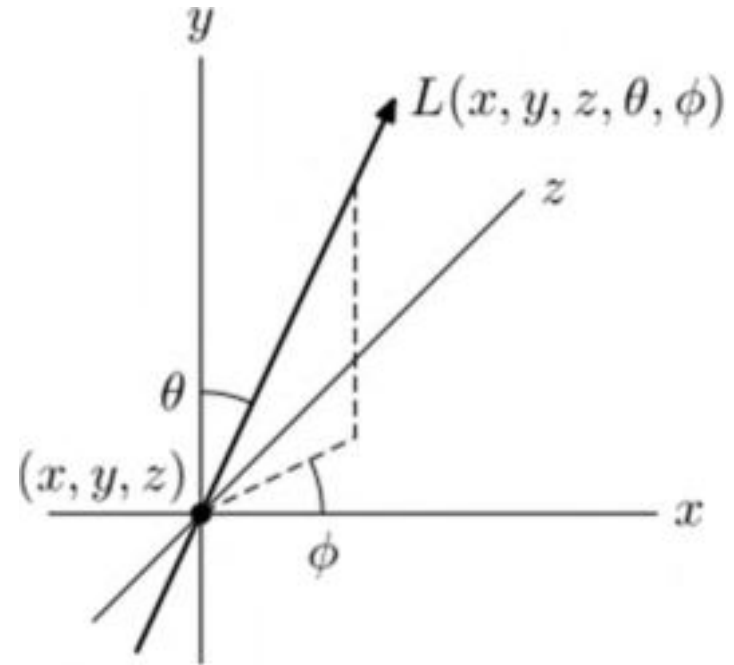


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Image Credit @ Y. Takaki

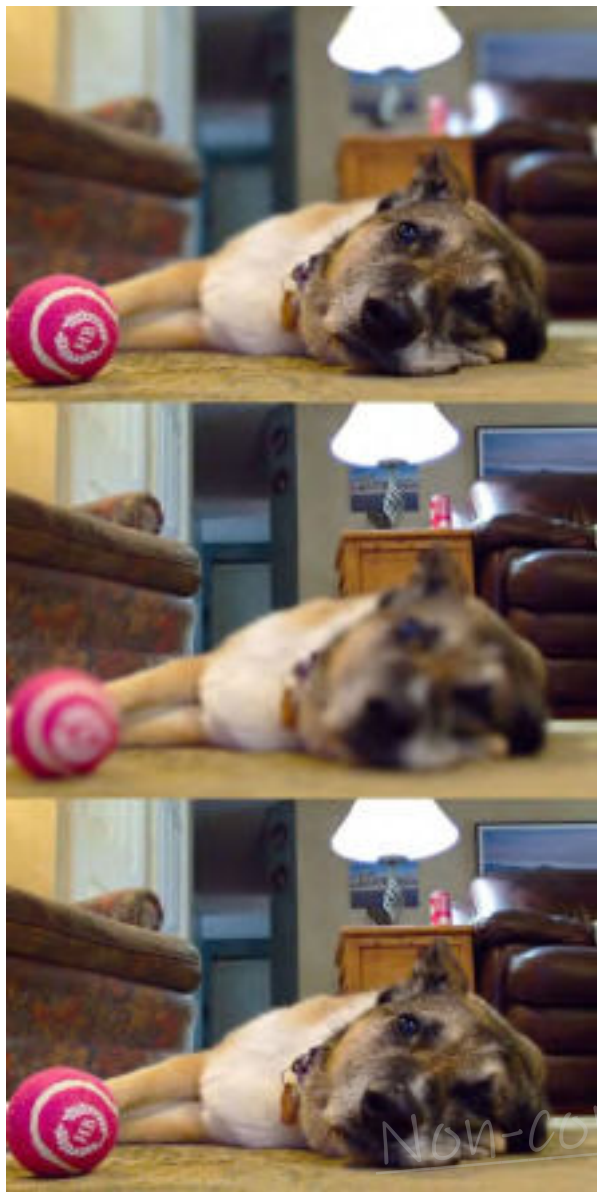
# Light Field

- A [vector function](#) that describes the amount of [light](#) flowing in every direction through every point in space. The space of all possible [light rays](#) is given by the [five-dimensional plenoptic function](#), and the magnitude of each ray is given by its [radiance](#).
- **Optics or Graphics?**
- **5D or 4D?**

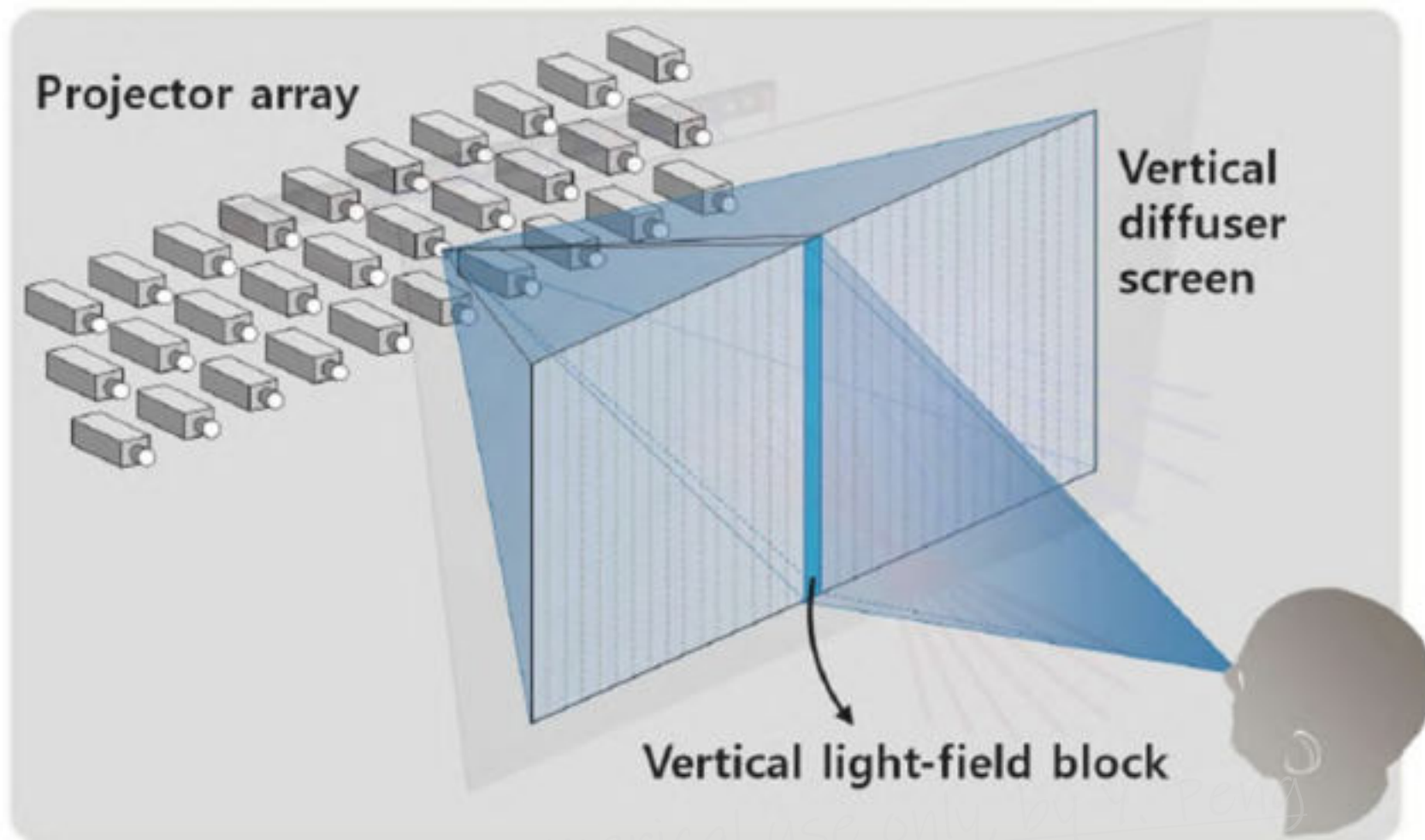


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Images from public domain



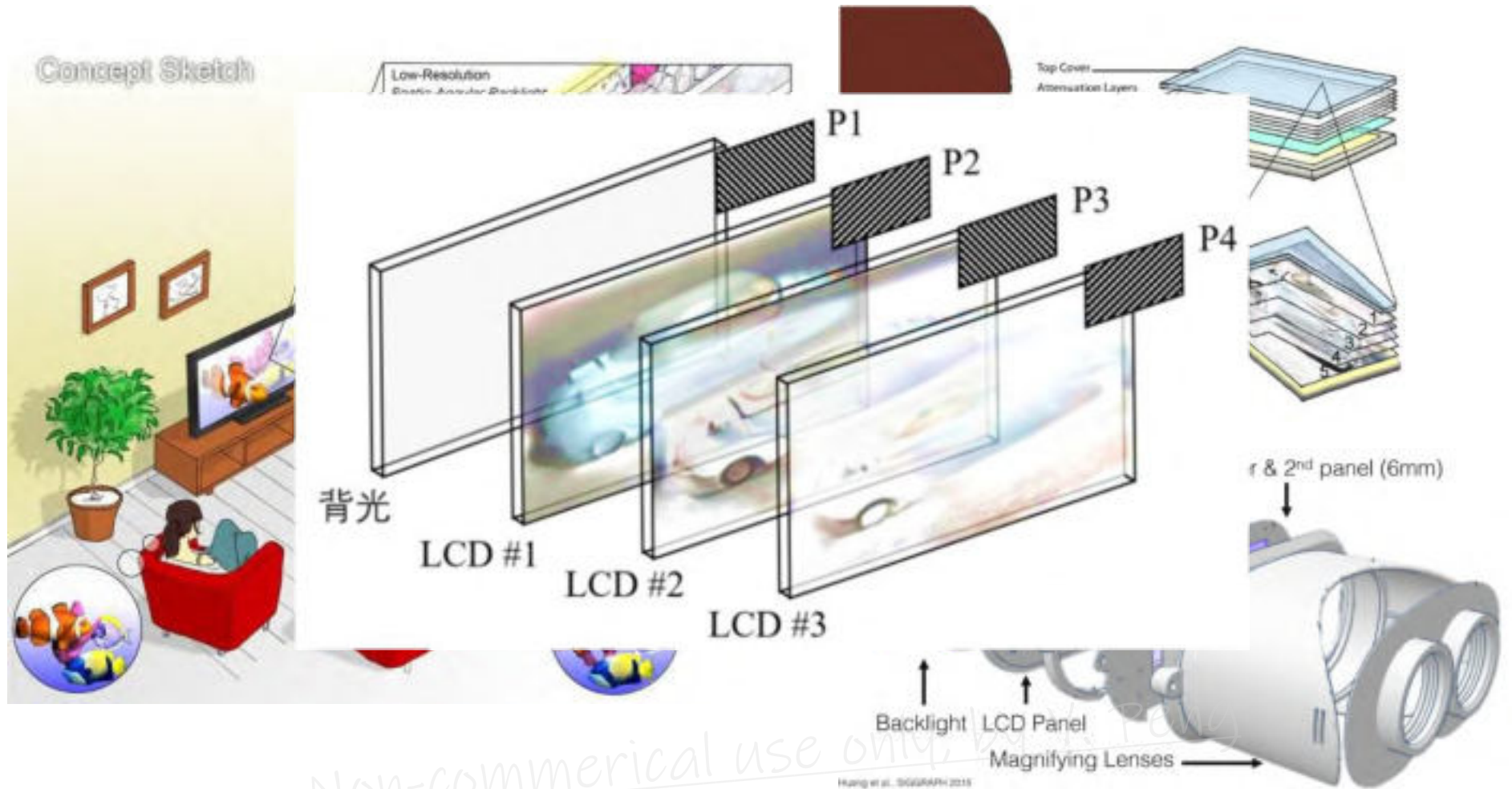




Non-commercial use only, by [illegible]

Images from public domain

# Light Field Acquisition and Display



Images from public domain

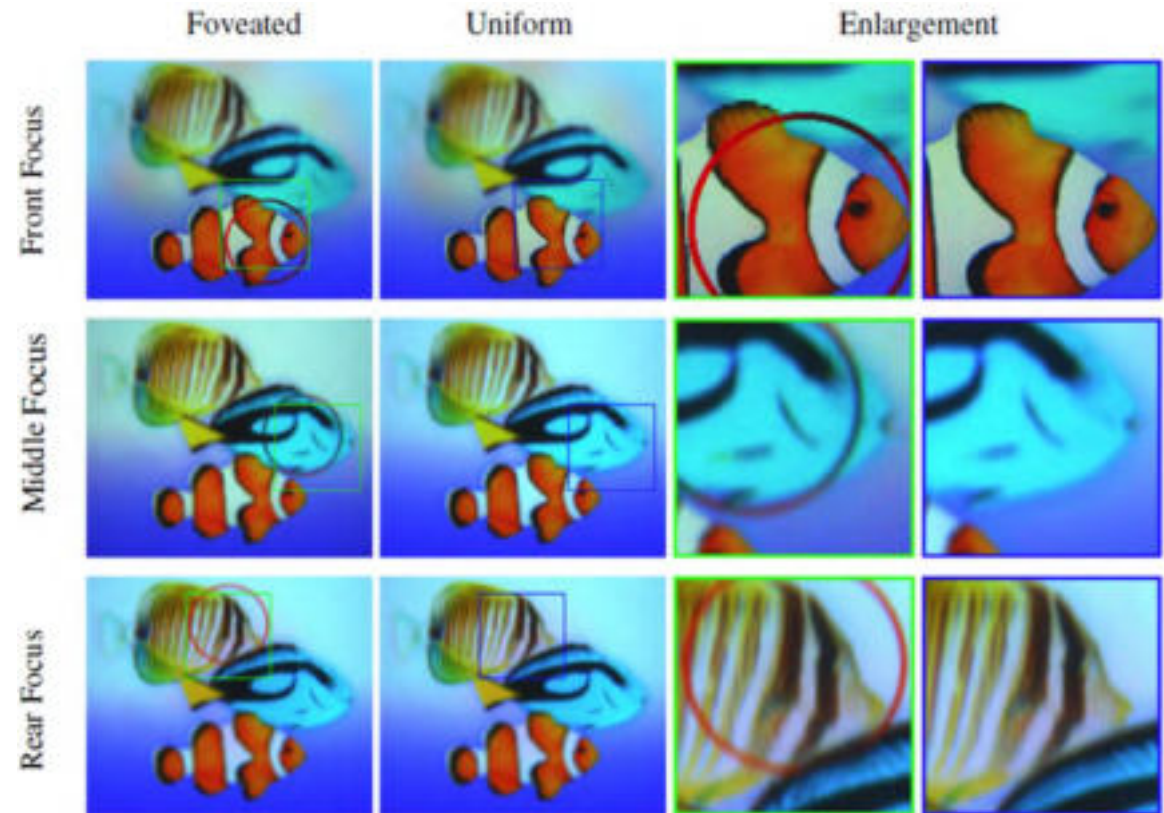
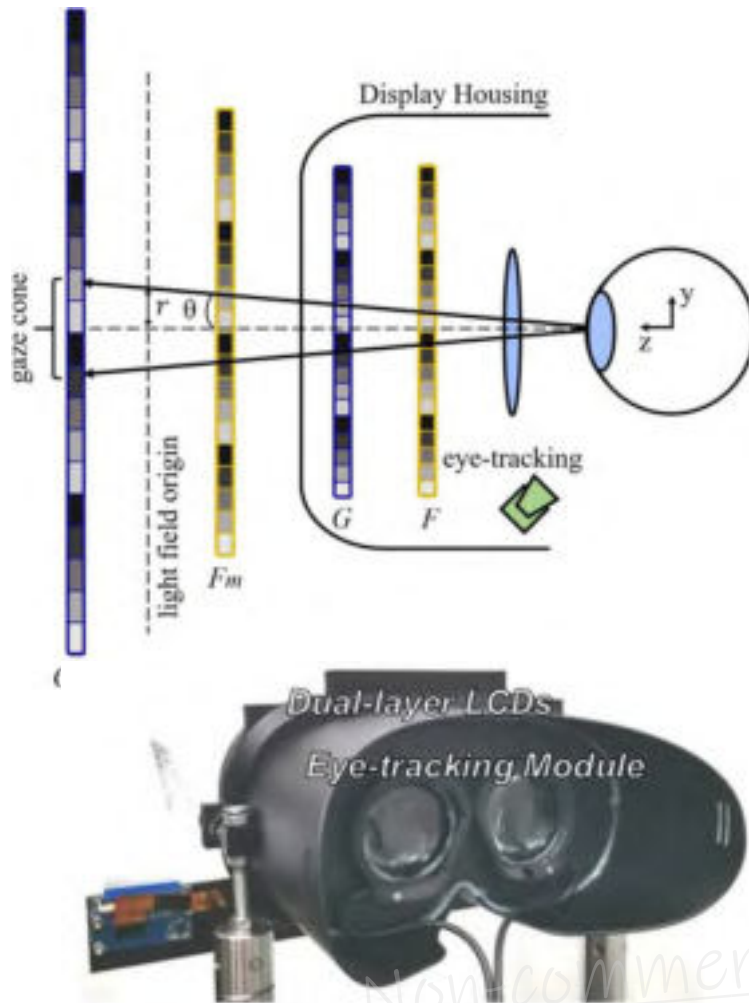
# Tensor Displays: Compressive Light Field Synthesis using Multilayer Displays with Directional Backlighting



[Wetzstein et al.]



# Light Field Stereo Displays



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Huang, F. C. et al., ACM Trans. Graph. 34(4), 60 (2015).  
Gao, C. et al., App. Opt. 60(28), 8634 (2021).



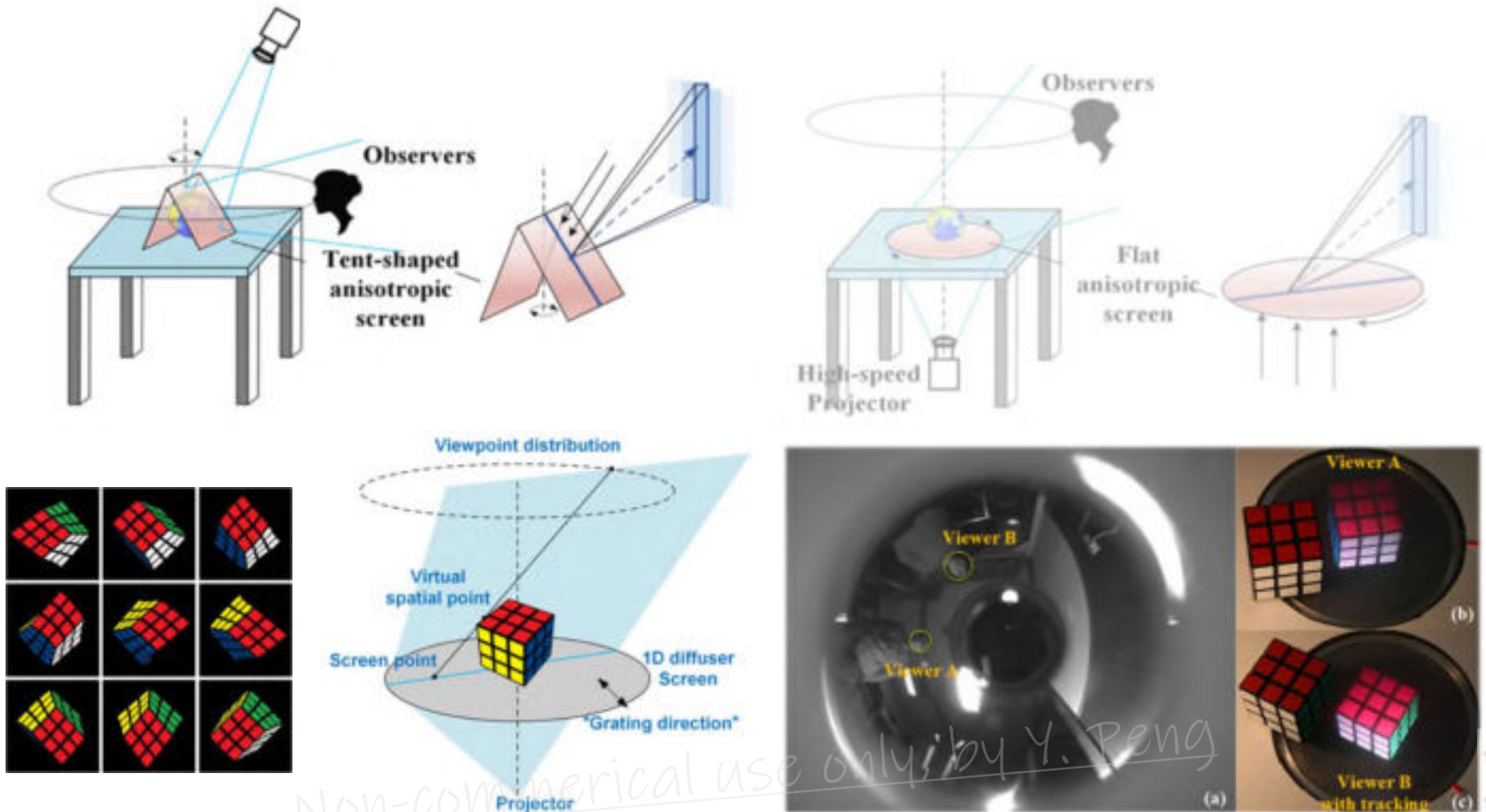
# Interactive Focal Stack Video See-through MR (IEEE VR)

Focal Stack Acquisition + Real-time Tracking & Rendering + Light Field Display = MR



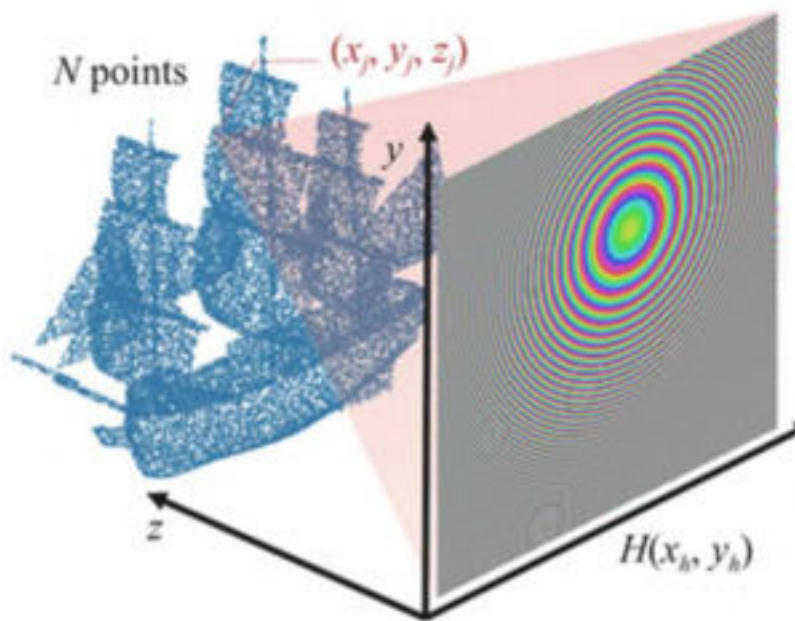
C Ebner, S Mori, P Mohr, Y Peng, D Schmalstieg, G Wetzstein, D Kalkofen - Video See-Through Mixed Reality with Focus Cues  
IEEE Transactions on Visualization and Computer Graphics 28 (5), 2022.

# Interactive Table-top Light Field Display & Rendering

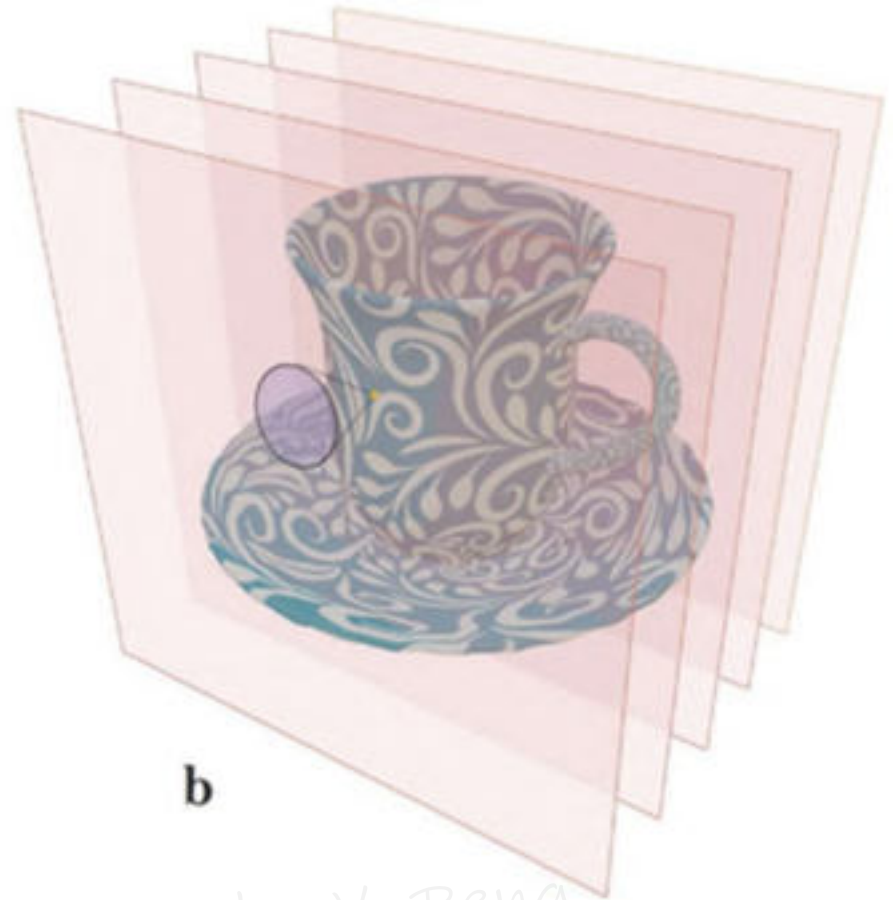


\* Research conducted during 2011-2016 (OSA OE '15, ACM SigAsia '16, IEEE JDT '16).

# Classical Computer-generated Hologram Schemes



**a**

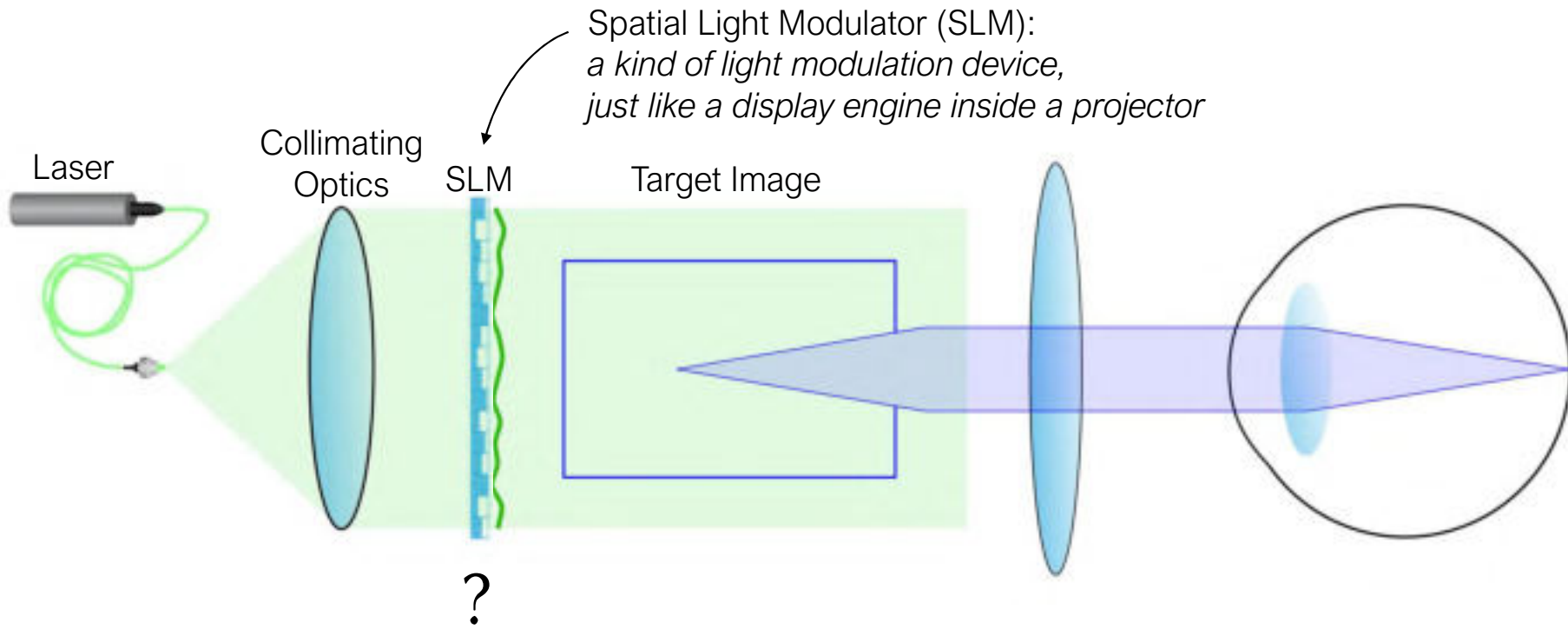


**b**

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[Figure Credits @ David Blinder, Tobias Birnbaum, Tomoyoshi Ito, Tomoyoshi Shimobaba]

# Holographic Near-eye Displays



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[Peng et al. 2020; Maimone et al. 2017; Shi et al. 2017; Padmanaban et al. 2019; ...]



# SLMs for Wave Modulation

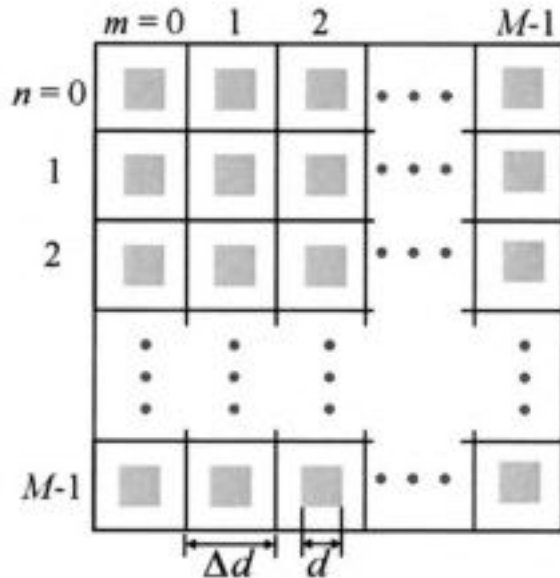
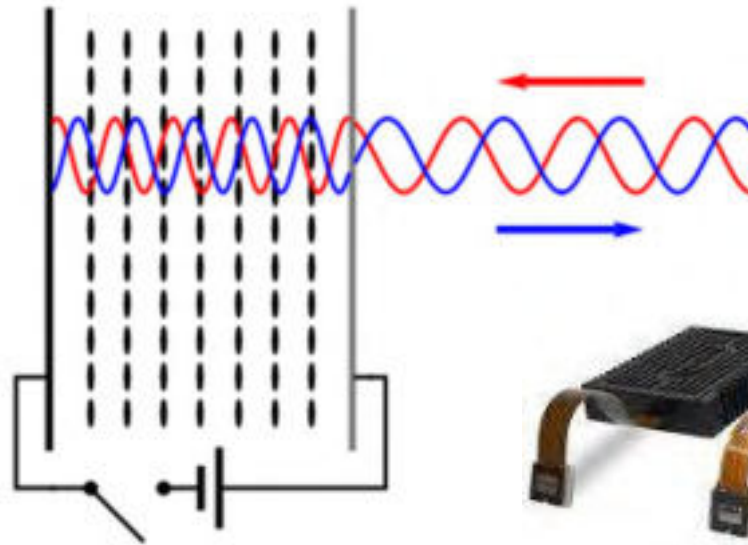


Fig. 1. Geometry of the  $M \times M$  phase-only spatial light modulator with a square pixel length  $d$  while  $\Delta d$  is the period length. The active phase-encoding area of a pixel is shaded gray.

[Palima et al. 2006]

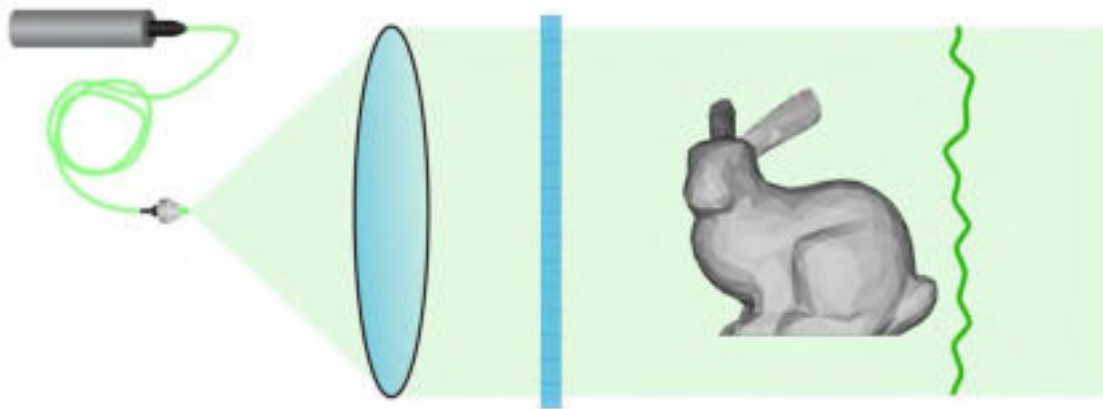


*Pixel pitch*  
*Resolution*  
*Grayscale*  
*Modulation range*  
*Refresh rate*



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# Computer-generated Holography: Direct Methods



SLM phase



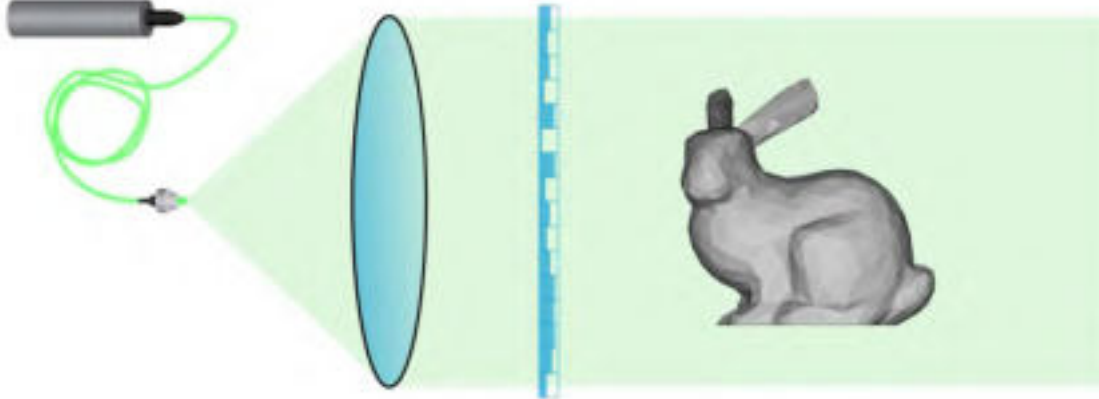
Target Image



← propagate  
backward

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# Computer-generated Holography: Direct Methods



SLM phase



Target Image



propagate  
backward

Free-space propagation:

$$u_{slm}(x, y) = \mathcal{F}^{-1} \left\{ \mathcal{F} \left\{ a(x, y) e^{i\phi(x, y)} \right\} \mathcal{H}(f_x, f_y, z) \right\}$$

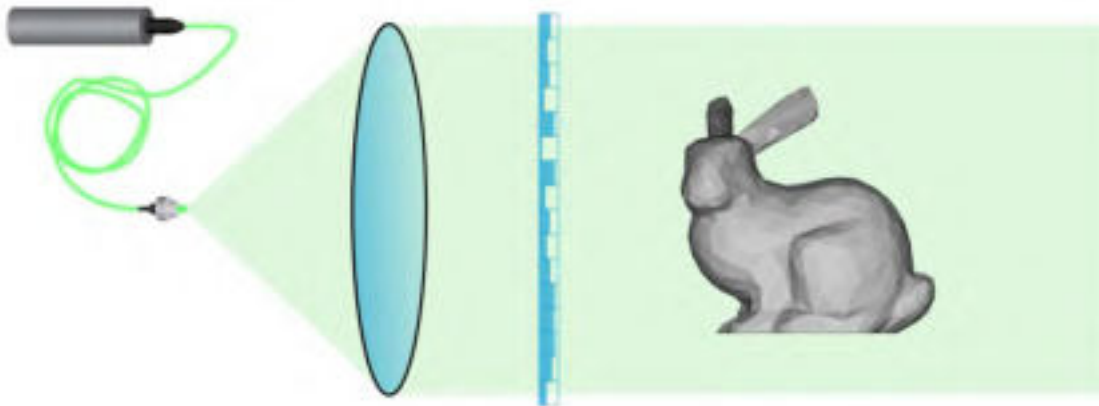
$$\mathcal{H}(f_x, f_y) = \begin{cases} e^{-i \frac{2\pi}{\lambda} \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} z} & \text{if } \sqrt{f_x^2 + f_y^2} < \frac{1}{\lambda} \\ 0 & \text{otherwise} \end{cases}$$

Computational complexity

$$O(N^2 \log N)$$

[Goodman, Fourier Optics]

# Computer-generated Holography: Direct Methods



SLM phase



Target Image



propagate  
backward

Double phase-amplitude coding:

$$u_{slm}(x, y) = a(x, y) e^{i\phi(x, y)} = 0.5 \left( e^{i\phi_1(x, y)} + e^{i\phi_2(x, y)} \right)$$

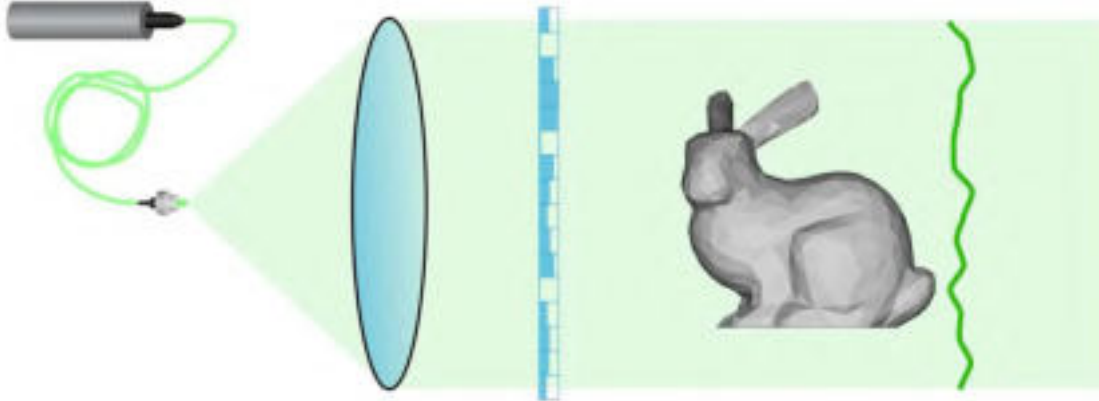
$$\phi_1(x, y) = \phi(x, y) - \cos^{-1}(a(x, y))$$

$$\phi_2(x, y) = \phi(x, y) + \cos^{-1}(a(x, y))$$

[Hsueh and Sawchuk 1978; Maimone et al. 2017]



# Computer-generated Holography: Iterative Methods



SLM phase



Target Image



propagate  
backward

propagate  
forward

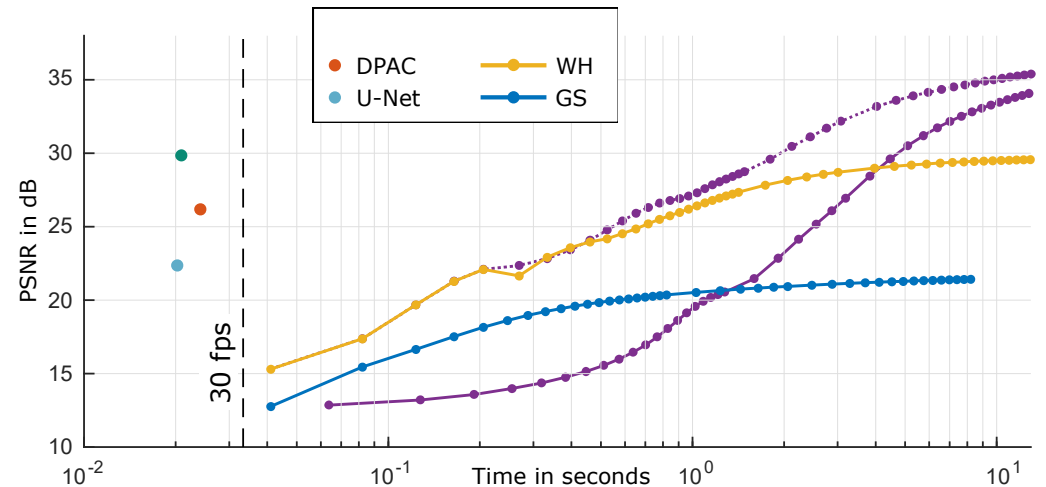
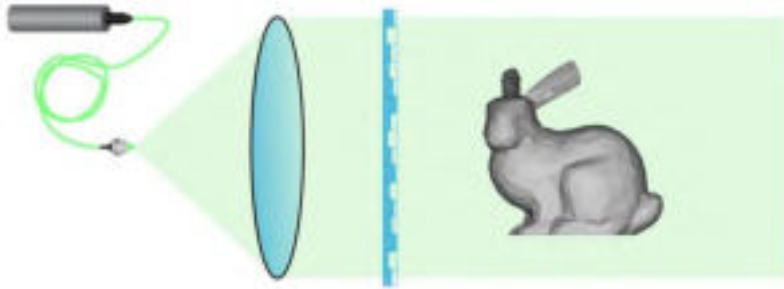
Free-space propagation:

$$u_{slm}(x, y) = \mathcal{F}^{-1} \left\{ \mathcal{F} \left\{ a(x, y) e^{i\phi(x, y)} \right\} \mathcal{H}(f_x, f_y, z) \right\}$$

$$\mathcal{H}(f_x, f_y) = \begin{cases} e^{-i \frac{2\pi}{\lambda} \sqrt{1 - (\lambda f_x)^2 - (\lambda f_y)^2} z} & \text{if } \sqrt{f_x^2 + f_y^2} < \frac{1}{\lambda} \\ 0 & \text{otherwise} \end{cases}$$

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# Computer-generated Holography



Quality

Run-time

\* DPAC: Double-phase amplitude coding  
WH: Wirtinger Holography  
GS: Gerchberg-Saxton  
SGD: Stochastic Gradient Descent

PSNR: Peak signal-to-noise ratio is an engineering term for the ratio between the maximum possible power of a signal and the power of corrupting noise that affects the fidelity of its representation.



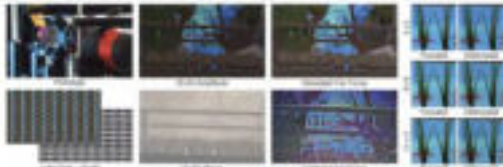
From *Heuristic* to  
*Deterministic*

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# Neural Holographic Near-eye Displays for VR/AR/MR

## Holographic Near-Eye Displays Based on Overlap-Add Stereograms

SRINATH PADMANABHAN, Stanford University,  
YIRAN PENG, Stanford University,  
GORDON WETZSTEIN, Stanford University



Overlap-add Stereograms  
ACM TOG '19

## Neural Holography with Camera-in-the-loop Training

YIRAN PENG, SUJITH CHOK, SRINATH PADMANABHAN, and GORDON WETZSTEIN, Stanford University



Fig. 1. Comparison of untrained generated holograms by G2D algorithm compared with a end-to-end holographic near-eye display. The first two columns depict images captured by a camera from a scene and after applying G2D. Wirtinger Holography accurately reconstructs an ill-structured G2D method that shows visible image quality issues like color shift. We conduct camera-in-the-loop end-to-end training to produce a better reconstructed holographic image quality (middle right). However, an untrained network architecture (bottom), that achieves a quality comparable to the best training method, appears to suffer from full-resolution G2D image quality.

Neural Holography  
ACM TOG '20

## Neural 3D Holography: Learning Accurate Wave Propagation Models for 3D Holographic Virtual and Augmented Reality Displays

SUJITH CHOK, MANU GOPALAN, and YIRAN PENG, Stanford University,  
JONGHYUN KIM, NVIDA, and Stanford University,  
GORDON WETZSTEIN, Stanford University



Fig. 1. Improved 3D untrained generated holograms (G2D) results compared with a fully-trained G2D. The bottom 3D image is a reference image. In the center, the generated image is shown. The top 3D image is a reference image. The bottom 3D image is a reference image.

Neural 3D Holography  
ACM TOG '21

## Time-multiplexed Neural Holography: A Flexible Framework for Holographic Near-eye Displays with Fast Heavily-quantized Spatial Light Modulators

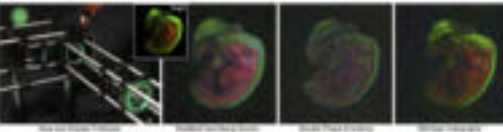
SUJITH CHOK, Stanford University, USA,  
MANU GOPALAN, Stanford University, USA,  
YIRAN PENG, Stanford University, USA,  
JONGHYUN KIM, NVIDA and Stanford University, USA,  
ANTHONY D'OTOOLE, Carnegie Mellon University, USA,  
GORDON WETZSTEIN, Stanford University, USA



Time-multiplexed Neural Holography  
ACM SIGGRAPH '22

## Wirtinger Holography for Near-Eye Displays

SRINATH CHAKRABARTHY, University of North Carolina at Chapel Hill,  
YIRAN PENG, Stanford University,  
JONATHAN KIM, Microsoft Research,  
HENRY FUCHS, University of North Carolina at Chapel Hill,  
FELIX HEIDE, Stanford University



Wirtinger Holography  
ACM TOG '19



Michelson Holography  
OSA Optica '21



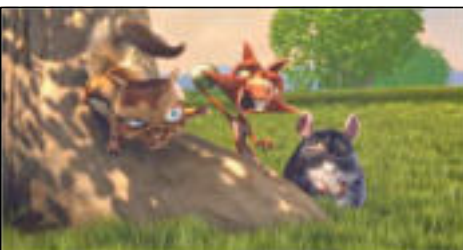
Partially-coherent Holography  
Science Advances '21

## Holographic Glasses for Virtual Reality

JONGHYUN KIM, NVIDA, USA and Stanford University, USA,  
MANU GOPALAN, SUJITH CHOK, and YIRAN PENG, Stanford University, USA,  
WALDE LOPES, NVIDA, USA,  
GORDON WETZSTEIN, Stanford University, USA



Holographic VR Glasses  
ACM SIGGRAPH '22





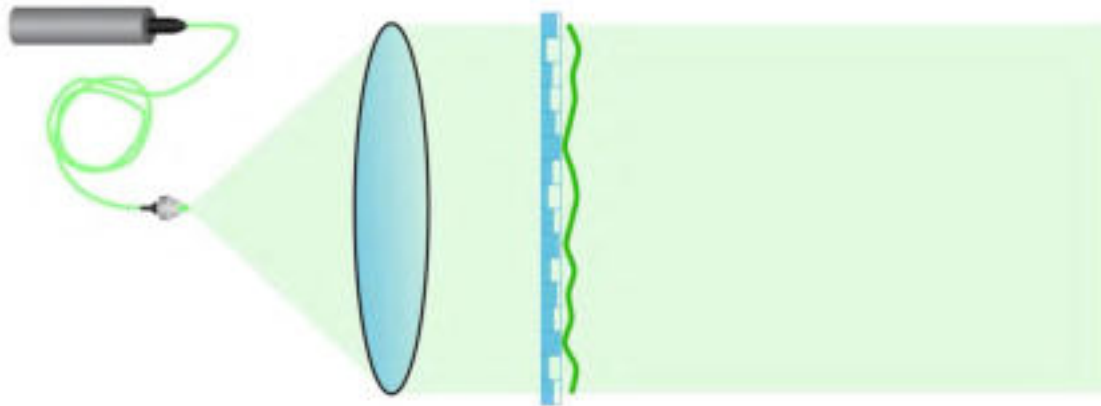
# Stochastic Gradient Descent (SGD) Optimization



backpropagate



$$\mathcal{L}(\text{Target}, \text{Simulation})$$



$$\underset{\phi}{\text{minimize}} \mathcal{L}(|\hat{f}(\phi)|, a_{\text{target}})$$

$\hat{f}$  Free-space propagation model

$f$  Unknown physical propagation,  $\hat{f} \neq f$

Iterations:

$$\phi^{(k)} \leftarrow \phi^{(k-1)} - \alpha \left( \frac{\partial \mathcal{L}}{\partial \phi} \right)^T \mathcal{L}(|\hat{f}(\phi^{(k-1)})|, a_{\text{target}})$$

\* Neural Holography, Y Peng, S Choi, N Padmanaban, G Wetzstein – ACM TOG, 2020.

# Challenges of Experimental Holography

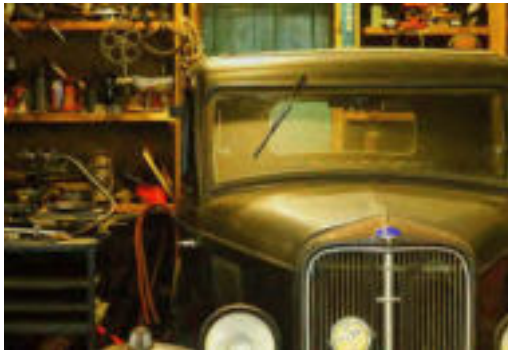
Gerchberg–Saxton  
[Gerchberg 1972]

Double Phase–Amplitude Coding  
[Maimone et al. 2017]

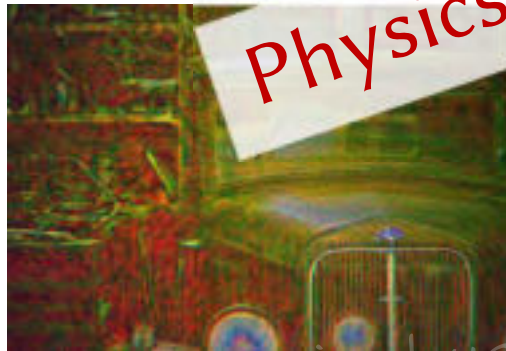
Wirtinger Holography  
[Chakravarthula et al. 2019]

SGD  
[Peng et al. 2020]

Simulated Results



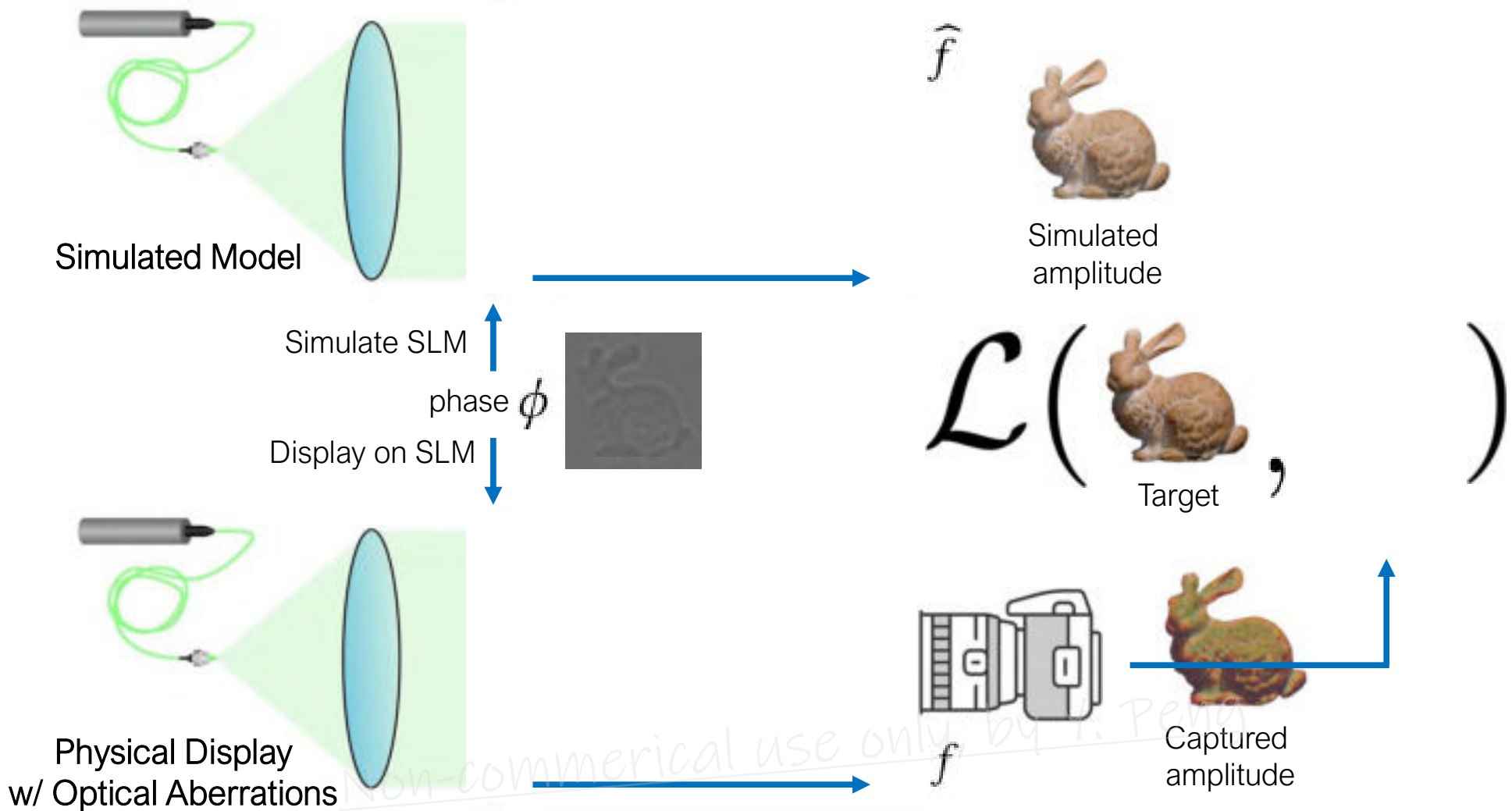
Model Mismatch



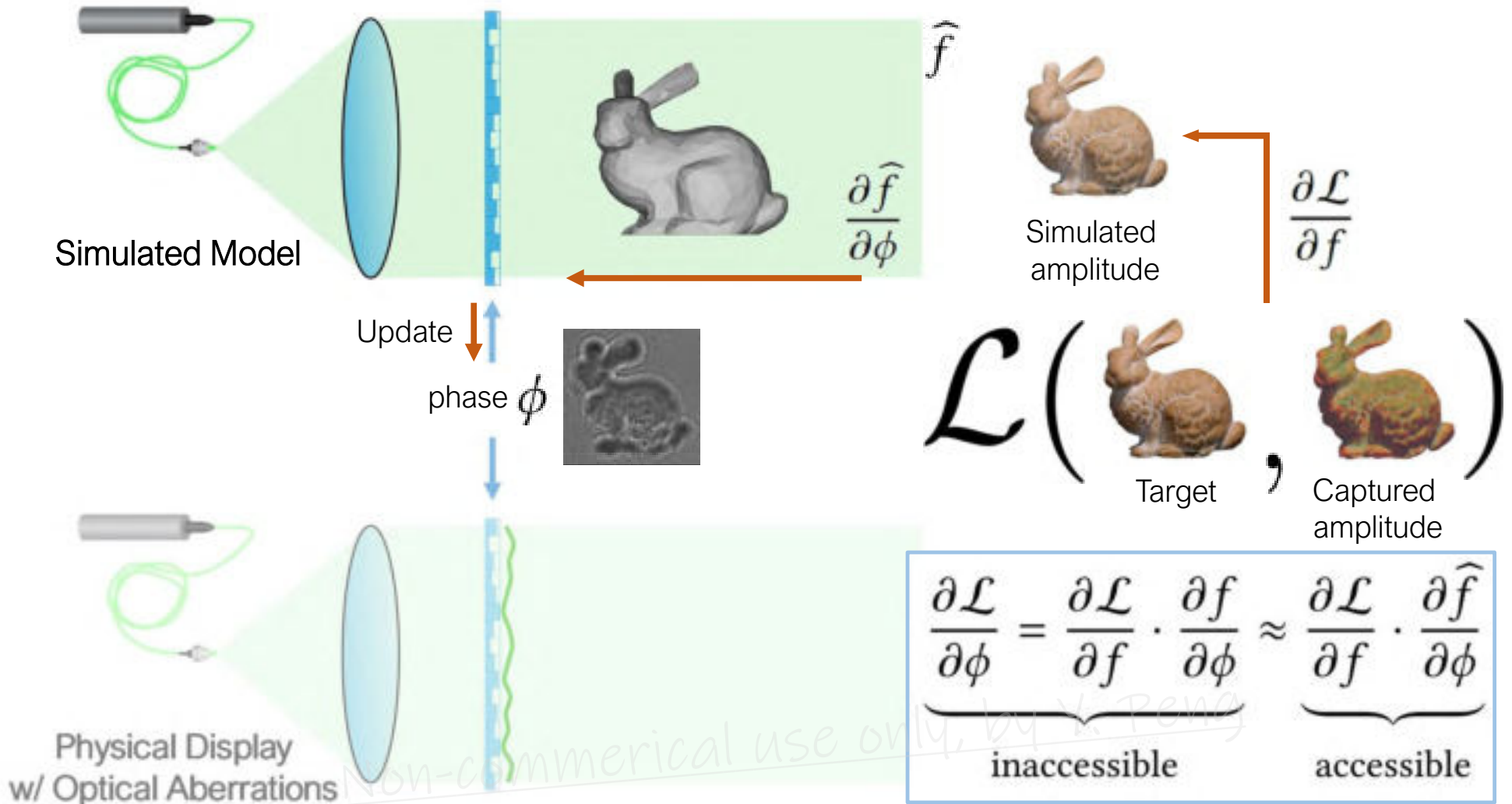
Physics Matters

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# Camera-in-the-loop (CITL) Optimization



# Camera-in-the-loop (CITL) Optimization





# CITL Hologram Optimization

SGD with Perfect Model



SGD with CITL



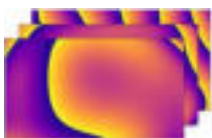
Non-commercial use only, by Y. Peng

# CITL Model Training

Model parameters  $\theta$



Source Intensity



Zernike Aberrations

backpropagate

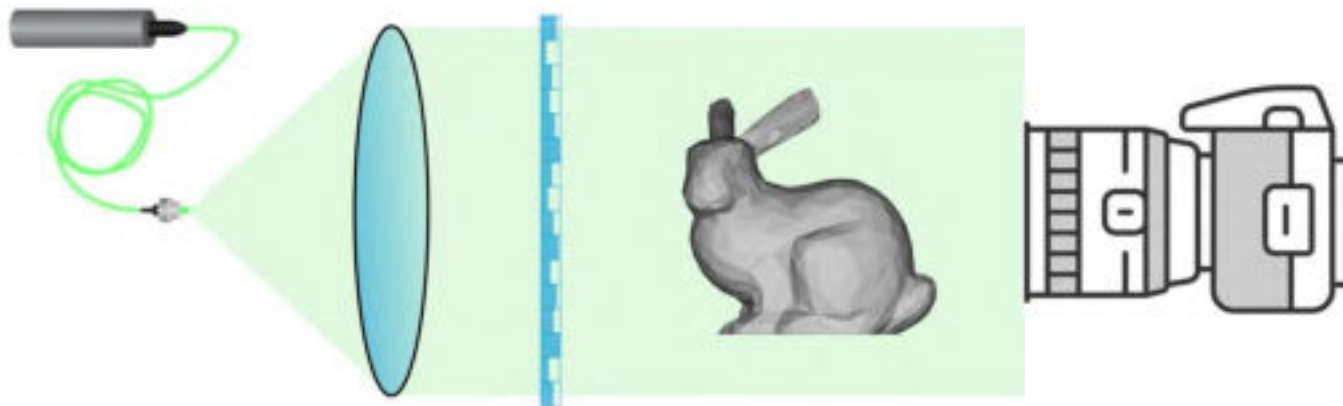
$\mathcal{L}$



Dataset



Captured images

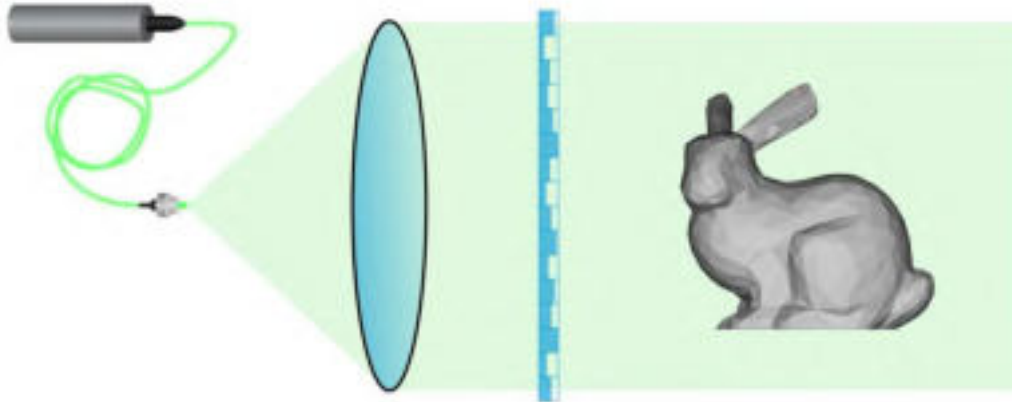


Training

$$\underset{\{\phi, \theta\}}{\text{minimize}} \mathcal{L}(|\hat{f}_{\theta}(\phi)|, a_{\text{target}})$$

Non-commercial use only

# CITL Model Training



Inference

$$\underset{\{\phi\}}{\text{minimize}} \mathcal{L}(|\hat{f}_{\theta}(\phi)|, a_{\text{target}})$$

Non-commercial use only



# Iterative Hologram Inference with CITL-trained Model

Wirtinger Holography (for reference)



SGD with CITL-trained Model



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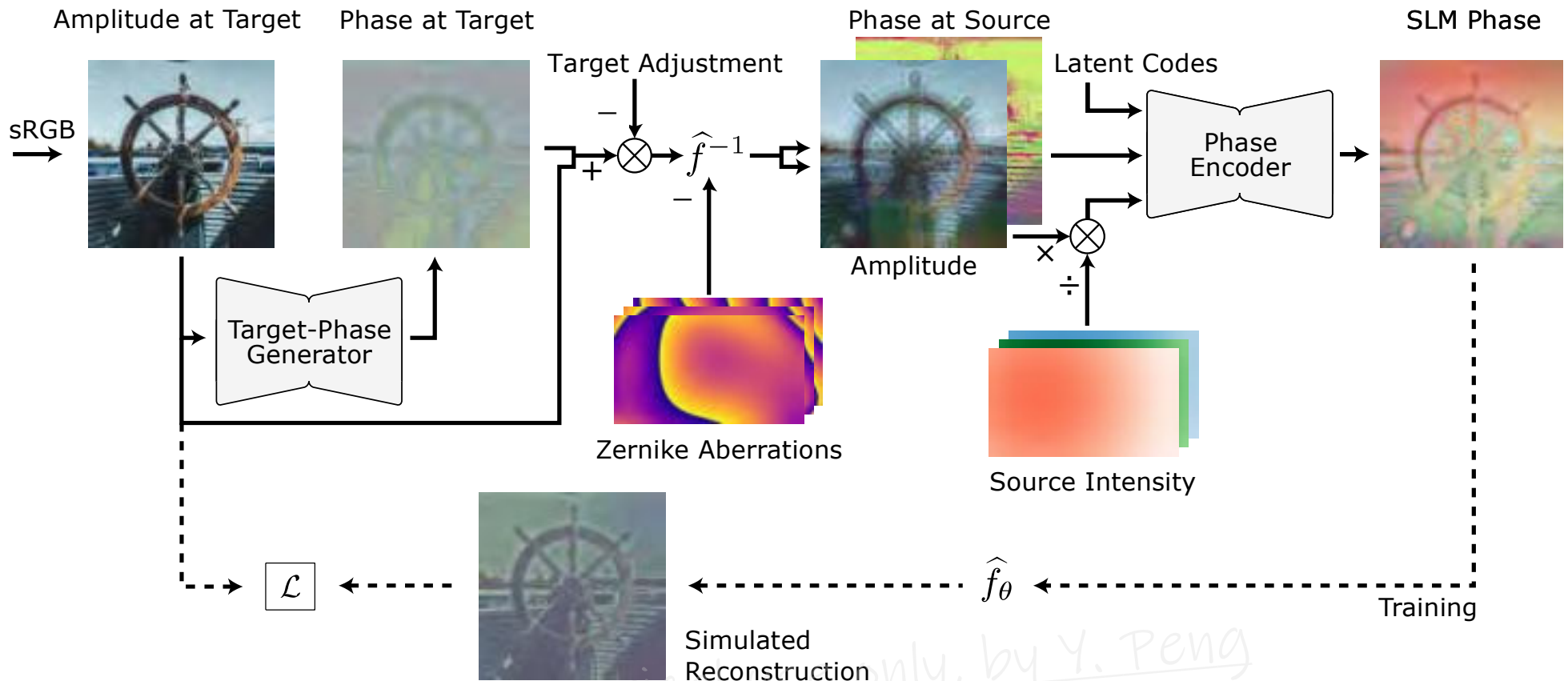




What about speed?

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# HoloNet (Inverse Network)



\* Neural Holography, Y Peng, S Choi, N Padmanaban, G Wetzstein – ACM TOG, 2020.



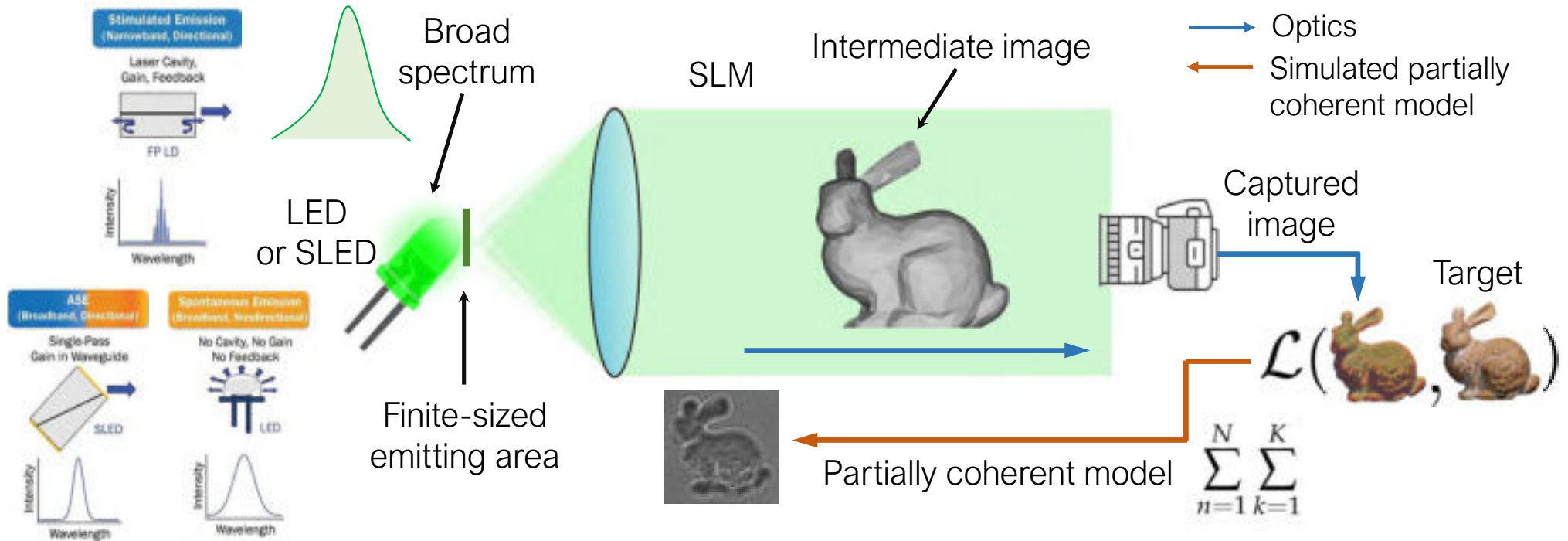
Speckle effect



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# Partially Coherent Neural Holography



- Introduce the *spatial or temporal incoherence*
- Backpropagate the loss along the *partially coherent model*

\* Partially-Coherent Neural Holography, Y. Peng\*, S. Choi\*, J. Kim, G. Wetzstein – Science Advances, 2021.



## Laser vs LED

Laser

LED



*Not for commercial use only, by Y. Peng*  
LEDs reduce speckle but introduce blur.

## LED vs SLED

LED

SLED



Both LEDs & SLEDs don't suffer from speckle, but SLEDs produce sharp images.

## Laser vs SLED



*no commercial use only, by Y. Peng*  
SLEDs maintain the image sharpness of lasers but greatly reduce speckle.



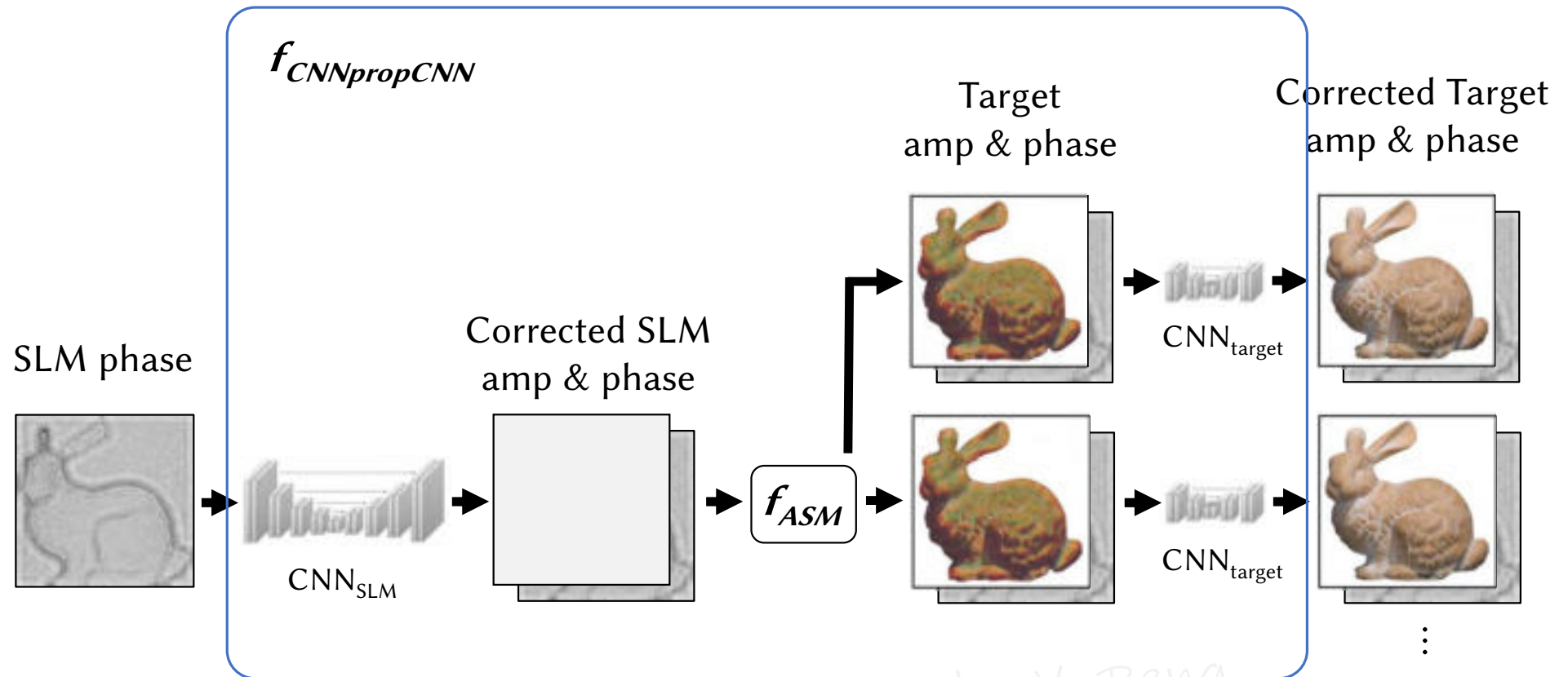


Better  
representation?

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# Neural 3D Holography with Better Model



\* Neural 3D Holography: Learning Accurate Wave Propagation Models for 3D Holographic Virtual and Augmented Reality Displays, S. Choi, M. Gopakumar, Y. Peng, J. Kim, G. Wetzstein – ACM SIGGRAPH Asia 21'.

SGD-NH

Peng et al. [2020]



SGD-ASM



SGD-CNNPropCNN  
Choi et al. [2021]

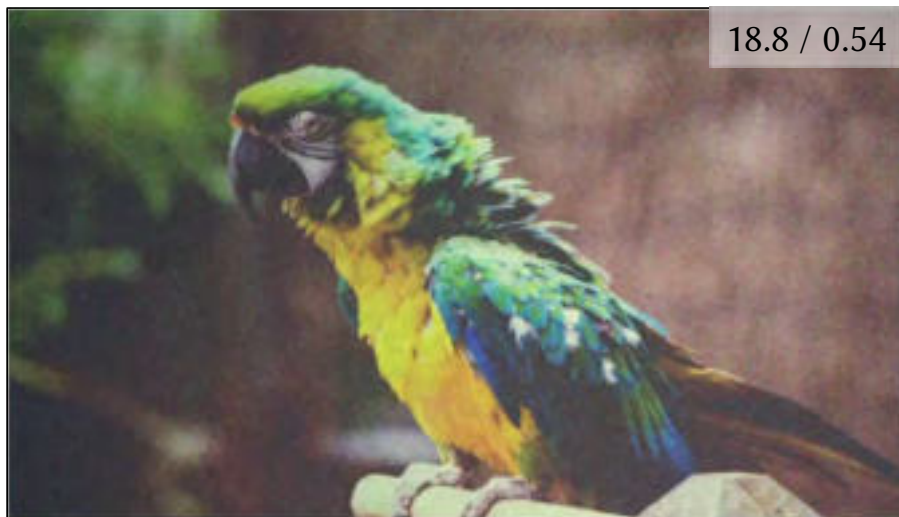


SGD-HIL  
Chak. et al. [2020]



Metrics show PSNR/SSIM, higher is better.

SGD-ASM



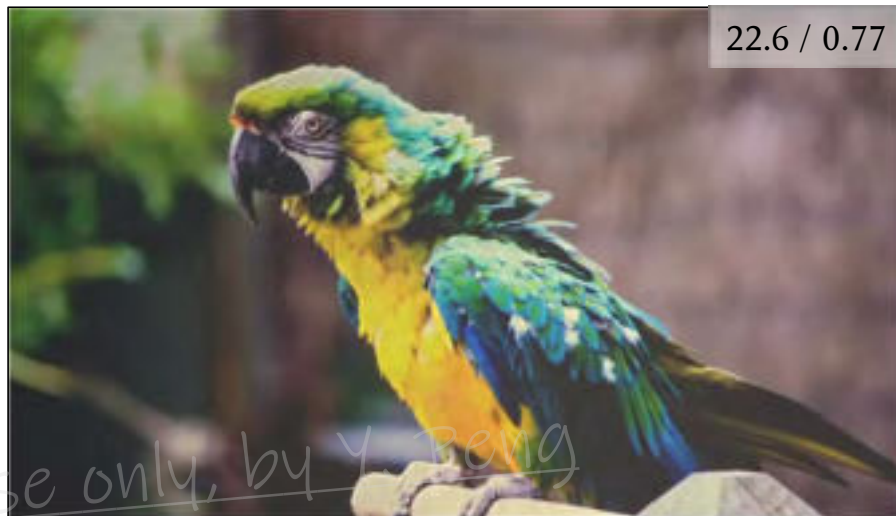
SGD-HIL  
Chak. et al. [2020]



SGD-NH  
Peng et al. [2020]



SGD-CNNPropCNN  
Choi et al. [2021]



Metrics show PSNR/SSIM, higher is better.



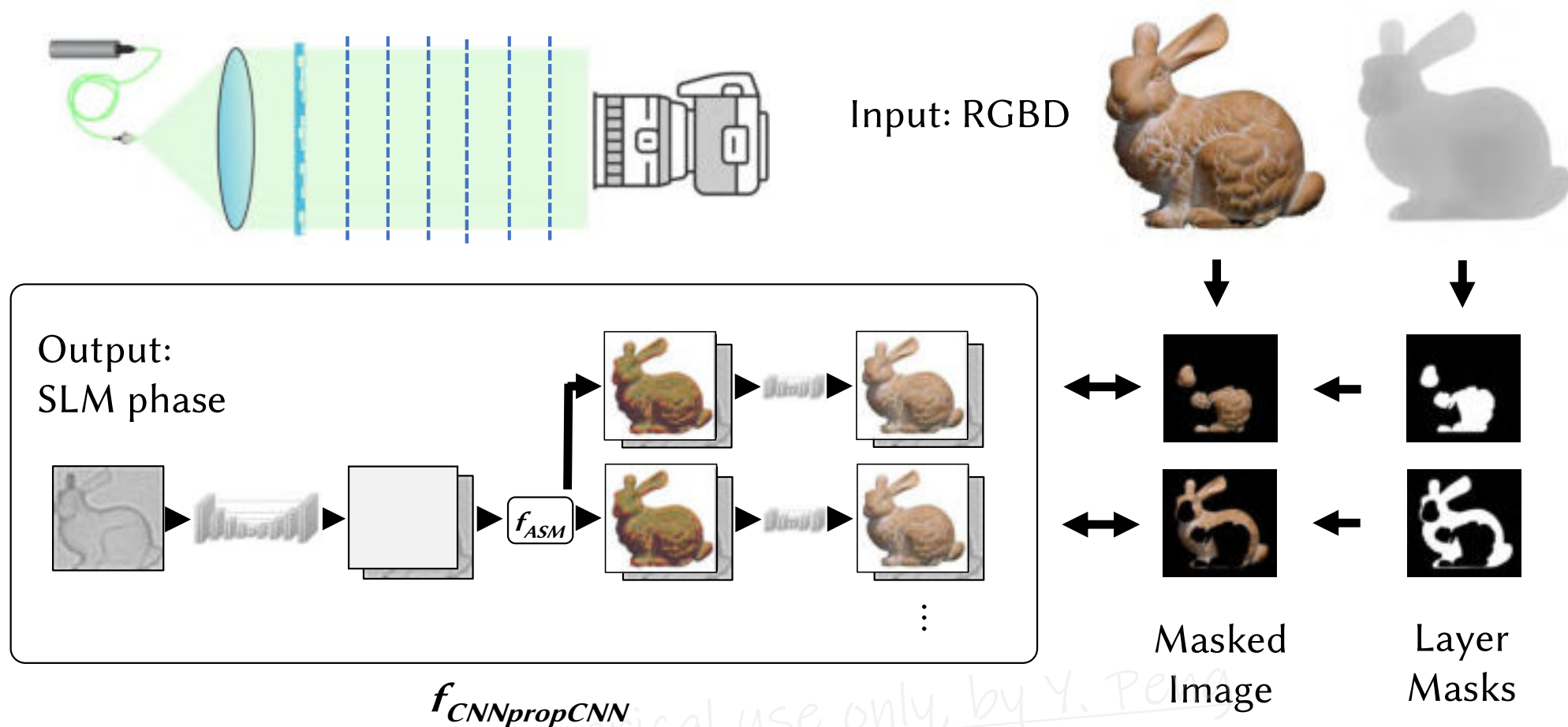


3D is the goal

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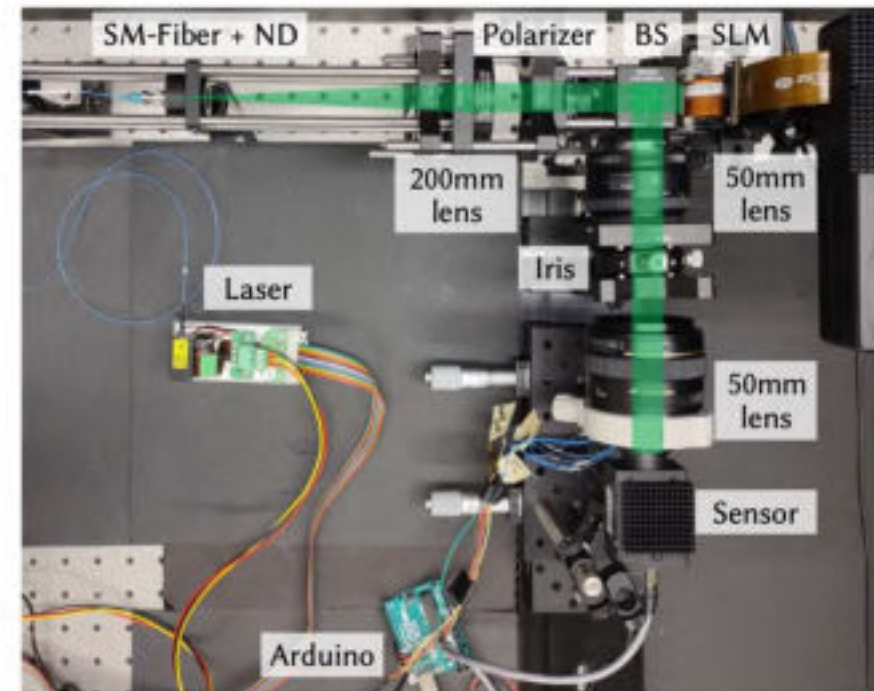
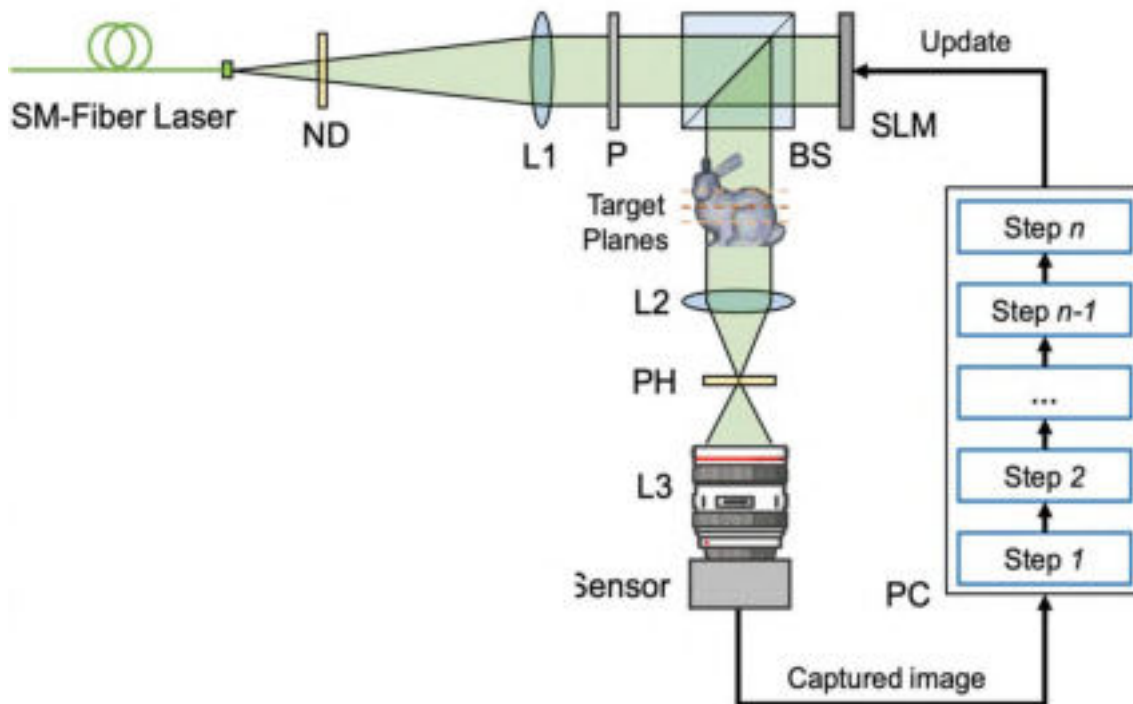


# Computing 3D Holograms



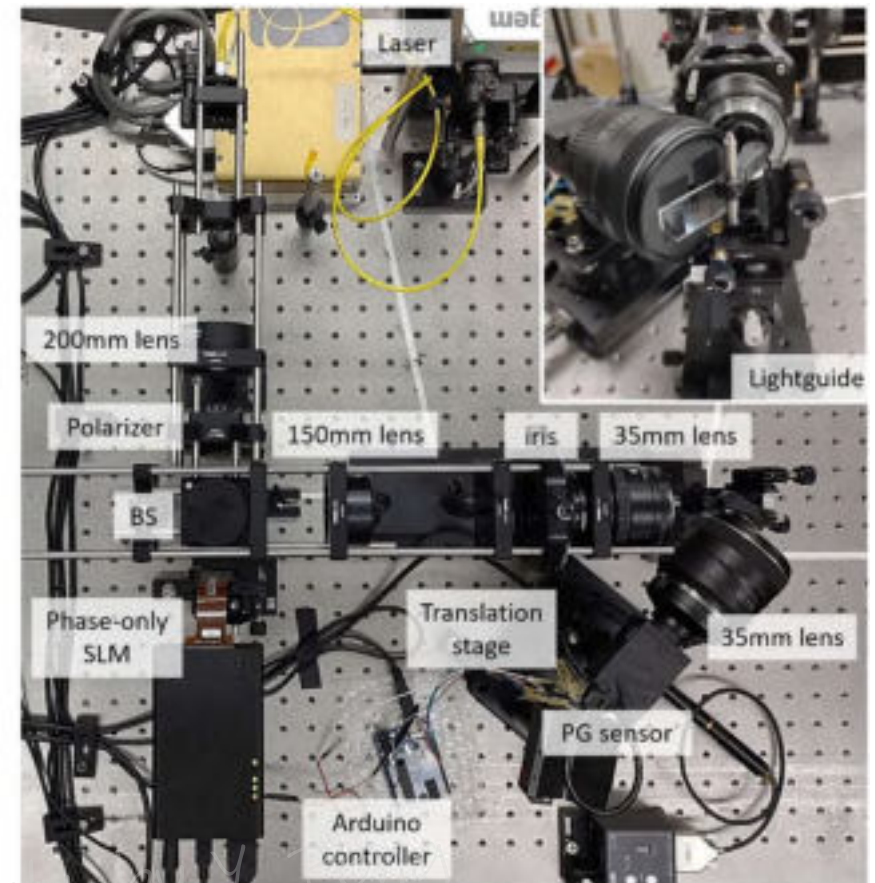
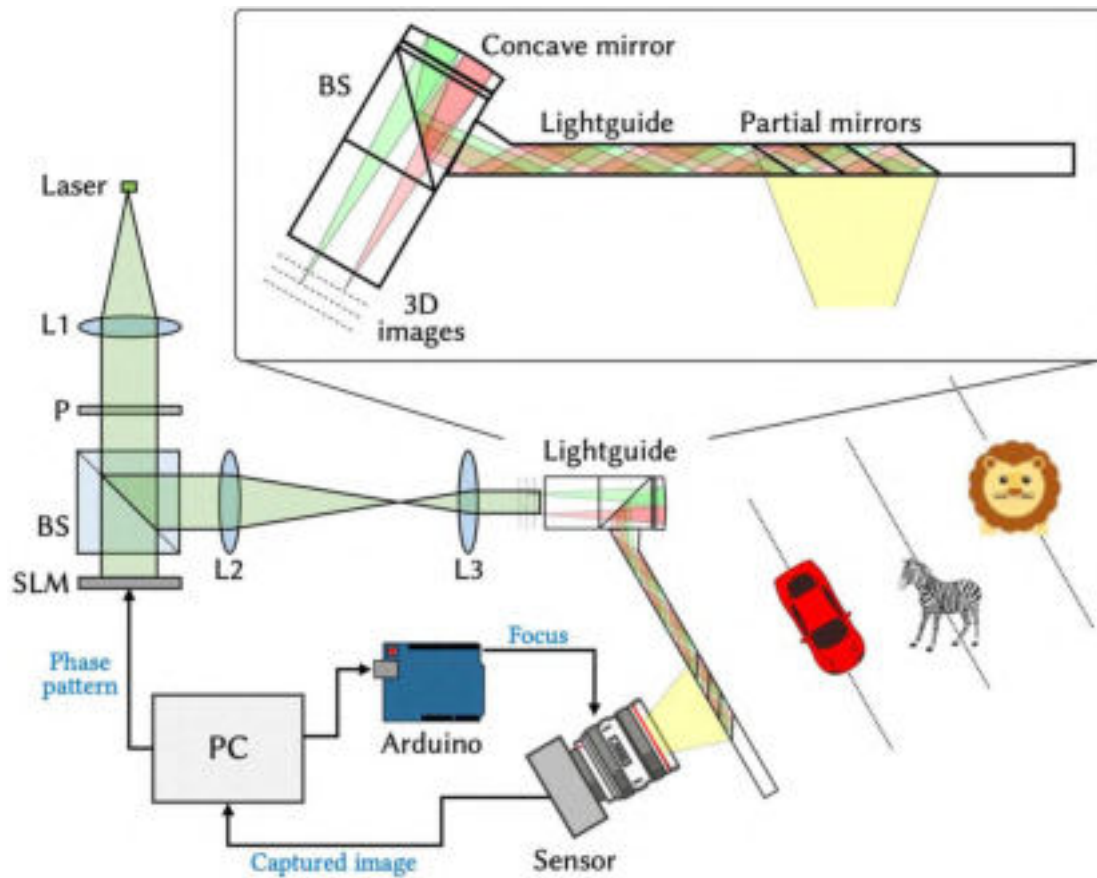
\* Neural 3D Holography: Learning Accurate Wave Propagation Models for 3D Holographic Virtual and Augmented Reality Displays, S. Choi, M. Gopakumar, Y. Peng, J. Kim, G. Wetzstein – ACM SIGGRAPH Asia 21’.

# VR Holographic Near-eye Display Prototype



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# AR Holographic Near-eye Display Prototype



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DPAC



SGD-CNNpropCNN



SGD-ASM



ADMM-CNNpropCNN



Far

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Focused

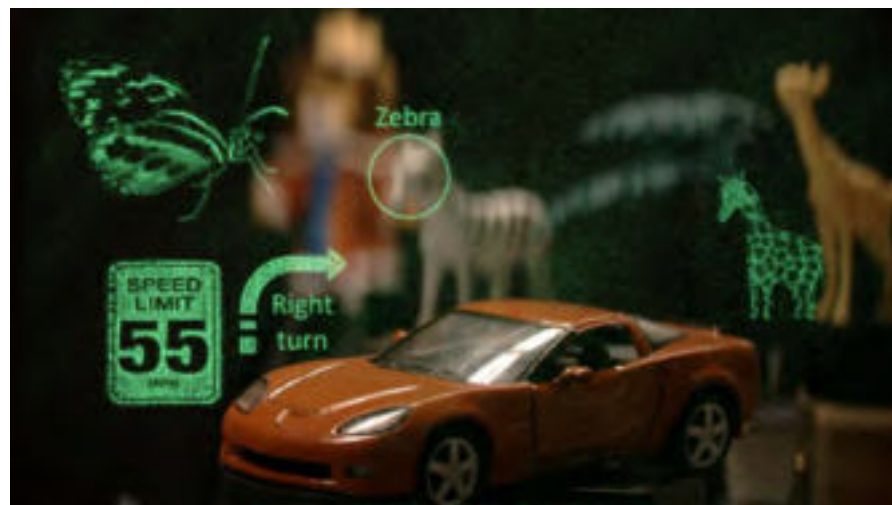
Near



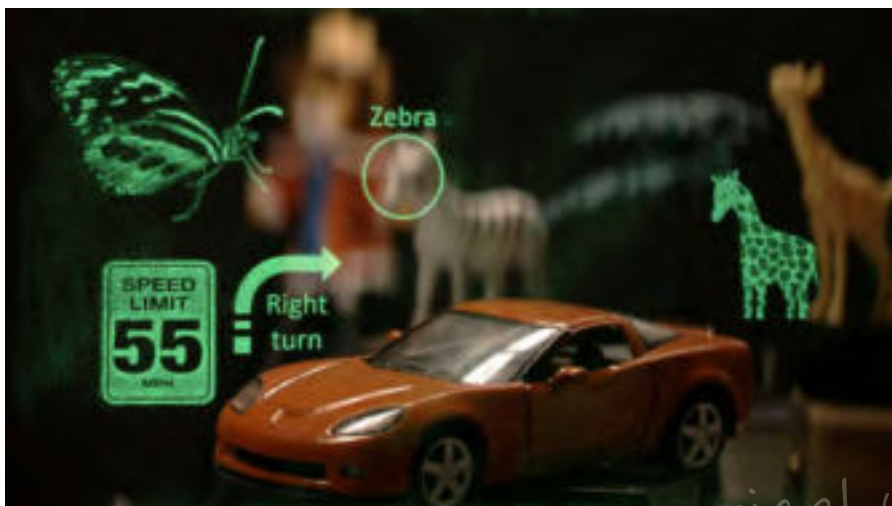
DPAC



SGD-ASM



SGD-CNNpropCNN



ADMM-CNNpropCNN



Far



Focused

Near

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# Towards Real-time Photorealistic 3D Holography with Deep Neural Networks (MIT's work)



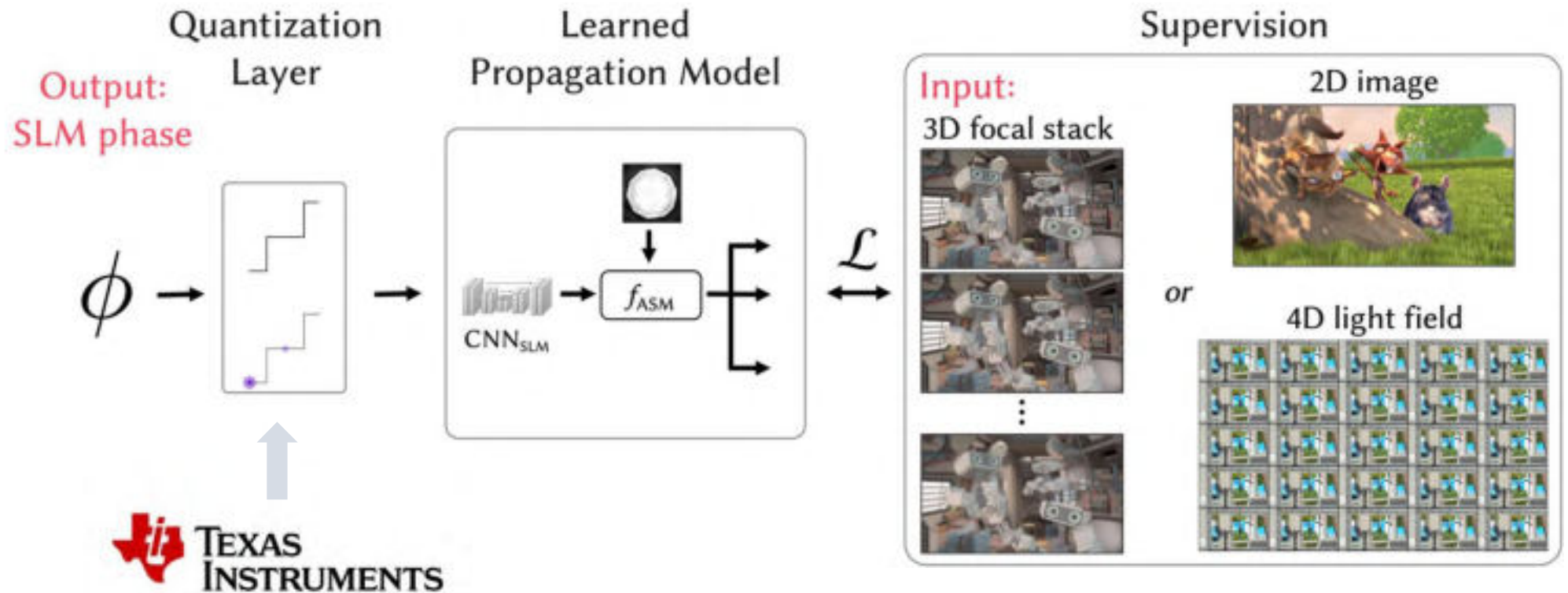


Natural focus cues  
matter

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# Time-multiplexed Neural Holography: Flexible CGH Framework



*Time-multiplexing Helps Bypass the SLM Bandwidth Limit*

S. Choi\*, M. Gopakumar\*, Y. Peng, J. Kim, G. Wetzstein, Time-multiplexed Neural Holography: A flexible framework for holographic near-eye displays with fast heavily-quantized spatial light modulators, ACM SIGGRAPH, 2022



# Time-multiplexed Neural Holography: Flexible CGH Framework with Natural Defocus (Stanford's work, SIGGRAPH 2022)



# Computationally Enabling Holographic Displays

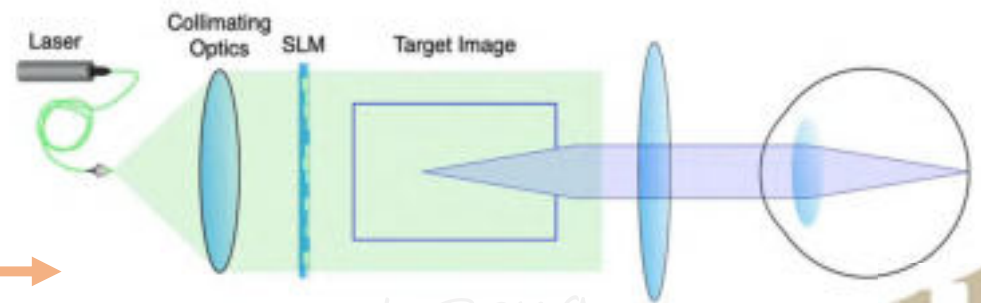
Computer-generated Holography



Machine intelligence



- Varifocal Displays
- Multiplane Displays
- Light Field Displays



Holographic Displays

Not every so-called HoloX is Holo

## CGH+ AI State-of-the-arts (Only part of)

- *Time-multiplexed neural holography: A flexible framework for holographic near-eye displays with fast heavily-quantized spatial light modulators*, S Choi, M Gopakumar, Y Peng, J Kim, G Wetzstein, ACM SIGGRAPH, 2022
- *Towards real-time photorealistic 3D holography with deep neural networks*, L Shi, B Li, C Kim, P Kellnhofer, W Matusik - Nature, 2021
- *Neural 3D holography: Learning accurate wave propagation models for 3D holographic virtual and augmented reality displays*, S Choi, M Gopakumar, Y Peng, J Kim, G Wetzstein - ACM Transactions on Graphics, 2021
- *Speckle-free holography with partially coherent light sources and camera-in-the-loop calibration*, Y Peng, S Choi, J Kim, G Wetzstein - Science Advances, 2021
- *Optimizing image quality for holographic near-eye displays with Michelson Holography*, S Choi, J Kim, Y Peng, G Wetzstein - OSA Optica, 2021
- *Neural holography*, Y Peng, S Choi, N Padmanaban, G Wetzstein - ACM Transactions on Graphics, 2020
- *Learned hardware-in-the-loop phase retrieval for holographic near-eye displays*, P Chakravarthula, E Tseng, T Srivastava, H Fuchs, F Heide - ACM Transactions on Graphics, 2020
- *Holographic near-eye displays based on overlap-add stereograms*, N Padmanaban, Y Peng, G Wetzstein - ACM Transactions on Graphics, 2019
- *Wirtinger holography for near-eye displays*, P Chakravarthula, Y Peng, J Kollin, H Fuchs, F Heide - ACM Transactions on Graphics, 2019
- ...

*Stanford, HKU, Meta Reality Labs, Nvidia Research, Princeton, Seoul National Univ., MIT, Tsinghua Univ., Zhejiang Univ., etc.*

Horizon

*A Long Way to Go*

**Limited eye-box!!!**

**Joint Design of Hardware & Software & Human Science**

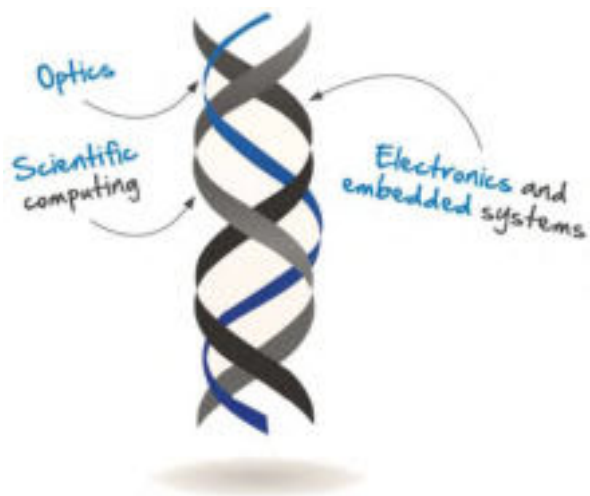
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WeChat Official Account: *IntelligentOptics*

## Intelligent Optics Sharing



感知 | 计算



成像 | 显示



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Thank  
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