Display Tech. for VR/AR

- Computational Light Field and Holography

GAMES 204

2022-11

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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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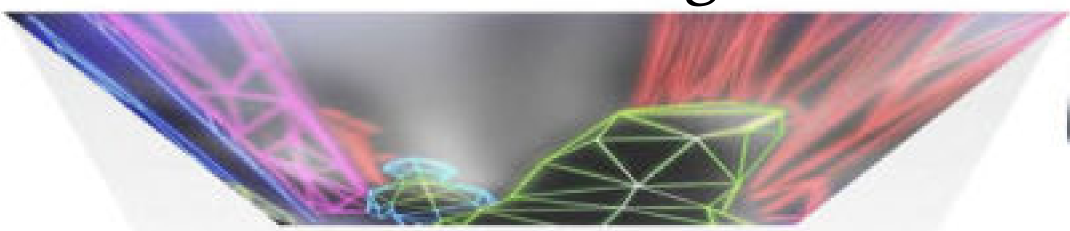
Accelerating Progress of Near-eye Displays

Virtual Image



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

Computational Near-eye Displays with Focus Cues

Gaze-contingent Varifocal Displays

Mechanical actuation or focus-tunable lens

Shiwa et al. 1996; Liu et al. 2008;
Konrad et al. 2016; Padmanaban et al. 2016, 2017; …

Multiplane Displays

High-speed SLMs or high system complexity

Rolland et al. 2000; Akeley et al. 2004
Liu et al. 2008; Love et al. 2009; …

Near-eye Light Field Displays

Resolution is limited by diffraction

Lanman and Luebke 2013;
Hua and Javidi 2014; Huang et al. 2015

Evolution of Holography

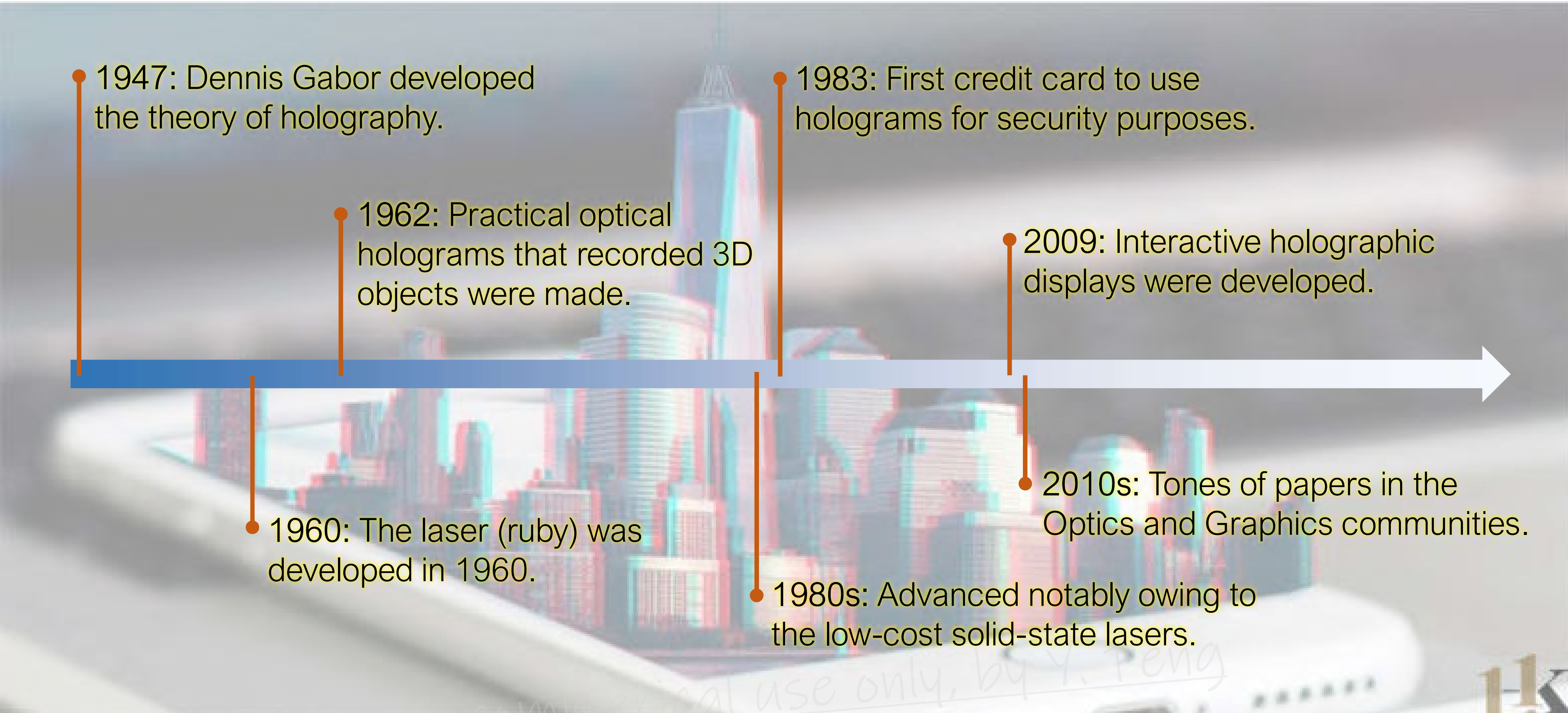


Image credit @ bbvaopenmind

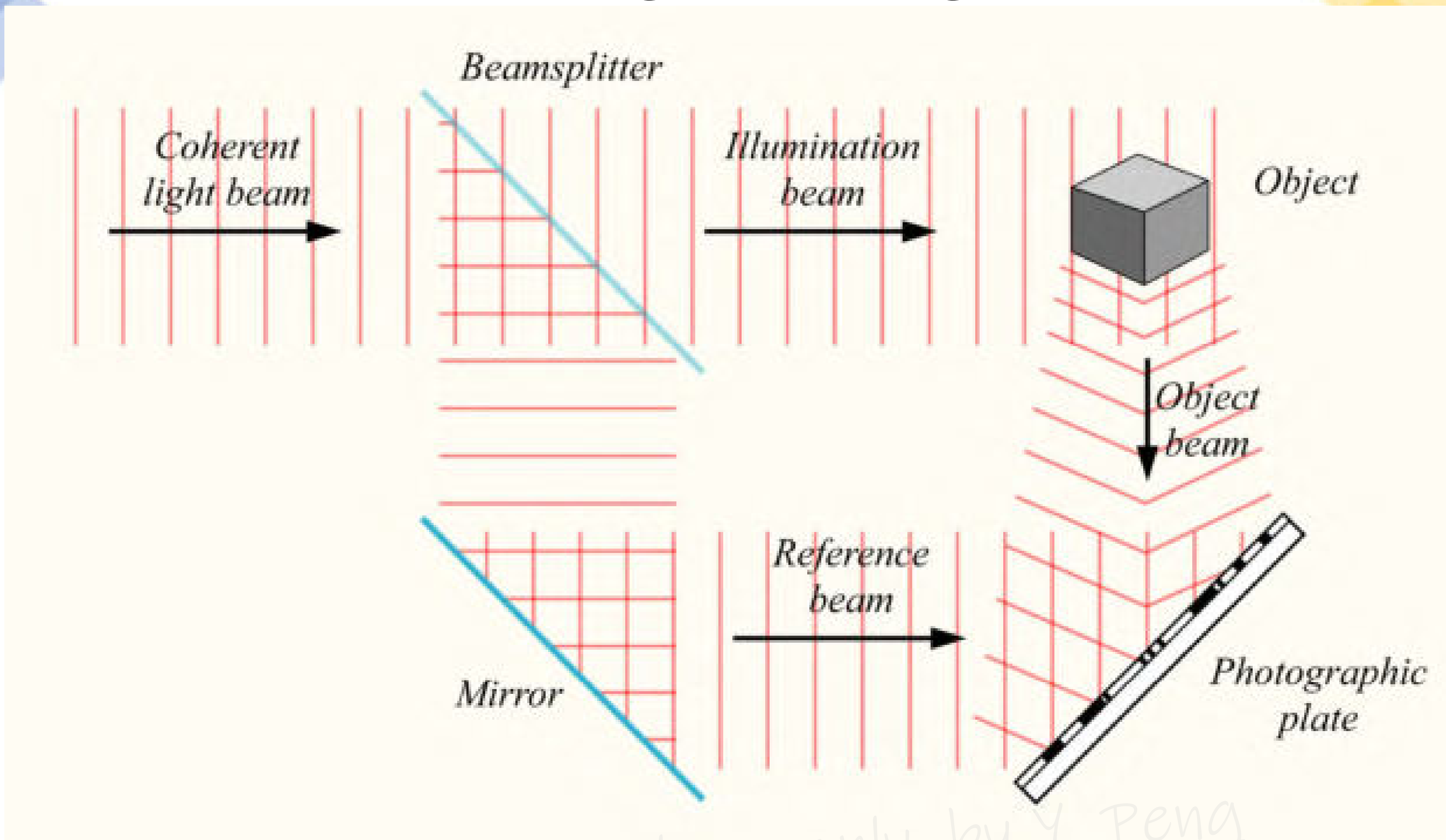
Holographic Displays (Holograms)

Photo from the ISDH2012 hologram exhibition in Saint Petersburg, Russia

https://www.youtube.com/watch?v=0ics3RVSn9w&fbclid=IwAR1k...

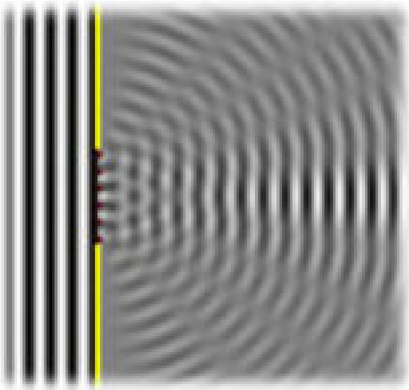
https://www.youtube.com/watch?v=sQS6_DbYIAw

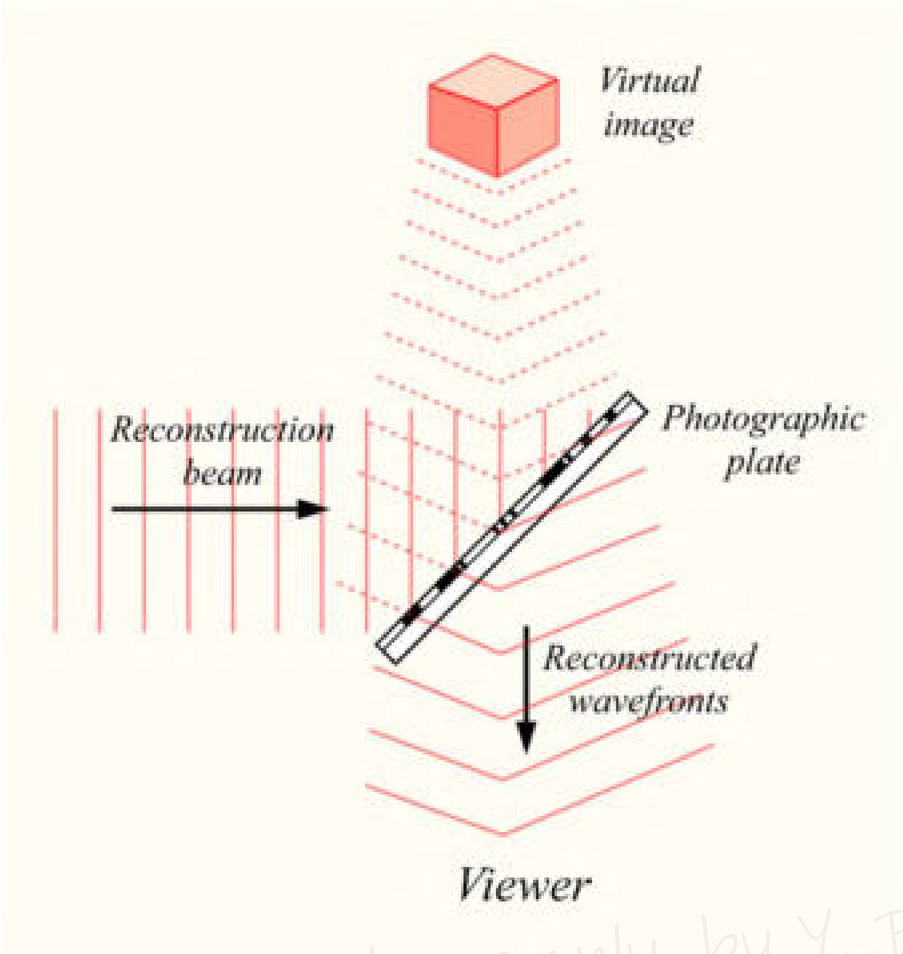
Recording the Hologram

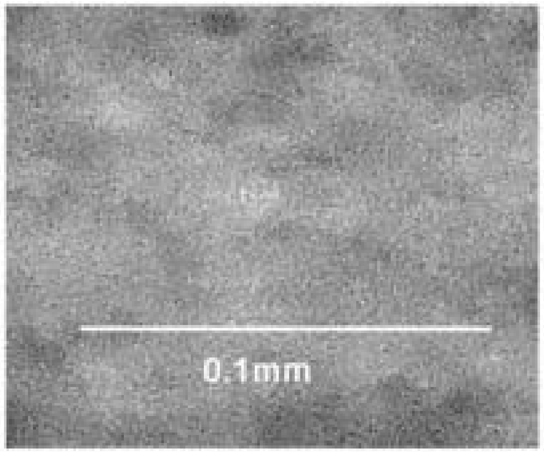


[Figure Credit: Wikipedia]

Reconstructing the Hologram







[Figure Credit: Wikipedia]

Multi-view *or* Light Field *or* Holography

From Ray Reconstruction to Wavefront Reconstruction

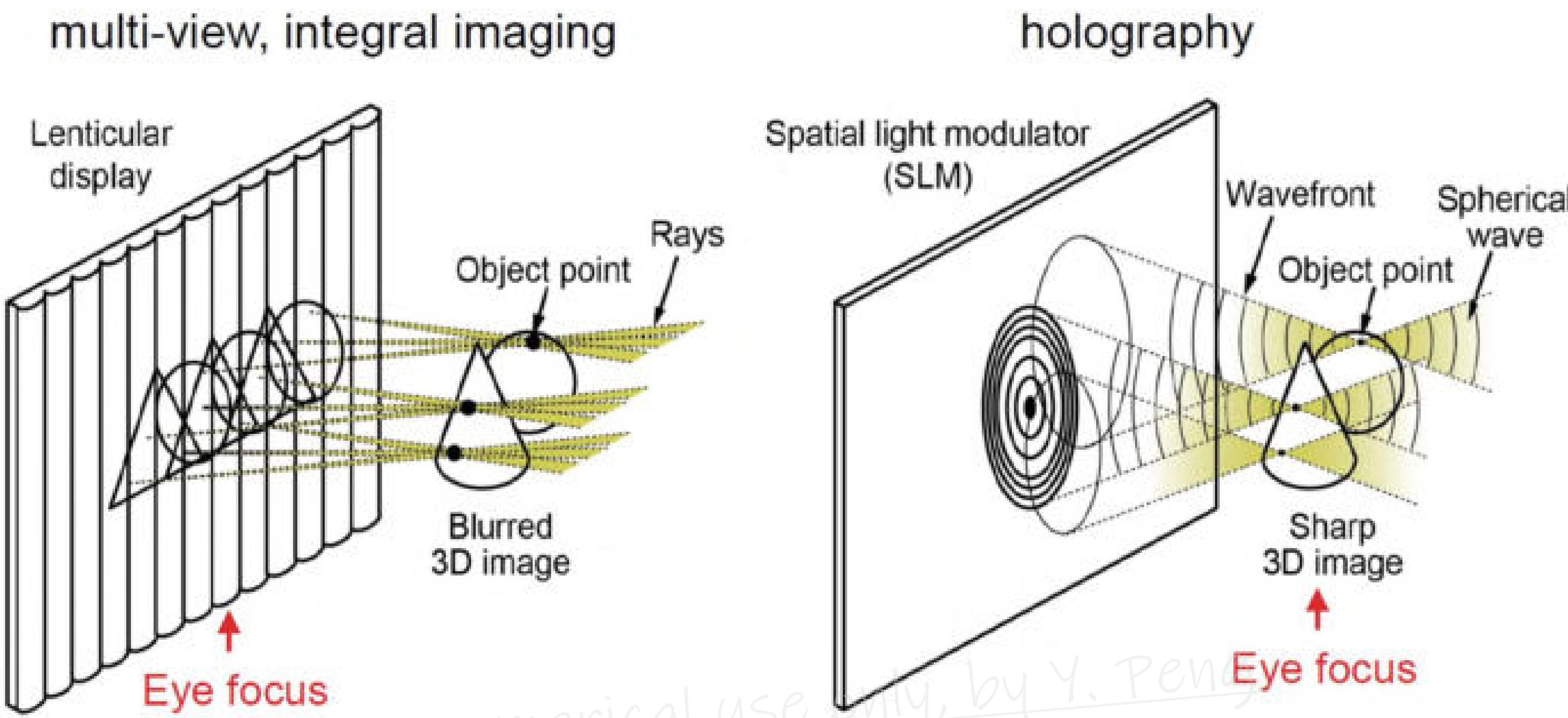
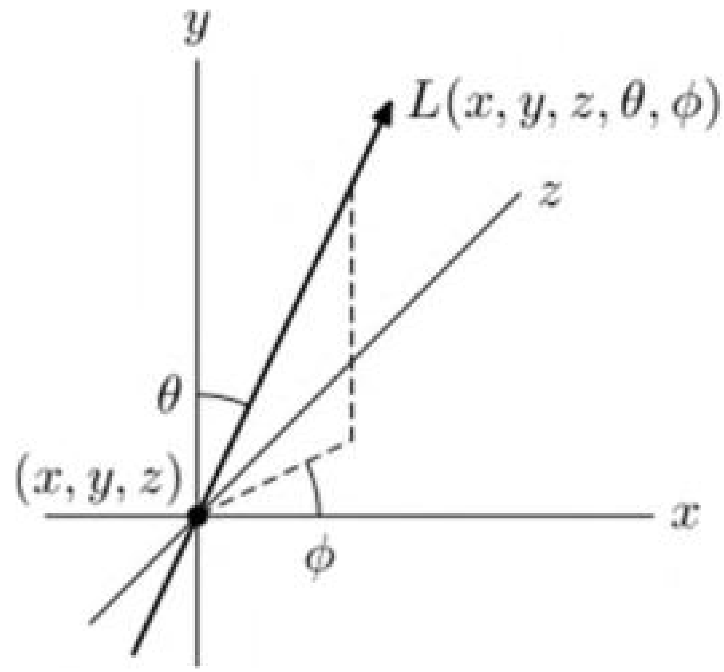
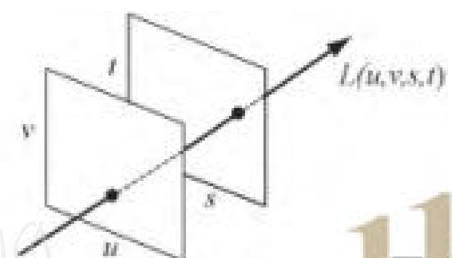


Image Credit @ Y. Takaki

Light Field

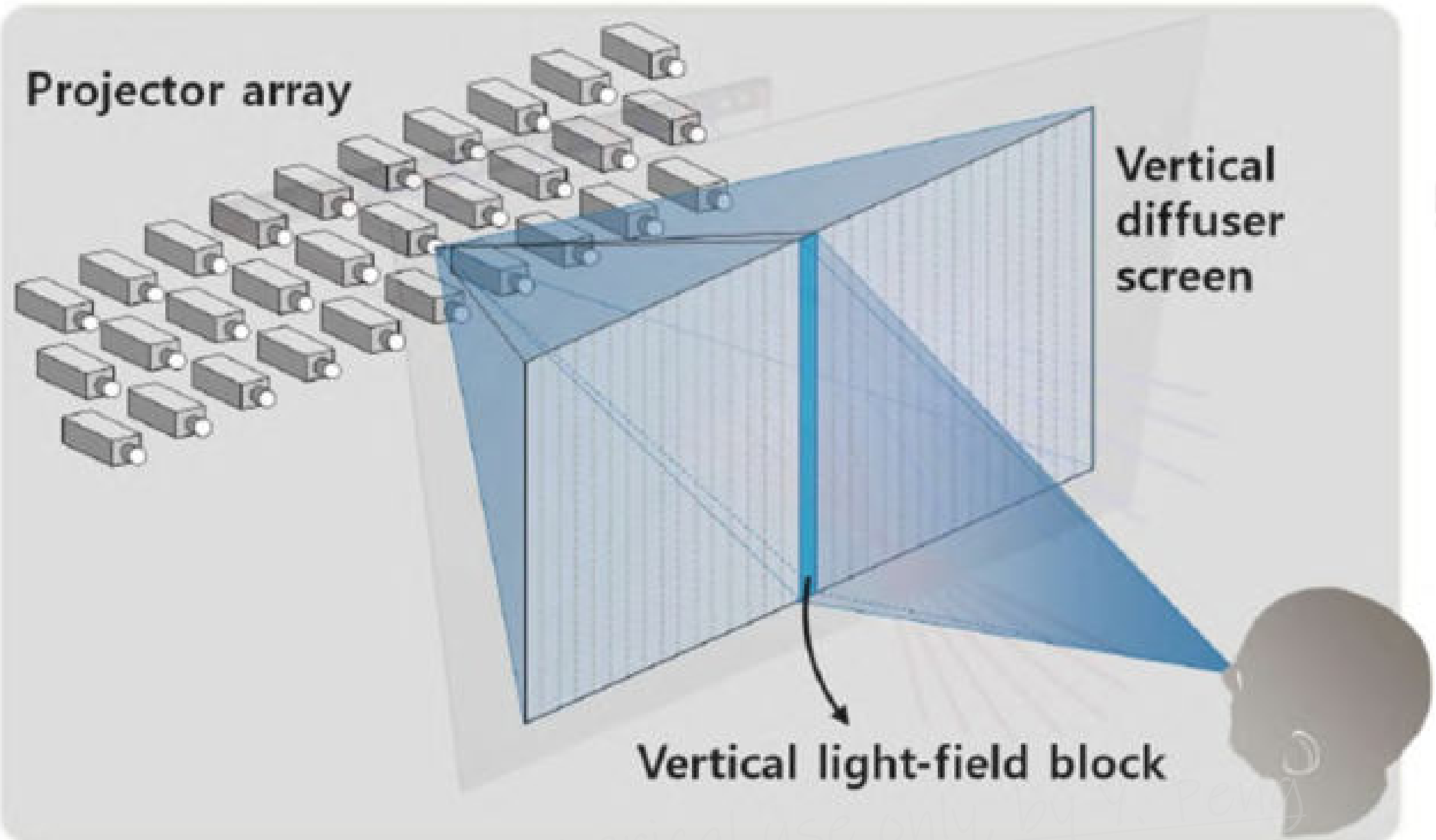
- A vector function that describes the amount of light flowing in every direction through every point in space. The space of all possible *light rays* is given by the five-dimensional **plenoptic function**, and the magnitude of each ray is given by its radiance.
- **Optics or Graphics?**
- **5D or 4D?**





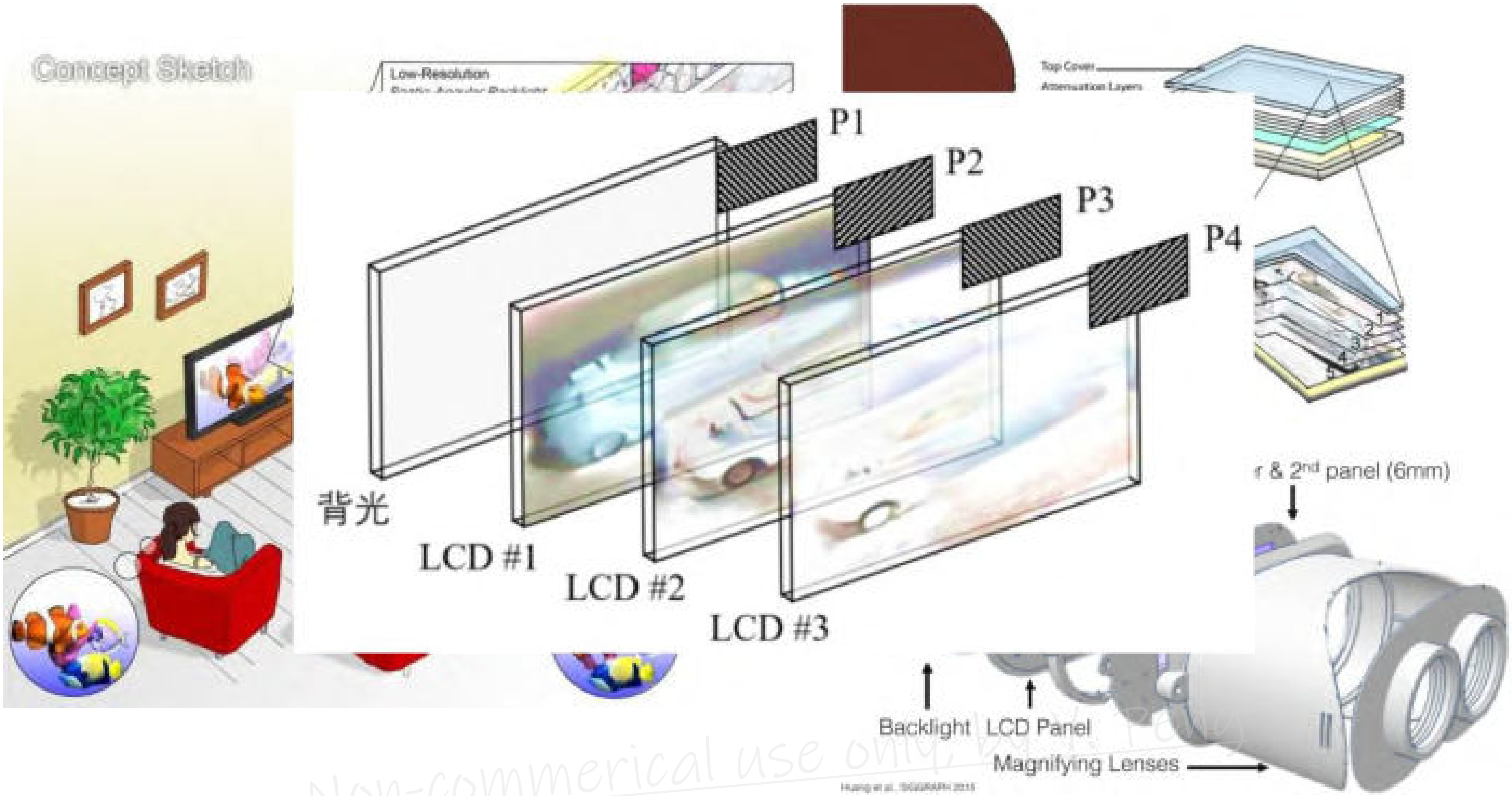
Images from public domain

Images from public domain



Images from public domain

Light Field Acquisition and Display

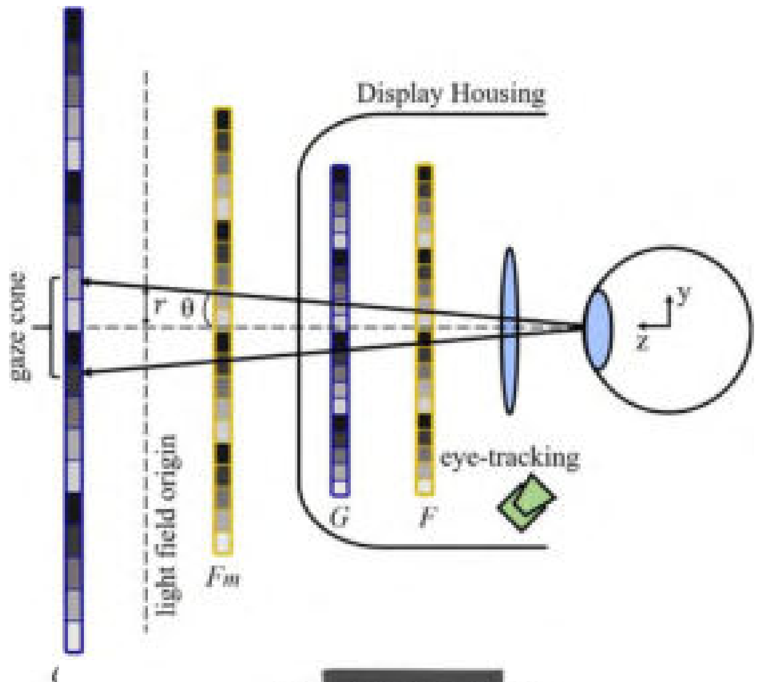


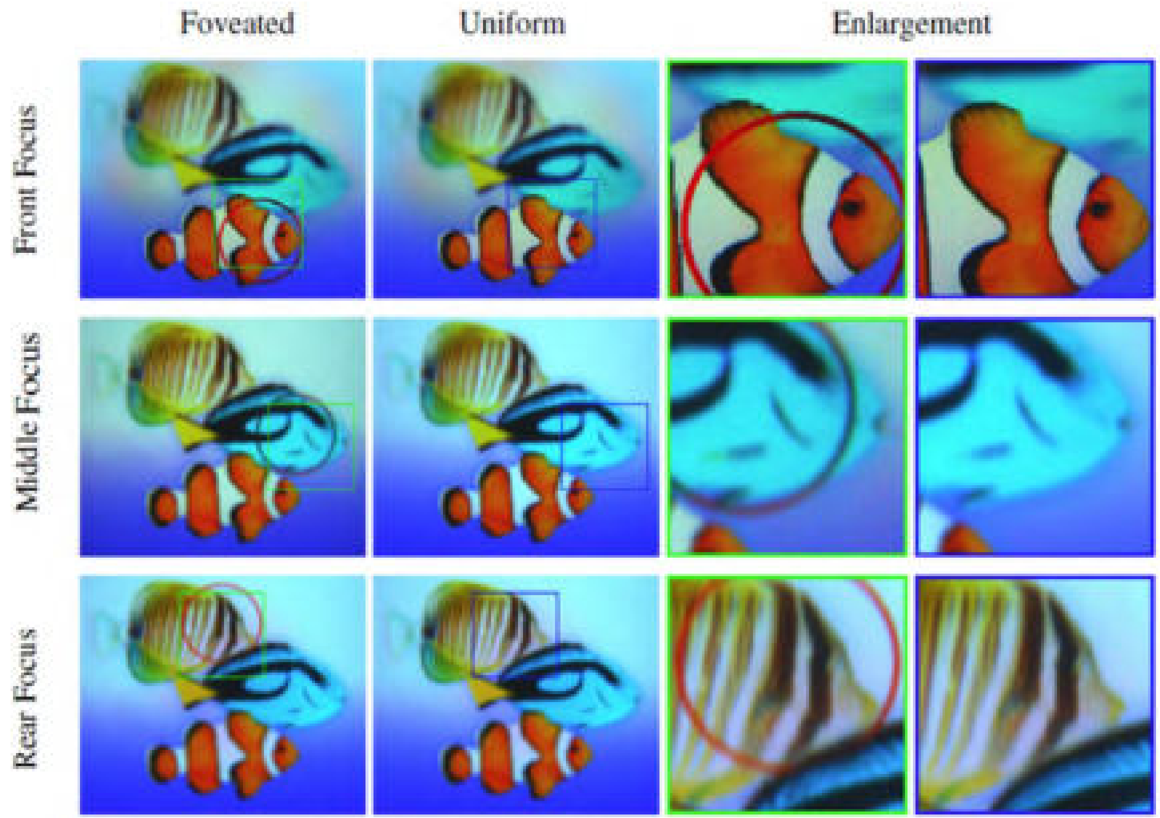
Images from public domain

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

[Wetzstein et al.]

Light Field Stereo Displays





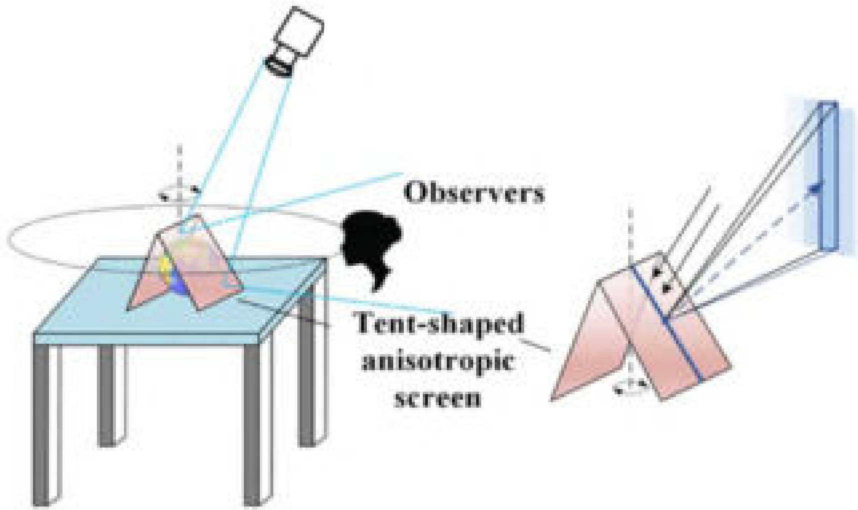
Huang, F. C. et al., ACM Trans. Graph. 34(4), 60 (2015).
Gao, C. et al., App. Opt. 60(28), 8634 (2021).

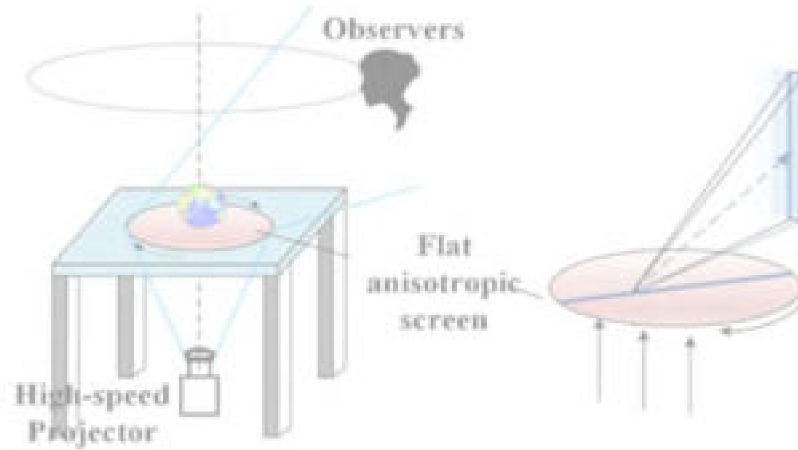
Interactive Focal Stack Video See-through MR (IEEE VR)

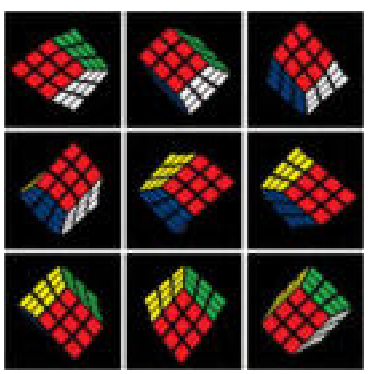
Focal Stack Acquisition + Real-time Tracking & Rendering + Light Field Display = MR

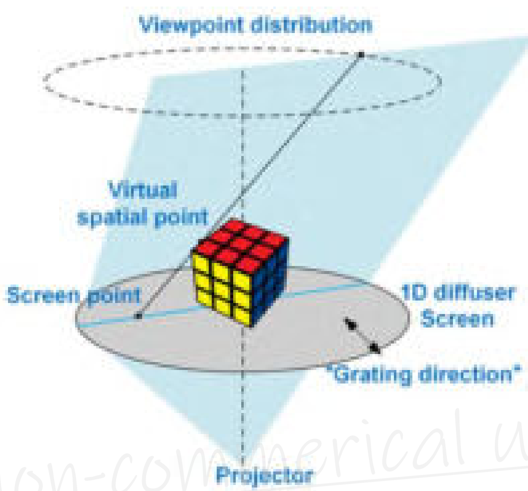
C Ebner, S Mori, P Mohr, Y Peng, D Schmalstieg, G Wetzstein, D Kalkofen - *Video See-Through Mixed Reality with Focus Cues*
IEEE Transactions on Visualization and Computer Graphics 28 (5), 2022.

Interactive Table-top Light Field Display & Rendering



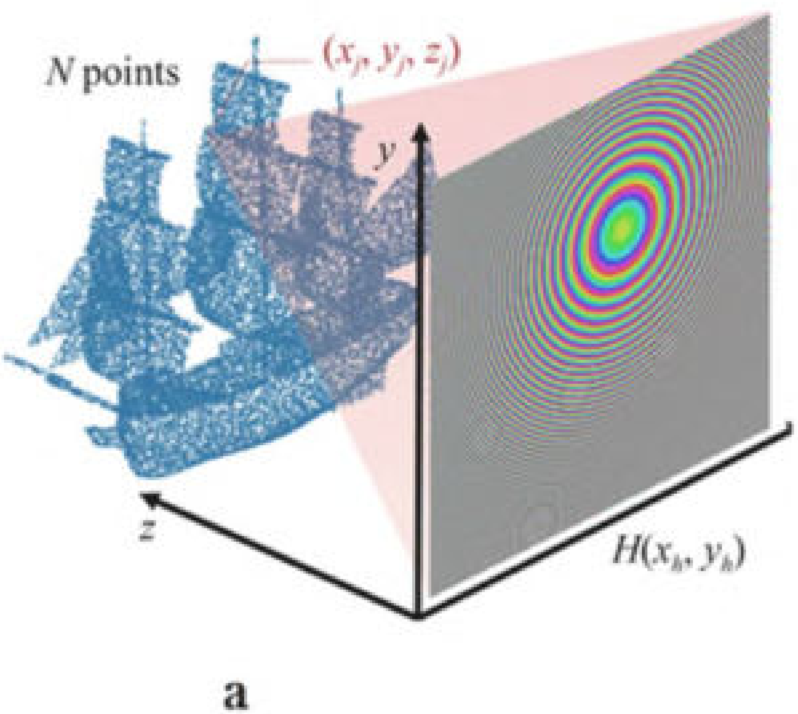


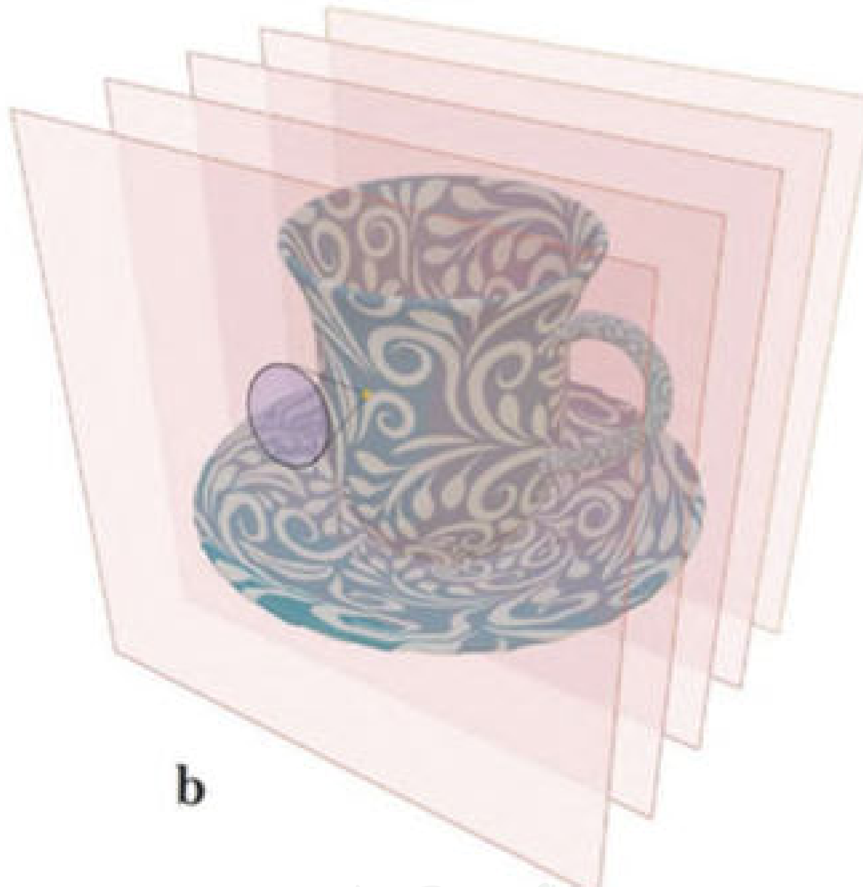




* *Research conducted during* 2011-2016 (OSA OE '15, ACM SigAsia '16, IEEE JDT '16).

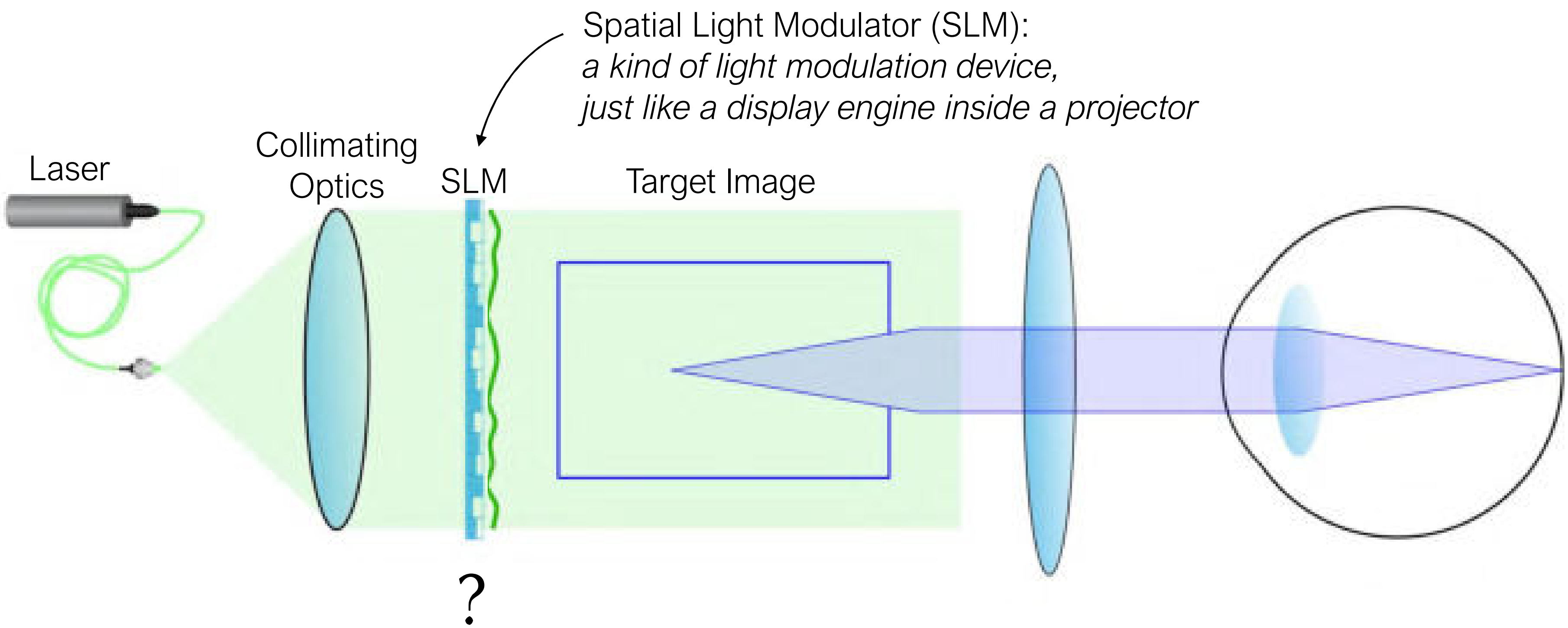
Classical Computer-generated Hologram Schemes





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

Holographic Near-eye Displays



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

SLMs for Wave Modulation

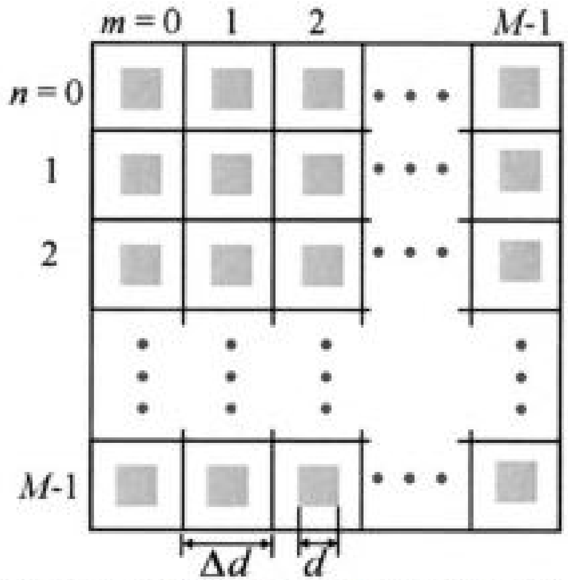
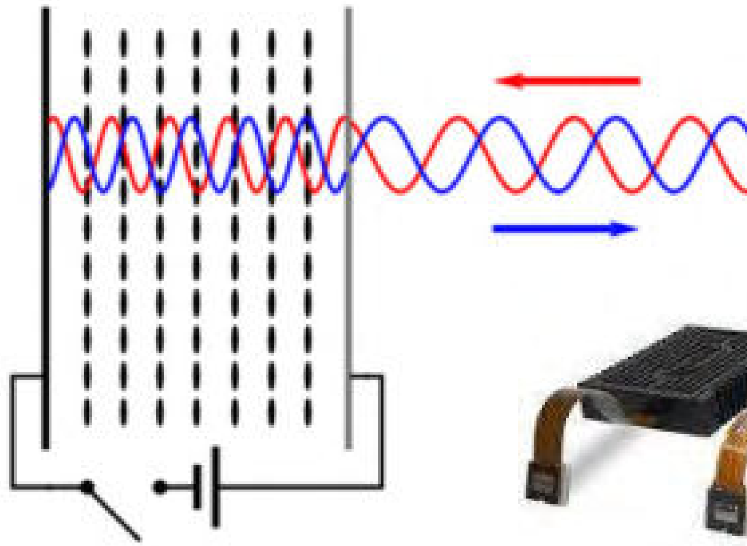


Fig. 1. Geometry of the $M \times M$ phase-only spatial light modulator with a square pixel length d while Δd is the period length. The active phase-encoding area of a pixel is shaded gray.

[Palima et al. 2006]



Pixel pitch
Resolution
Grayscale
Modulation range
Refresh rate

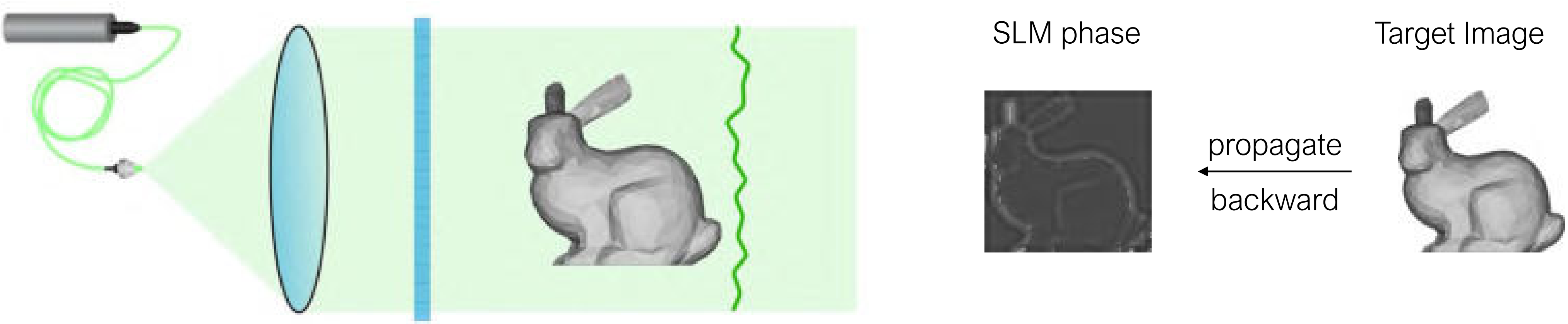
HOLOEYE

santec

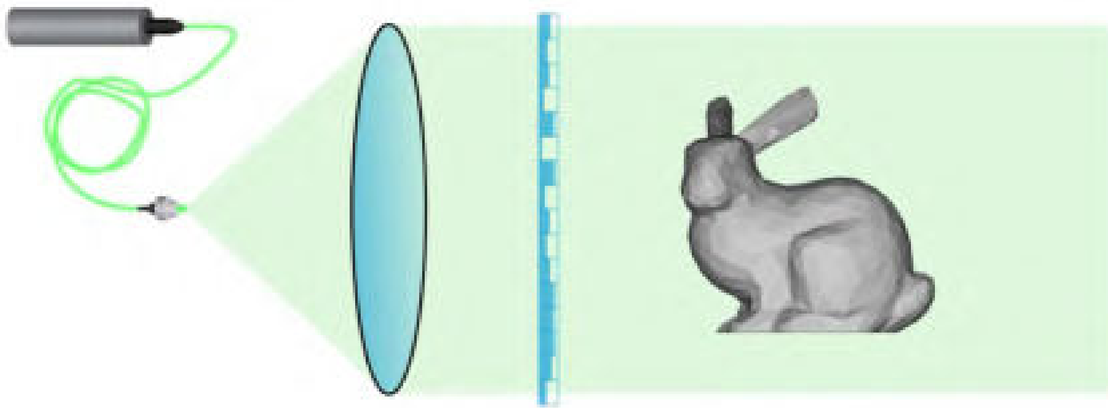
HAMAMATSU
PHOTON IS OUR BUSINESS

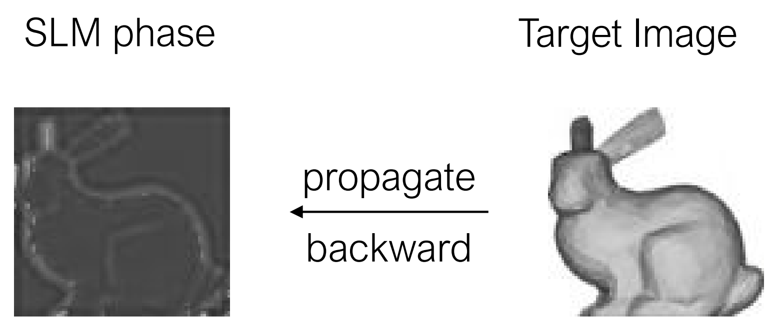
TEXAS INSTRUMENTS

Computer-generated Holography: Direct Methods



Computer-generated Holography: Direct Methods





Free-space propagation:

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

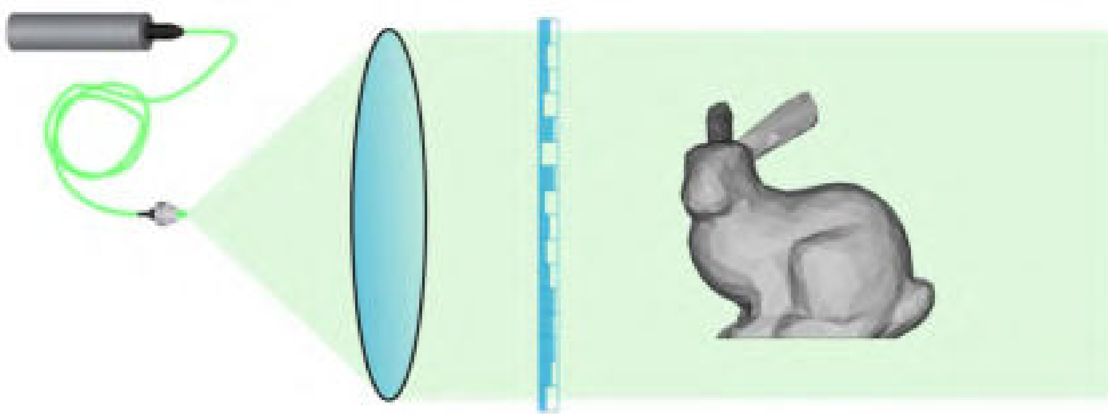
$$\mathcal{H}\left(f_x, f_y\right) = \begin{cases} e^{-i\frac{2\pi}{\lambda}\sqrt{1-(\lambda f_x)^2-(\lambda f_y)^2}\,z} & \text{if } \sqrt{f_x^2+f_y^2} < \frac{1}{\lambda} \\ 0 & \text{otherwise} \end{cases}$$

Computational complexity

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

[Goodman, Fourier Optics]

Computer-generated Holography: Direct Methods

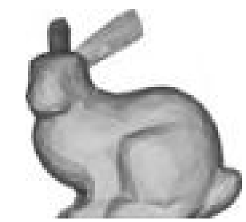


SLM phase

propagate

backward

Target Image



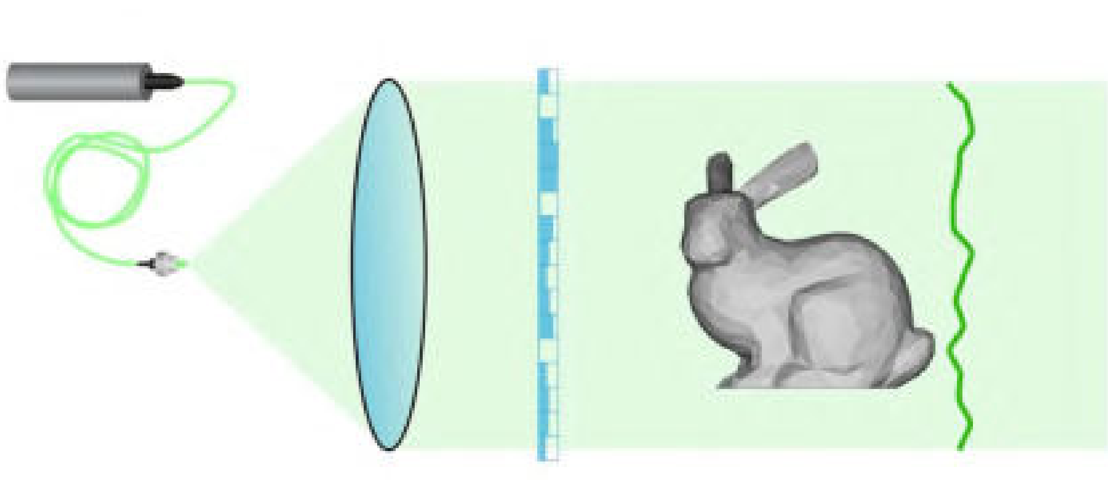
Double phase-amplitude coding:

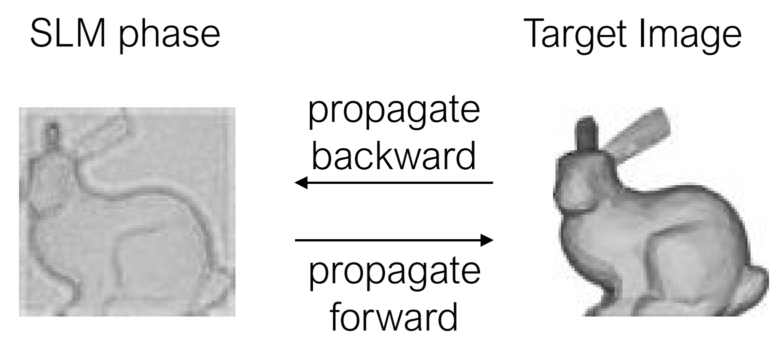
$$u_{slm}(x, y) = a(x, y)\, e^{i\phi(x,y)} = 0.5\left(e^{i\phi_1(x,y)} + e^{i\phi_2(x,y)}\right)$$

$$\phi_1(x, y) = \phi(x, y) - \cos^{-1}(a(x, y))$$
$$\phi_2(x, y) = \phi(x, y) + \cos^{-1}(a(x, y))$$

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

Computer-generated Holography: Iterative Methods



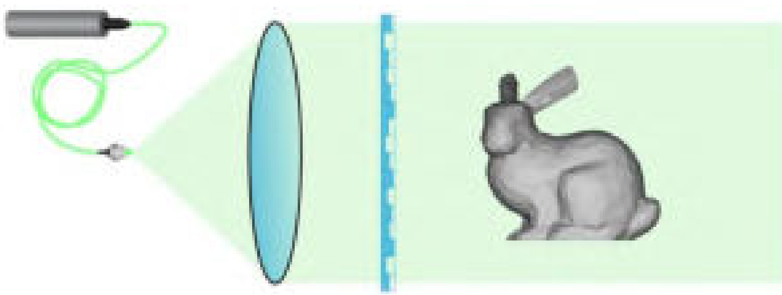


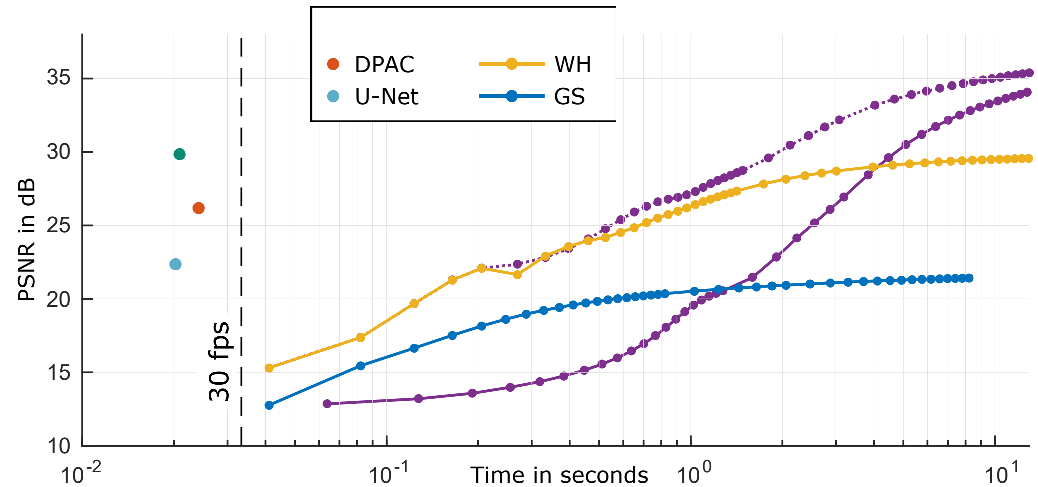
Free-space propagation:

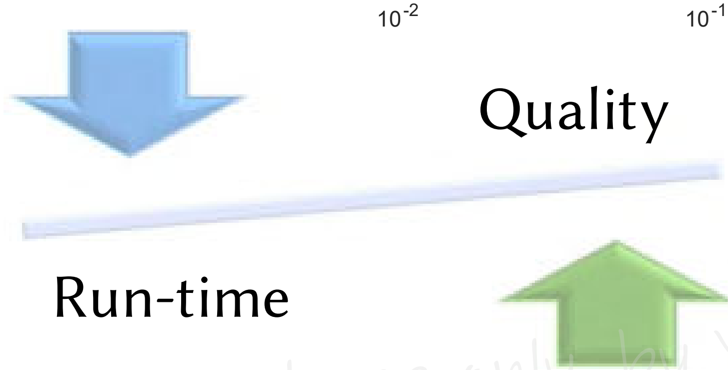
$$u_{slm}(x,y) = \mathcal{F}^{-1}\left\{\mathcal{F}\left\{a(x,y)\,e^{i\phi(x,y)}\right\}\mathcal{H}(f_x, f_y, z)\right\}$$

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

Computer-generated Holography





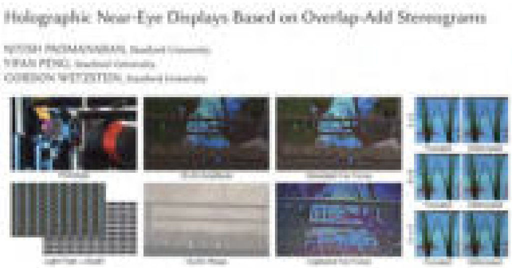


* *DPAC: Double-phase amplitude coding*
WH: Wirtinger Holography
GS: Gerchberg-Saxton
SGD: Stochastic Gradient Descent

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*

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


Holographic Near-Eye Displays Based on Overlap-Add Stereograms

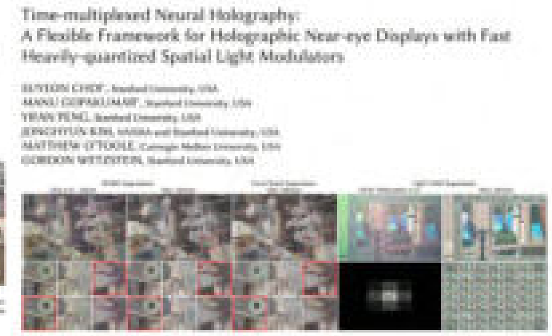
Overlap-add Stereograms
ACM TOG '19


Neural Holography with Camera-in-the-loop Training

Neural Holography
ACM TOG '20


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

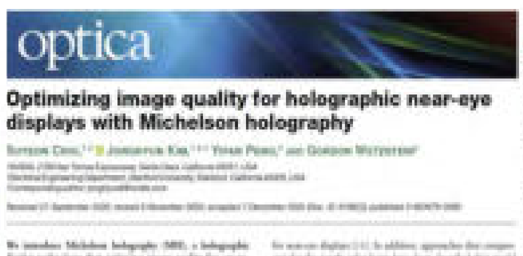
Neural 3D Holography
ACM TOG '21


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

Time-multiplexed Neural Holography
ACM SIGGRAPH '22

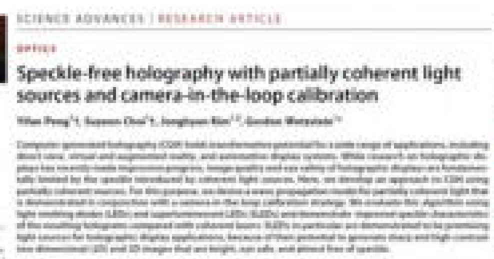

Wirtinger Holography for Near-Eye Displays

Wirtinger Holography
ACM TOG '19


optica

Optimizing image quality for holographic near-eye displays with Michelson holography

Michelson Holography
OSA Optica '21

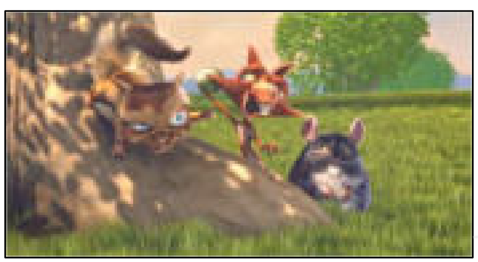

SCIENCE ADVANCES | RESEARCH ARTICLE

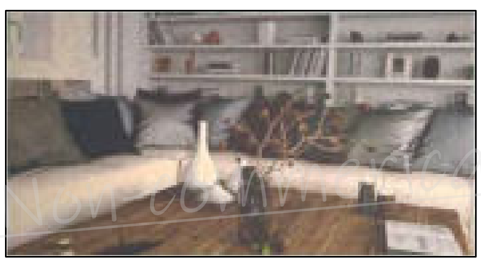
Speckle-free holography with partially coherent light sources and camera-in-the-loop calibration

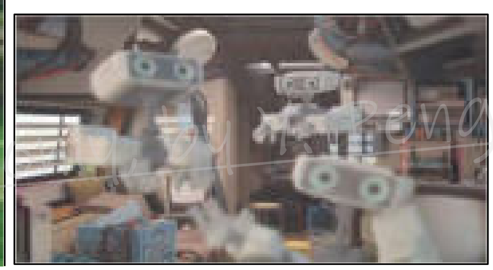
Partially-coherent Holography
Science Advances '21

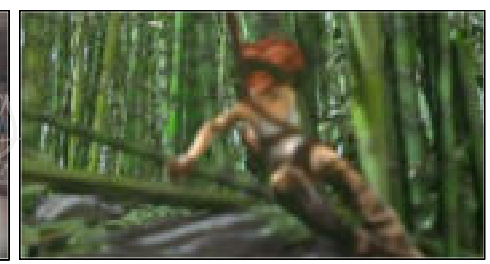

Holographic Glasses for Virtual Reality

Holographic VR Glasses
ACM SIGGRAPH '22

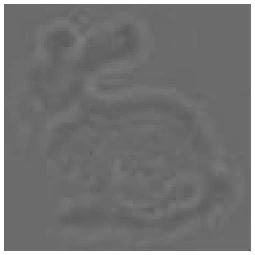








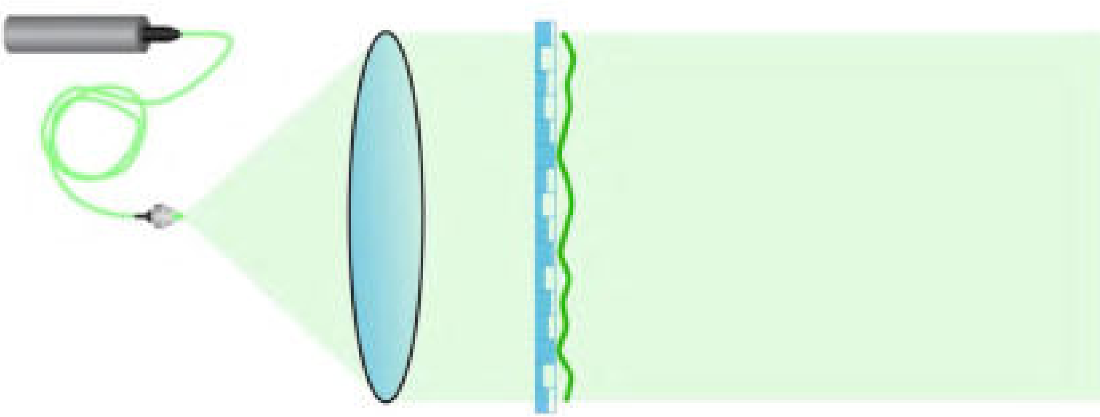
Stochastic Gradient Descent (SGD) Optimization



backpropagate

$\mathcal{L}\Big($  ,  $\Big)$

Target Simulation



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

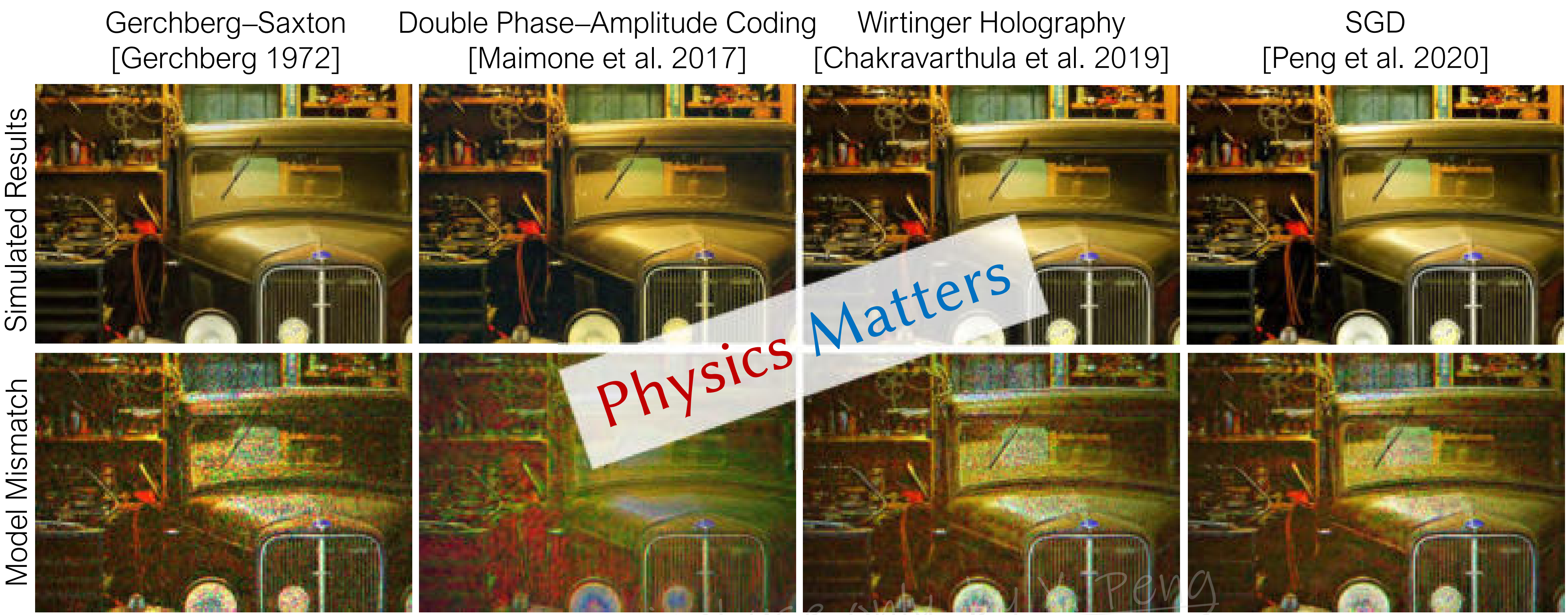
$\widehat{f}$ Free-space propagation model

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

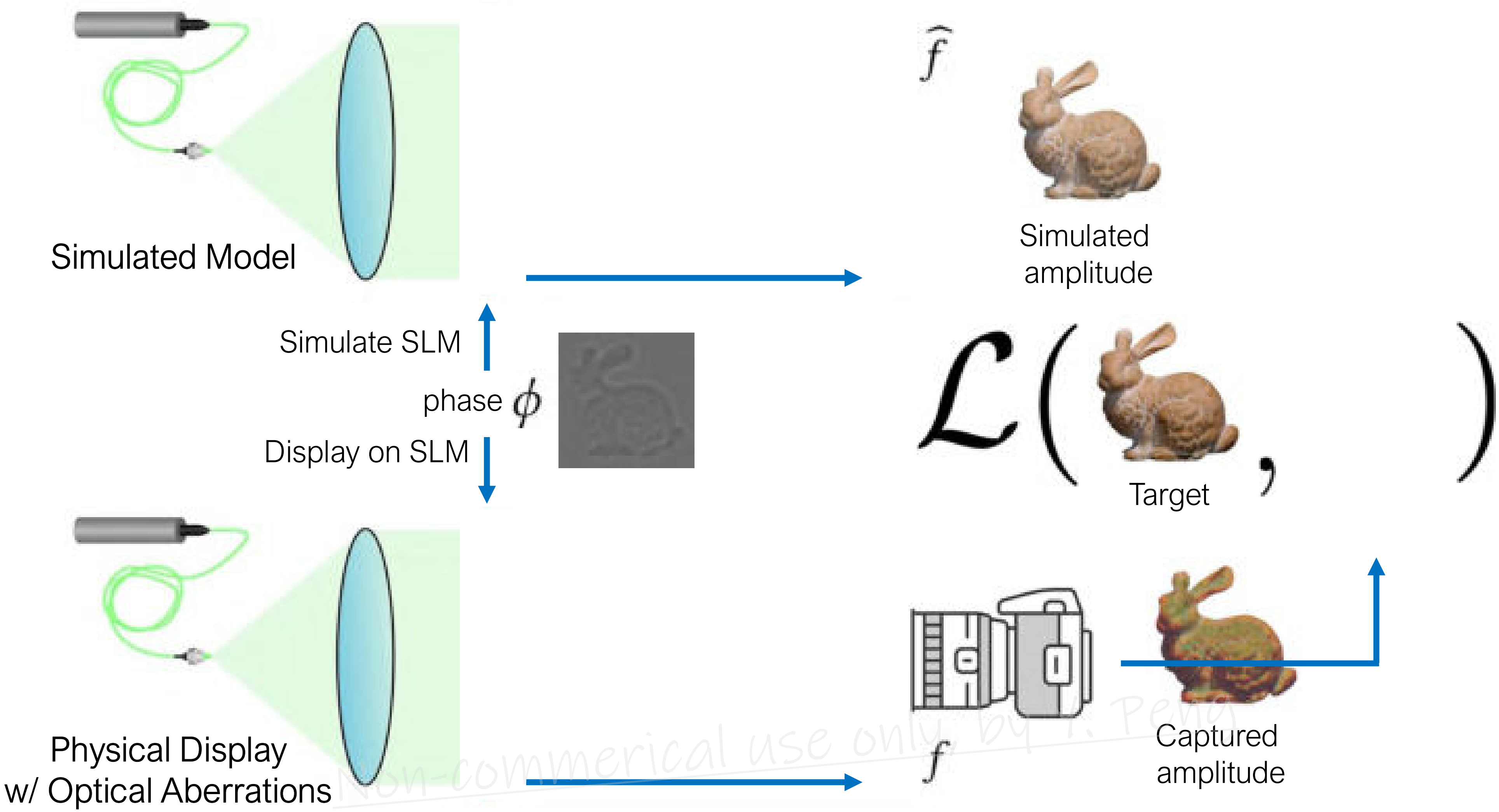
Iterations: $\boxed{\phi^{(k)}} \leftarrow \phi^{(k-1)} - \alpha \boxed{\left(\frac{\partial \mathcal{L}}{\partial \phi}\right)^T} \boxed{\mathcal{L}\left(\left|\widehat{f}\left(\phi^{(k-1)}\right)\right|, a_{\text{target}}\right)}$

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

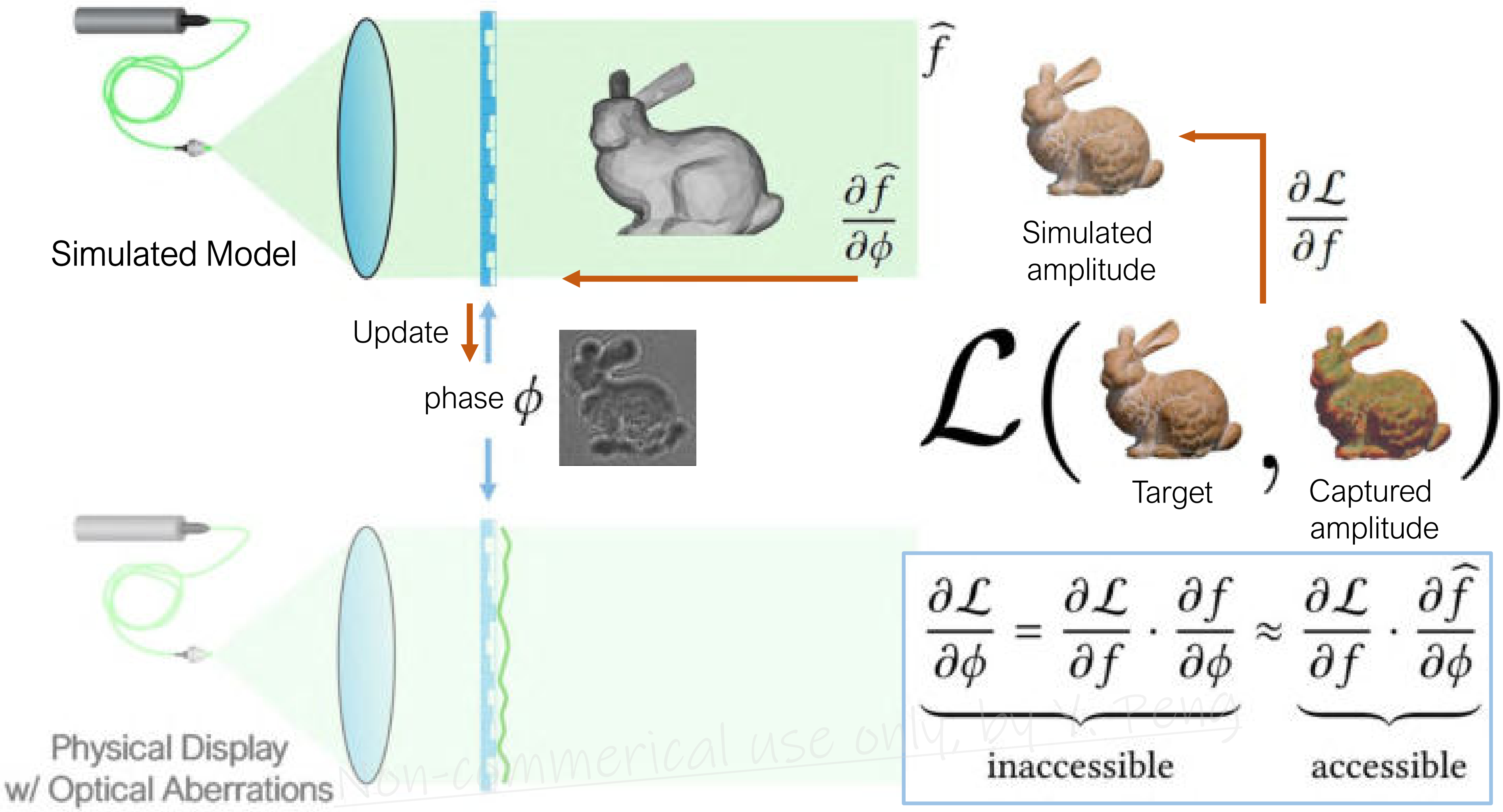
Challenges of Experimental Holography



Camera-in-the-loop (CITL) Optimization



Camera-in-the-loop (CITL) Optimization

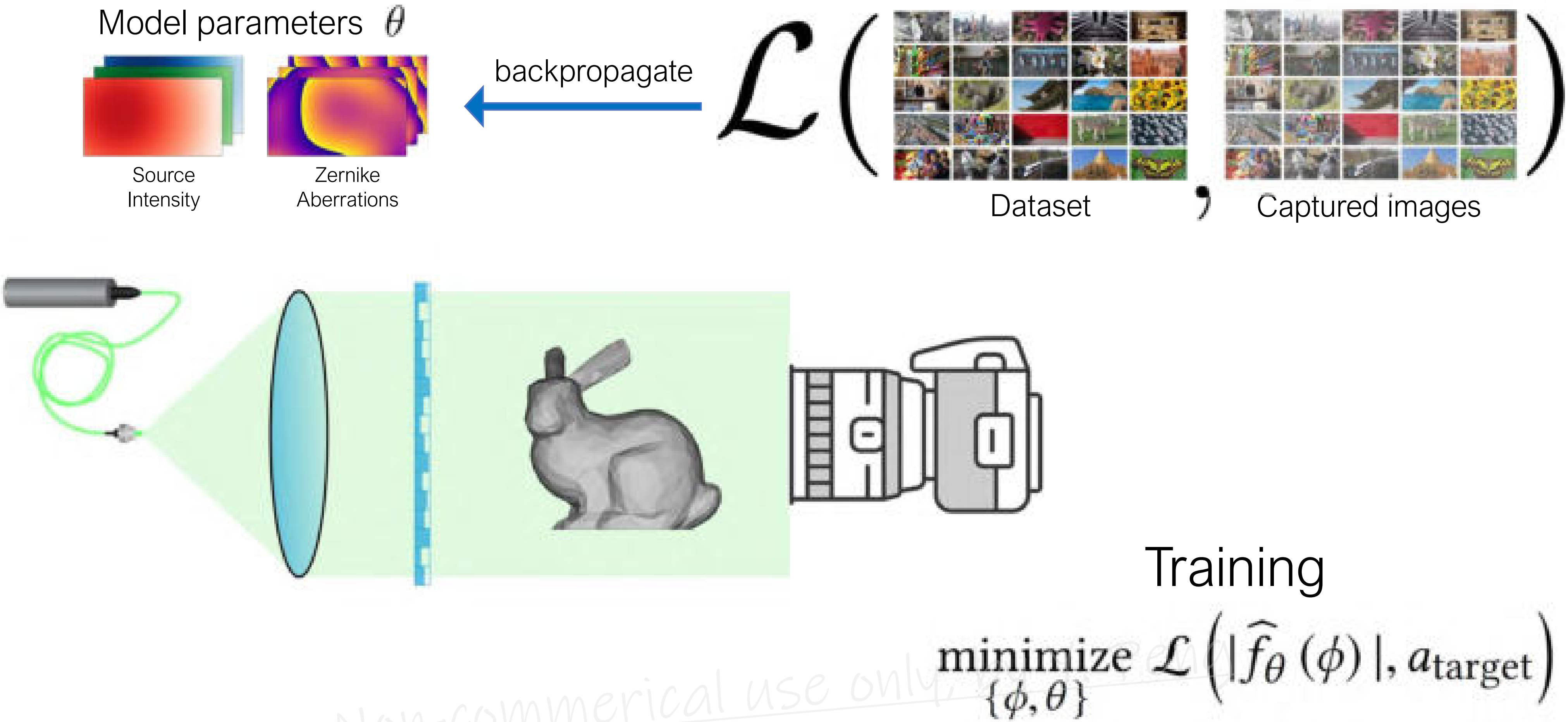


CITL Hologram Optimization

SGD with Perfect Model

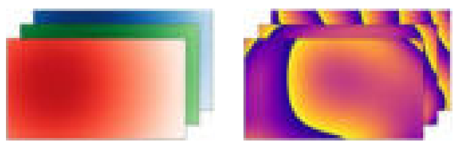
SGD with CITL

CITL Model Training



CITL Model Training

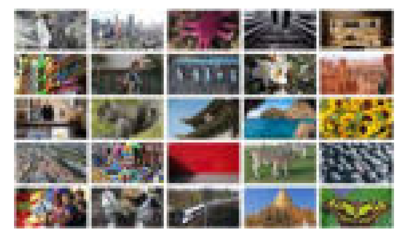
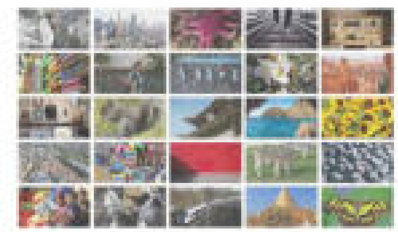
Model parameters θ



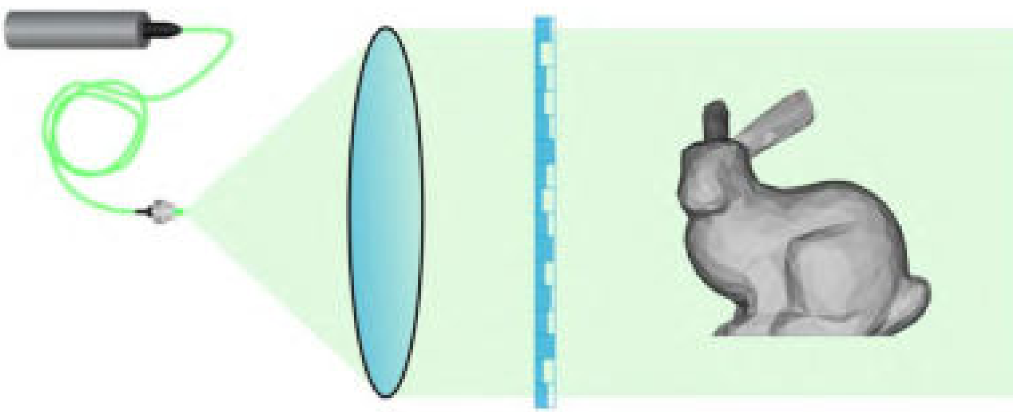
Source Intensity

Zernike Aberrations

backpropagate

$\mathcal{L}\Big($  ,  $\Big)$

Dataset , Captured images



Inference

$$\underset{\{\phi\}}{\text{minimize}}\ \mathcal{L}\left(\left|\widehat{f_\theta}\left(\phi\right)\right|, a_{\text{target}}\right)$$

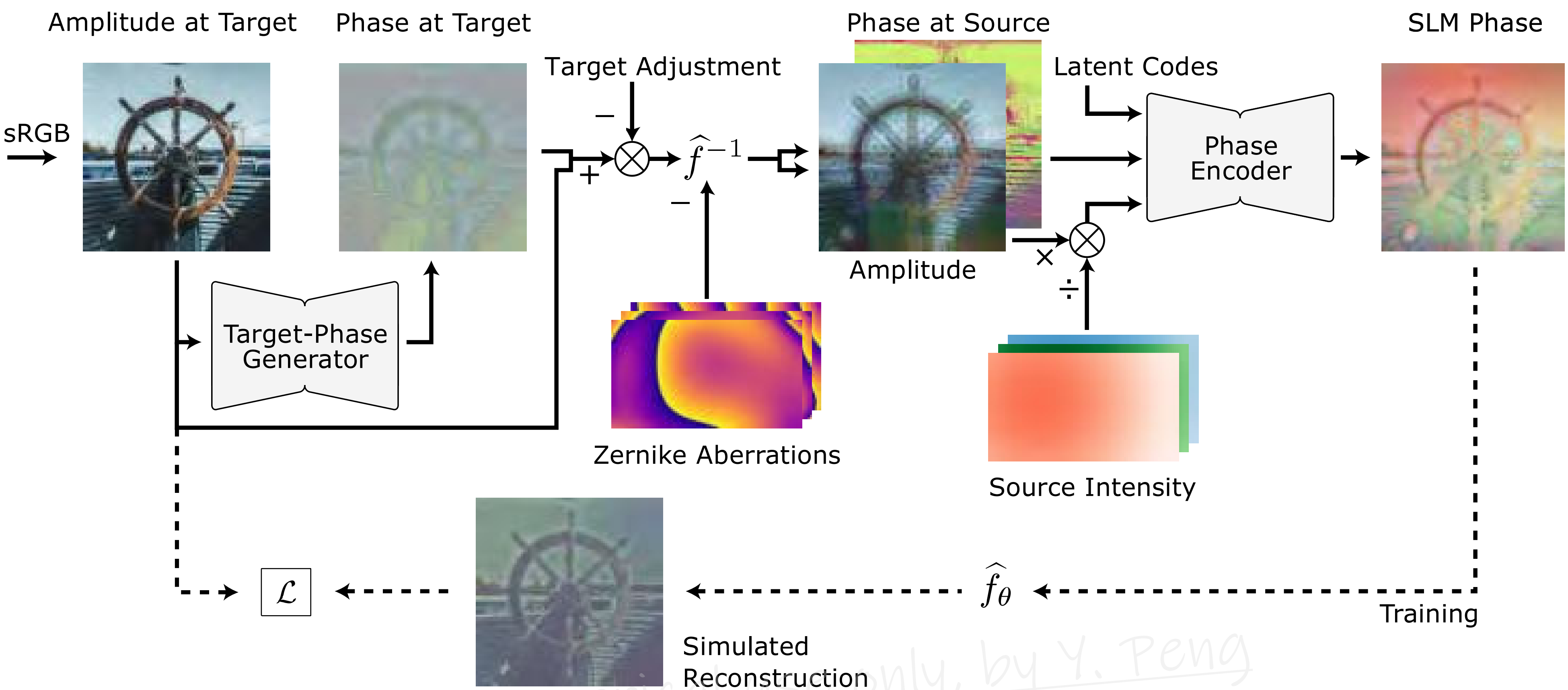
Iterative Hologram Inference with CITL-trained Model

Wirtinger Holography (for reference)

SGD with CITL-trained Model

What about speed?

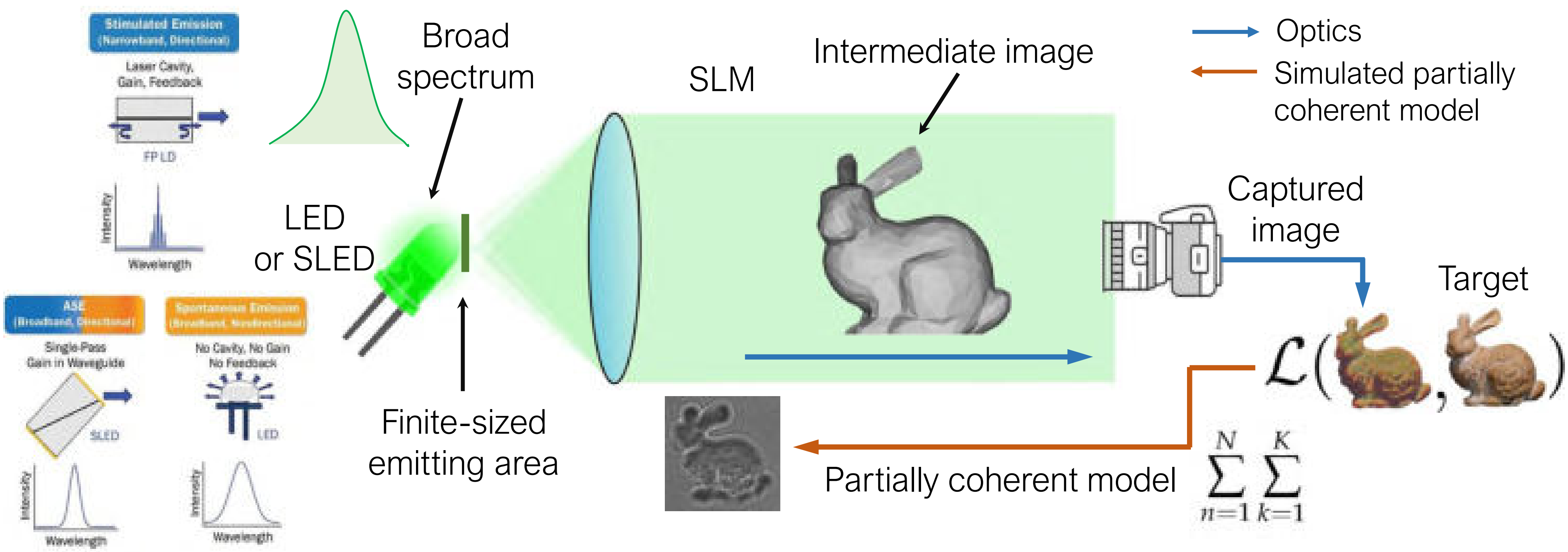
HoloNet (Inverse Network)



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

Speckle effect

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

LEDs reduce speckle but introduce blur.

LED *vs* SLED

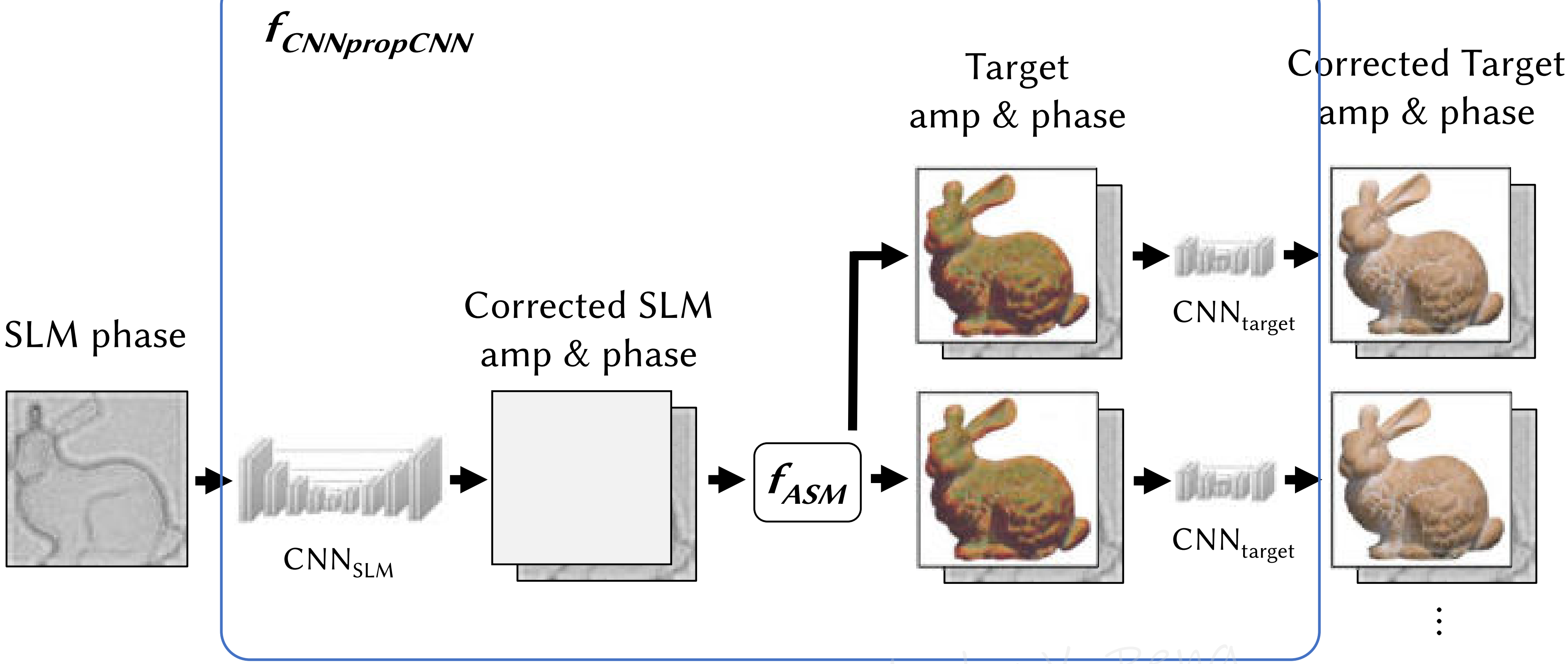
Both LEDs & SLEDs don't suffer from speckle, but SLEDs produce sharp images.

Laser *vs* SLED

SLEDs maintain the image sharpness of lasers but greatly reduce speckle.

Better representation?

Neural 3D Holography with Better Model



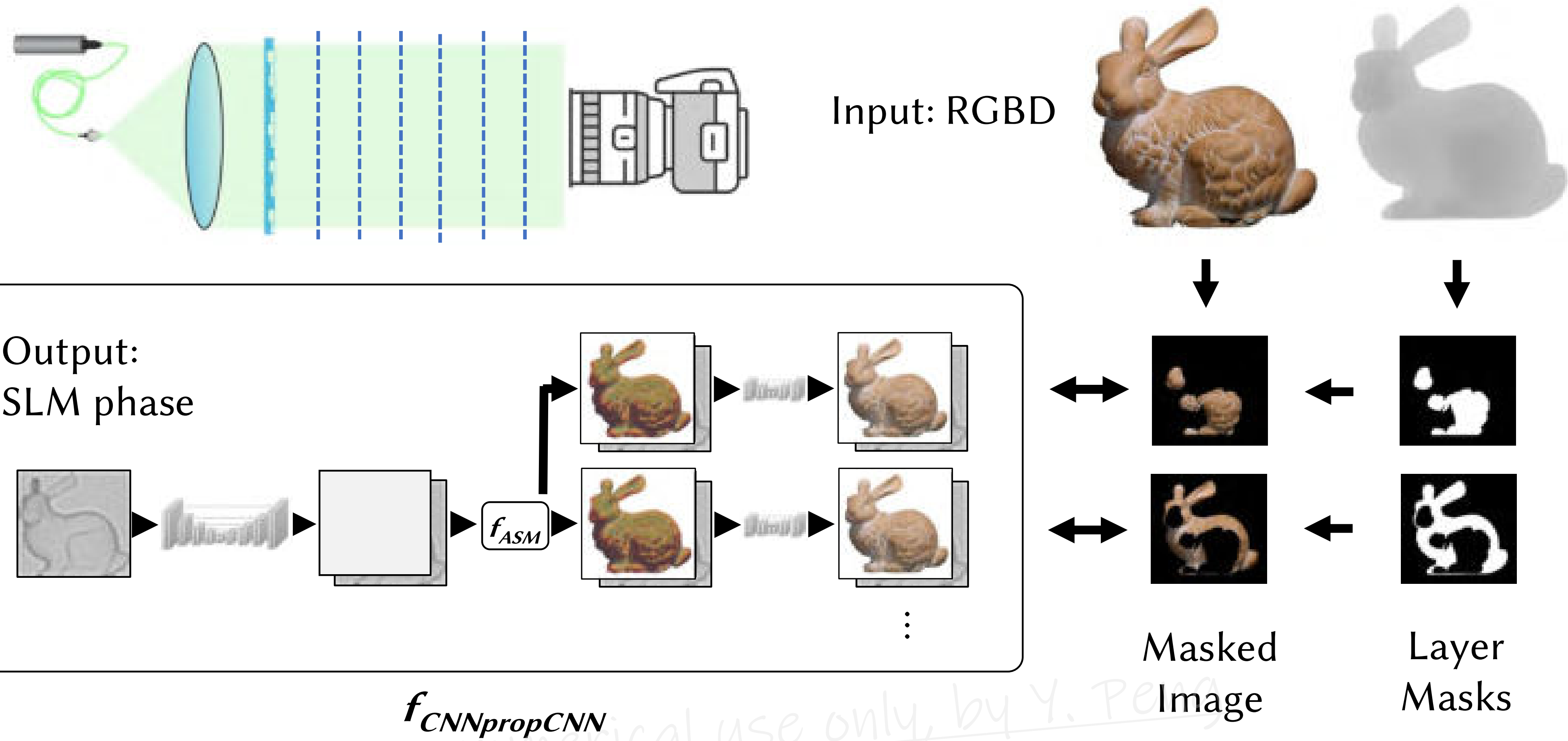
* Neural 3D Holography: Learning Accurate Wave Propagation Models for 3D Holographic Virtual and Augmented Reality Displays, *S. Choi, M. Gopakumar, Y. Peng, J. Kim, G. Wetzstein* – ACM SIGGRAPH Asia 21'.

Metrics show PSNR/SSIM, higher is better.

Metrics show PSNR/SSIM, higher is better.

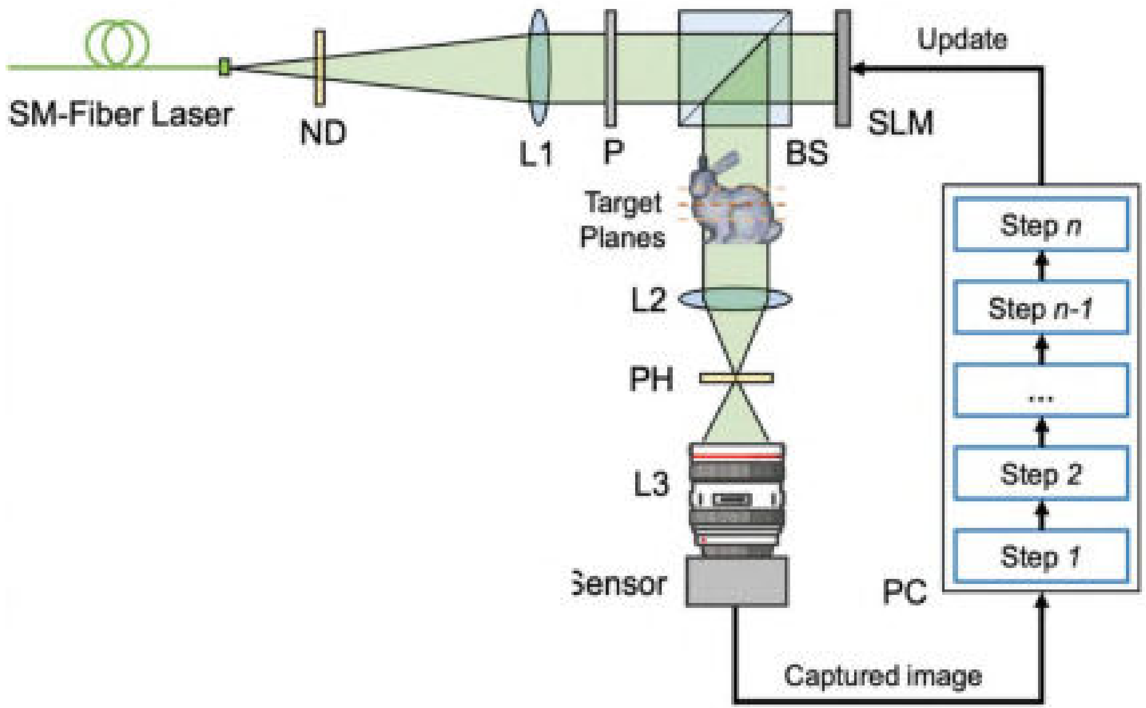
3D is the goal

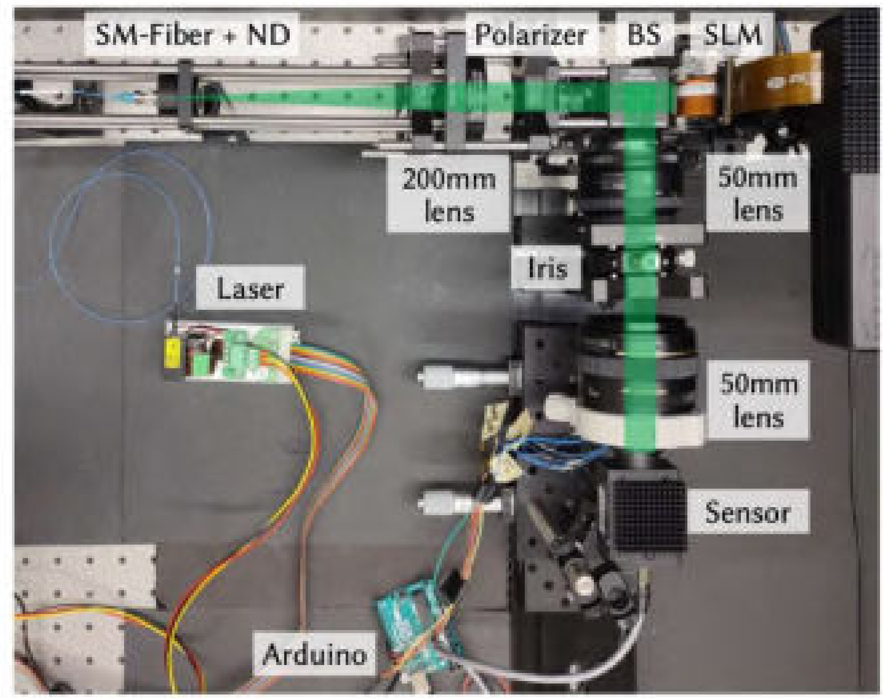
Computing 3D Holograms



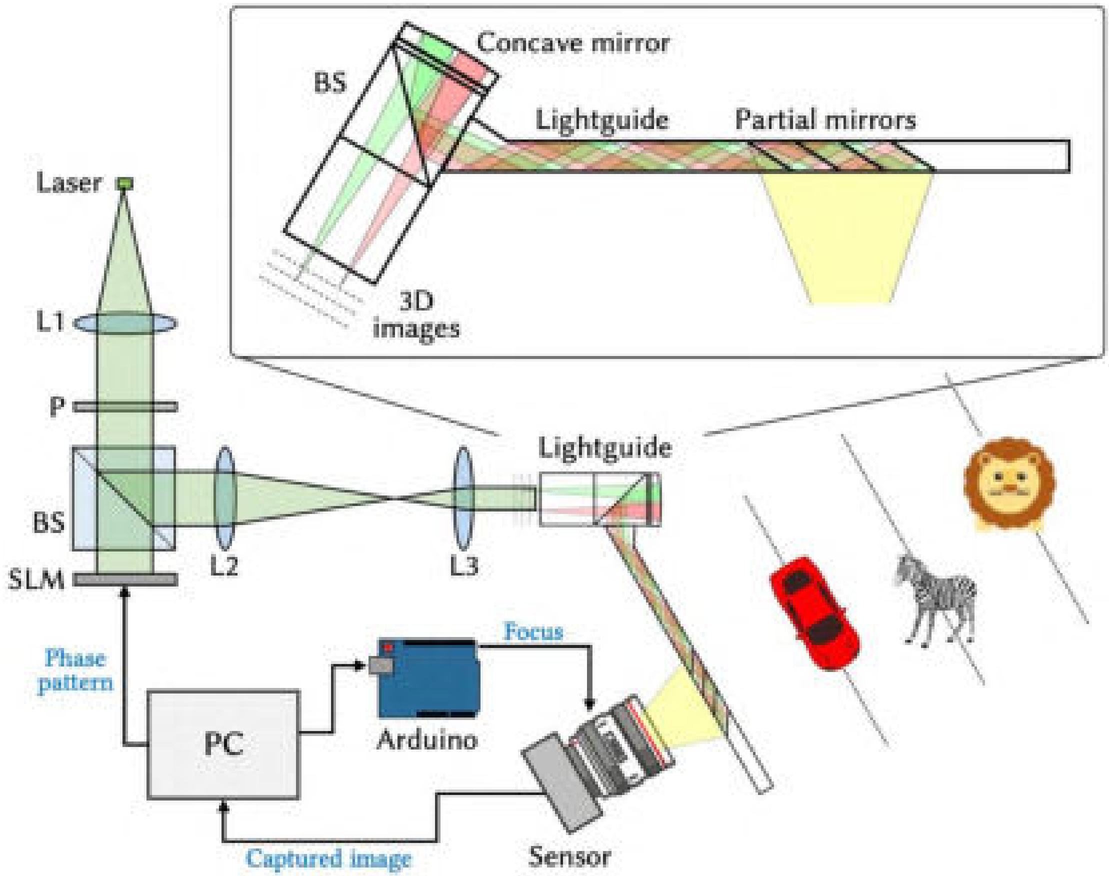
* Neural 3D Holography: Learning Accurate Wave Propagation Models for 3D Holographic Virtual and Augmented Reality Displays, *S. Choi, M. Gopakumar, Y. Peng, J. Kim, G. Wetzstein* – ACM SIGGRAPH Asia 21'.

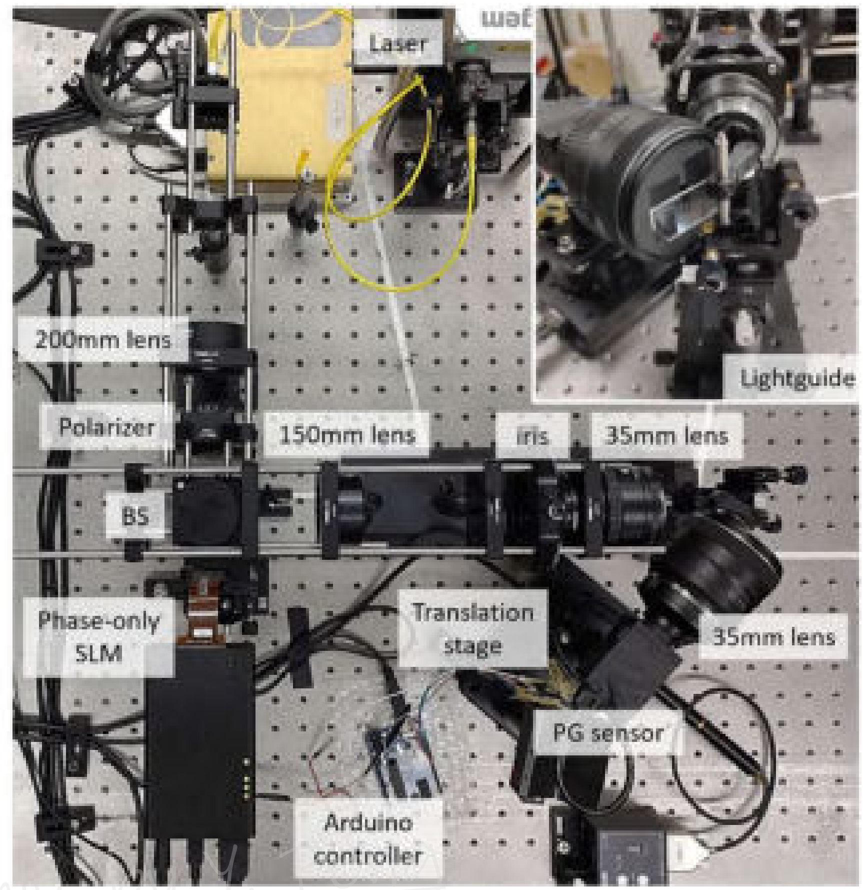
VR Holographic Near-eye Display Prototype

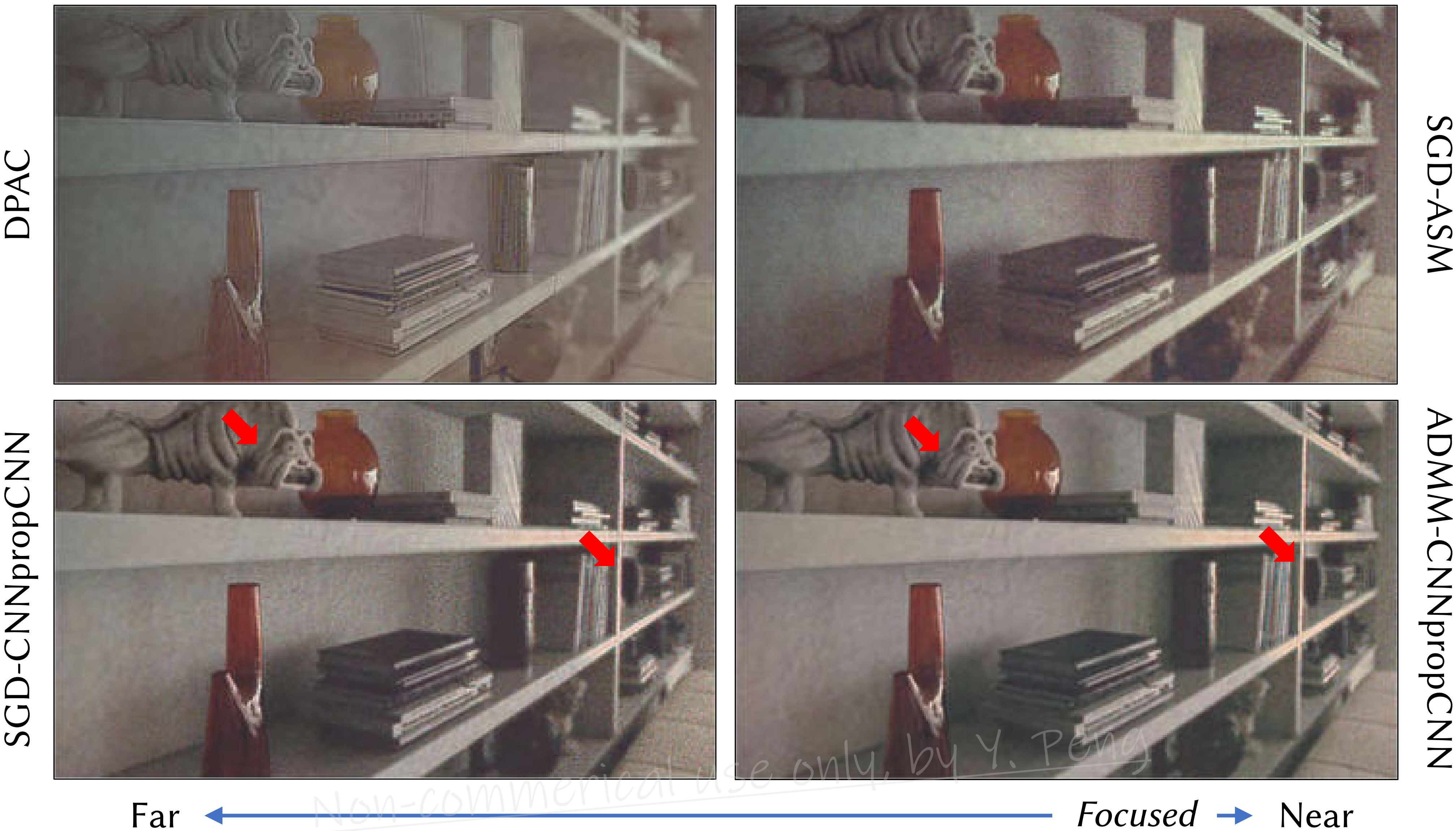




AR Holographic Near-eye Display Prototype





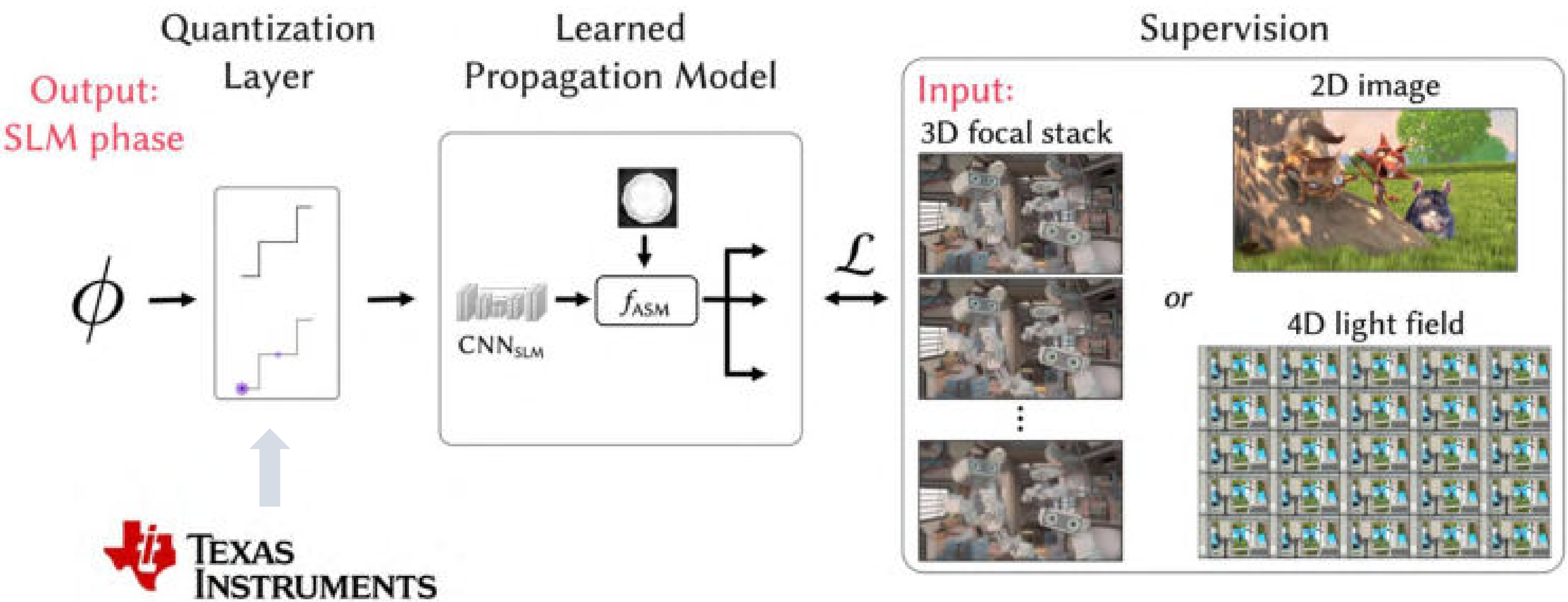

DPAC
SGD-ASM
SGD-CNNpropCNN
ADMM-CNNpropCNN
Far
Focused
Near


DPAC
SGD-ASM
SGD-CNNpropCNN
ADMM-CNNpropCNN
Zebra
SPEED LIMIT
55
Right
turn
Far
Focused
Near

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

Natural focus cues matter

Time-multiplexed Neural Holography: Flexible CGH Framework



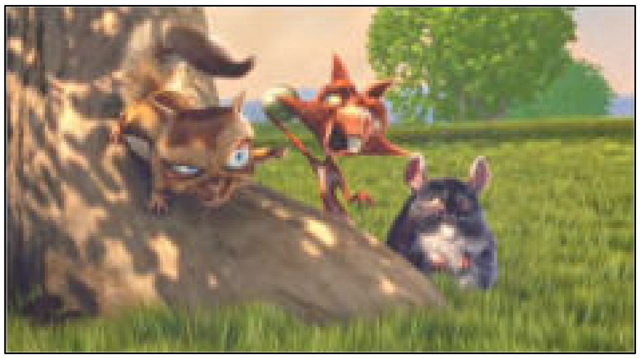
Time-multiplexing Helps Bypass the SLM Bandwidth Limit

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

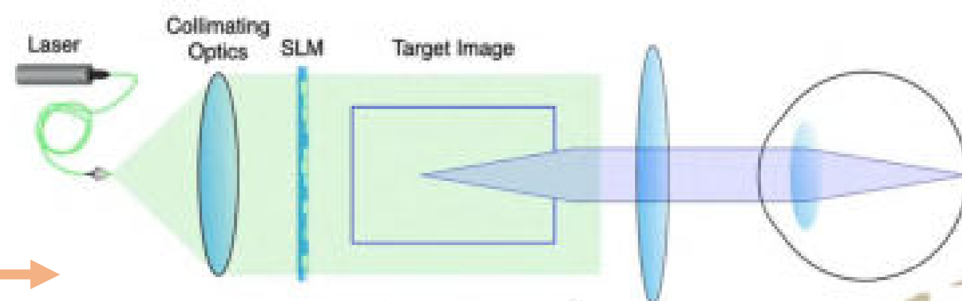
Time-multiplexed Neural Holography: Flexible CGH Framework with Natural Defocus (Stanford's work, SIGGRAPH 2022)

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

Limited eye-box!!!

Joint Design of Hardware & Software

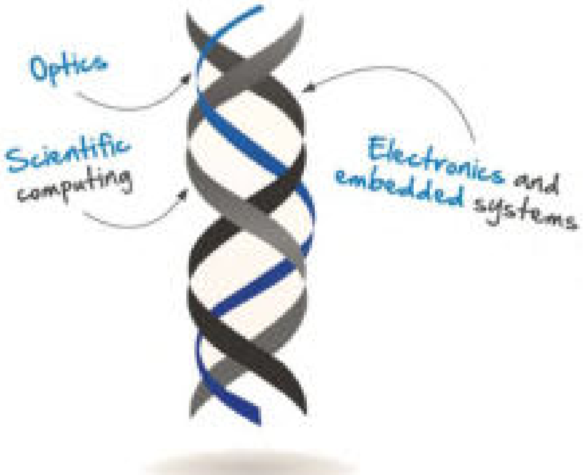
& Human Science

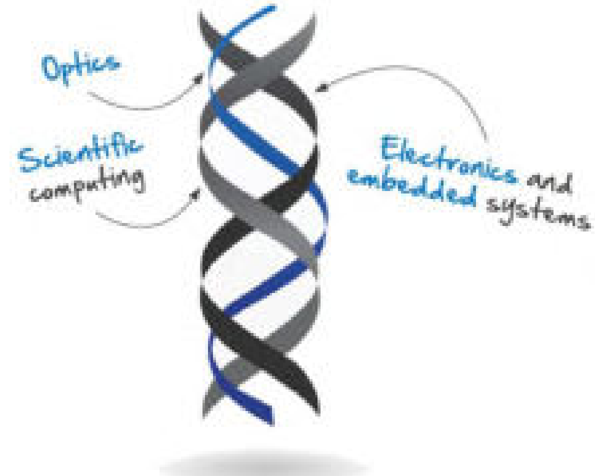
WeChat Official Account: *IntelligentOptics*

Intelligent **O**ptics **S**haring

感知 | 计算

成像 | 显示





Thank You

Thank You

Web: eee.hku.hk/~evanpeng/