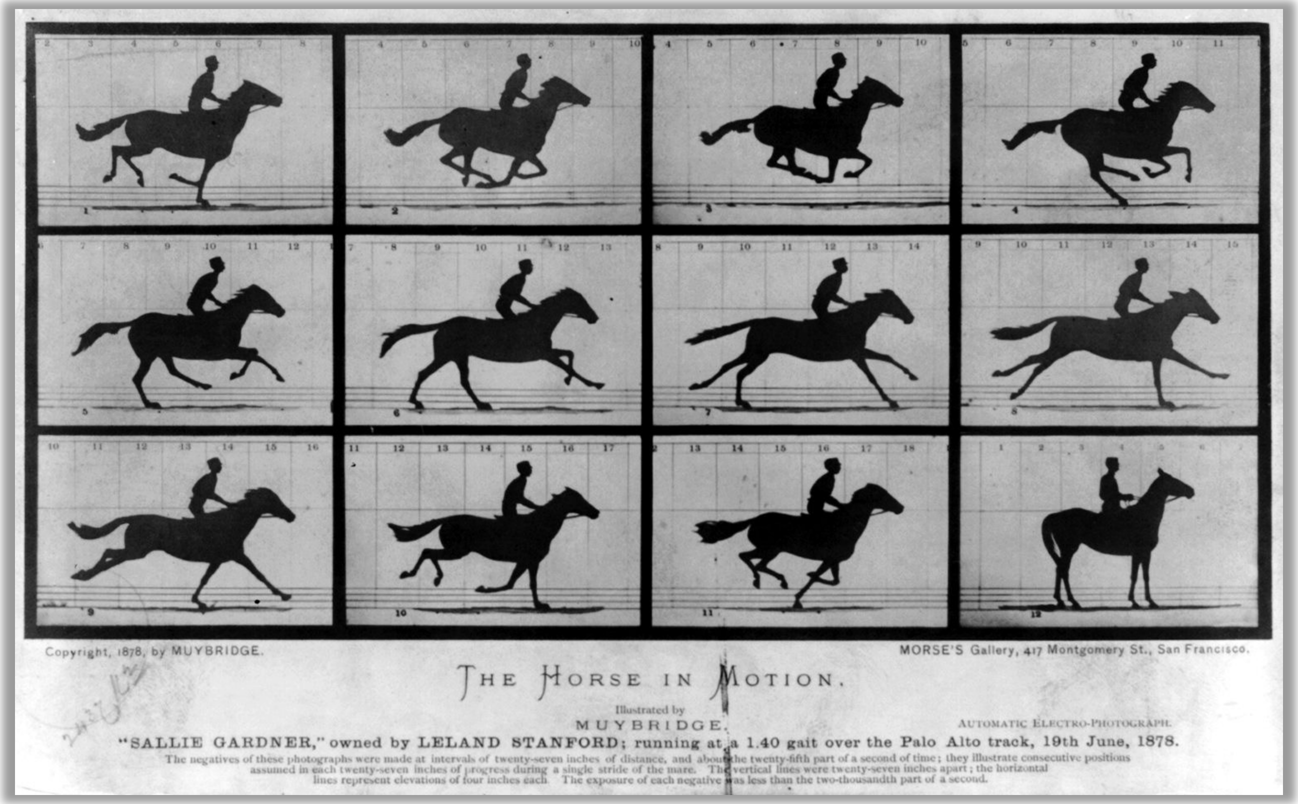
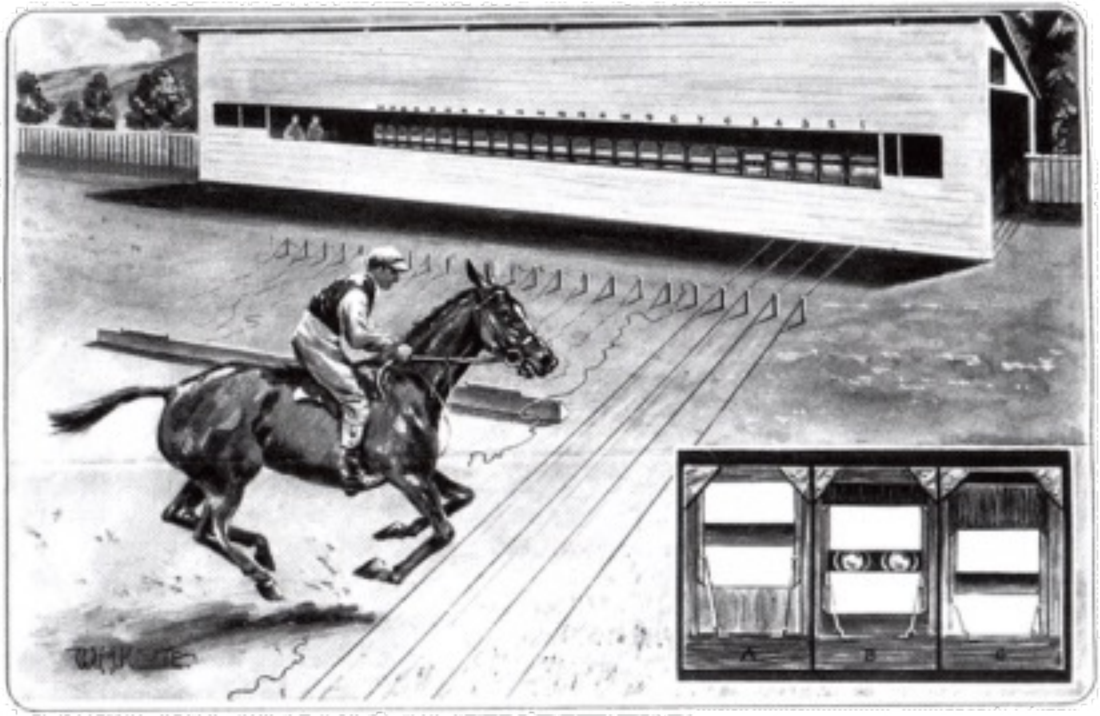
Introduction, Overview, Fast Forward

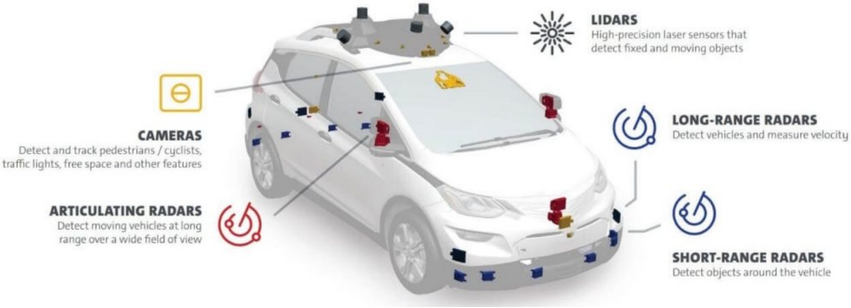
EE367/CS448I: Computational Imaging
stanford.edu/class/ee367
Lecture 1

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




LIDARS
High-precision laser sensors that detect fixed and moving objects
CAMERAS
Detect and track pedestrians / cyclists, traffic lights, free space and other features
LONG-RANGE RADARS
Detect vehicles and measure velocity
ARTICULATING RADARS
Detect moving vehicles at long range over a wide field of view
SHORT-RANGE RADARS
Detect objects around the vehicle


Nikon

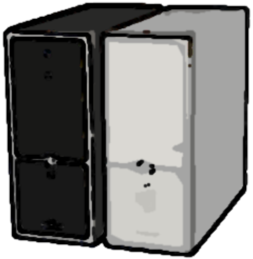

SIGMA


Image: National Geographic

What is Computational Imaging?

+

+



optics

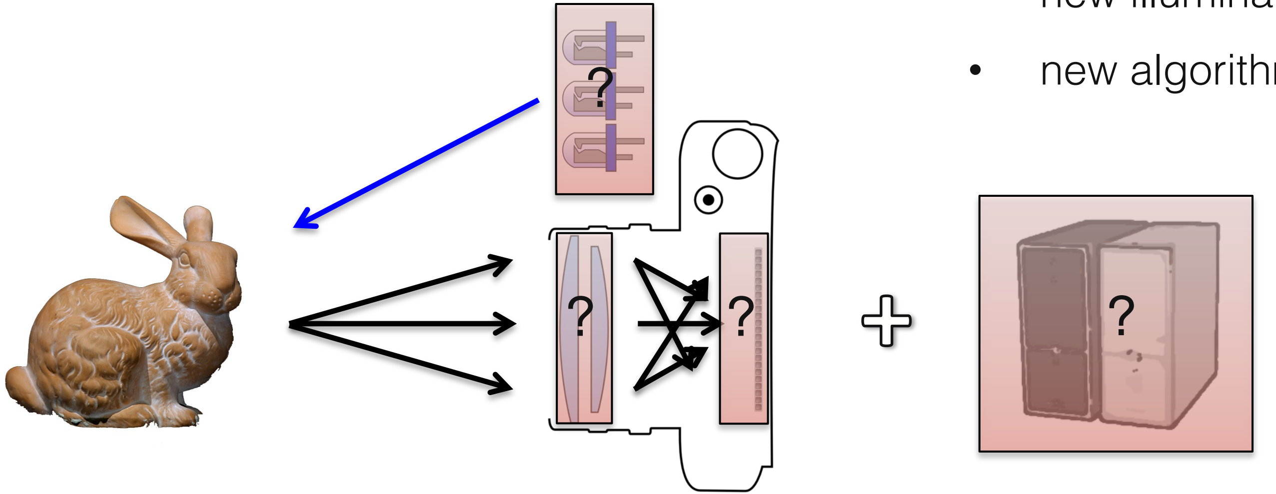
sensing

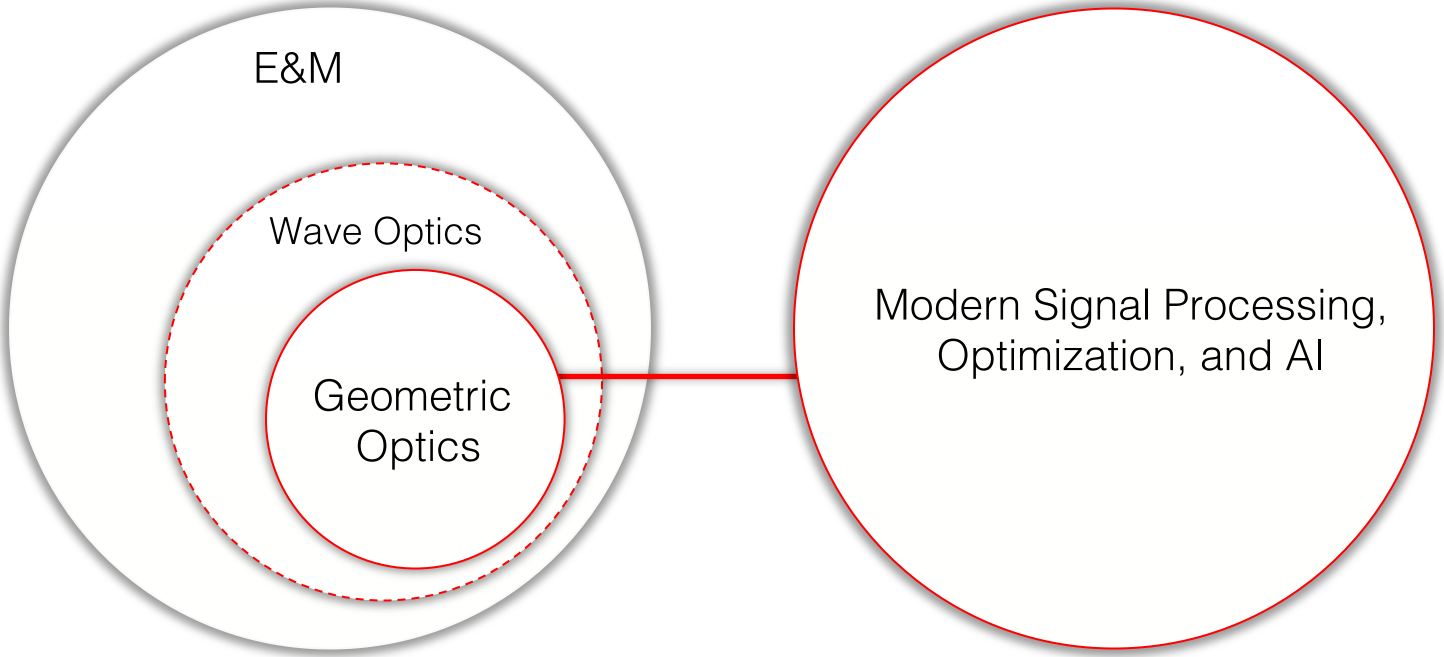
computation

What is Computational Imaging?

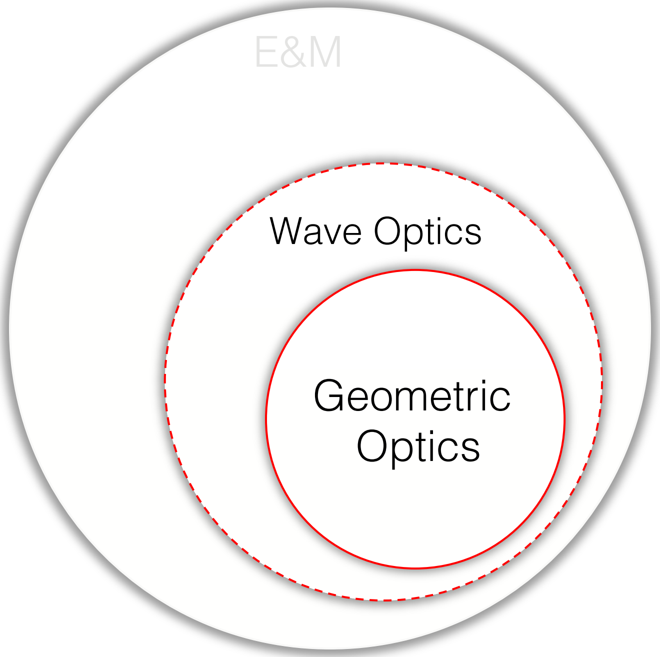
1. optically encode scene information
2. computationally recover information

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




E&M
Wave Optics
Geometric Optics
Modern Signal Processing, Optimization, and AI

What is Light?



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

Instructors

Gordon Wetzstein

Qingqing Zhao (TA)

Axel Levy (TA)

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

12MP
Telephoto camera

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

12MP
Ultra Wide camera

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

48MP
Main camera

24 mm focal length
2.44 μm quad pixel
f/1.78 aperture

Apple iPhone 15 pro max

Google Night Sight

Light Field Cameras

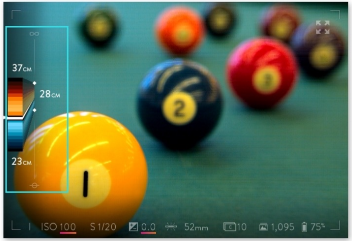
Light L16

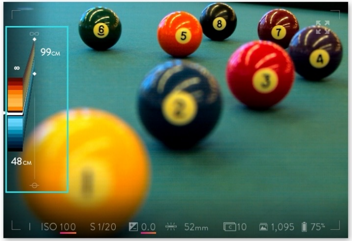
Lytro Illum

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.

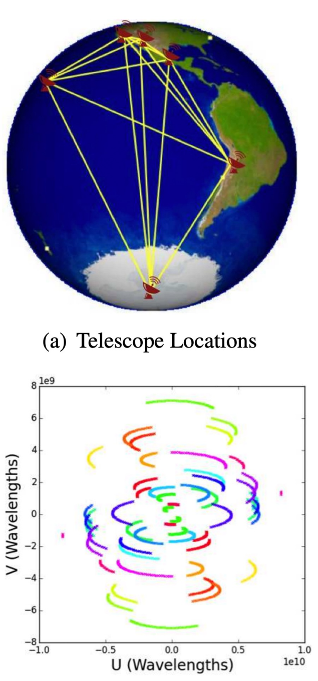
2x for torso tracking.

1x for gesture tracking.

1x time-of-flight sensor.

Source: Apple

Imaging Black Holes

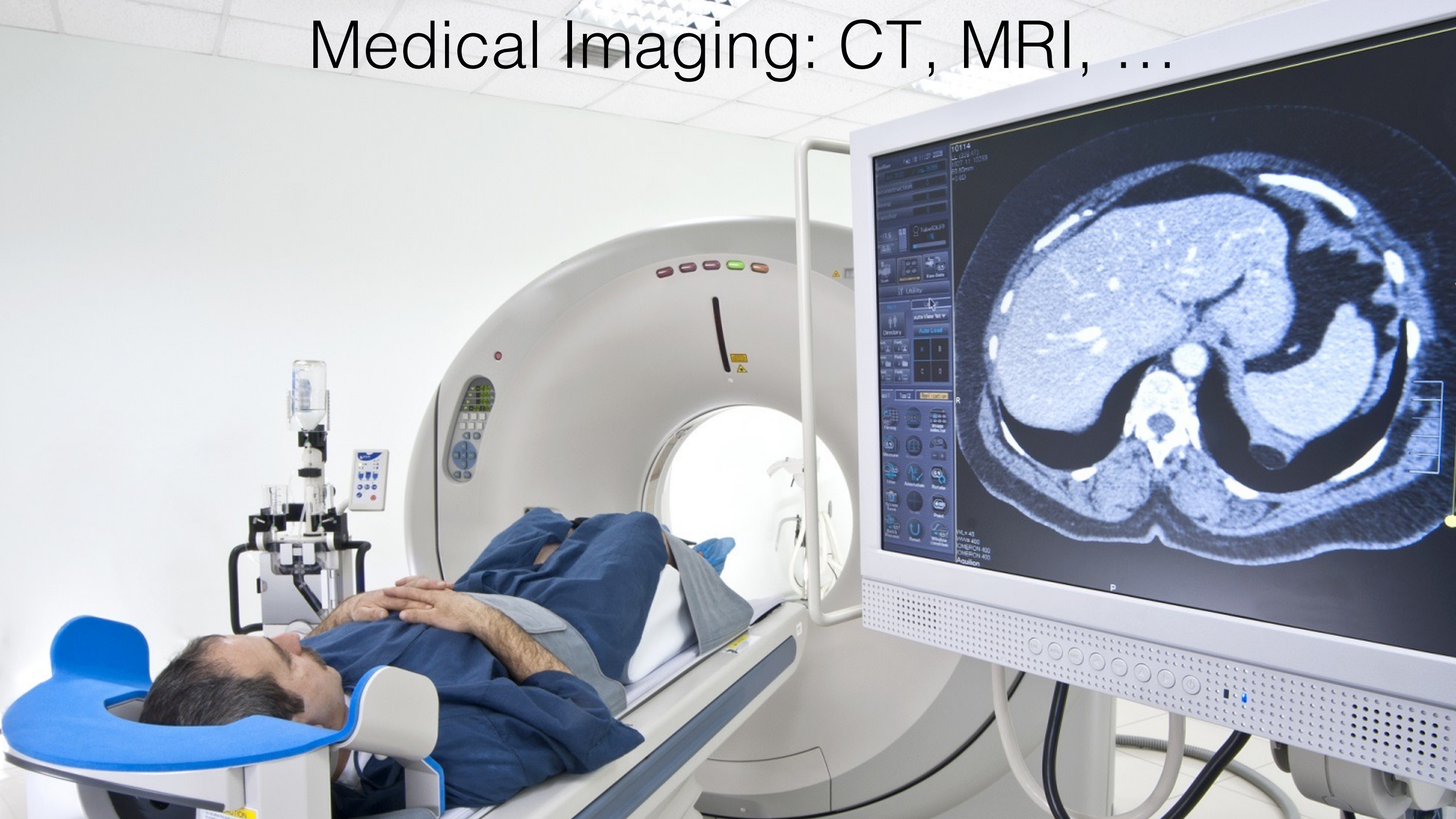


(a) Telescope Locations

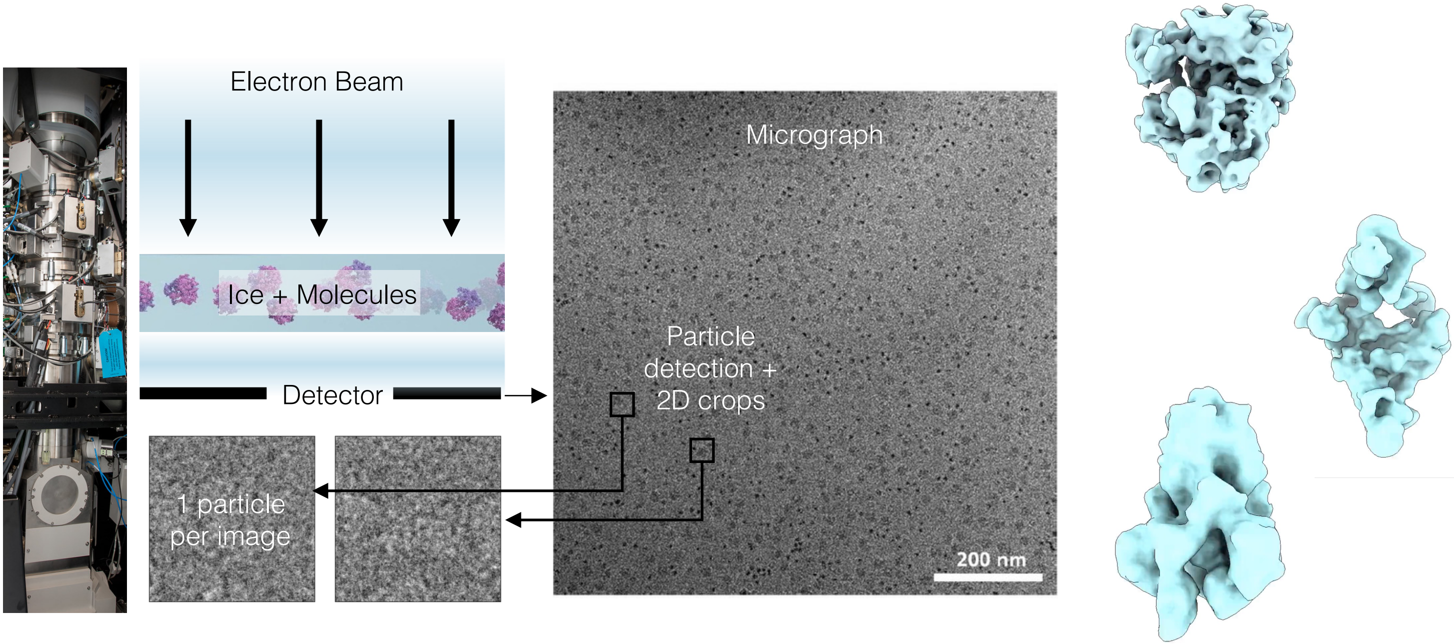
(b) Spatial Frequency Coverage

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

Medical Imaging: CT, MRI, …



Imaging Proteins with Cryo-EM



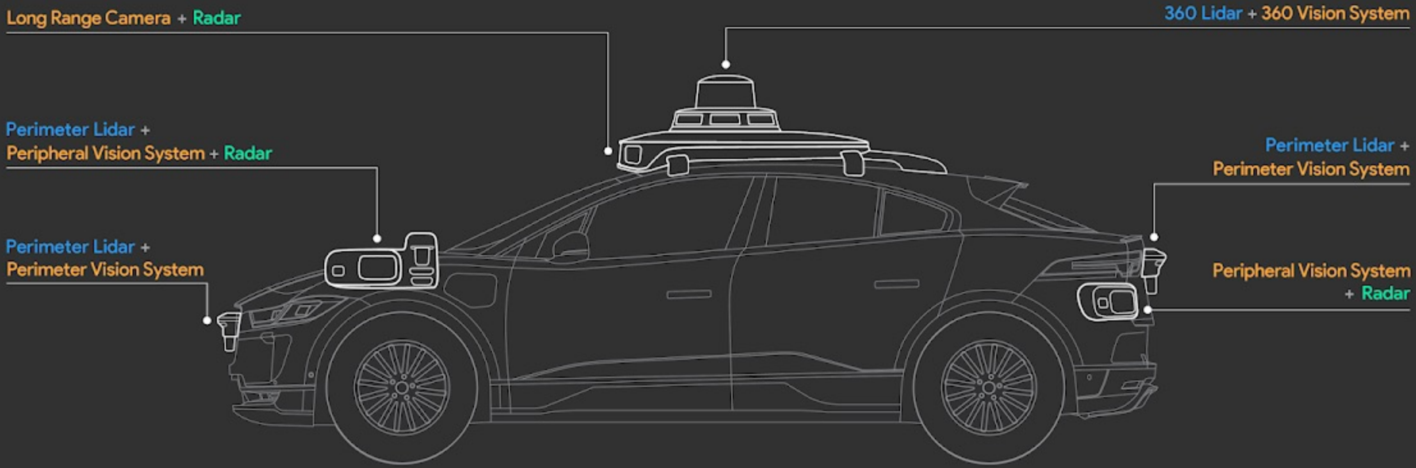
Levy et al., ECCV 2022; NeurIPS 2022

Neural Radiance Fields (NeRFs) for View Interpolation

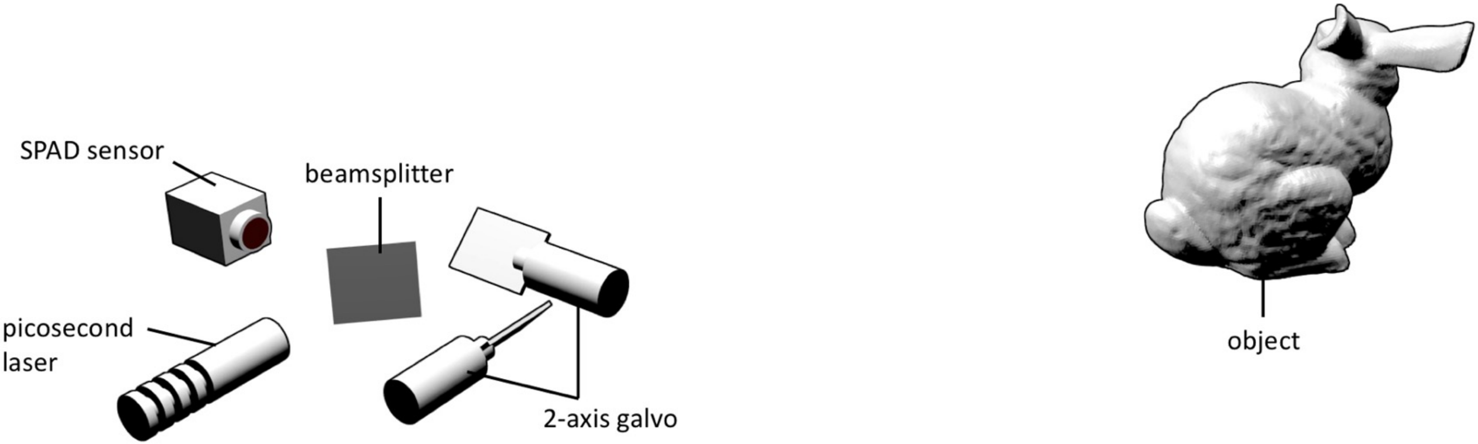
Mildenhall et al., ECCV 2020

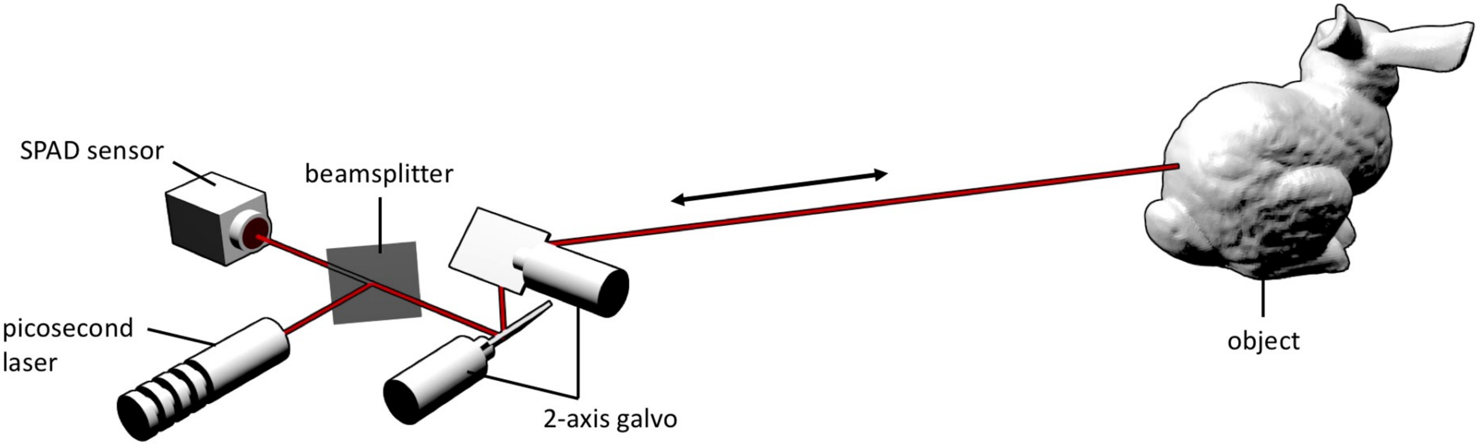
Source: Waymo

Self-driving Car Sensors



Source: Waymo


SPAD sensor
beamsplitter
picosecond
laser
2-axis galvo
object


SPAD sensor
beamsplitter
picosecond
laser
2-axis galvo
object

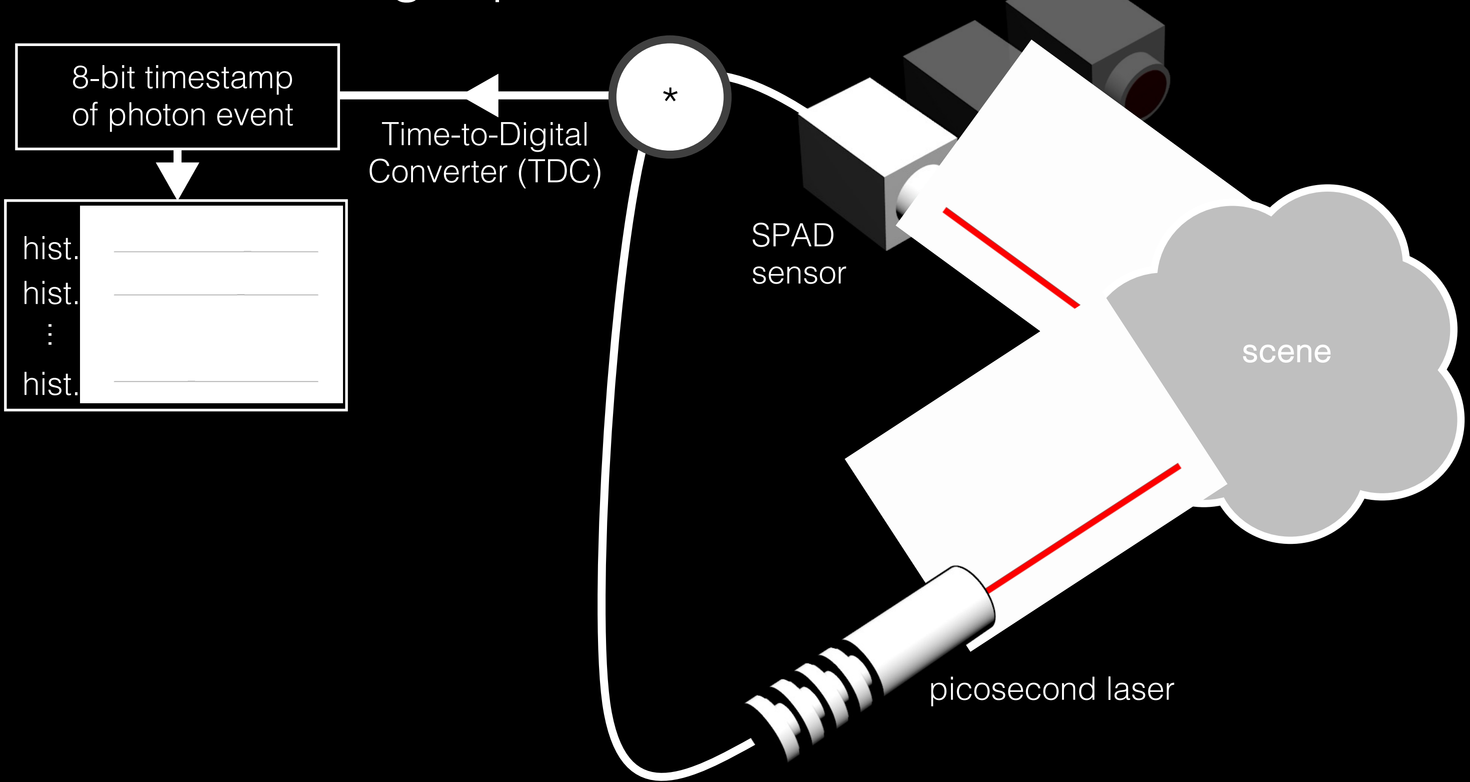
3D Imaging for Autonomous Vehicles

LIDAR (light detection and ranging)
Velodyne VLS-128

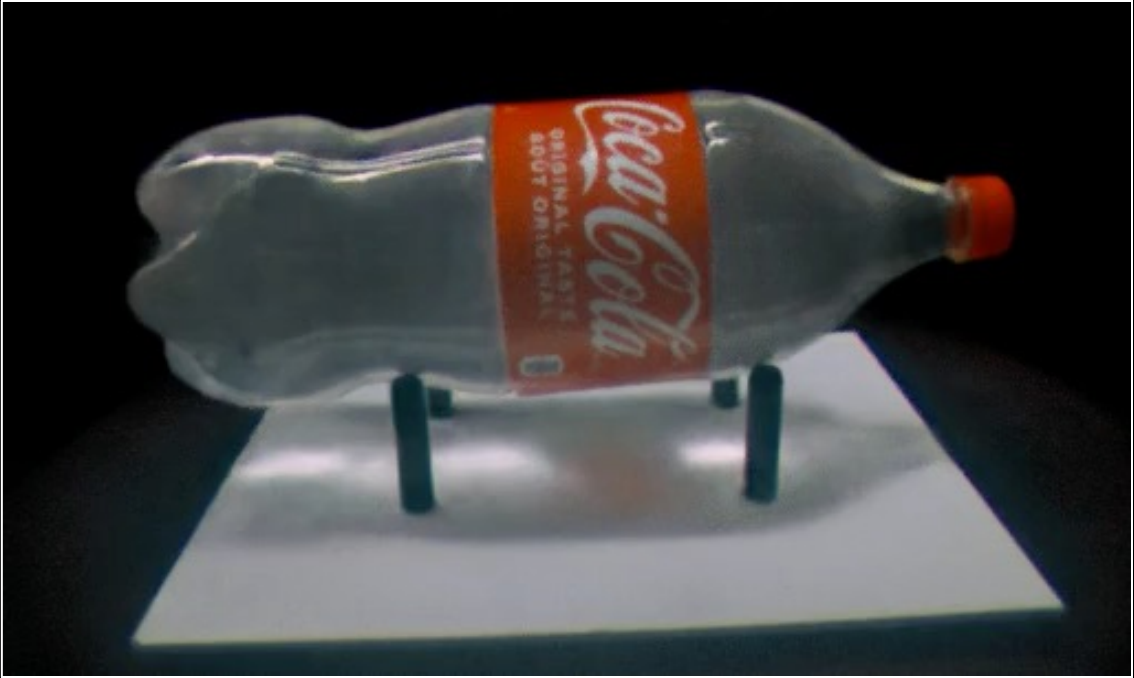
3D Imaging for Autonomous Vehicles

LIDAR (light detection and ranging)
Velodyne VLS-128

Single-photon Avalanche Diodes...



Flying with Photons

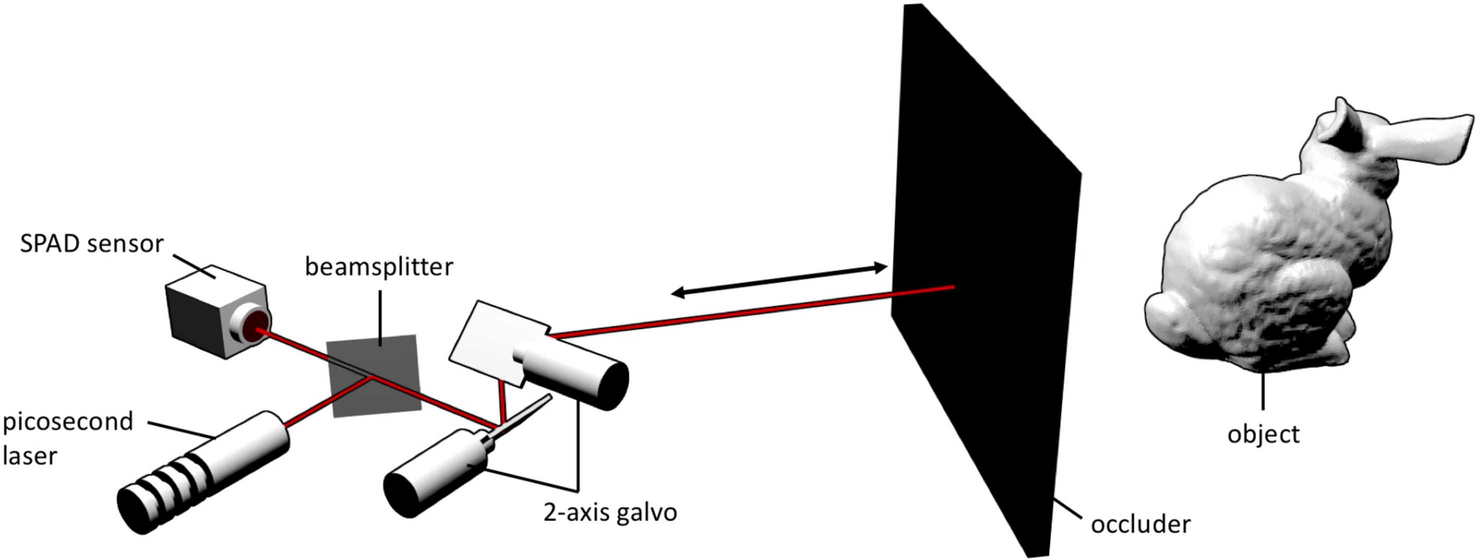


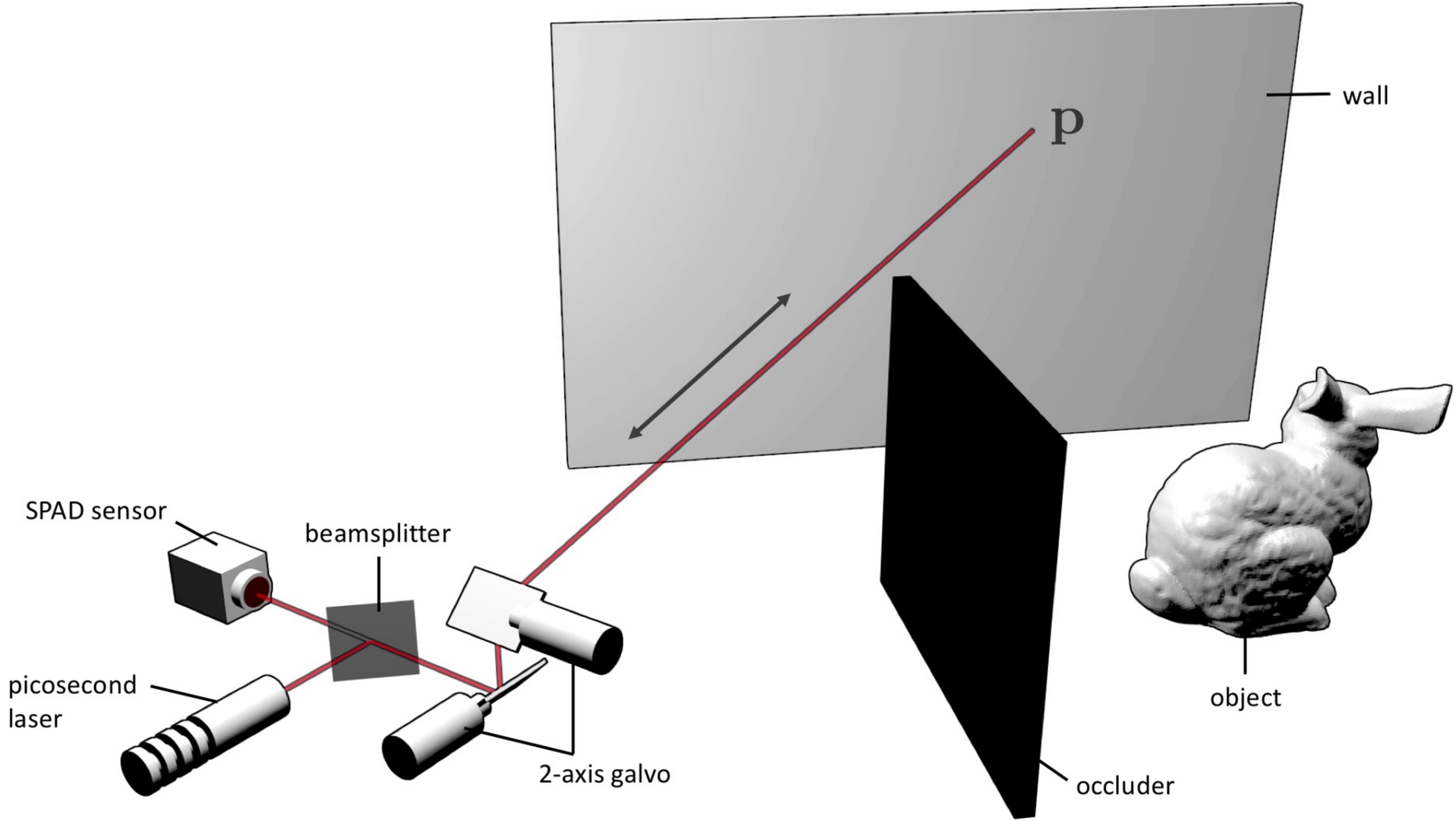
Malik et al., ECCV 2024

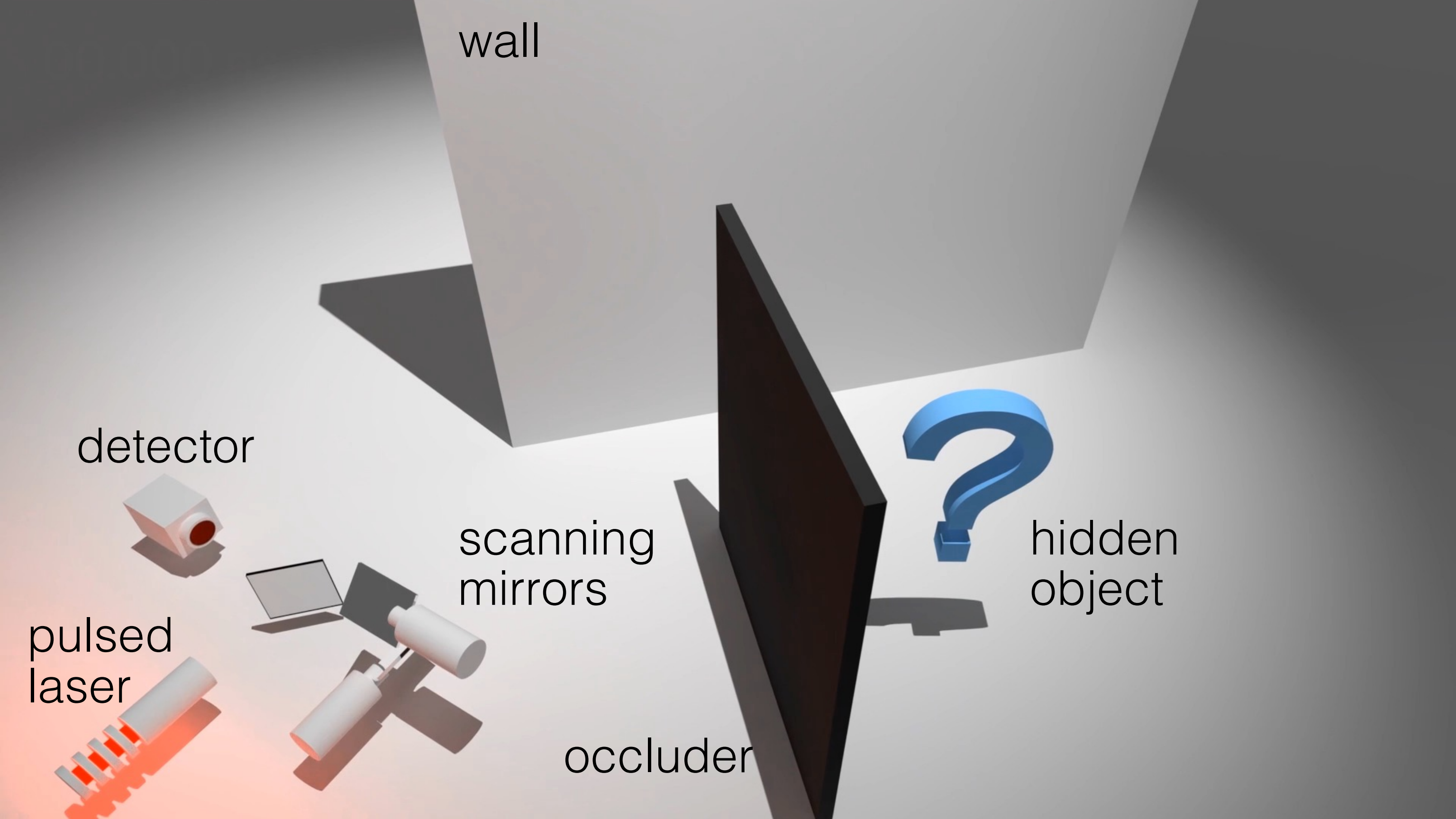
regular image

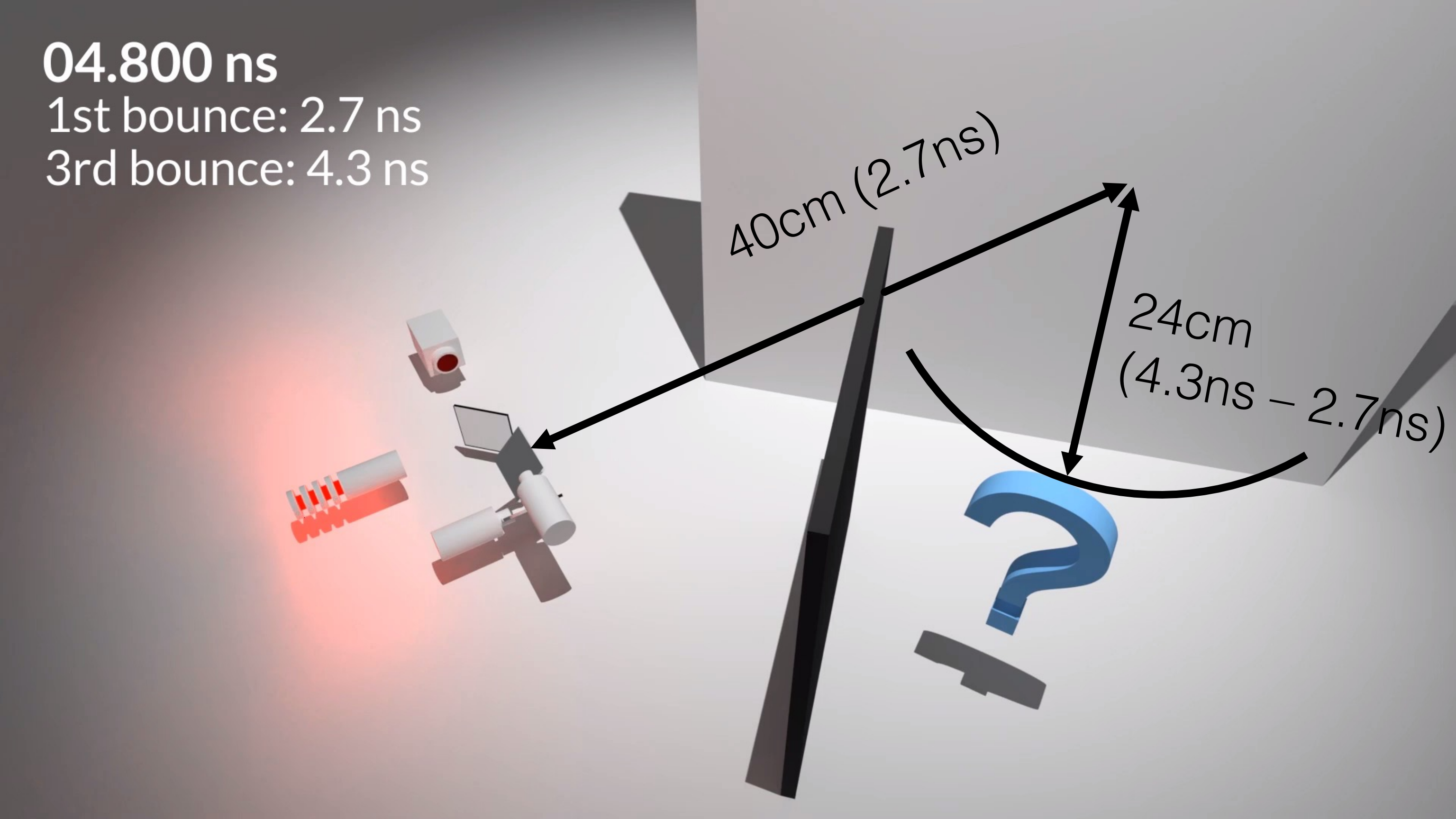
transient image with novel-view synthesis

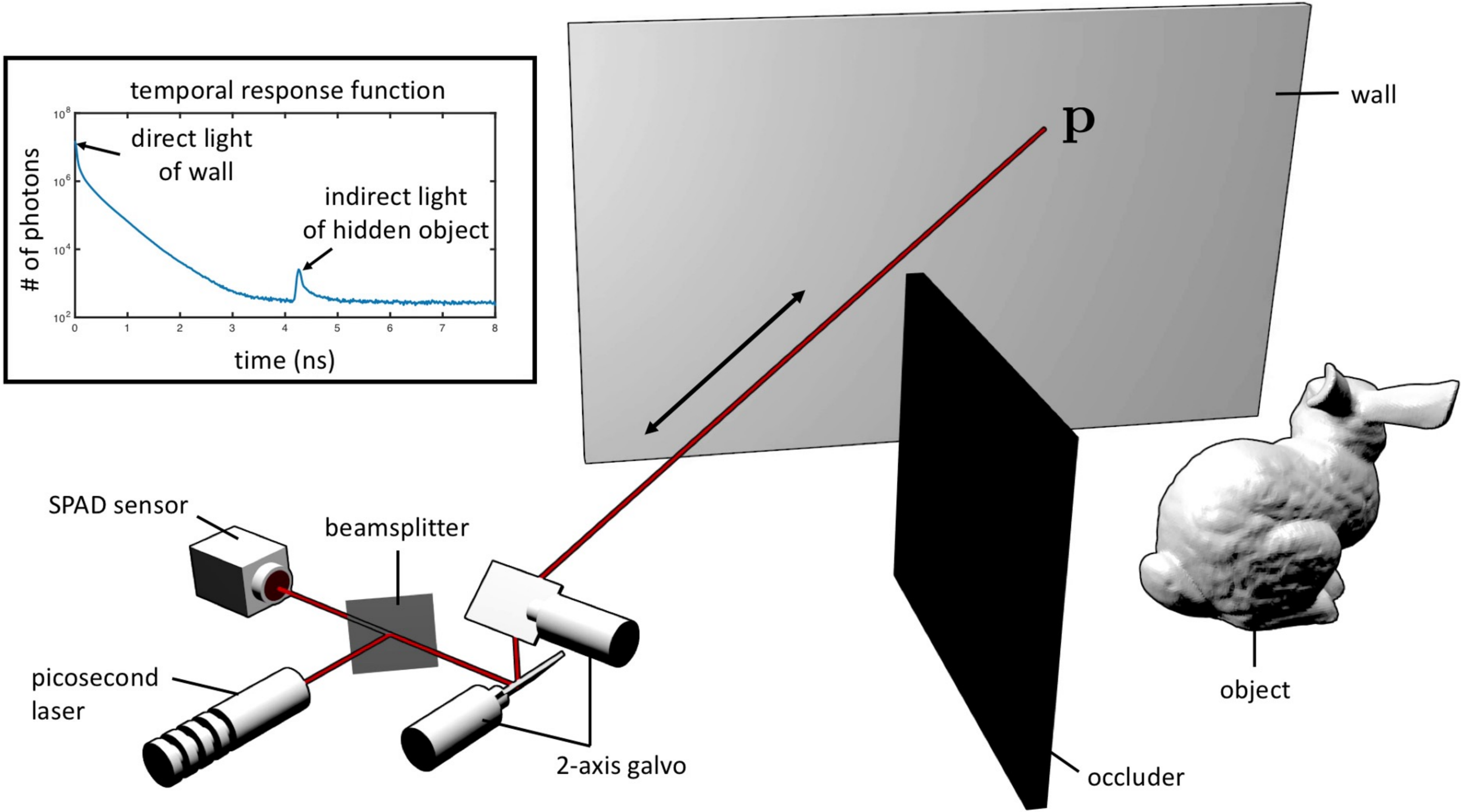
Malik et al., ECCV 2024

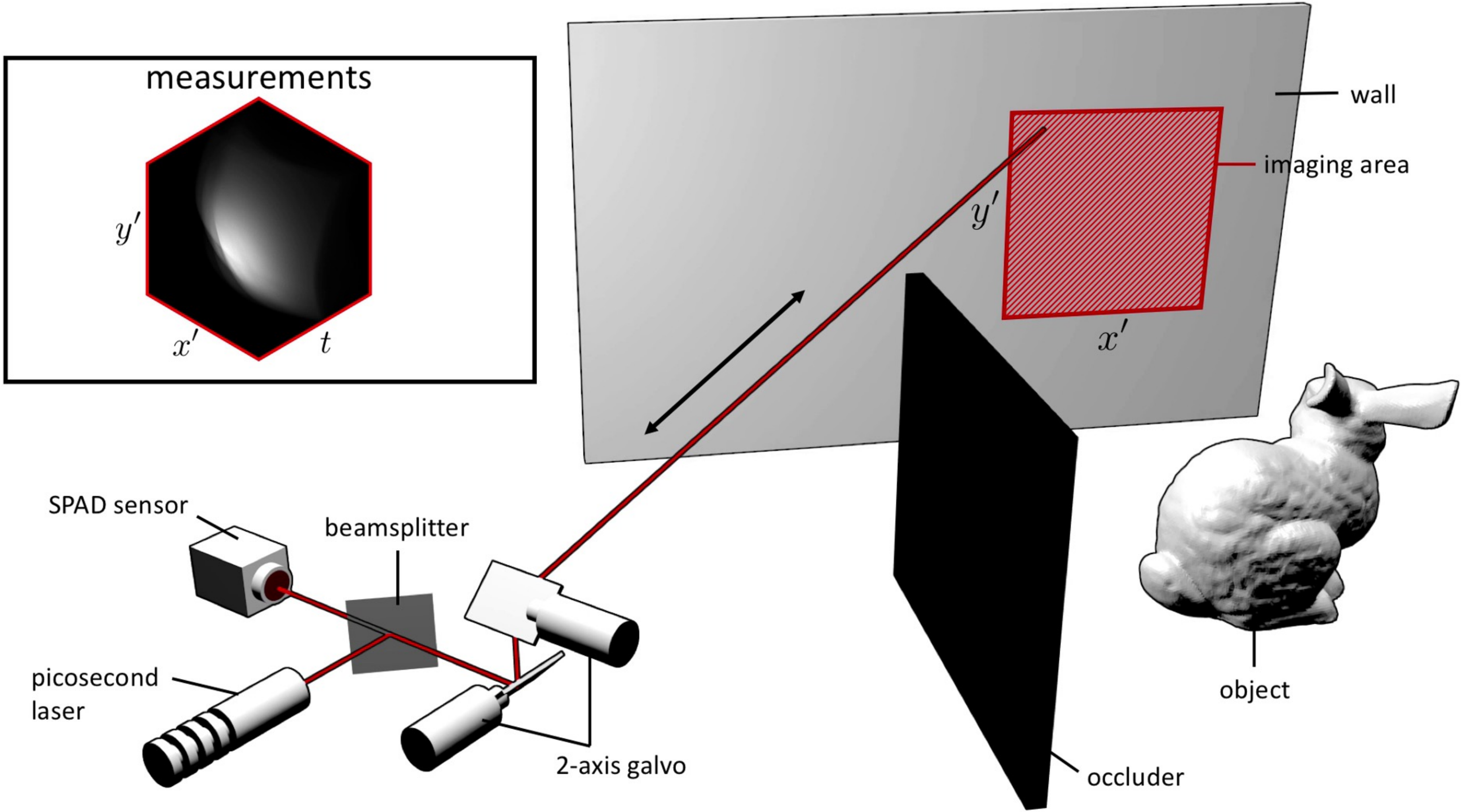

SPAD sensor
beamsplitter
picosecond
laser
2-axis galvo
occluder
object


wall
p
SPAD sensor
beamsplitter
picosecond
laser
2-axis galvo
occluder
object


wall
detector
scanning
mirrors
hidden
object
pulsed
laser
occluder

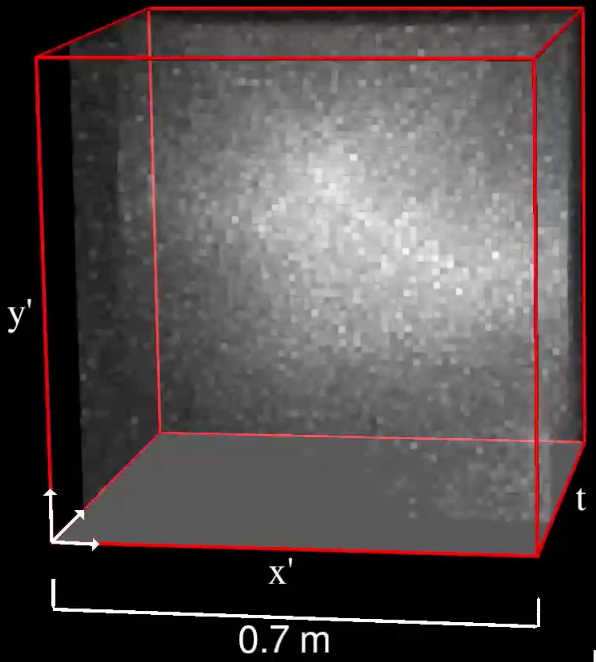

04.800 ns
1st bounce: 2.7 ns
3rd bounce: 4.3 ns
40cm (2.7ns)
24cm
(4.3ns – 2.7ns)


temporal response function
direct light
of wall
indirect light
of hidden object
# of photons
time (ns)
p
wall
SPAD sensor
beamsplitter
picosecond
laser
2-axis galvo
occluder
object



measurements
y'
x'
t
wall
imaging area
y'
x'
SPAD sensor
beamsplitter
picosecond
laser
2-axis galvo
occluder
object

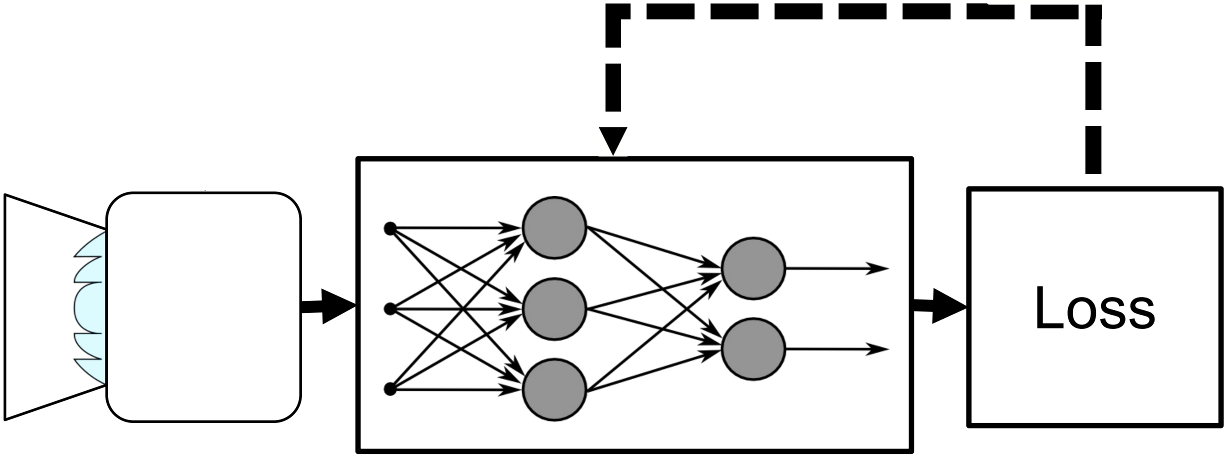
Retroreflective Mannequin Measurements



O'Toole et al., Nature 2018

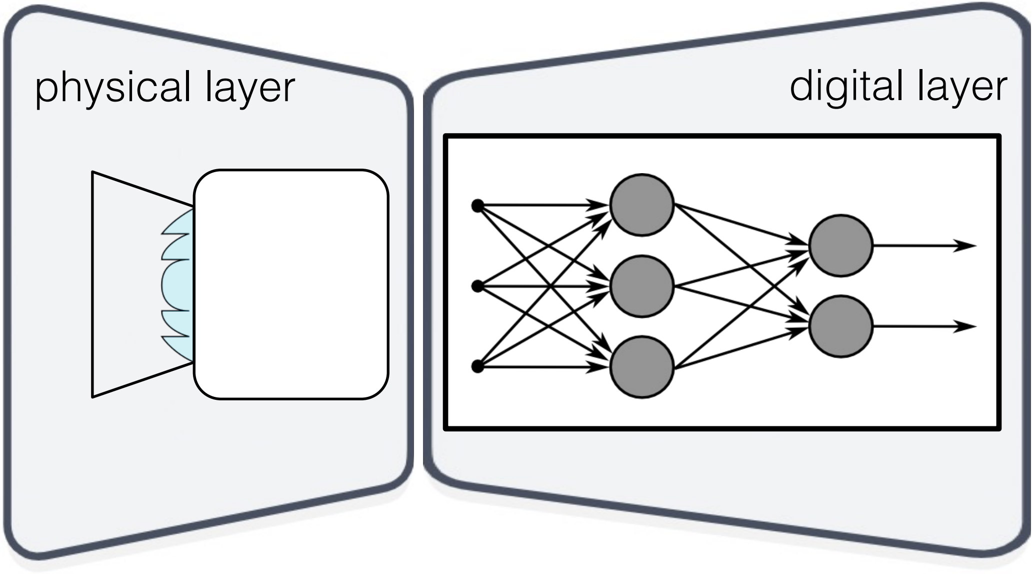
Maximum Intensity Projection

Deep Optics



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

Deep Optics

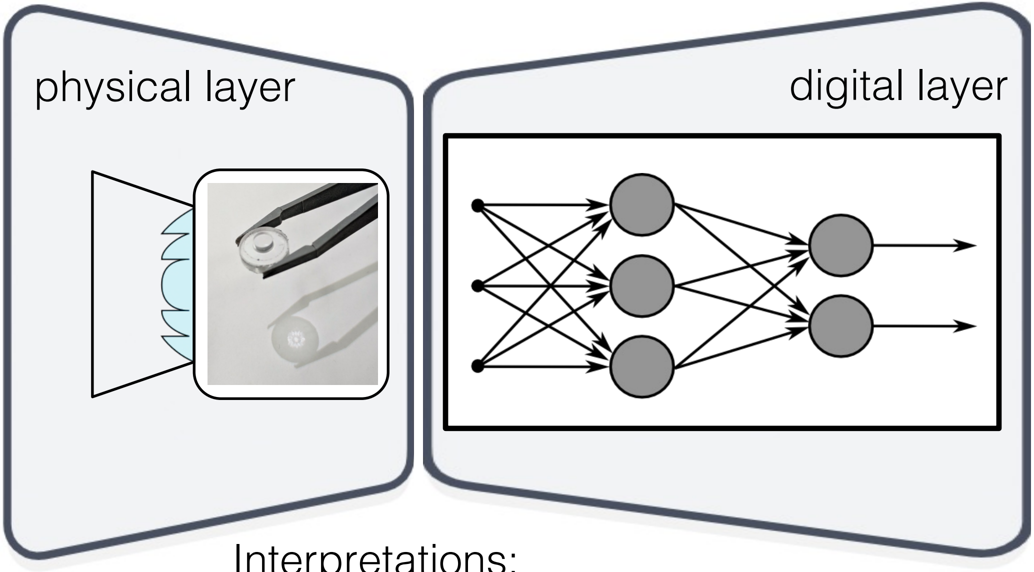


Training:

end-to-end in simulation

Loss

Deep Optics

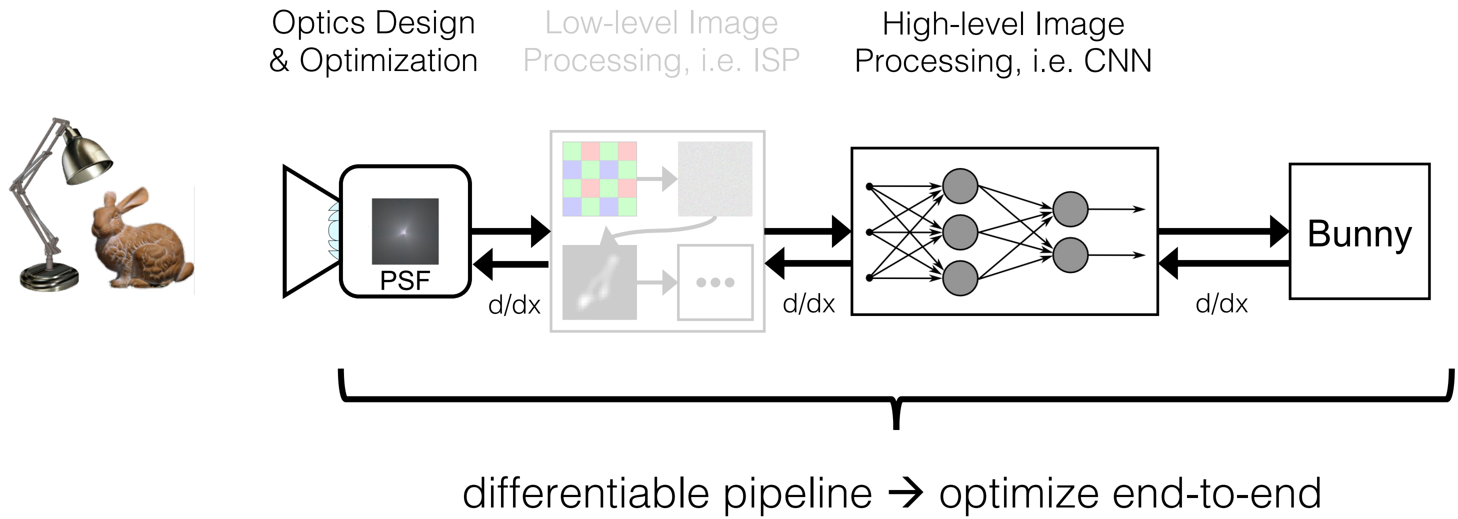


Inference:

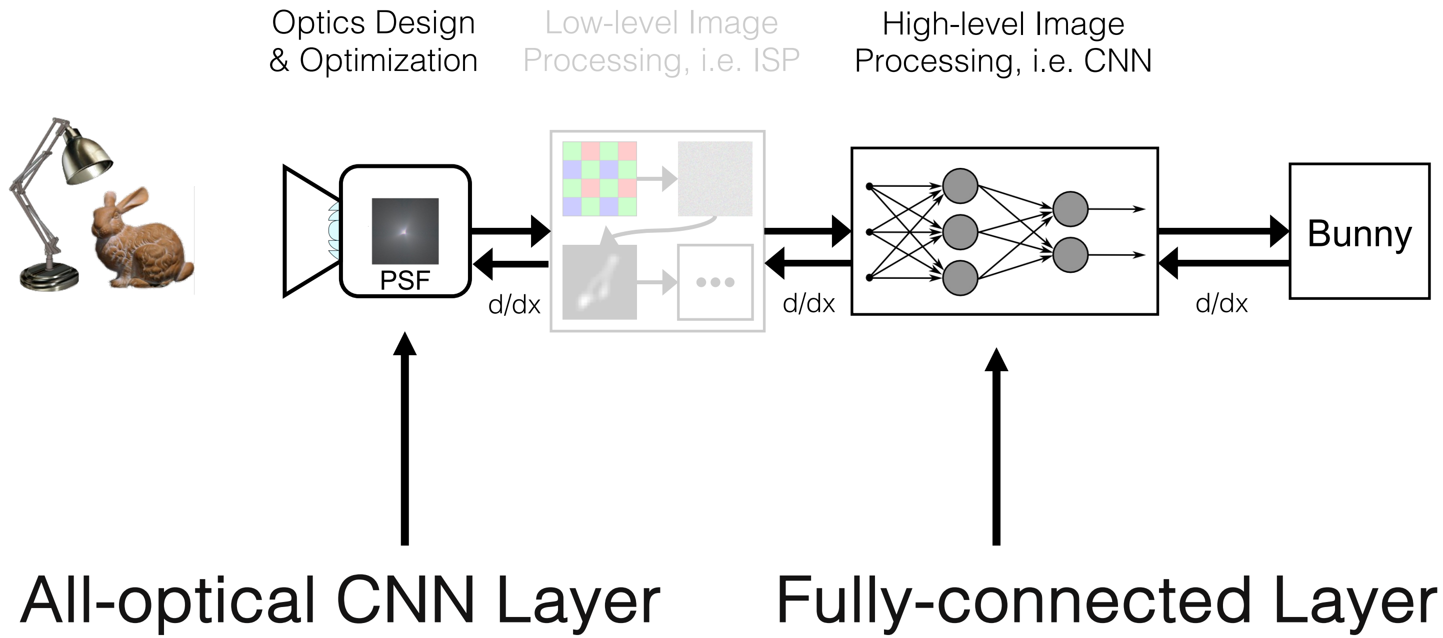
fabricate lens or other physical components, run network

Interpretations:

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

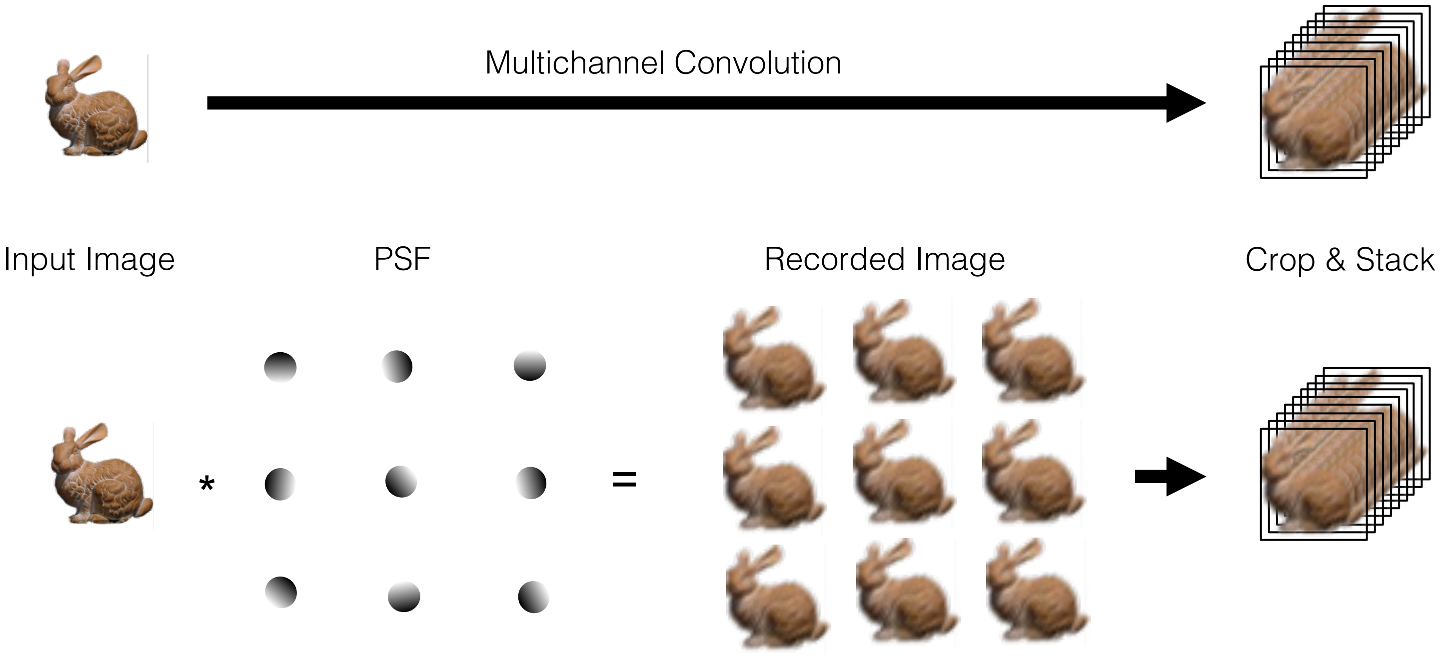


Learning Optics & CNN



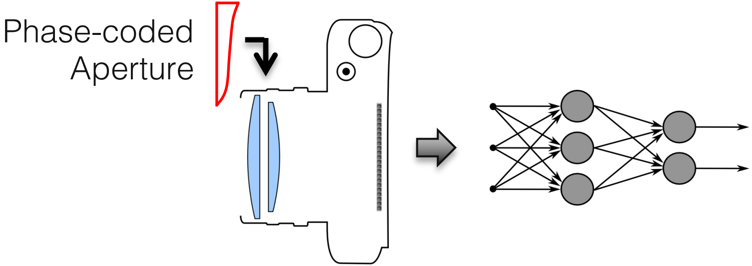
Optics Design & Optimization
Low-level Image Processing, i.e. ISP
High-level Image Processing, i.e. CNN
PSF
d/dx
d/dx
d/dx
Bunny
All-optical CNN Layer
Fully-connected Layer

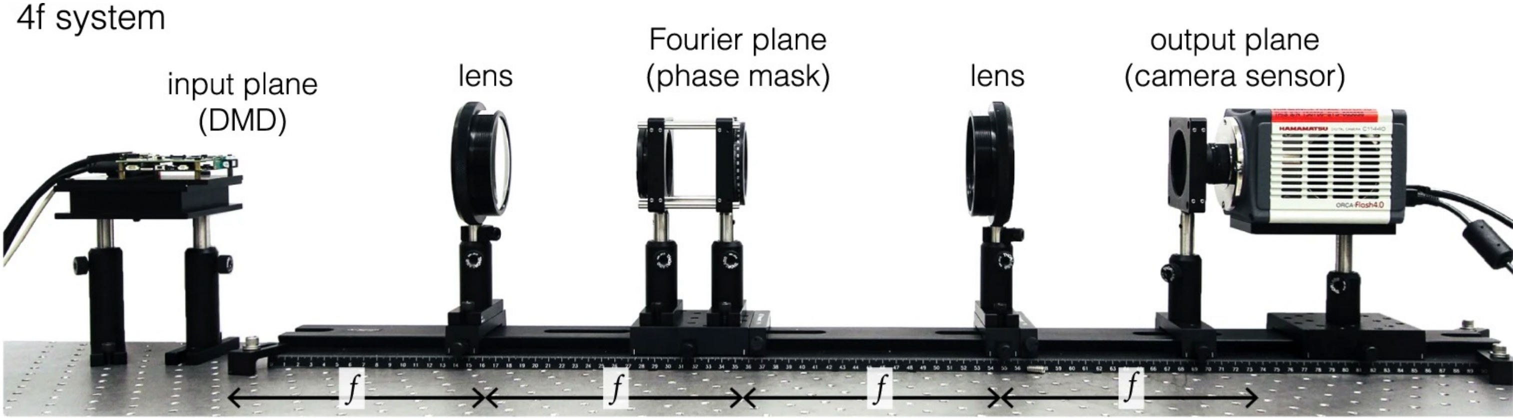
Conventional CNN Layer



All-optical CNN Layer

Hybrid Optical-Electronic CNNs





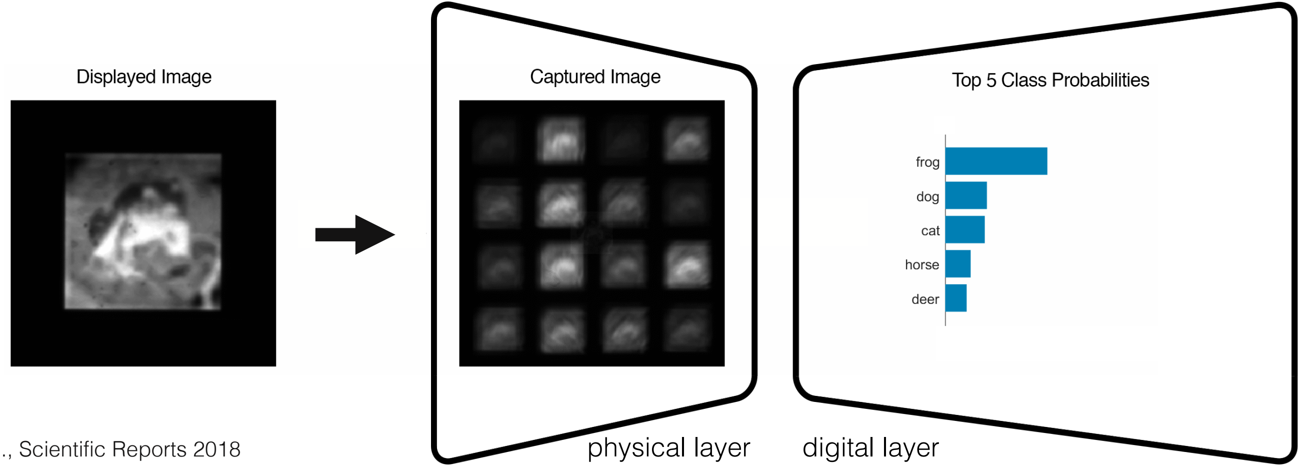
Chang et al., Scientific Reports 2018

Chang et al., Scientific Reports 2018

Hybrid Optical-Electronic CNNs

Results:

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

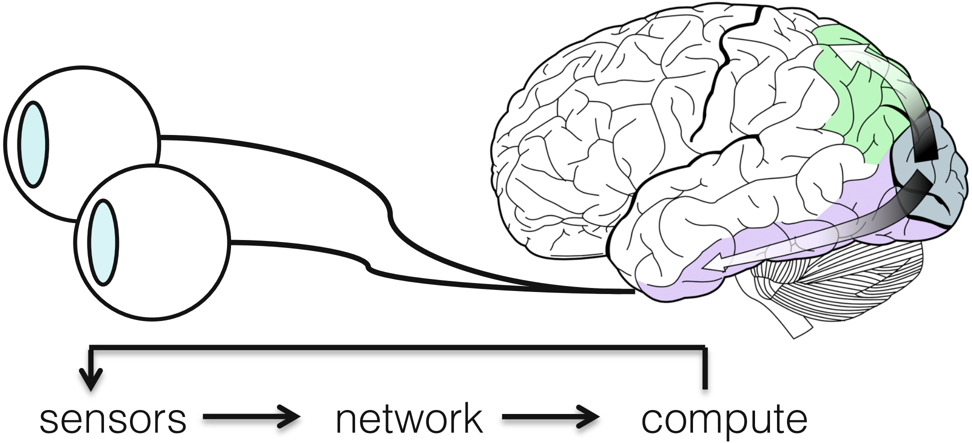


Chang et al., Scientific Reports 2018

Fast Forward

The Human Visual System

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



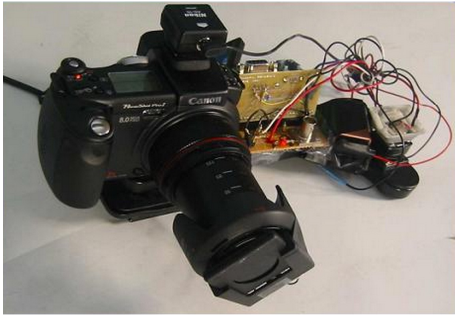
wikipedia

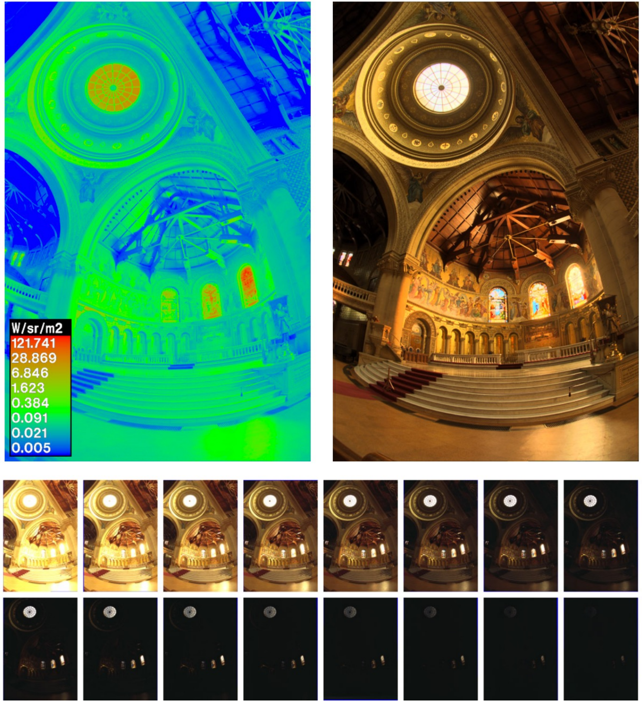
Digital Photography

- 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
- …

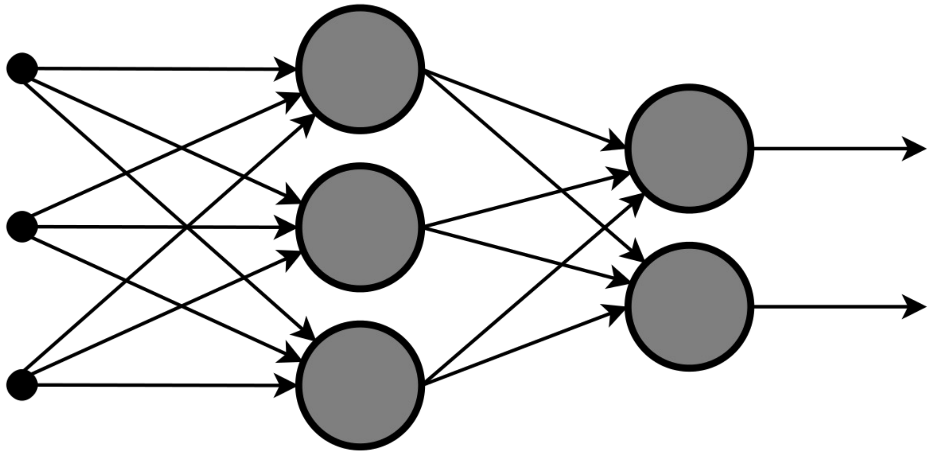




Debevec & Malik, 1997

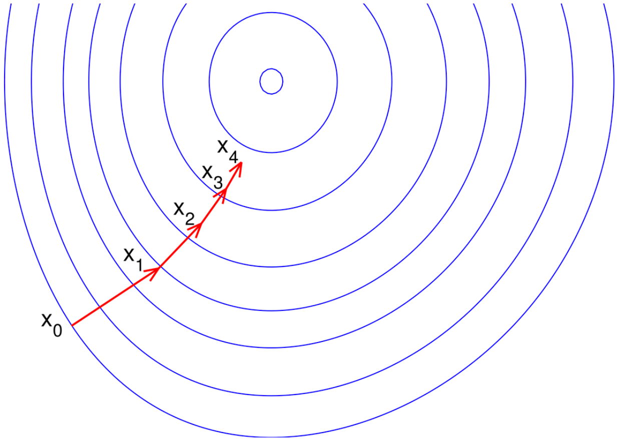
AI for Computational Imaging

- Convolutional neural networks
- DnCNN
- U-Net
- …



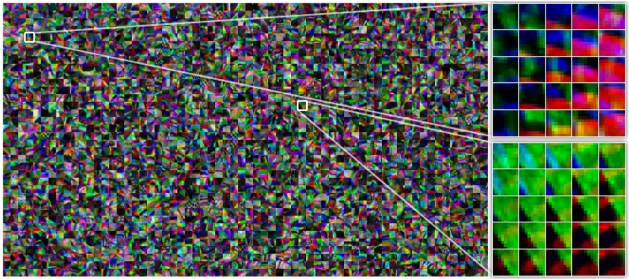
Optimization & AI

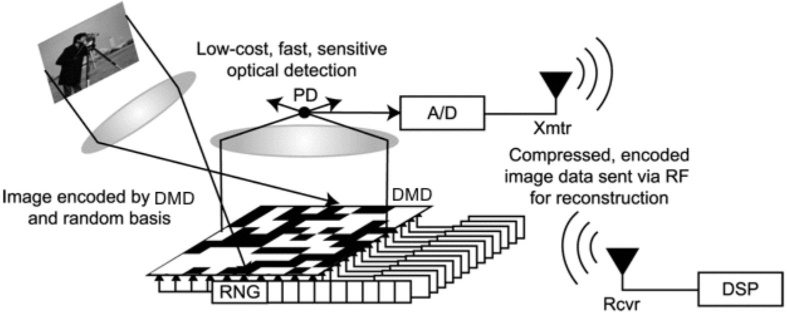
- Proximal gradient methods (HQS, ADMM)
- Iterative optimization with deep priors
- Solving general inverse problems in imaging
- Introduction to diffusion models
- Solving inverse problems with diffusion model priors
- …



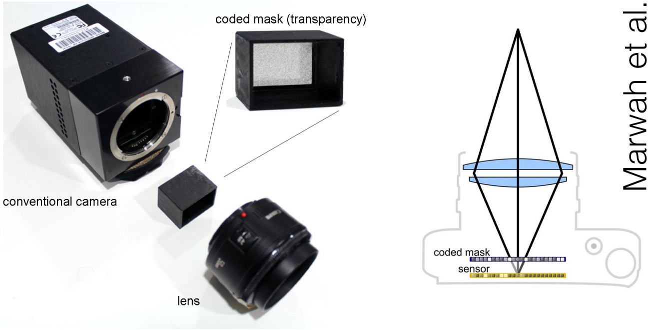
Compressive Imaging

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



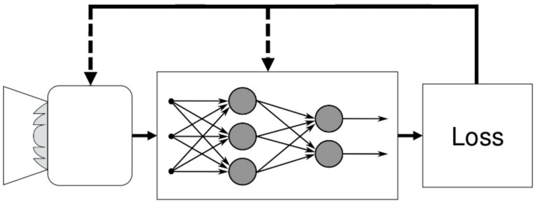


Wakin et al. 2006

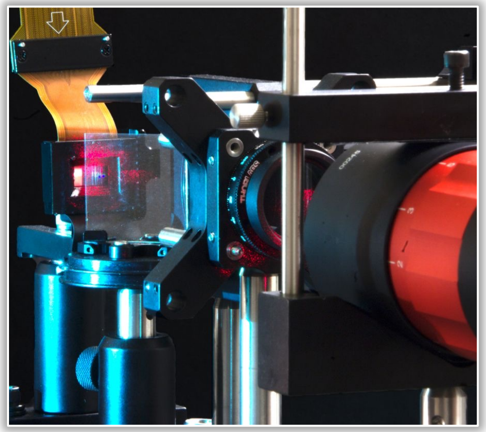


Marwah et al., 2013

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

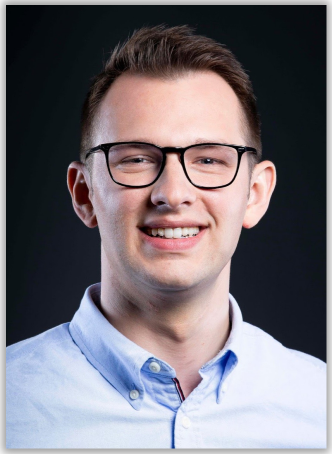
Recordings from last year's lectures on canvas!

Dr. Orly Liba

Google Research

Axel Levy

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 368: Digital Imaging Processing

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

- EE292E / SCIEN - weekly colloquium, info here: 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*

Requirements and Grading

- 6 assignments: 50%
- in-class midterm: 20%
- major final project (teams of ≤ 3): 30%
  - discuss project ideas with TA & instructor!
  - project proposal due: 02/21, 23:59pm
  - final presentation (in-person poster session): Wed 3/12
  - reports and source code due: Fri 3/14, 23:59pm

Resources (see course website!)

- website: stanford.edu/class/ee367
- contact: ee367-win2425-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 (canvas)

  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 Packard 101 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 - create account (see entry code on website)
- Pre-recorded weekly problem session on canvas

Midterm

- Feb 26: 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!

- <u>Feb 21</u>: 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 12: in-person project poster + demo session
  - see poster template on website
  - More details later

- SCPD students: can submit narrated video presentation

Course Projects

- <u>Mar 14</u>: 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
- …

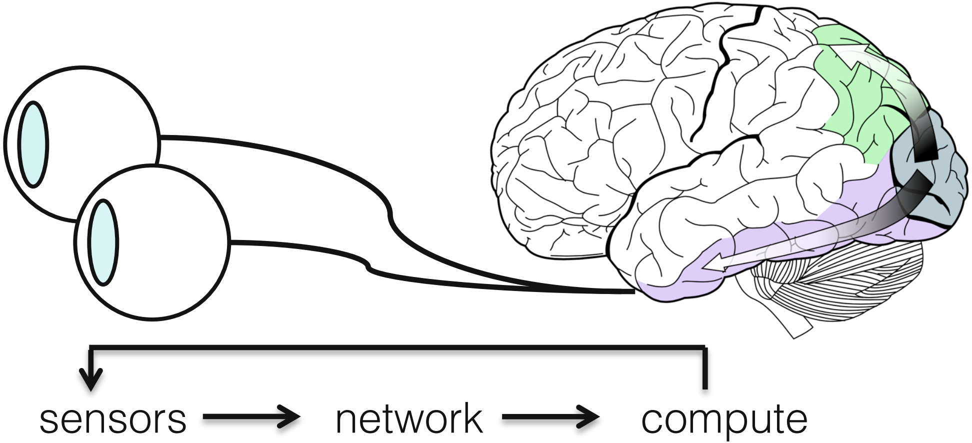
Possible Course Projects

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

We may also design a fallback project for you, in case can't come up with any good ideas. More details later …

Next Class: The Human Visual System

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



wikipedia