

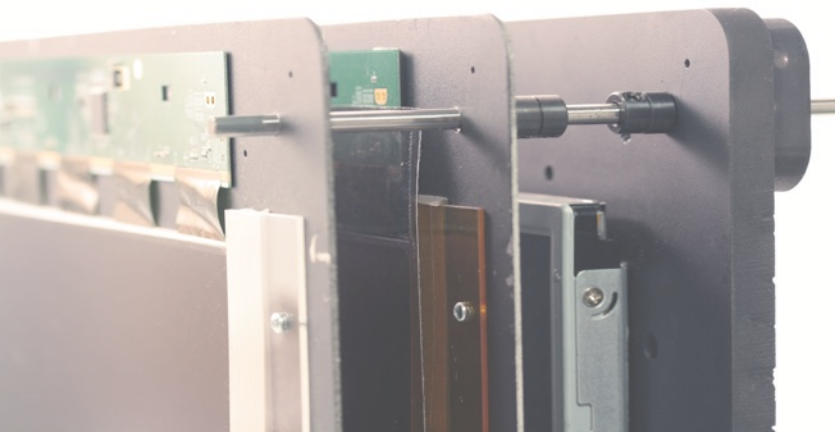
# Introduction, Overview, Fast Forward

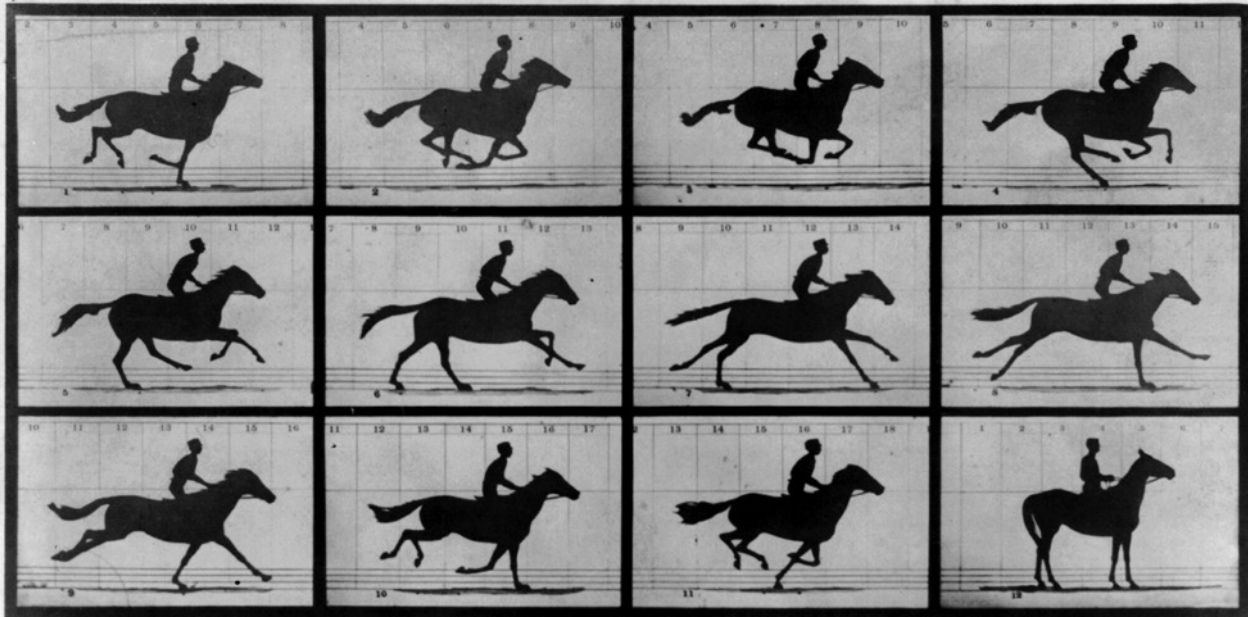
EE367/CS448I: Computational Imaging

[stanford.edu/class/ee367](http://stanford.edu/class/ee367)

Lecture 1

Gordon Wetzstein  
Stanford University





Copyright, 1878, by MUYBRIDGE.

MORSE'S Gallery, 417 Montgomery St., San Francisco.

## THE HORSE IN MOTION.

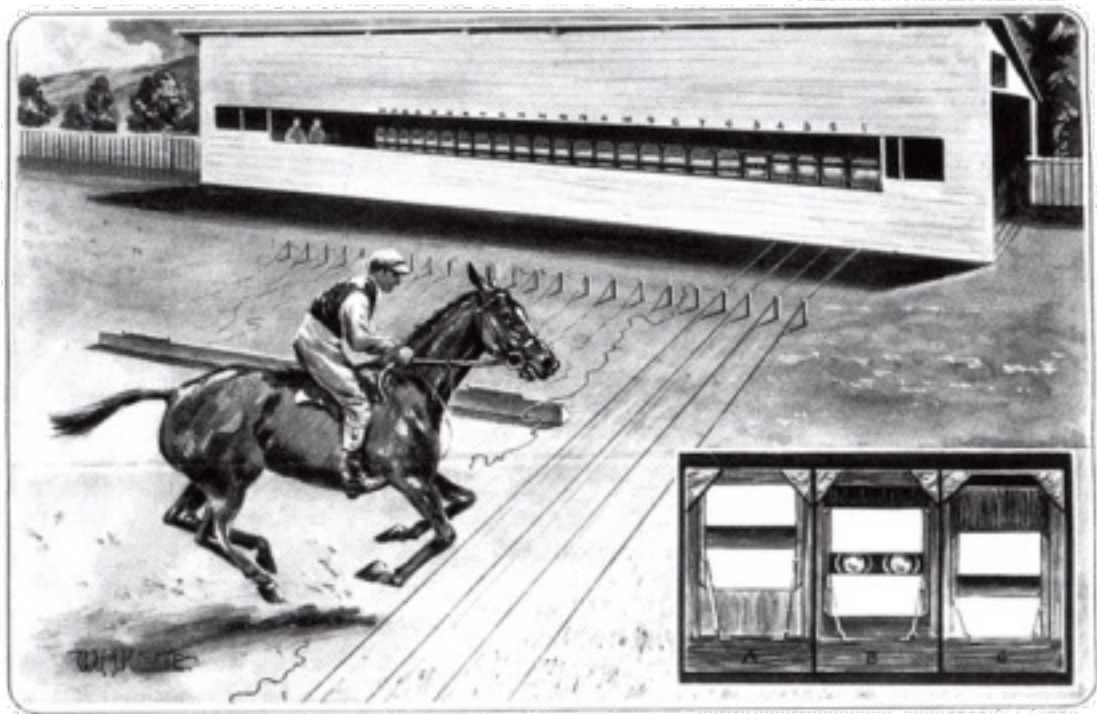
Illustrated by  
MUYBRIDGE.

AUTOMATIC ELECTRO-PHOTOGRAPH.

"SALLIE GARDNER," owned by LELAND STANFORD; running at a 1.40 gait over the Palo Alto track, 19th June, 1878.

The negatives of these photographs were made at intervals of twenty-seven inches of distance, and about the twenty-fifth part of a second of time; they illustrate consecutive positions assumed in each twenty-seven inches of progress during a single stride of the mare. The vertical lines were twenty-seven inches apart; the horizontal lines represent elevations of four inches each. The exposure of each negative was less than the two-thousandth part of a second.

# Muybridge's Multi-Camera Array at Stanford





**CAMERAS**

Detect and track pedestrians / cyclists, traffic lights, free space and other features

**ARTICULATING RADARS**

Detect moving vehicles at long range over a wide field of view



**LIDARS**

High-precision laser sensors that detect fixed and moving objects



**LONG-RANGE RADARS**

Detect vehicles and measure velocity



**SHORT-RANGE RADARS**

Detect objects around the vehicle

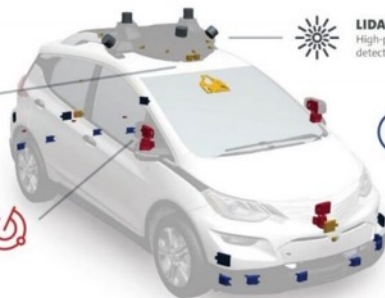




Image: National Geographic

# What is Computational Imaging?



optics

+



sensing

+

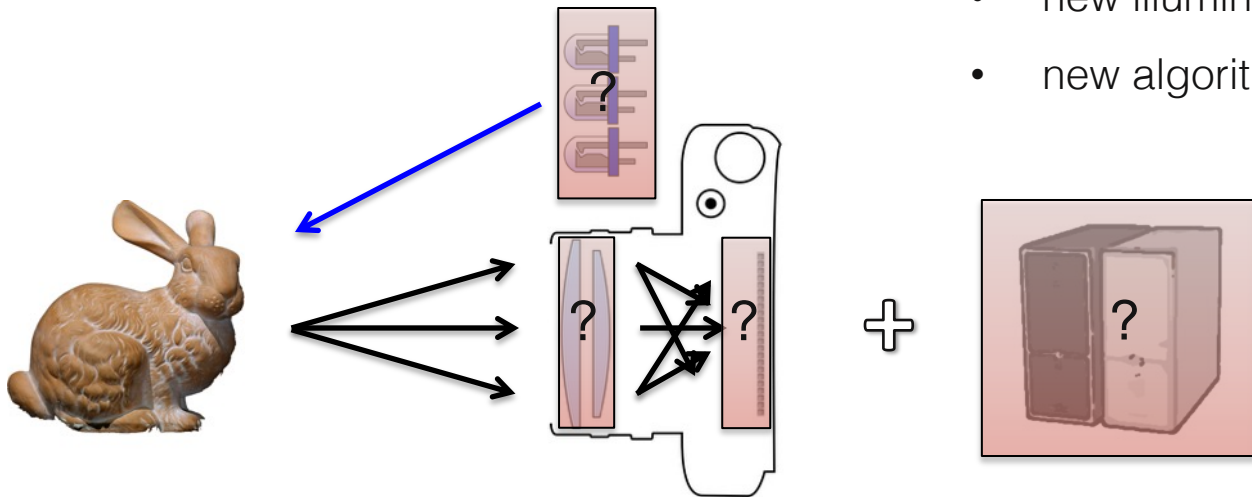


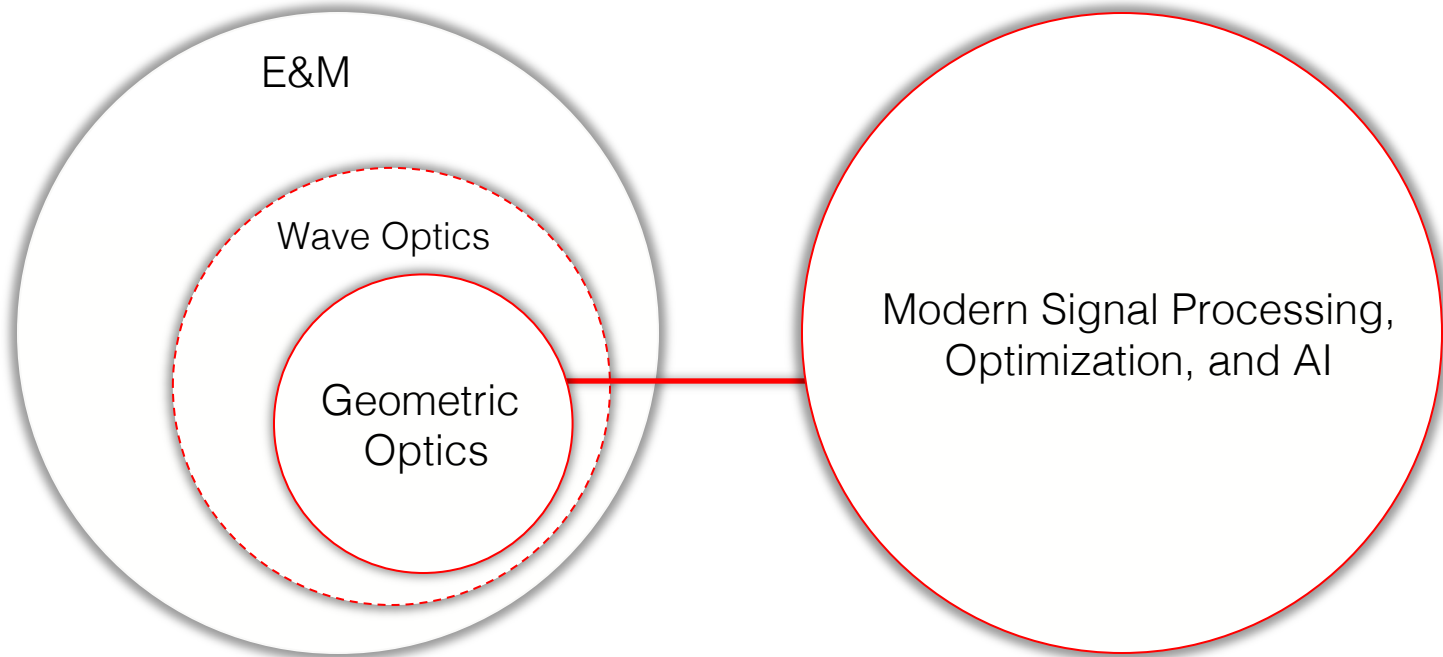
computation

# What is Computational Imaging?

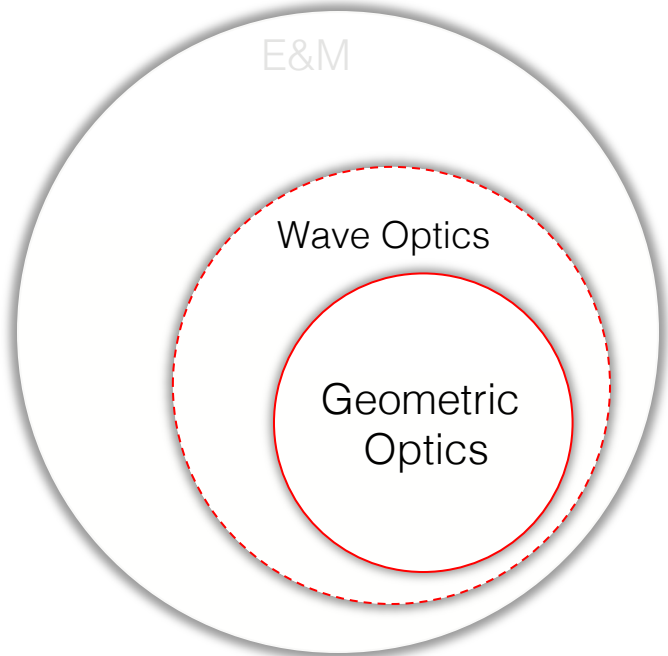
1. optically encode scene information
2. computationally recover information

- new optics
- new sensors
- new illumination
- new algorithms





# What is Light?



- light as rays
- unit: (spectral) radiance
- properties: wavelength, polarization, direction, ...
- only brief introduction & outlook for wave optics

# Instructors



Gordon Wetzstein



Minseo (Sonia) Kim

# Motivating Examples of Products, Research, and Development in Computational Imaging

12MP  
**Ultra Wide camera**

13 mm focal length  
120° field of view  
f/2.2 aperture

12MP  
**Telephoto camera**

120 mm focal length  
5x optical zoom  
f/2.8 aperture

48MP  
**Main camera**

24 mm focal length  
2.44  $\mu\text{m}$  quad pixel  
f/1.78 aperture



Apple iPhone 15 pro max

# Google Night Sight



# Light Field Cameras

Light L16



Lytro Illum



Facebook Surround 360



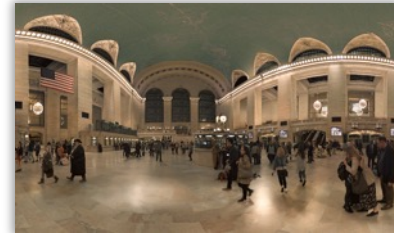
High-res 81MP



Post-capture Refocus



360° surround with parallax



# Apple Vision Pro (supposedly) has 14 cameras!

4x front- and side-facing for SLAM.

2x for pass through.

4x for eye & face tracking.

2x for torso tracking.

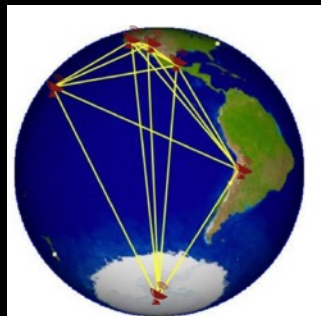
1x for gesture tracking.

1x time-of-flight sensor.

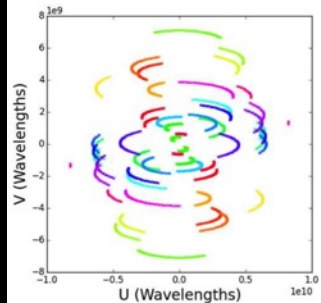


Source: Apple

# Imaging Black Holes



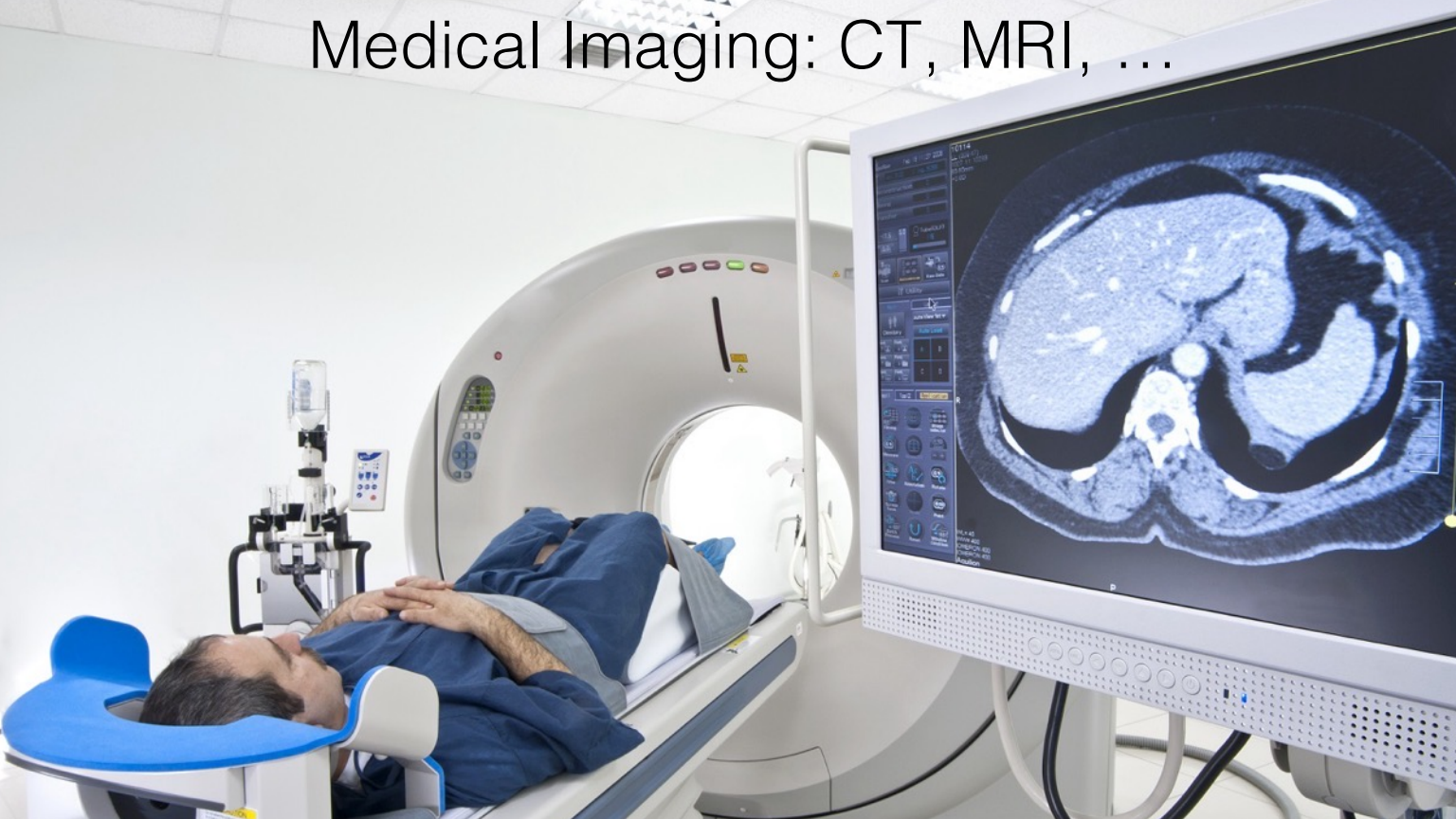
(a) Telescope Locations



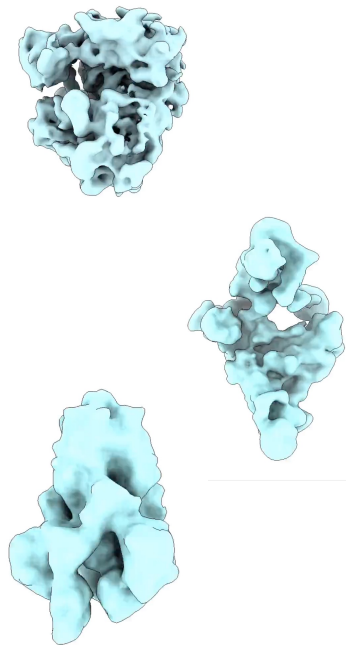
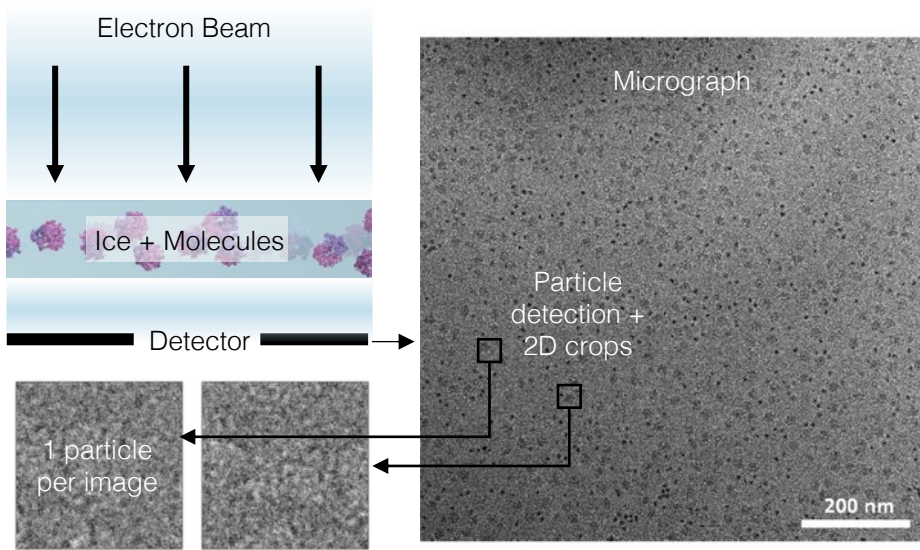
(b) Spatial Frequency Coverage

Akiyama et al., The Astrophysical Journal Letters, 2019  
Bouman et al., CVPR 2016

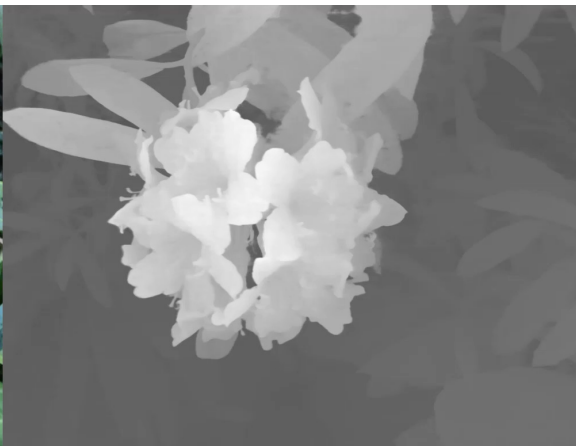
# Medical Imaging: CT, MRI, ...



# Imaging Proteins with Cryo-EM



# Neural Radiance Fields (NeRFs) for View Interpolation





Source: Waymo

# Self-driving Car Sensors

Long Range Camera + Radar

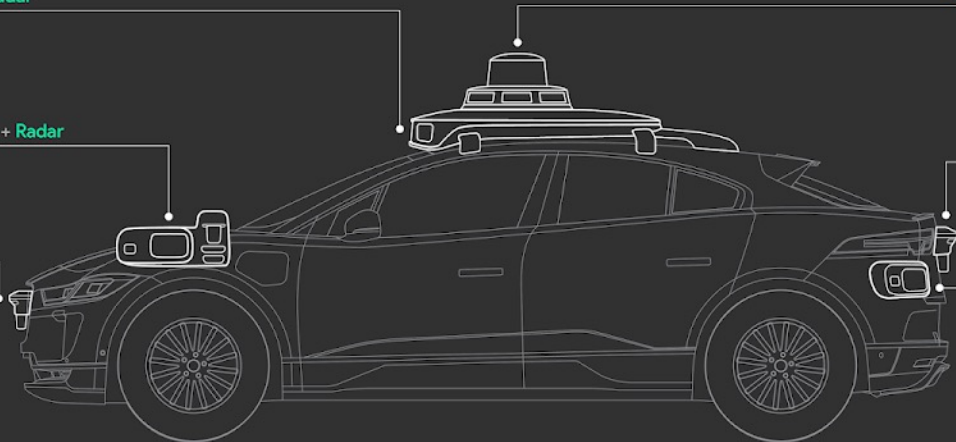
360 Lidar + 360 Vision System

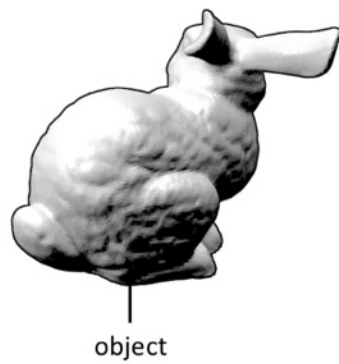
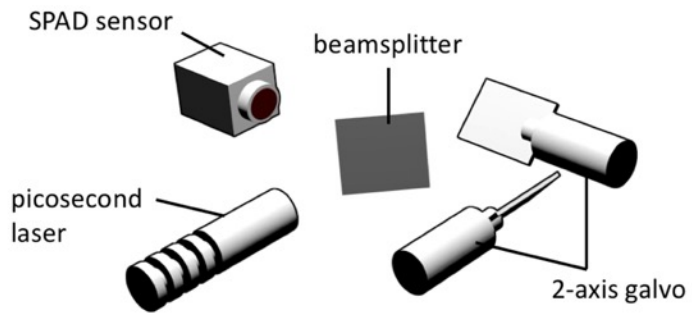
Perimeter Lidar +  
Peripheral Vision System + Radar

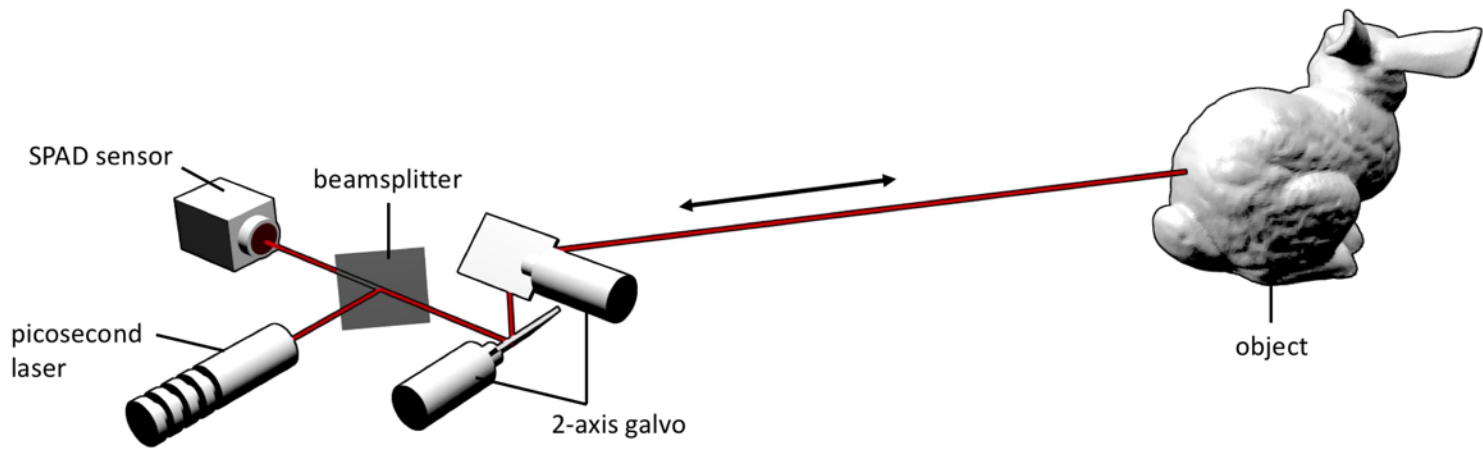
Perimeter Lidar +  
Perimeter Vision System

Perimeter Lidar +  
Perimeter Vision System

Peripheral Vision System  
+ Radar







# 3D Imaging for Autonomous Vehicles



LIDAR (light detection and ranging)  
Velodyne VLS-128



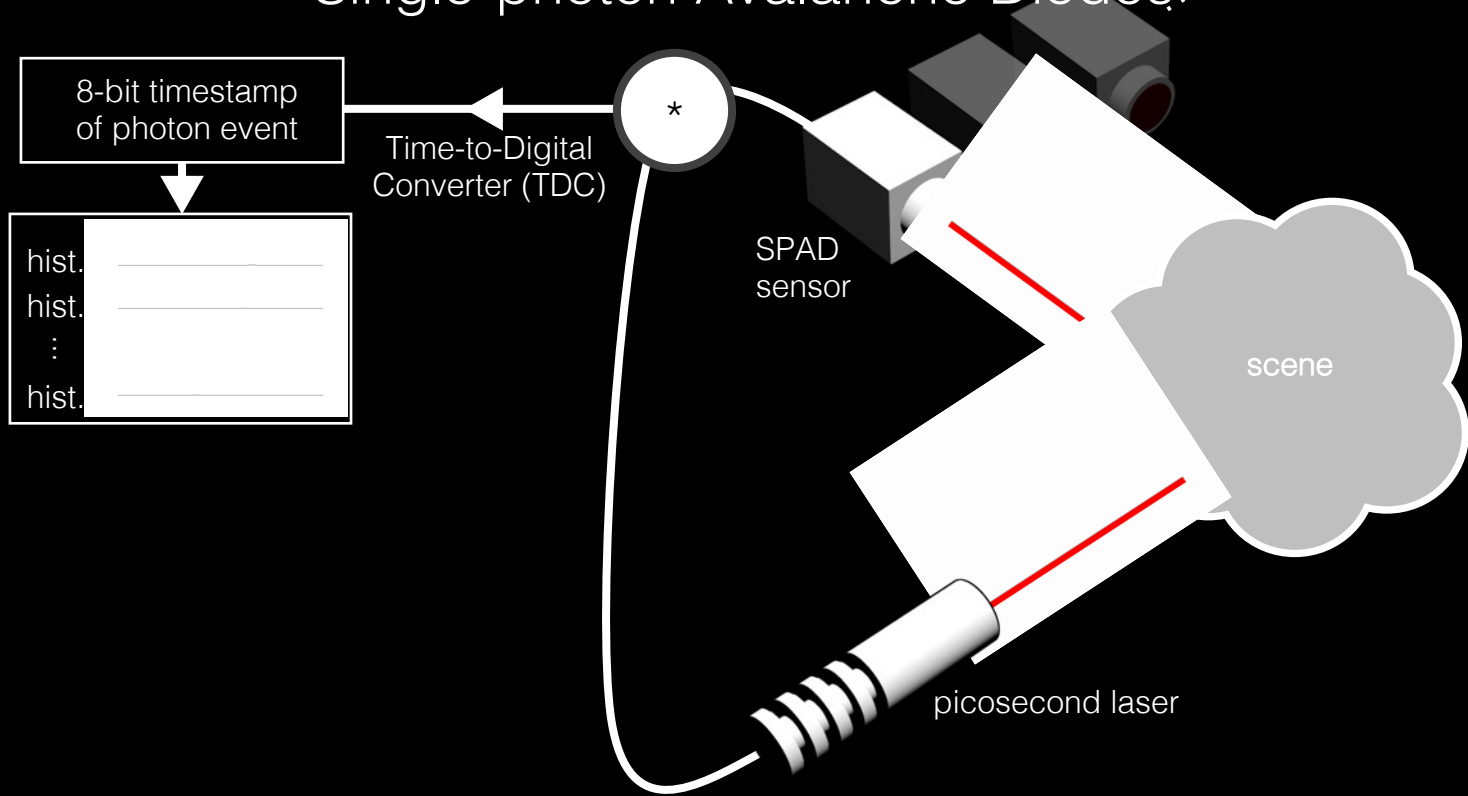
# 3D Imaging for Autonomous Vehicles



LIDAR (light detection and ranging)  
Velodyne VLS-128



# Single-photon Avalanche Diodes..



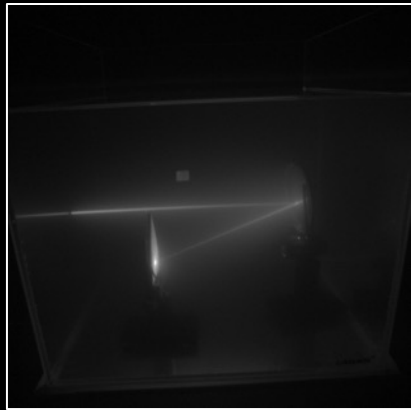
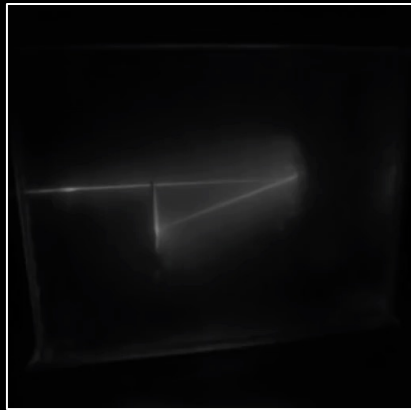
# Flying with Photons

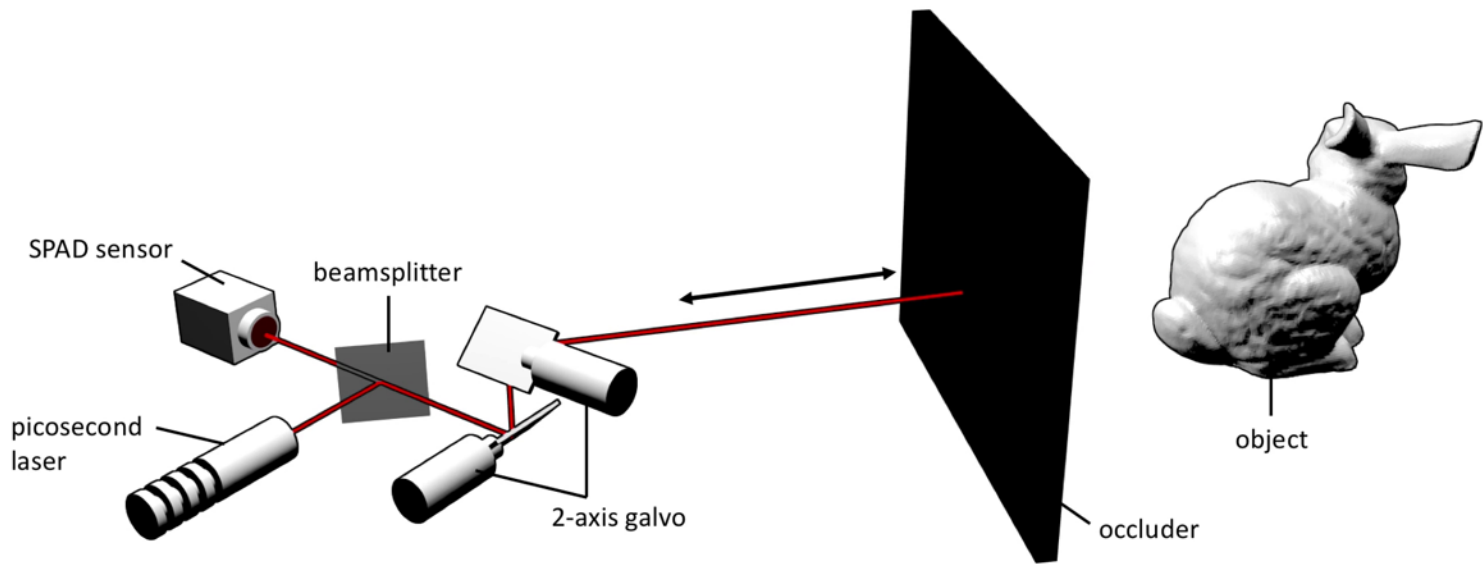


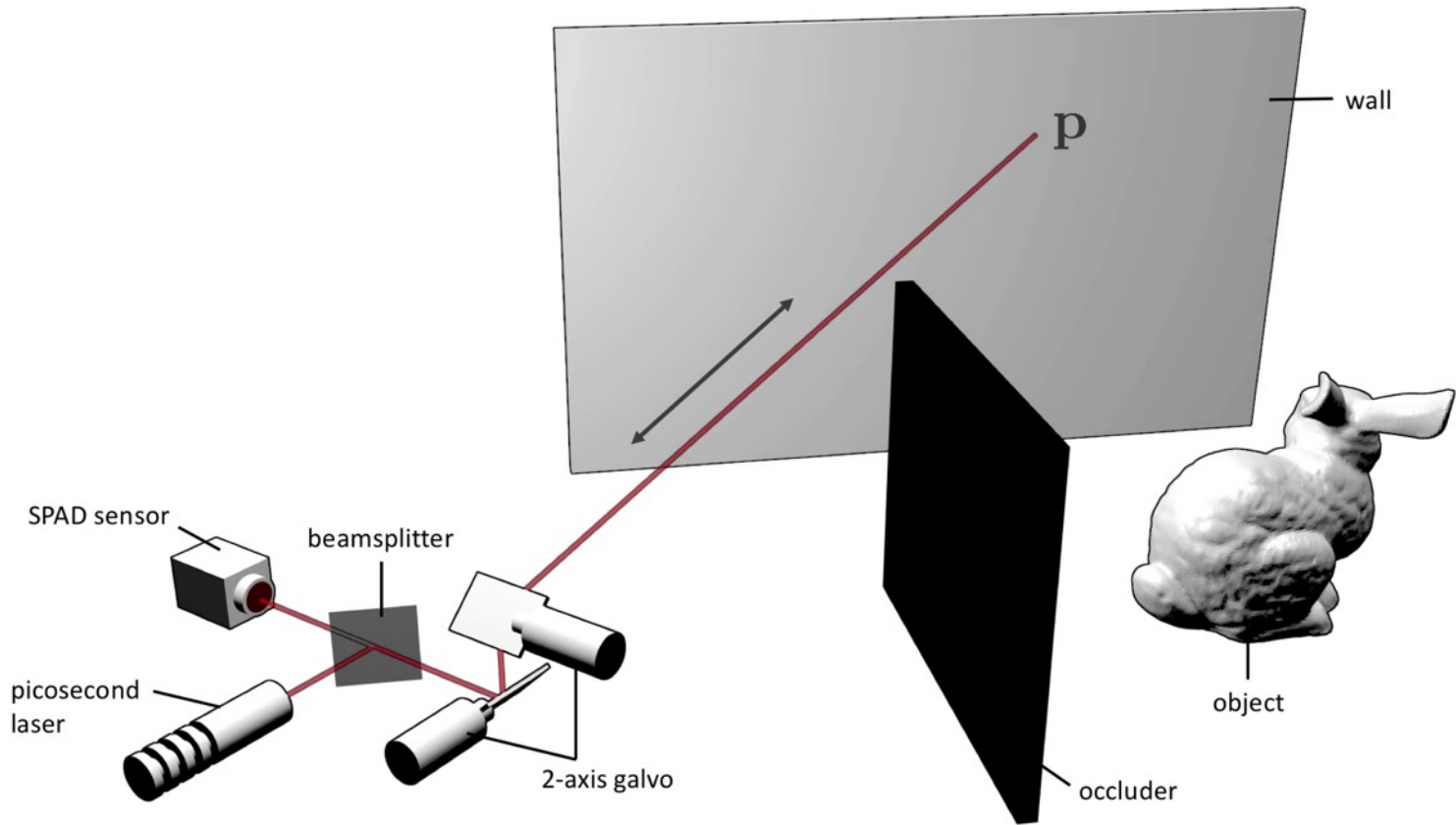
transient image with  
novel-view synthesis



regular image







wall

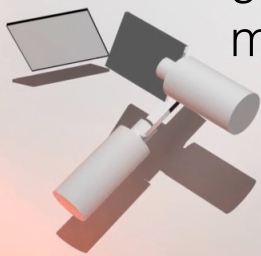
detector



pulsed laser



scanning mirrors



occluder

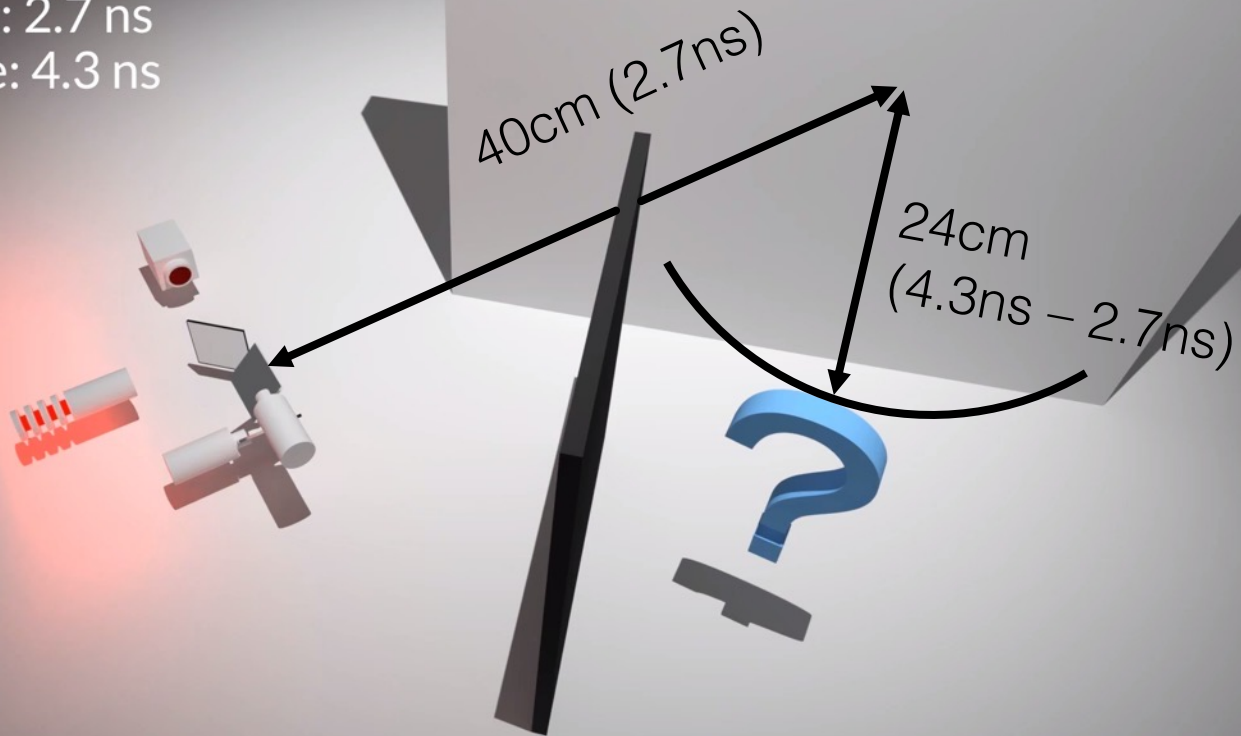


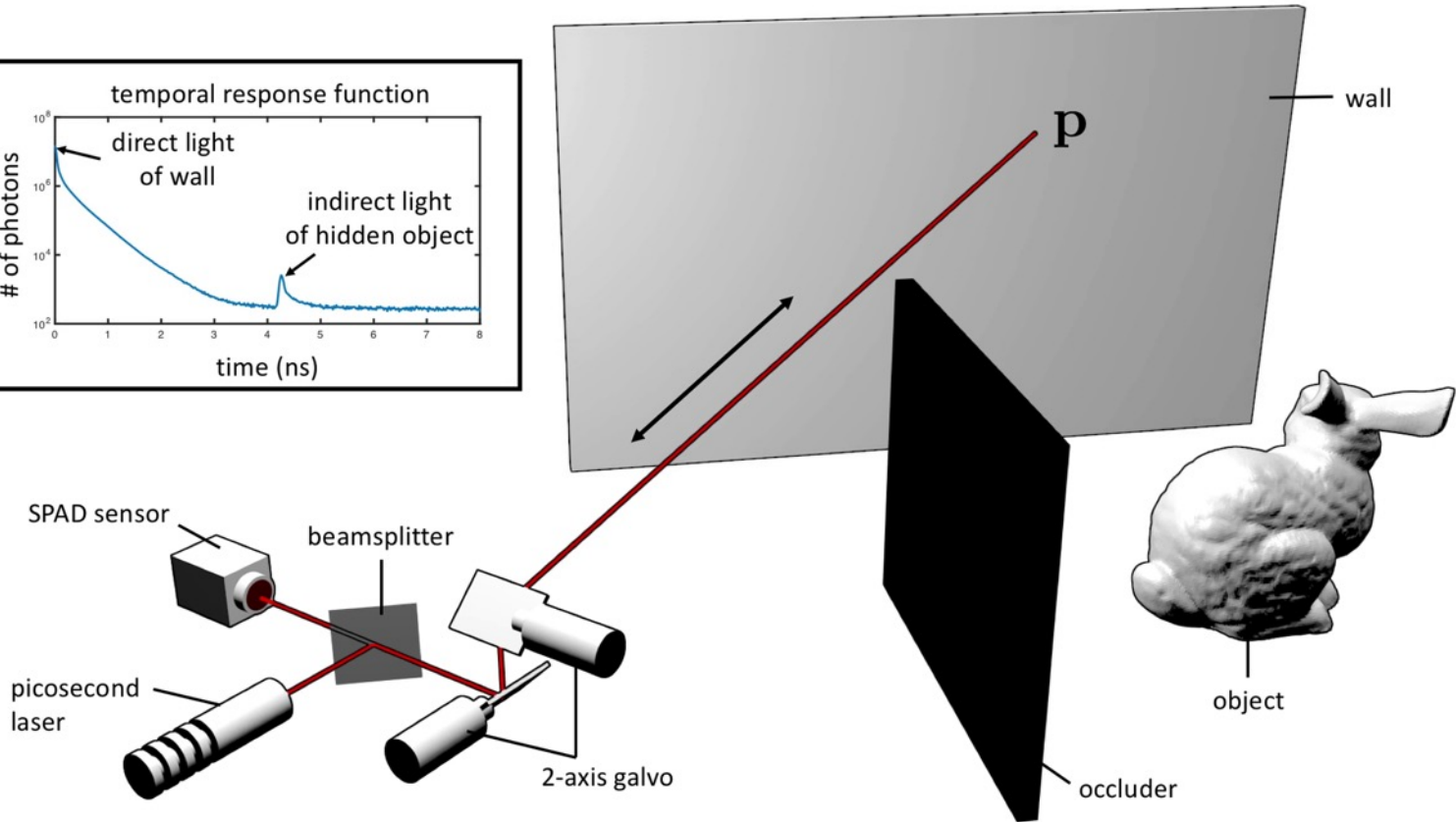
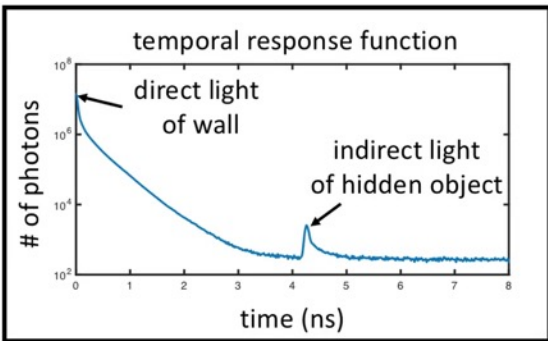
hidden object

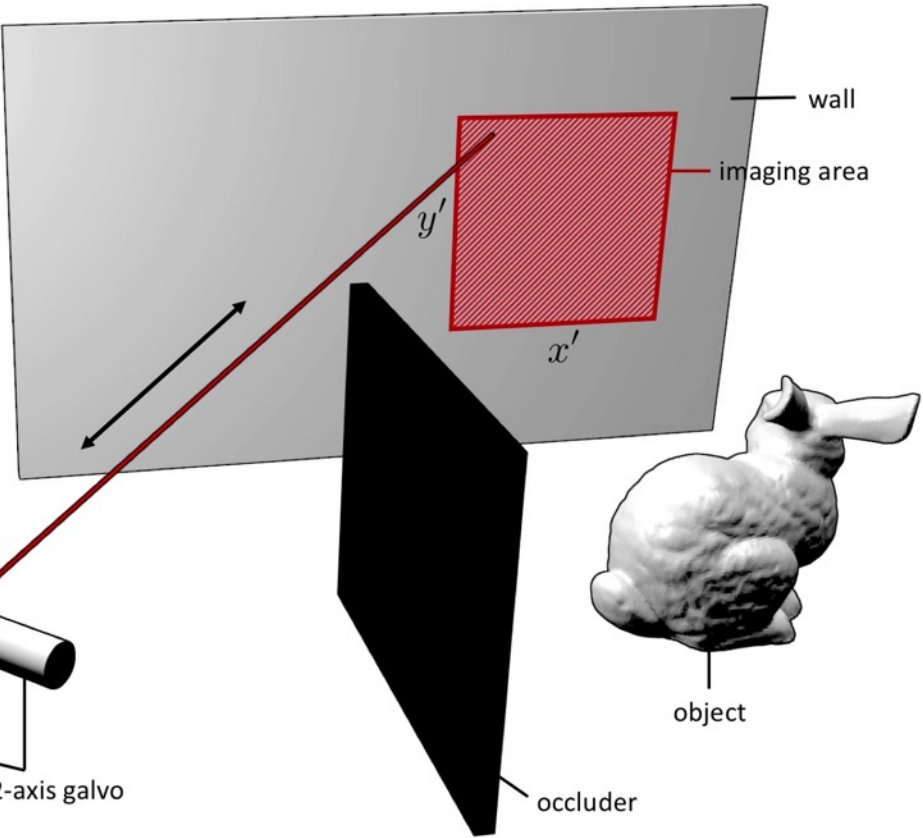
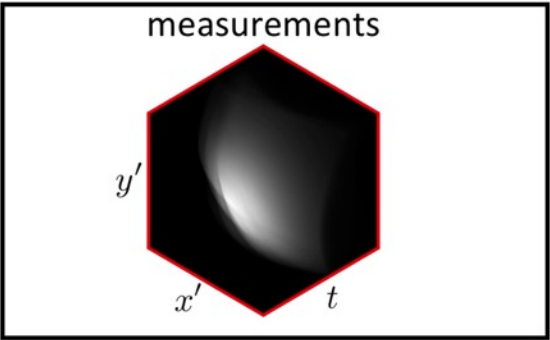
**04.800 ns**

1st bounce: 2.7 ns

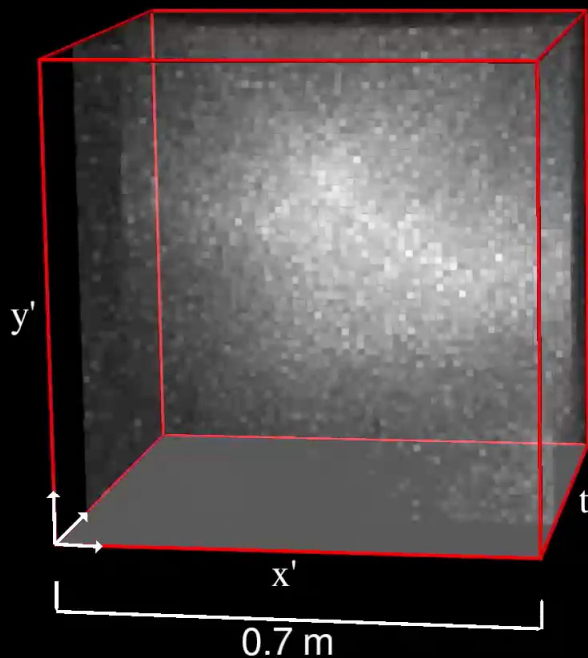
3rd bounce: 4.3 ns





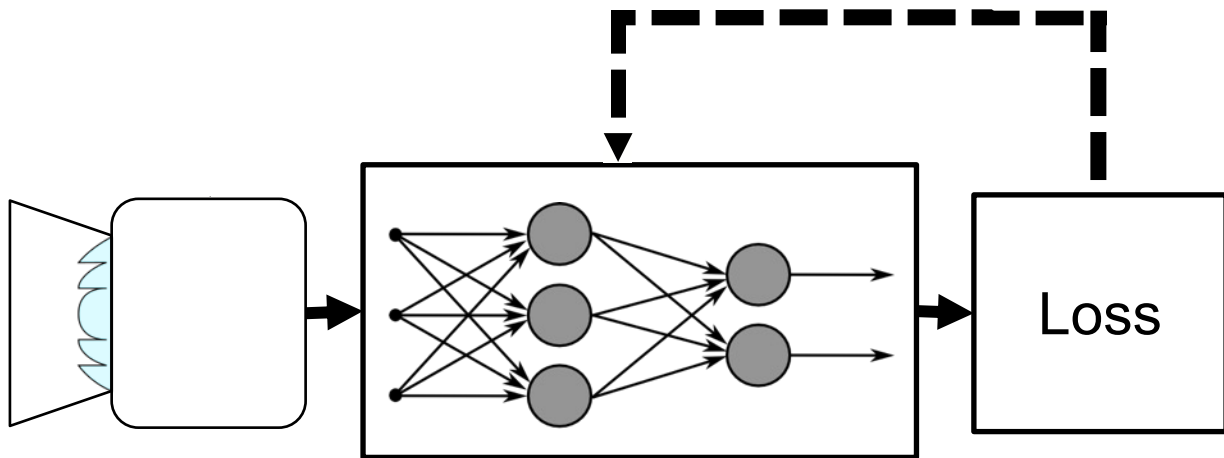


# Retroreflective Mannequin Measurements



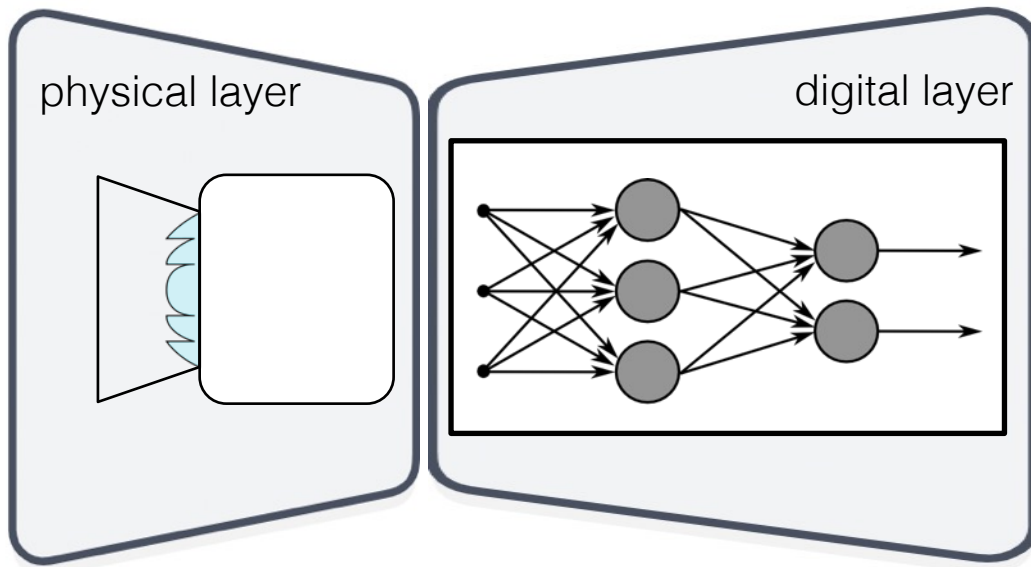
Maximum Intensity Projection

# Deep Optics



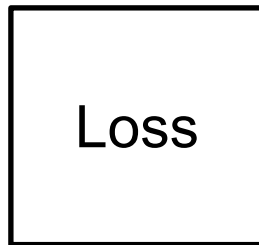
Jointly optimize optics and image processing end-to-end!

# Deep Optics



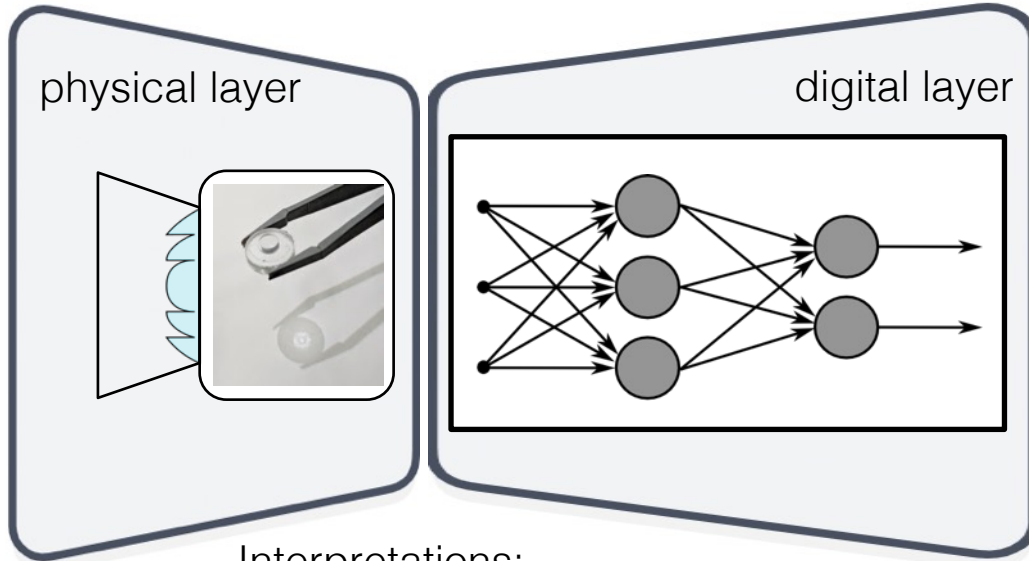
*Training:*

end-to-end in  
simulation



# Deep Optics

*Inference:*



fabricate lens or other physical components, run network

Interpretations:

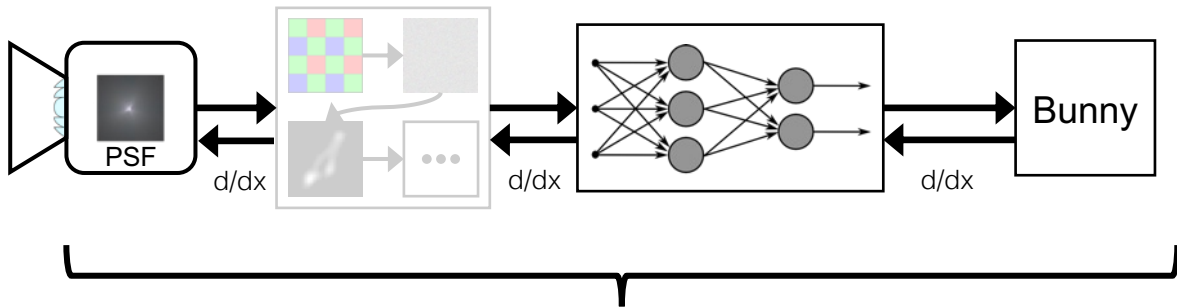
- Optical encoder, electronic decoder system
- Hybrid optical-electronic neural network



Optics Design  
& Optimization

Low-level Image  
Processing, i.e. ISP

High-level Image  
Processing, i.e. CNN



differentiable pipeline  $\rightarrow$  optimize end-to-end

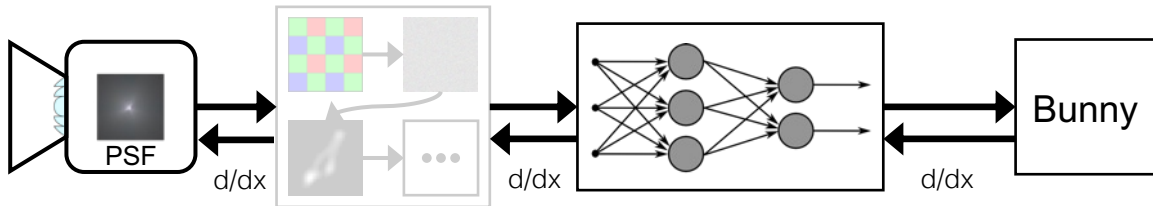
# Learning Optics & CNN



Optics Design  
& Optimization

Low-level Image  
Processing, i.e. ISP

High-level Image  
Processing, i.e. CNN



All-optical CNN Layer

Fully-connected Layer

# Conventional CNN Layer



Multichannel Convolution



Input Image

PSF

Recorded Image

Crop & Stack



\*

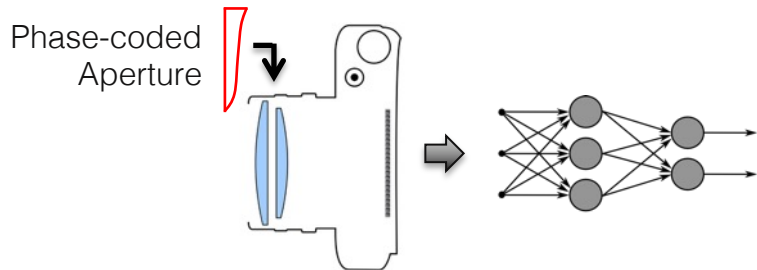


=



# All-optical CNN Layer

# Hybrid Optical-Electronic CNNs



4f system

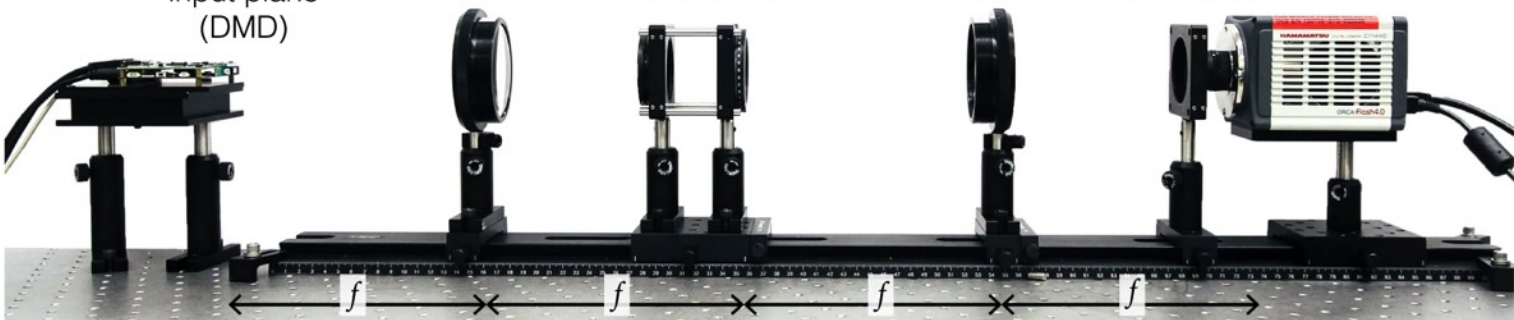
input plane  
(DMD)

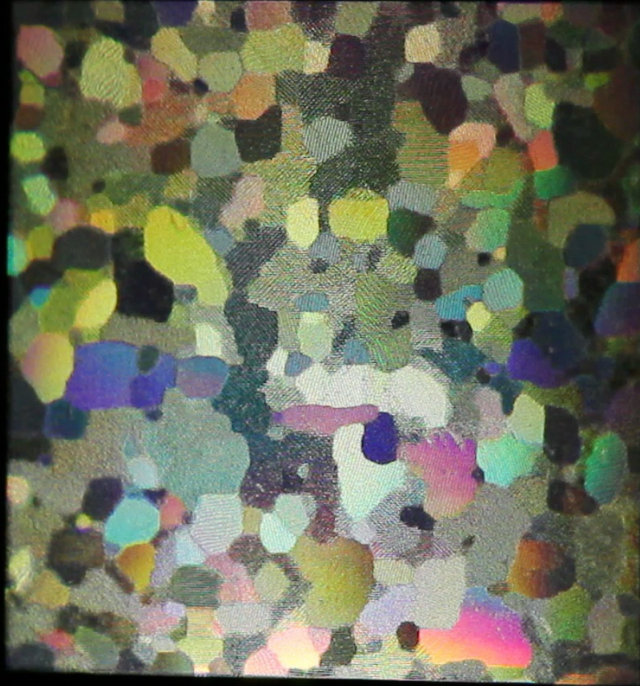
lens

Fourier plane  
(phase mask)

lens

output plane  
(camera sensor)

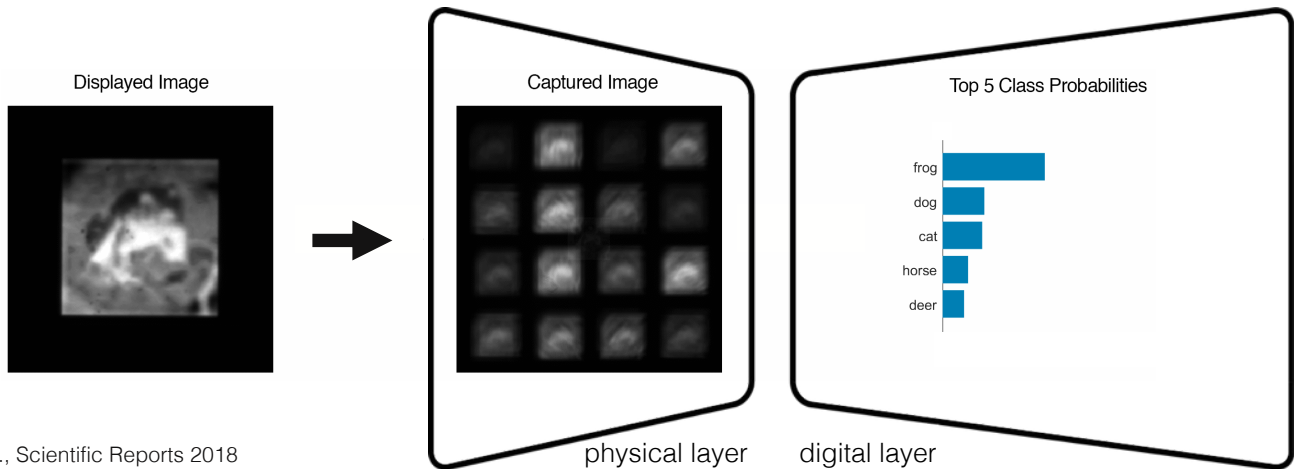




# Hybrid Optical-Electronic CNNs

## Results:

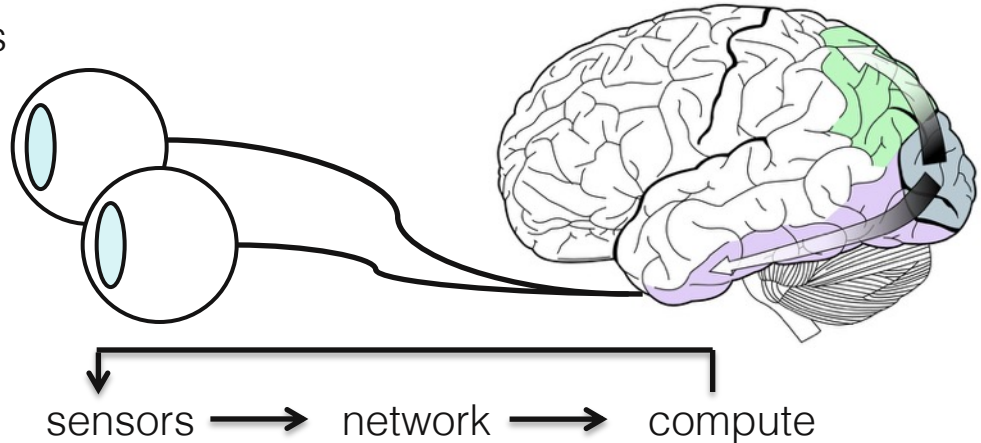
- 2x classification accuracy for same power
- half power for same classification accuracy



Fast Forward

# The Human Visual System

- anatomy of the eye
- acuity, color, 3D vision
- contrast sensitivity
- conflicts in displays
- refractive errors



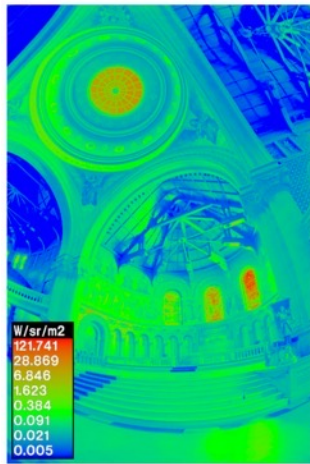
# Digital Photography

- optics
- aperture
- depth of field
- field of view
- exposure
- noise
- color filter arrays
- imaging processing pipeline



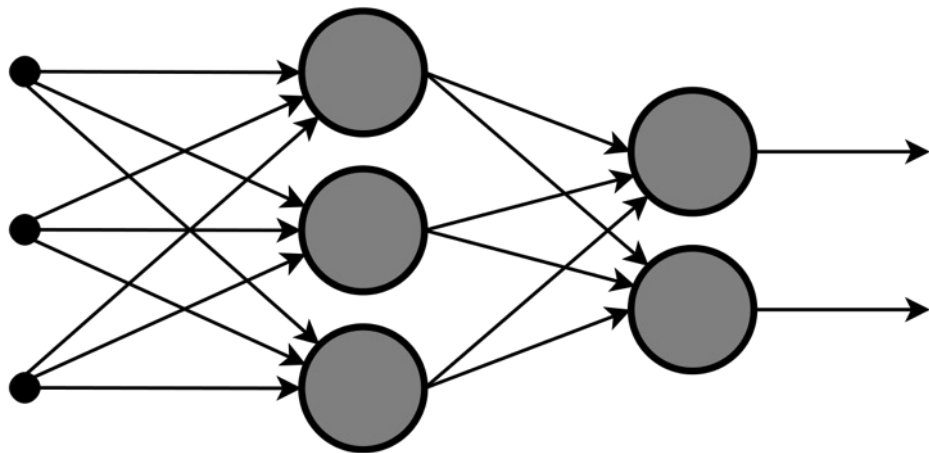
# Computational Photography

- High-dynamic range imaging
- Tone mapping
- Burst photography & night sight
- Coded apertures
- ...



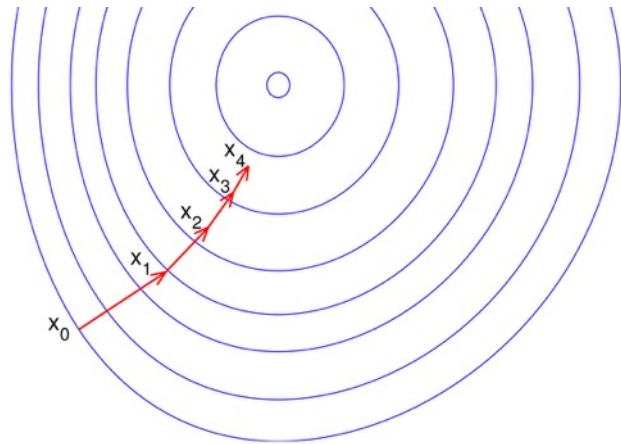
# AI for Computational Imaging

- Convolutional neural networks
- DnCNN
- U-Net
- ...



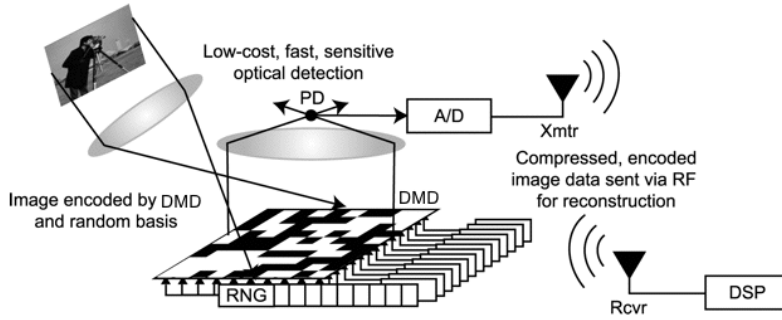
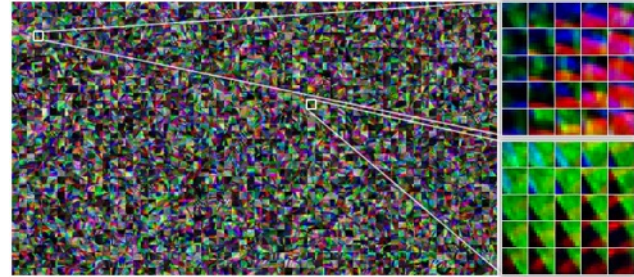
# Optimization & AI

- Proximal gradient methods (HQS, ADMM)
- Iterative optimization with deep priors
- Solving general inverse problems in imaging
- Introduction to diffusion models
- Solving inverse problems with diffusion model priors
- ...

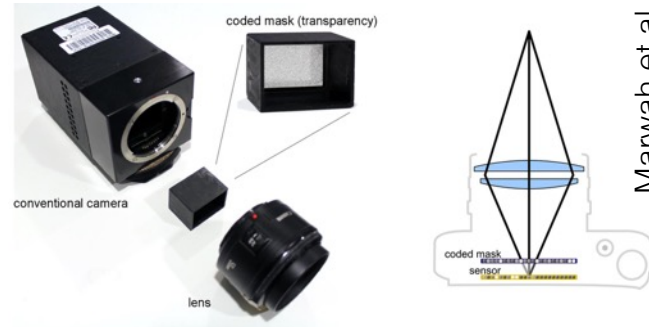


# Compressive Imaging

- single pixel camera
- compressive hyperspectral imaging
- compressive light field imaging
- ...



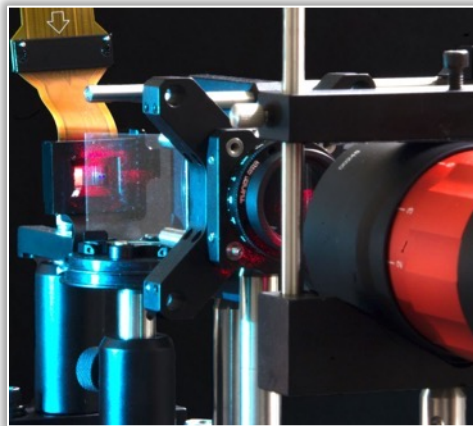
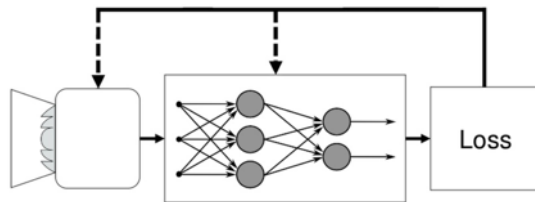
Wakin et al. 2006



Marwah et al., 2013

# Introduction to Wave Optics and Deep Optics

- Diffraction & interference
- The diffraction limit
- End-to-end optimization of optics & image processing
- Phase retrieval
- Computer-generated holography

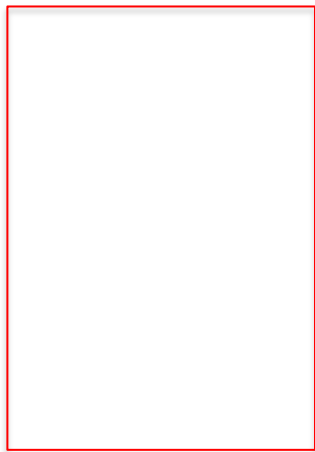


# Guest Lectures

Recordings from last year's lectures on canvas!



Dr. Orly Liba  
Google Research



???  
Stanford PhD



Prof. David Lindell  
University of Toronto



Prof. Katie Bouman  
Caltech

# Class Details

# (no formal) Prerequisites (but ...)

- strong *programming skills*, ideally Python
- *linear algebra* (EE 263 or equivalent)
- basic knowledge of *Fourier transforms* (EE 261 or equivalent)
- maybe a bit of (statistical) signal processing (EE 278), but not absolutely required
- basic computer graphics or computer vision could be helpful, but also not required

# Related, Possibly Helpful Classes

## Active Stanford Classes:

- EE 292E                    Image Systems Engineering Seminar (1 unit)
- EE 267:                    Virtual Reality (DIY HMD)
- CS 148:                    Introduction to Computer Graphics and Imaging
- PSYCH 221:                Applied Vision and Image Systems Engineering
- EE 364A:                   Convex Optimization I
- EE 227:                    Robot Perception

## Archived Classes:

- CS 178:                    Digital Photography
- CS 448A:                   Computational Photography

# Related, Possibly Helpful Classes

Also helpful

- CS 131: Computer Vision: Foundations and Applications
- CS 231A: Computer Vision: From 3D Reconstruction to Recognition
- other computer vision courses:  
EE 231B, CS 231M, CS 328, CS 331A, CS 331B, CS 431
- graphics courses: CS 248, CS 348B, CS 448

# Imaging-related Activities at Stanford

- SCI – Stanford Computational Imaging Group
  - [www.computationalimaging.org](http://www.computationalimaging.org)
- EE292E / SCIEN - weekly colloquium, info here: [scien.stanford.edu](http://scien.stanford.edu)
  - lots of interesting talks & interesting people
  - free food & drinks
  - every Wed, 4:30-5:50 pm in Packard 101
  - sign up for the mailing list at *[scien.stanford.edu](http://scien.stanford.edu)*

# Requirements and Grading

- 6 assignments: 50%
- in-class midterm: 20%
- major final project (teams of  $\leq 3$ ): 30%
  - discuss project ideas with TA & instructor!
  - project proposal due: **02/20, 23:59pm**
  - final presentation (in-person poster session): **Wed 3/11**
  - reports and source code due: **Fri 3/13, 23:59pm**

# Resources (see course website!)

- website: [stanford.edu/class/ee367](https://stanford.edu/class/ee367)
- contact: [ee367-win2526-staff@lists.stanford.edu](mailto:ee367-win2526-staff@lists.stanford.edu)
- office hours (TA): Wed 3-4:30pm, Location (website) & Zoom (canvas)  
discuss: homeworks, labs, lectures
- office hours (Instructor): Mon 3-4 pm, Packard 236 & Zoom (email me!)  
discuss: projects, course material, misc.
- Forum: Ed Discussion (canvas)

# Tentative Schedule

<http://stanford.edu/class/ee367/>

# What we don't discuss

- no medical imaging, but same concept apply – medical imaging projects are encouraged!
- outlook on wave optics / diffractive imaging but not focus on this topic

# Lectures and Problem sessions

- 2 lectures per week: Mo & We 1:30 – 2:50 pm in Gates B3 in person (recording will be available on canvas after class)
- 1 problem session (first 6 weeks): in person, see website (recording will be available on canvas after class)
- attendance strongly recommended, but everything is recorded

# Assignments

- 6 assignments: mix of theory, programming, and HW1 has a bit of hands-on building
- out every Wed (starting this week), due Fri week after at 11:59pm (midnight)
- no late days! (unless something exceptional comes up)
- you can submit until that Sat 11:59pm (midnight) with 30% penalty on the full score (24h late=70% max score on HW), after that 0%
- discussion among students encouraged, but must submit own solution and acknowledge others that you discussed this with
- submission via [www.gradescope.com](http://www.gradescope.com) - create account (see entry code on website)
- Pre-recorded weekly problem session on canvas

# Midterm

- Feb 25: 80 minute, in-class midterm in Packard 101 (or remote with permission)
- open book: you can use internet, lecture material, etc.
- bring laptop!
- writing small Python scripts may be helpful but not required

# Course Projects & Proposal

- individual or teams of up to 3 people
- 30% of your grade – plan on ~50-60 h per person!
- Feb 21: short project proposal = 1-2 pages with
  - motivation
  - related work
  - project overview
  - milestones, timeline & goals
  - at least 3 scientific references
  - we may ask you to revise the proposal, will assign a mentor to your team

# Course Projects

- Mar 11: in-person project poster + demo session
  - see poster template on website
  - More details later
- SCPD students: can submit narrated video presentation

# Course Projects

- Mar 13: report + source code due (at midnight)
- report = conference paper format ~6 pages with
  - abstract
  - introduction
  - related work
  - theory
  - analysis
  - results
  - discussion and conclusion
  - references
  - see latex template on website

# Course Projects

- must also submit source code along with report!
- proposals, reports, source will be available on course website
  - only use non-copyrighted material
  - especially SCPD students: no projects that require NDA or company secrets
  - may request that source code / report may not be public – contact staff

# Possible Course Projects

- be experimental!
- can use your own (related) research
- optimization or deep learning for your favorite inverse problem in imaging
- ...

# Possible Course Projects

See previous course projects (proposals, reports, code, posters) on the course website!

**We also provide a default project with starter code for you:  
solving inverse problems in imaging with diffusion model priors**

feel free to pick this project, it's a bit more structured, like a longer homework

# Next Class: The Human Visual System

- anatomy of the eye
- acuity, color, 3D vision
- contrast sensitivity
- conflicts in displays
- refractive errors

