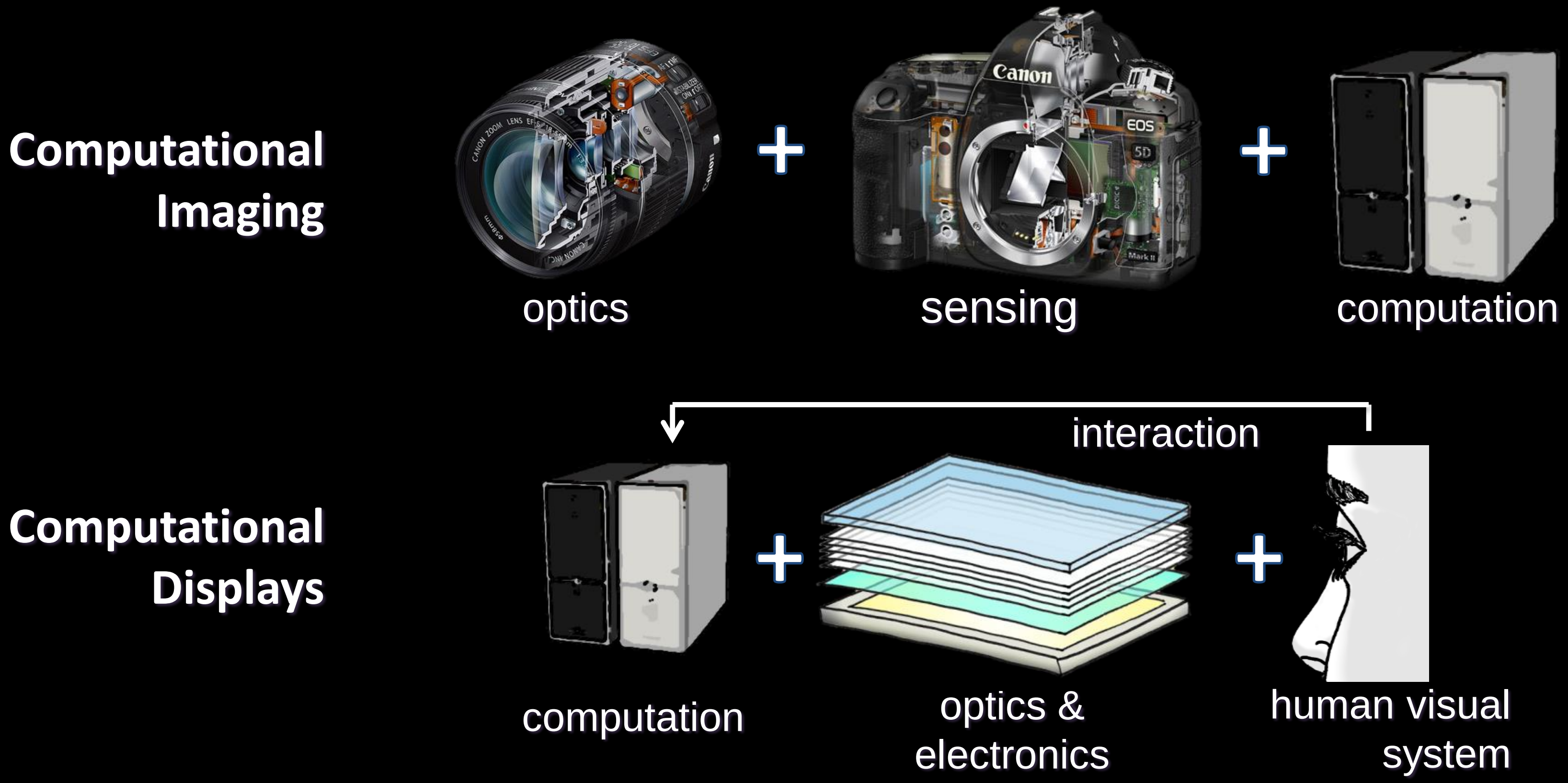
Probing Light Paths for 3D Shape and Indirect Appearance

Matthew O'Toole

Stanford University

Stanford Computational Imaging (SCI)

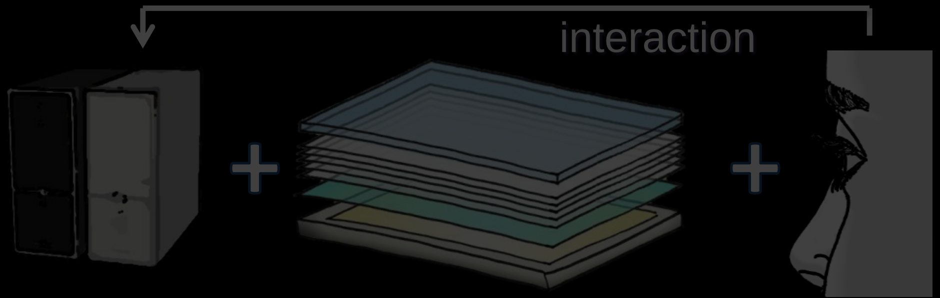


Stanford Computational Imaging (SCI)

Computational Imaging

optics + sensing + computation

Computational Displays



computation + optics & electronics + human visual system

Stanford Computational Imaging (SCI)

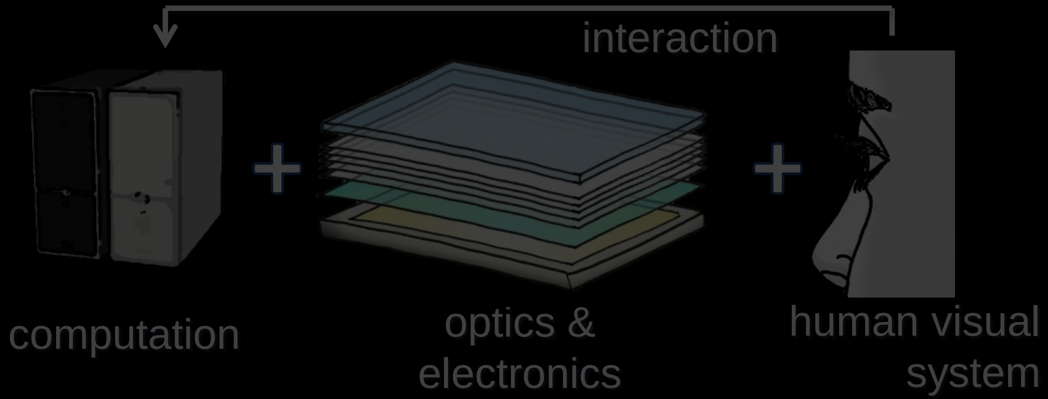
Computational Imaging

HDR Imaging [Debevec, Nayar, …]

Super-resolution [Baker, …]

Light Fields [Levoy, …]

Computational Displays



Stanford Computational Imaging (SCI)

Computational Imaging

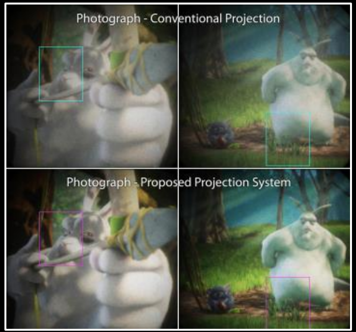
HDR Imaging [Debevec, Nayar, ...]

Super-resolution [Baker, ...]

Light Fields [Levoy, ...]

Computational Displays

HDR Display [Seetzen, …]



Super-resolution [Hirsch, Heide, …]

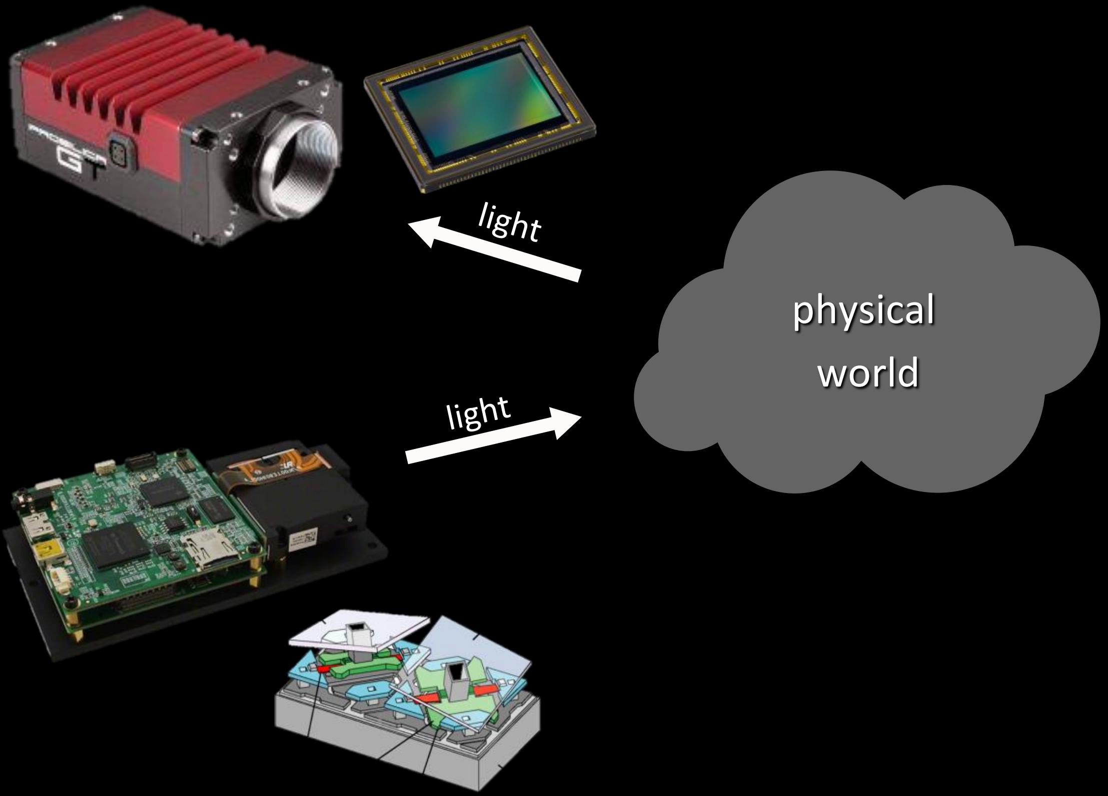
Light Fields [Wetzstein, …]

Stanford Computational Imaging (SCI)

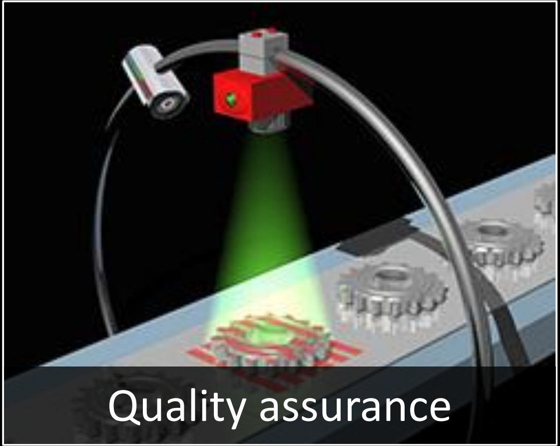
Computational Imaging

+

Computational Displays



active lighting applications

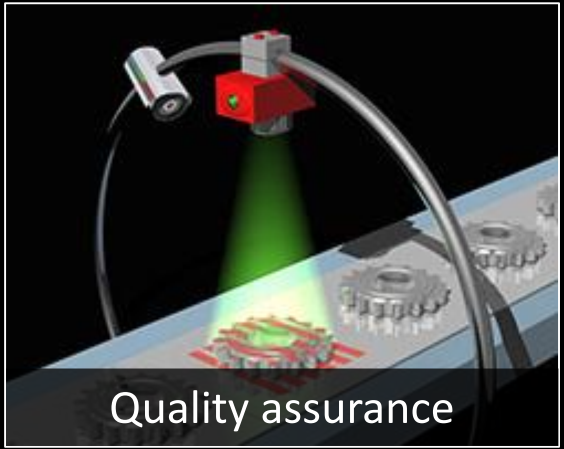


Quality assurance

Autonomous vehicles

Tracking

active lighting applications

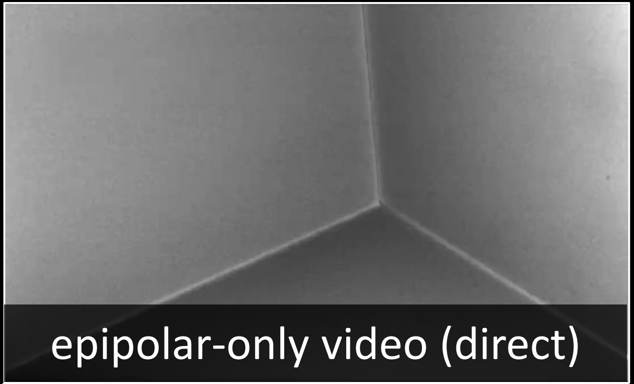


common issues:

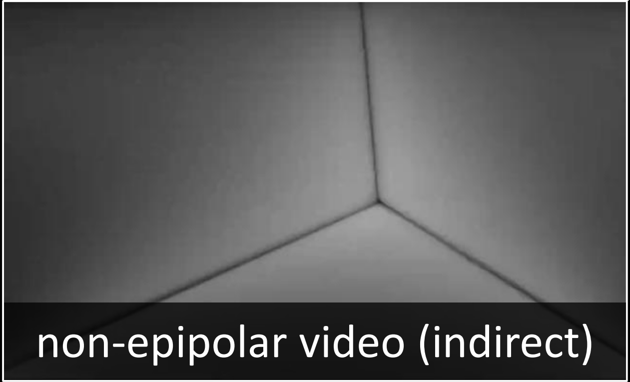
- assumes light transport is well-behaved
- easily overwhelmed by bright ambient sources (e.g. sunlight)

transport probing

transport probing

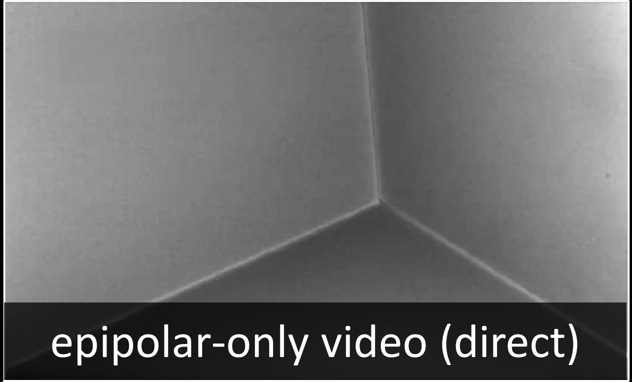


epipolar-only video (direct)



non-epipolar video (indirect)

transport probing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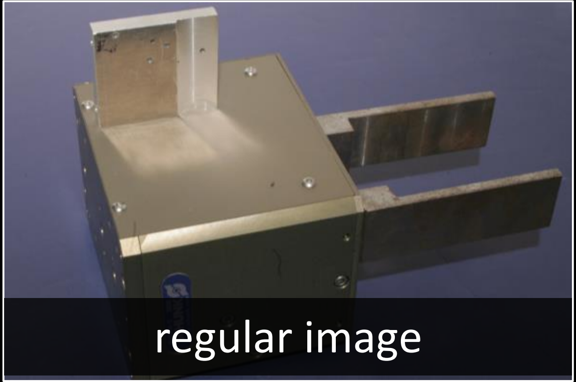
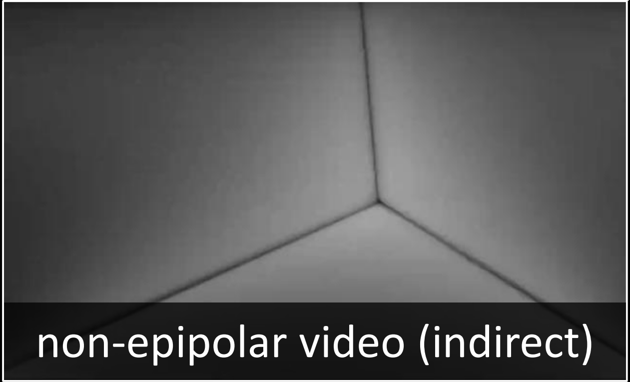
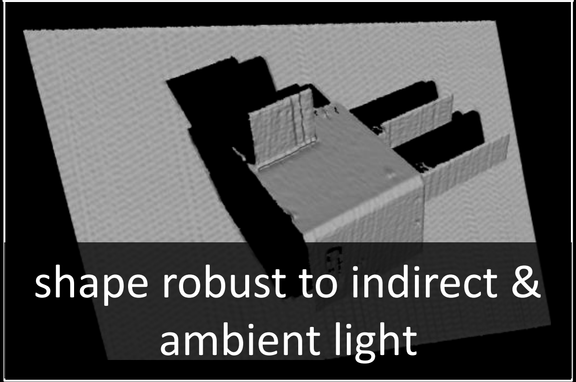
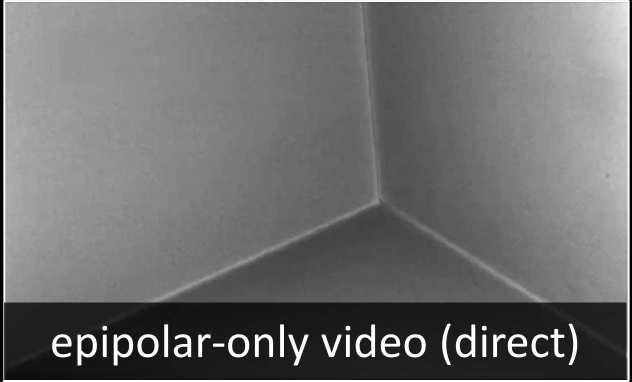

regular image


non-epipolar video (indirect)


shape robust to indirect & ambient light

transport probing



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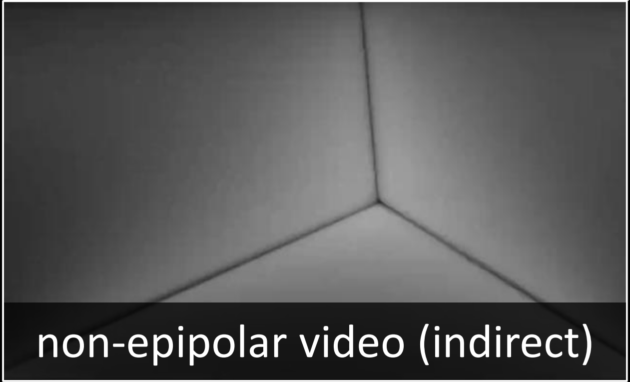

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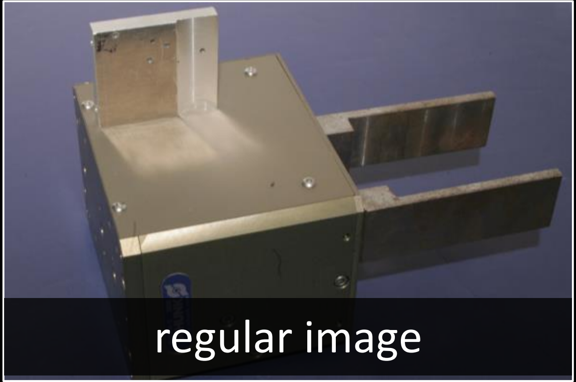
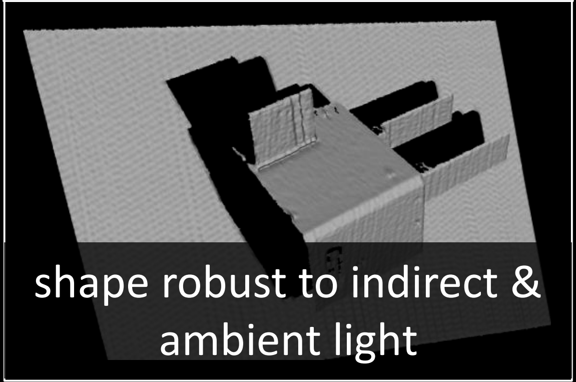
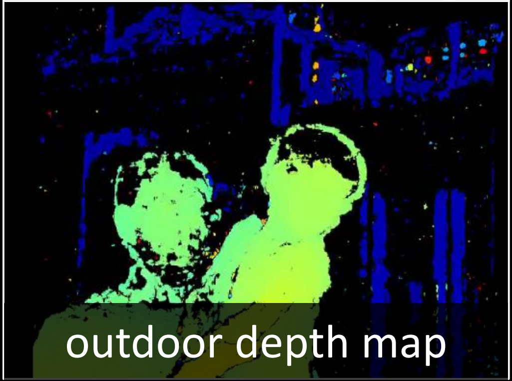


regular image



shape robust to indirect & ambient light

outdoor video under full sunlight

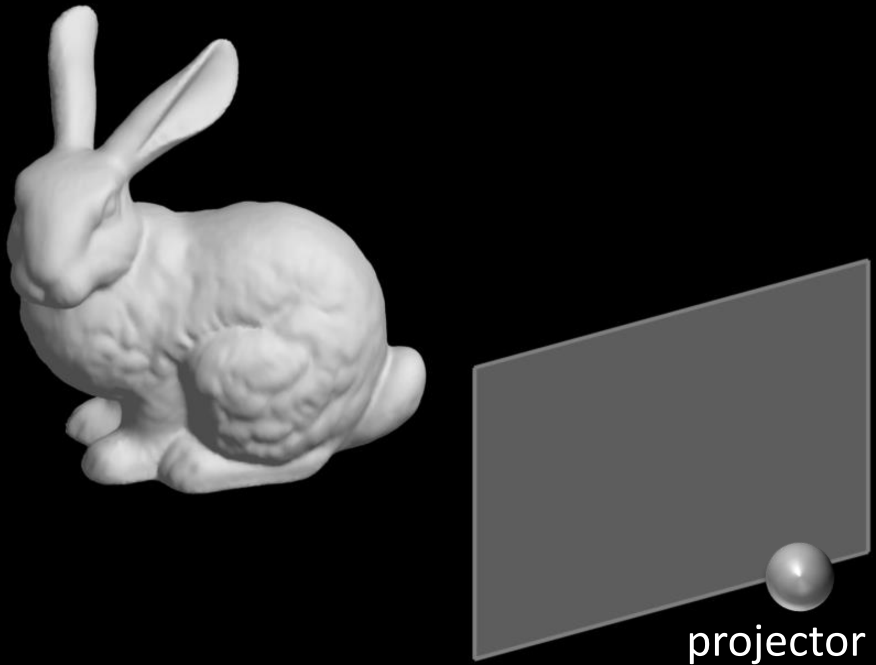


outdoor depth map

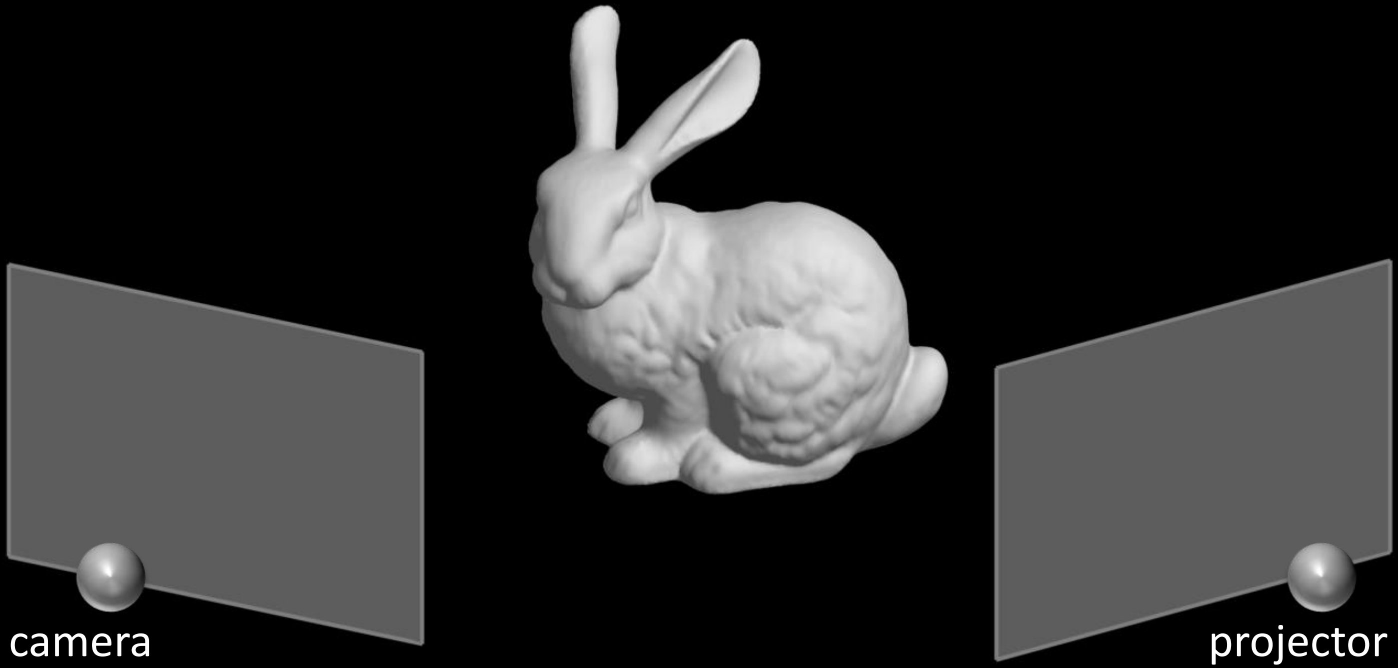
transport probing

basic light paths

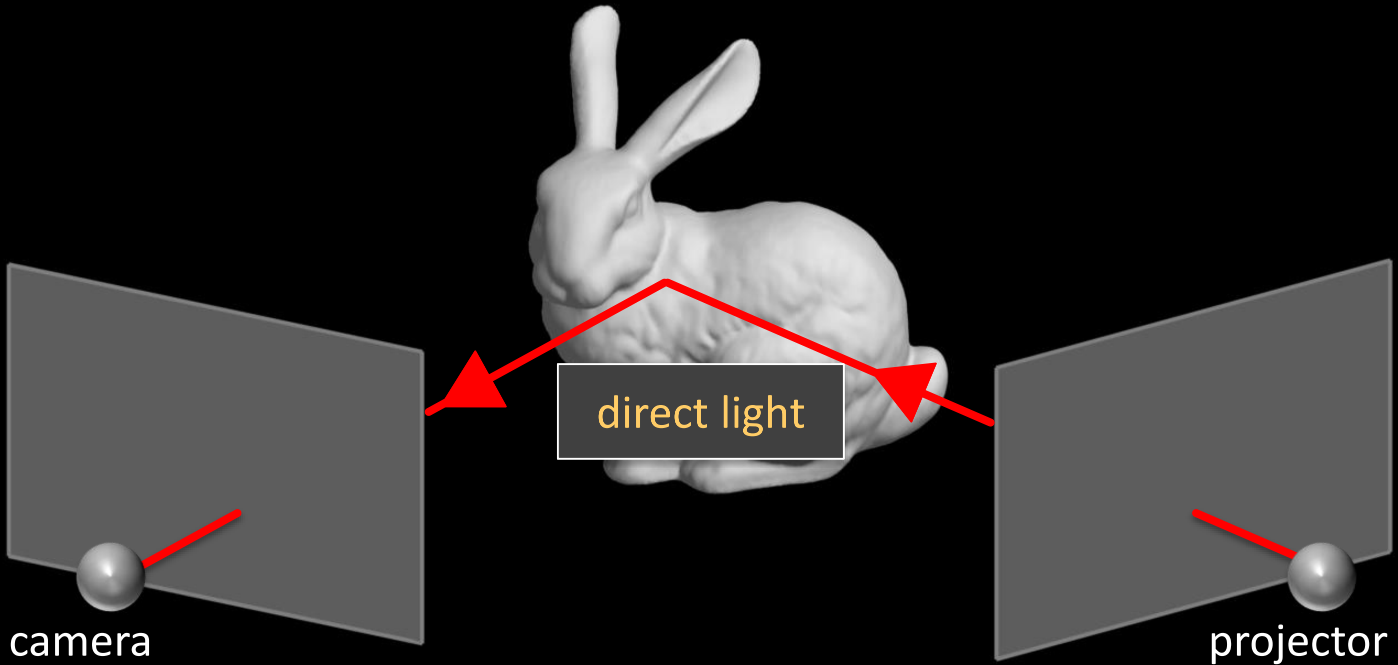
basic light paths



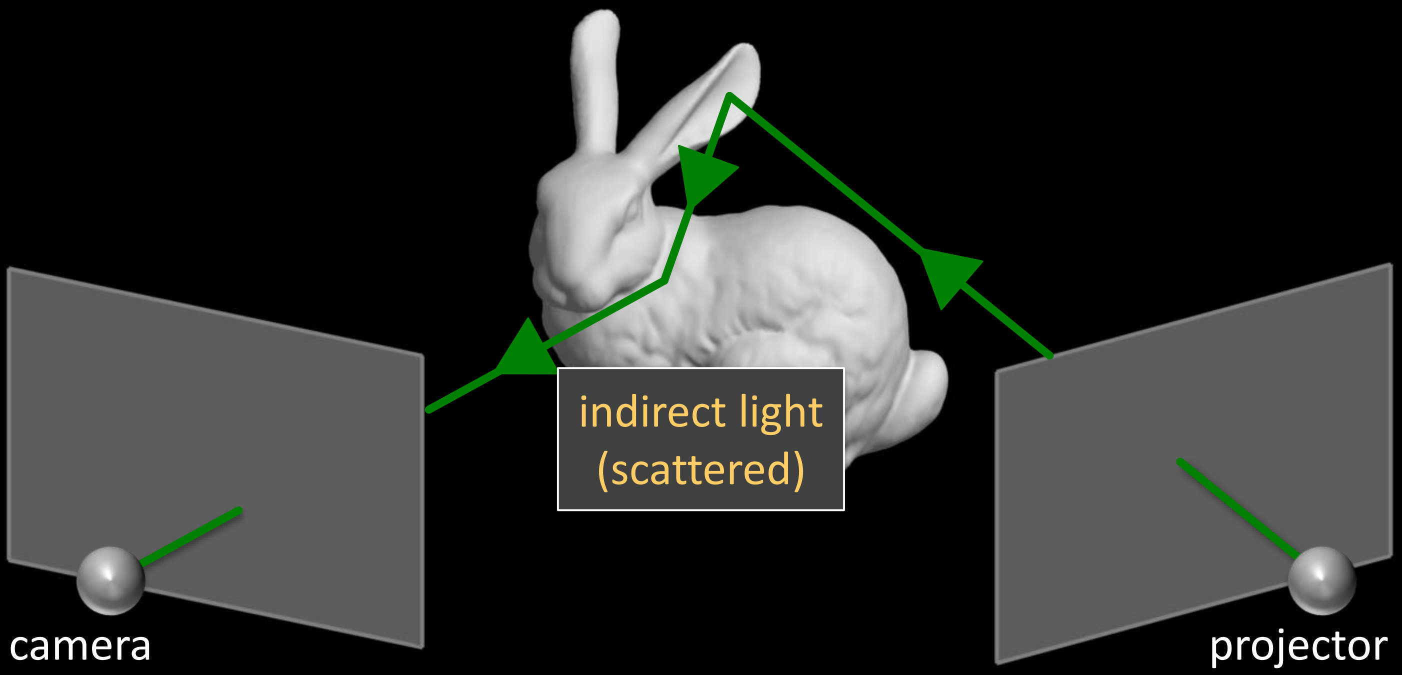
basic light paths



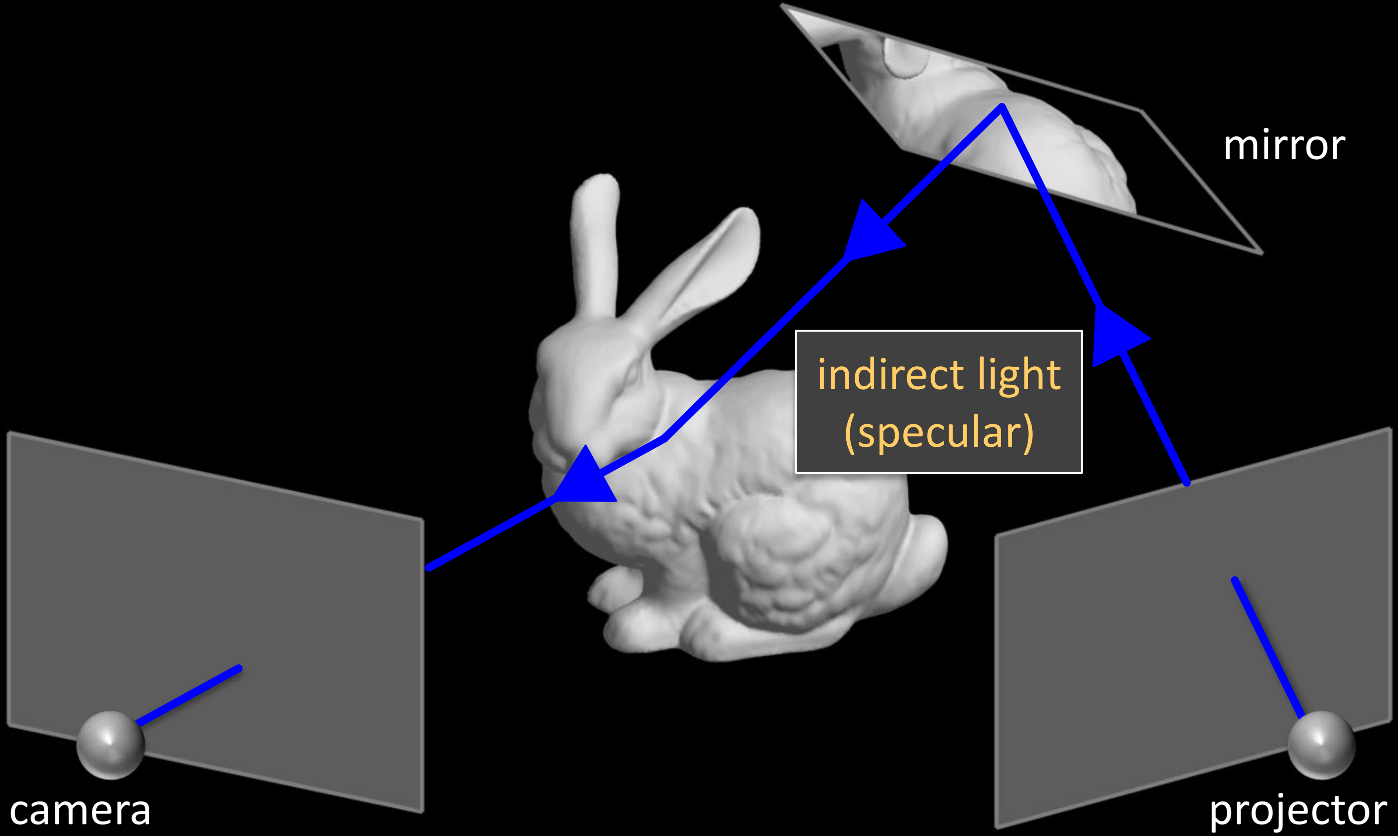
basic light paths



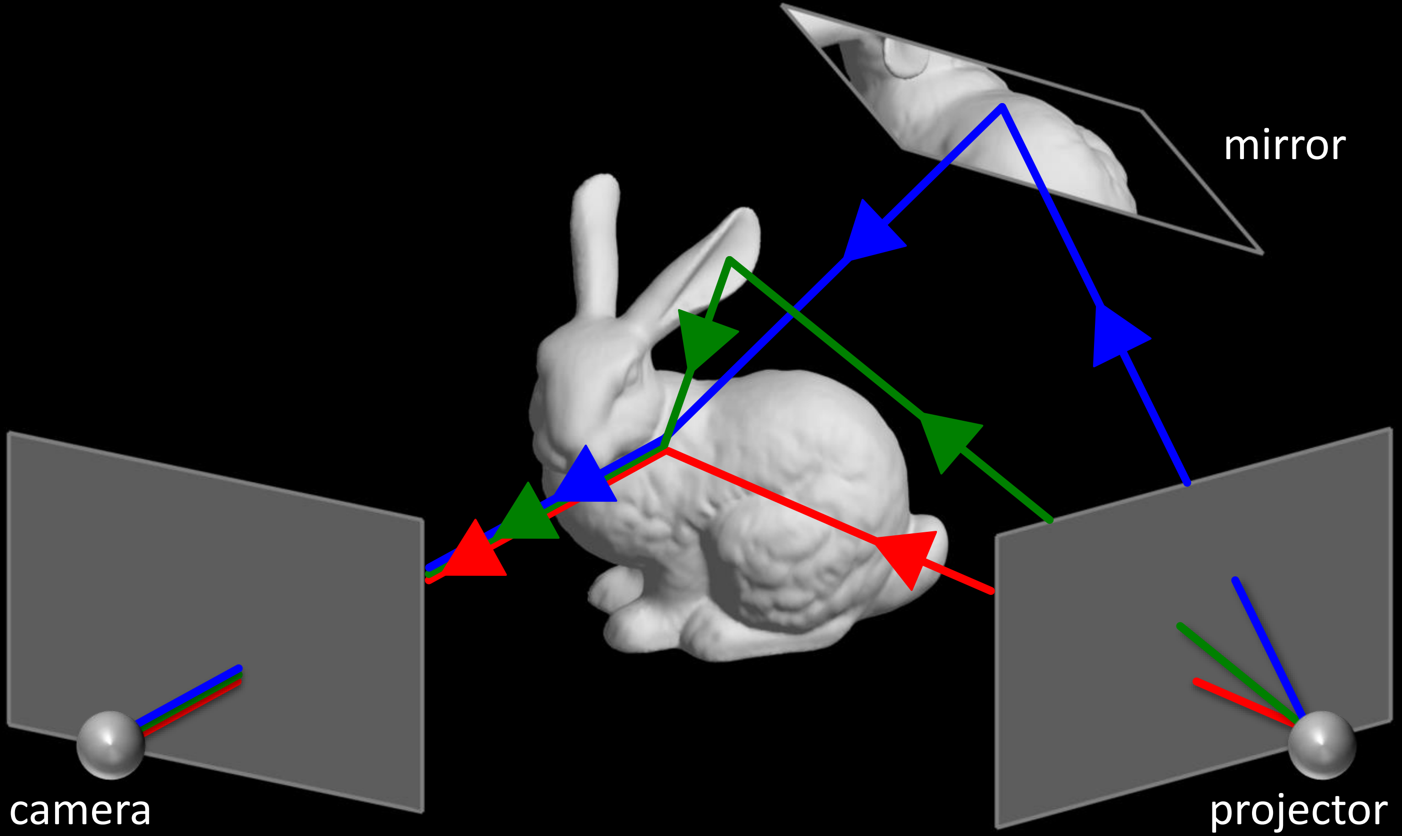
basic light paths



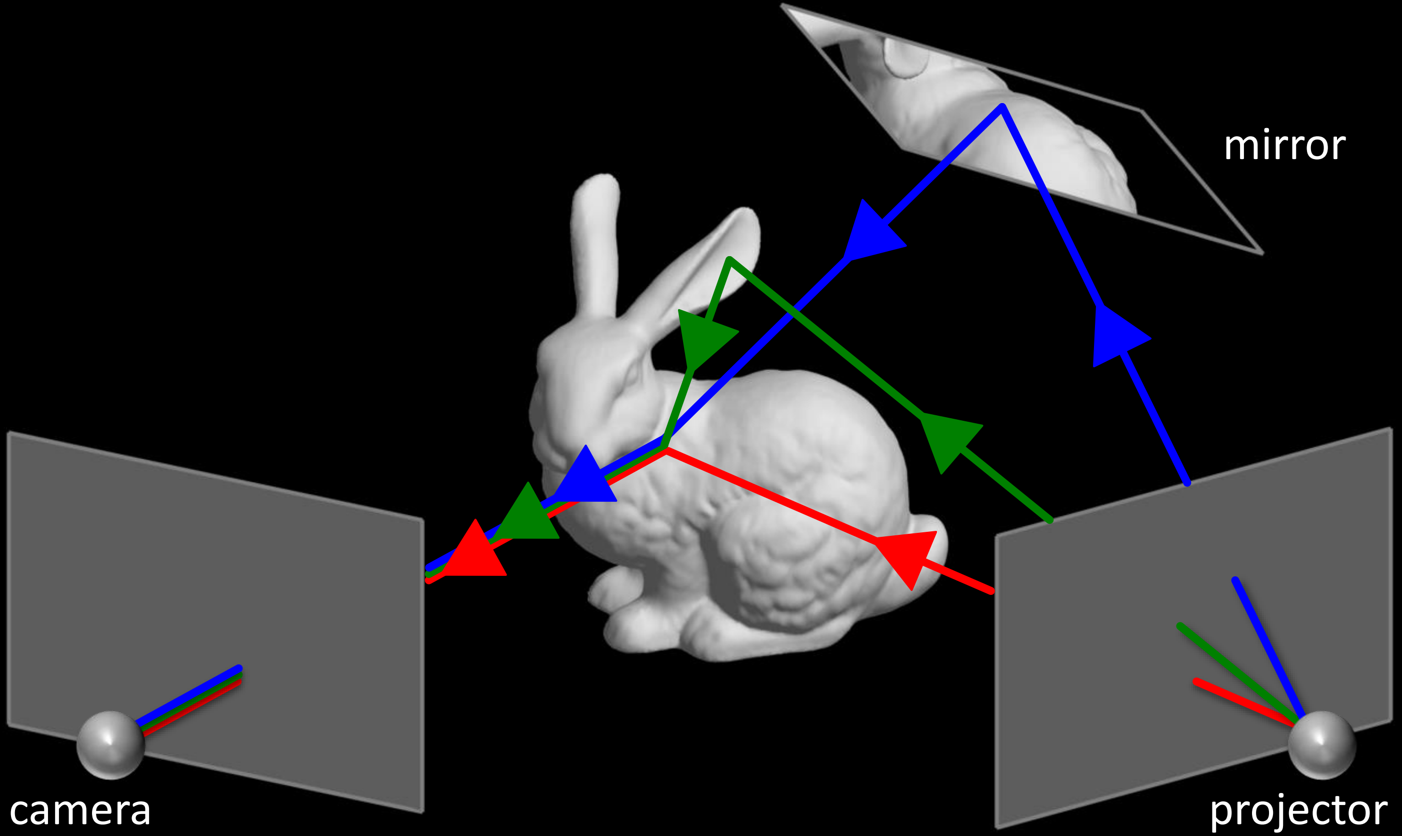
basic light paths



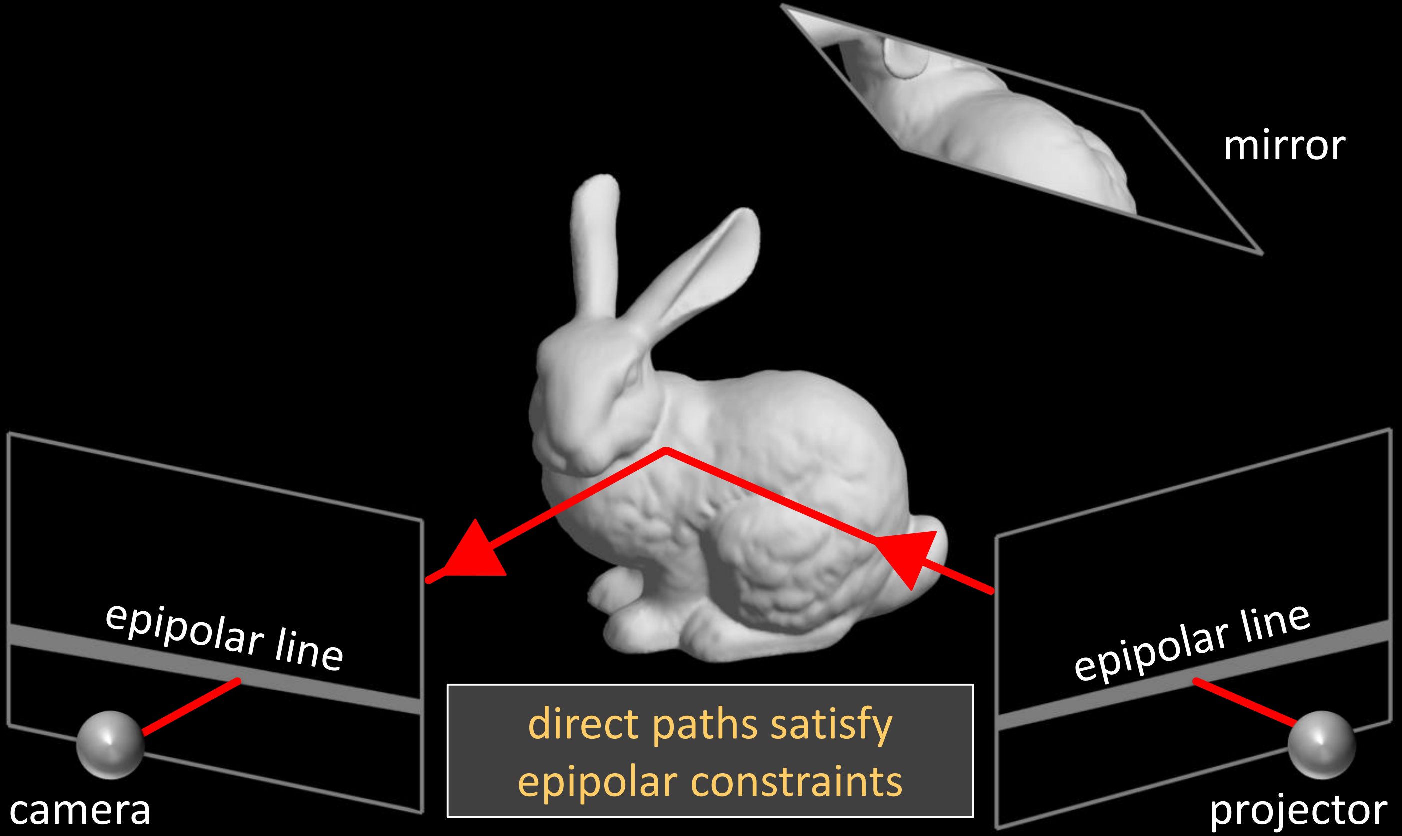
basic light paths



basic light paths

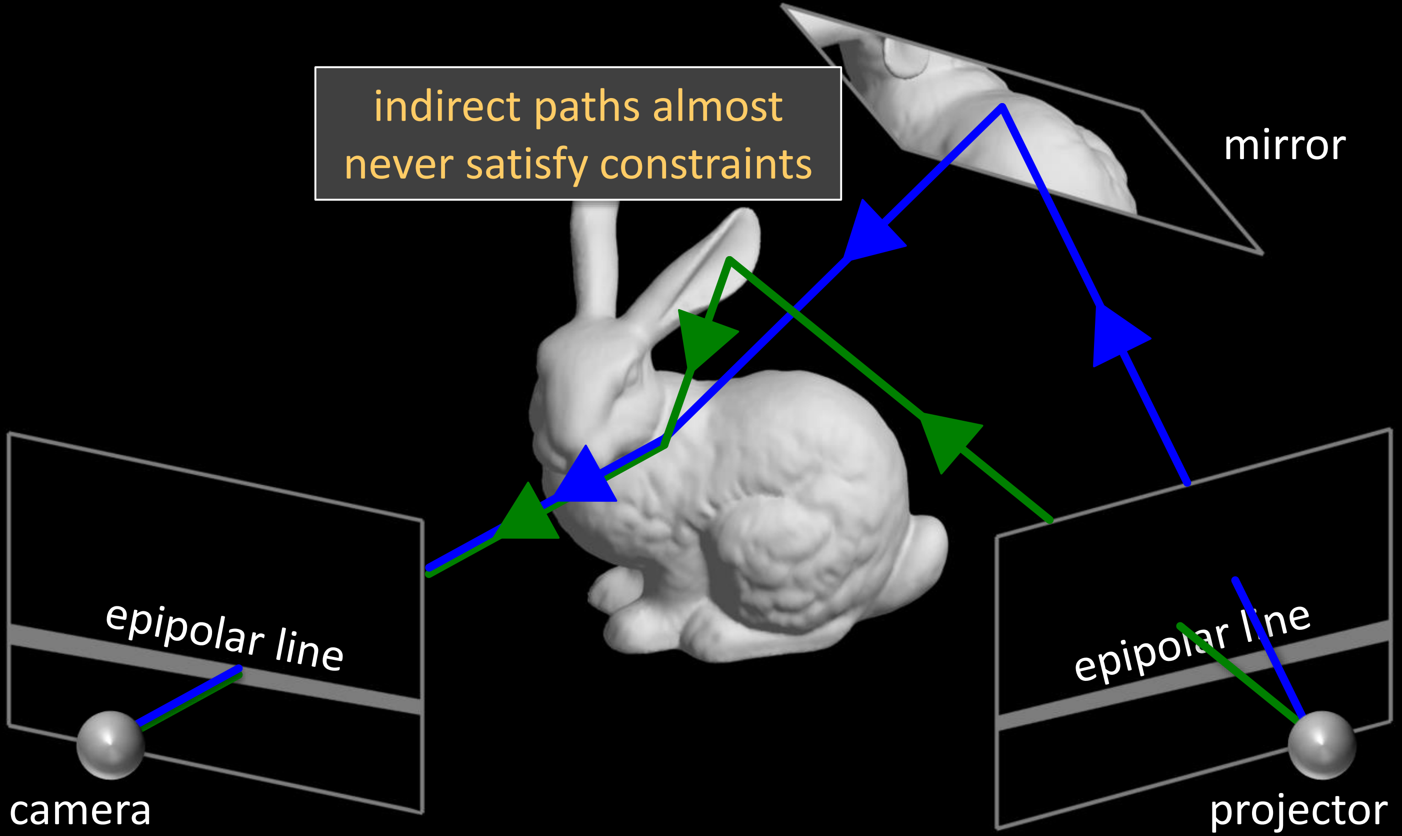


epipolar constraint & light transport



direct paths satisfy
epipolar constraints

epipolar constraint & light transport



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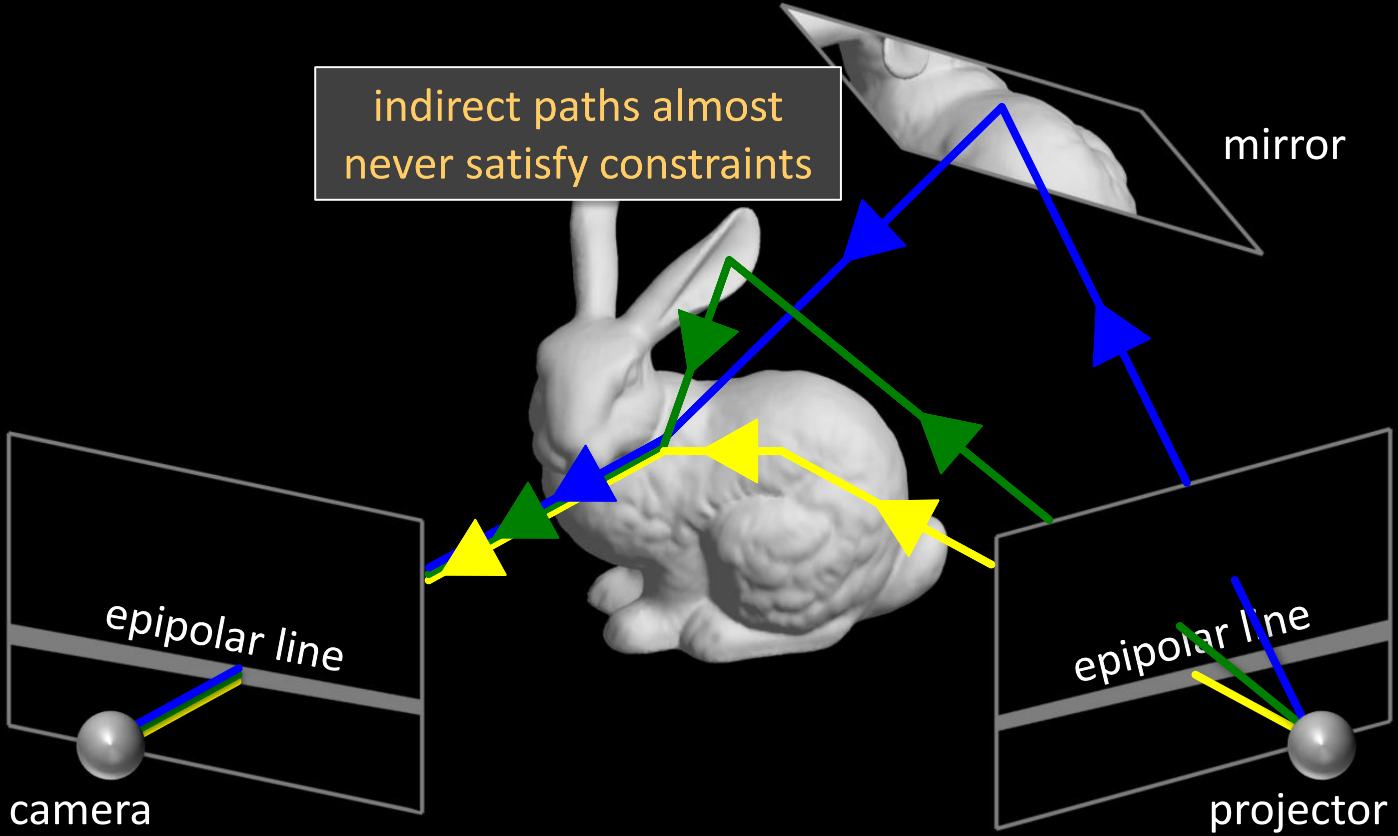
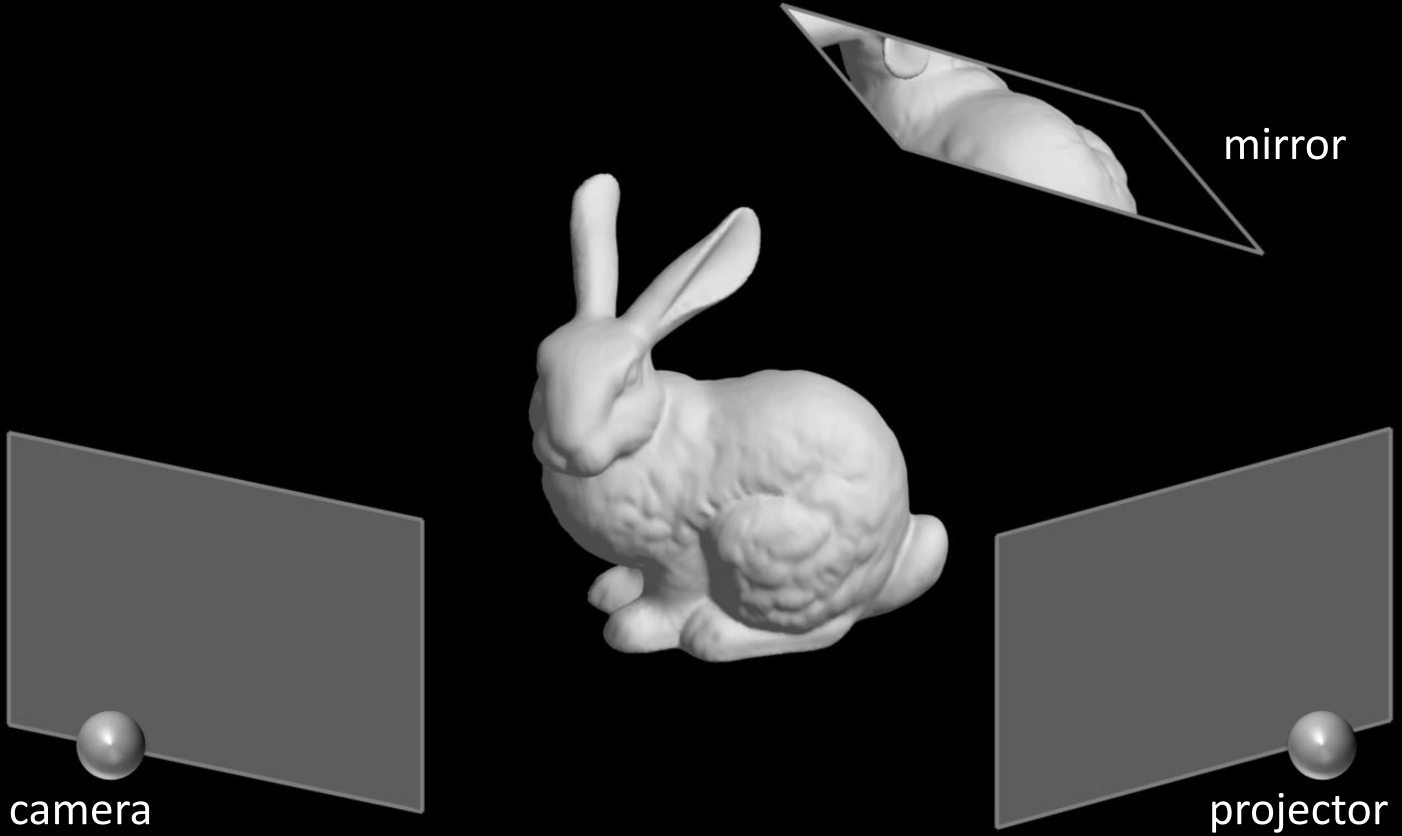


blocking epipolar paths with patterns & masks



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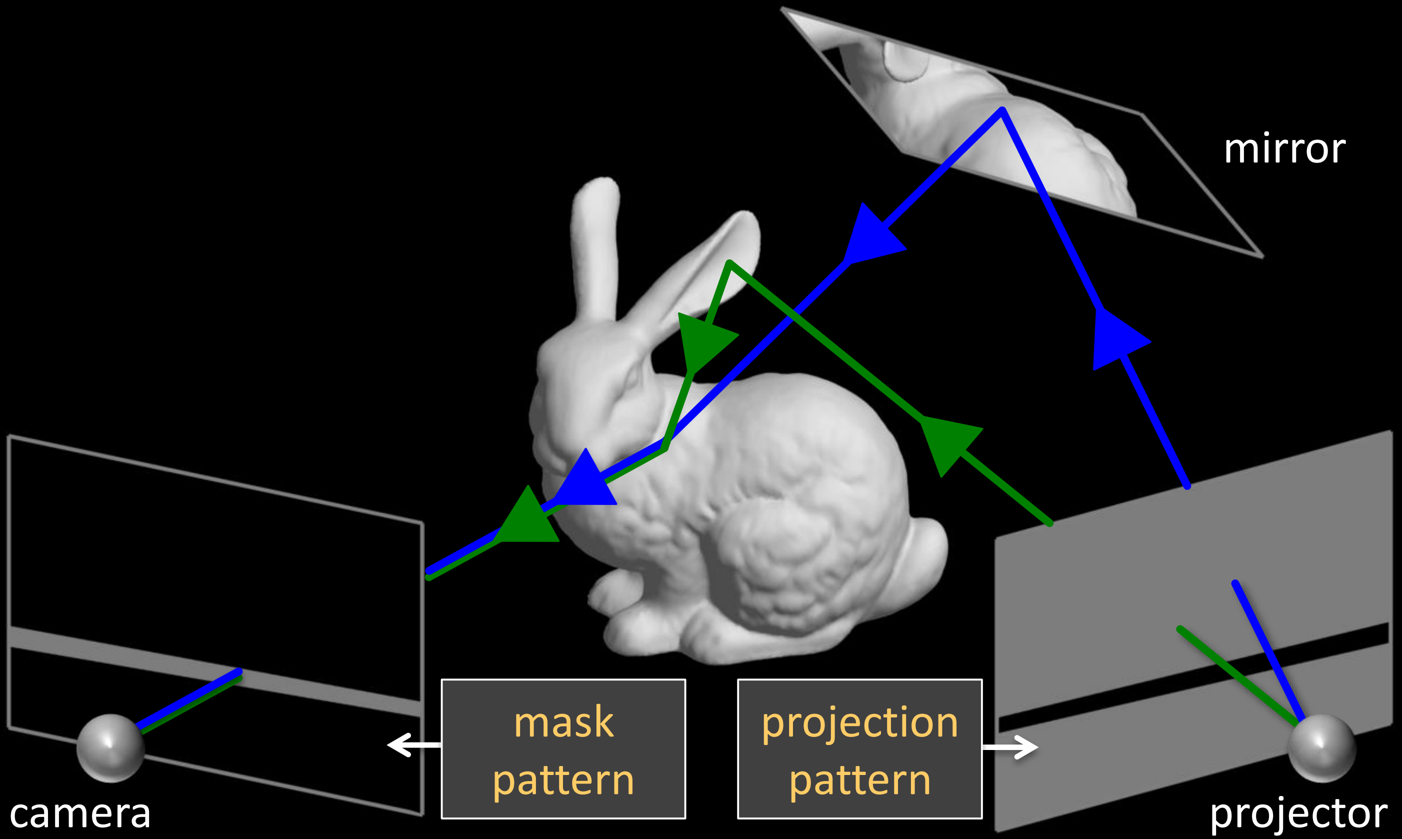

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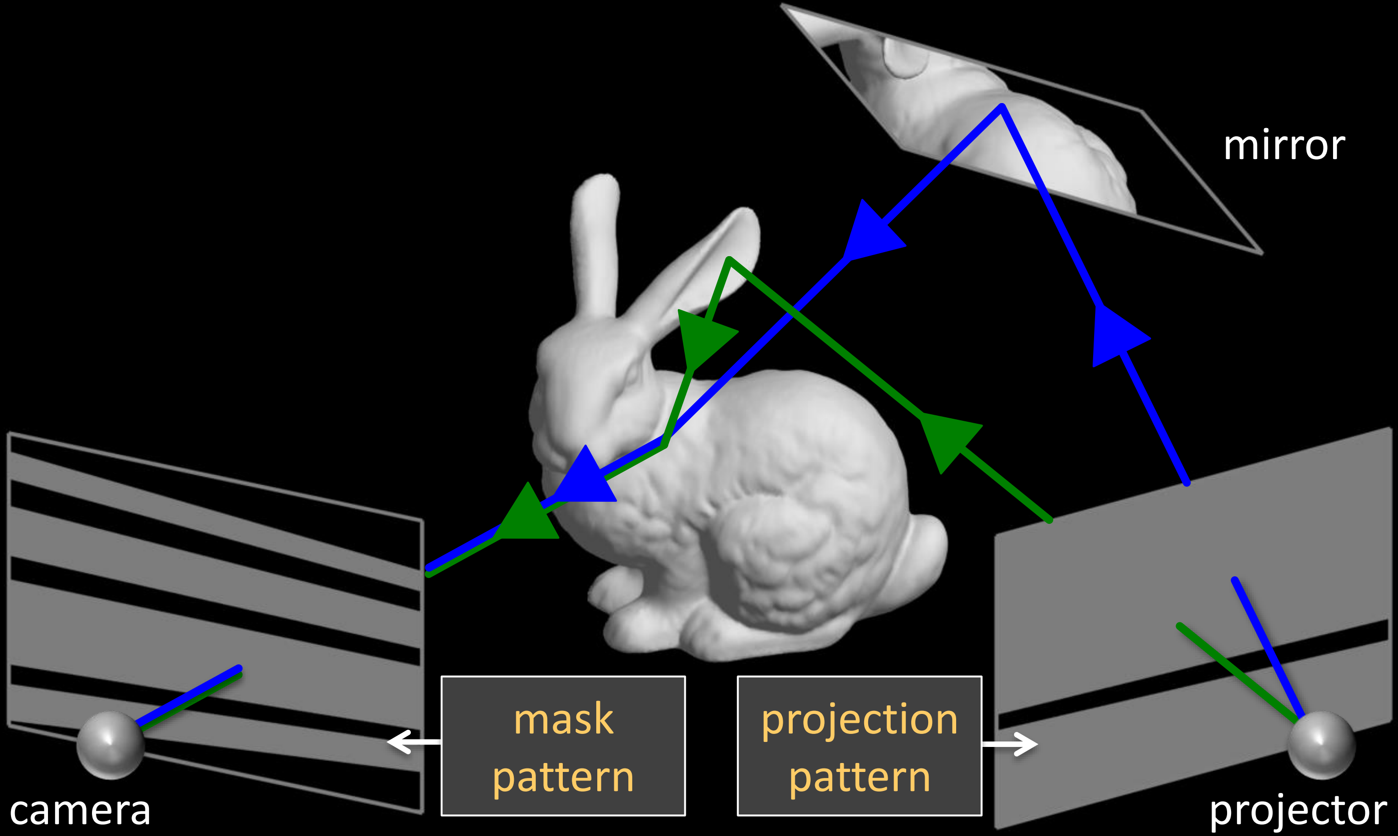

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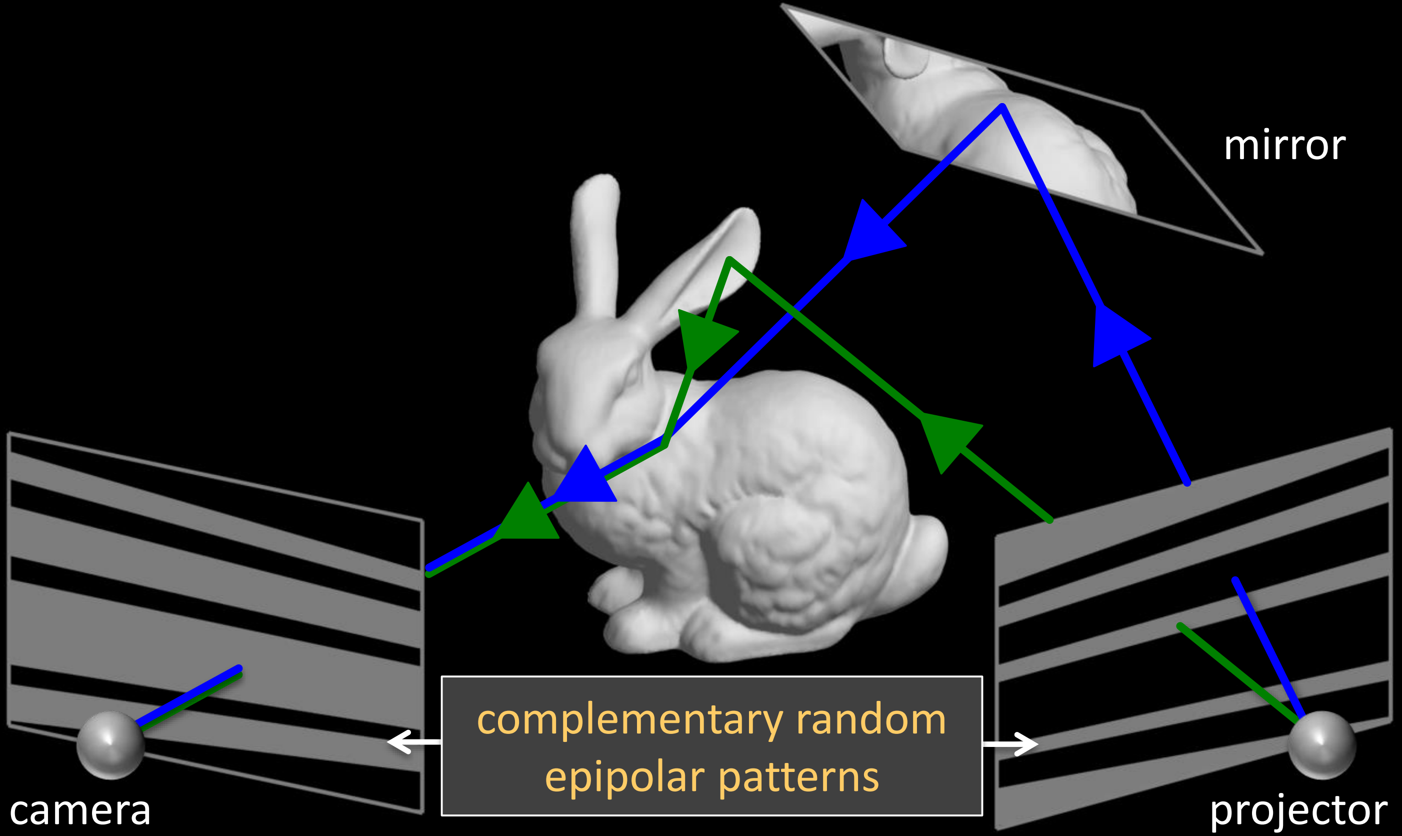

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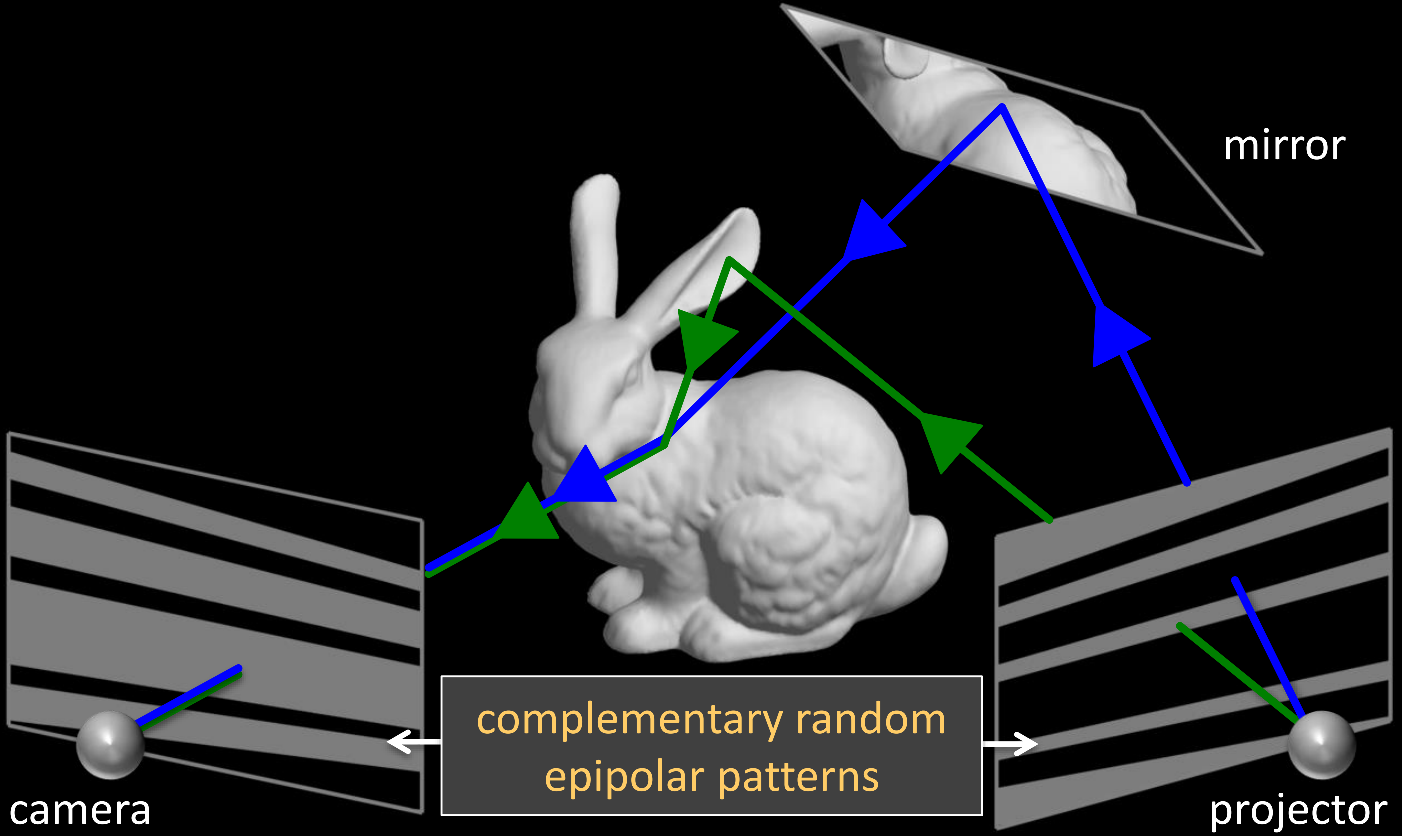

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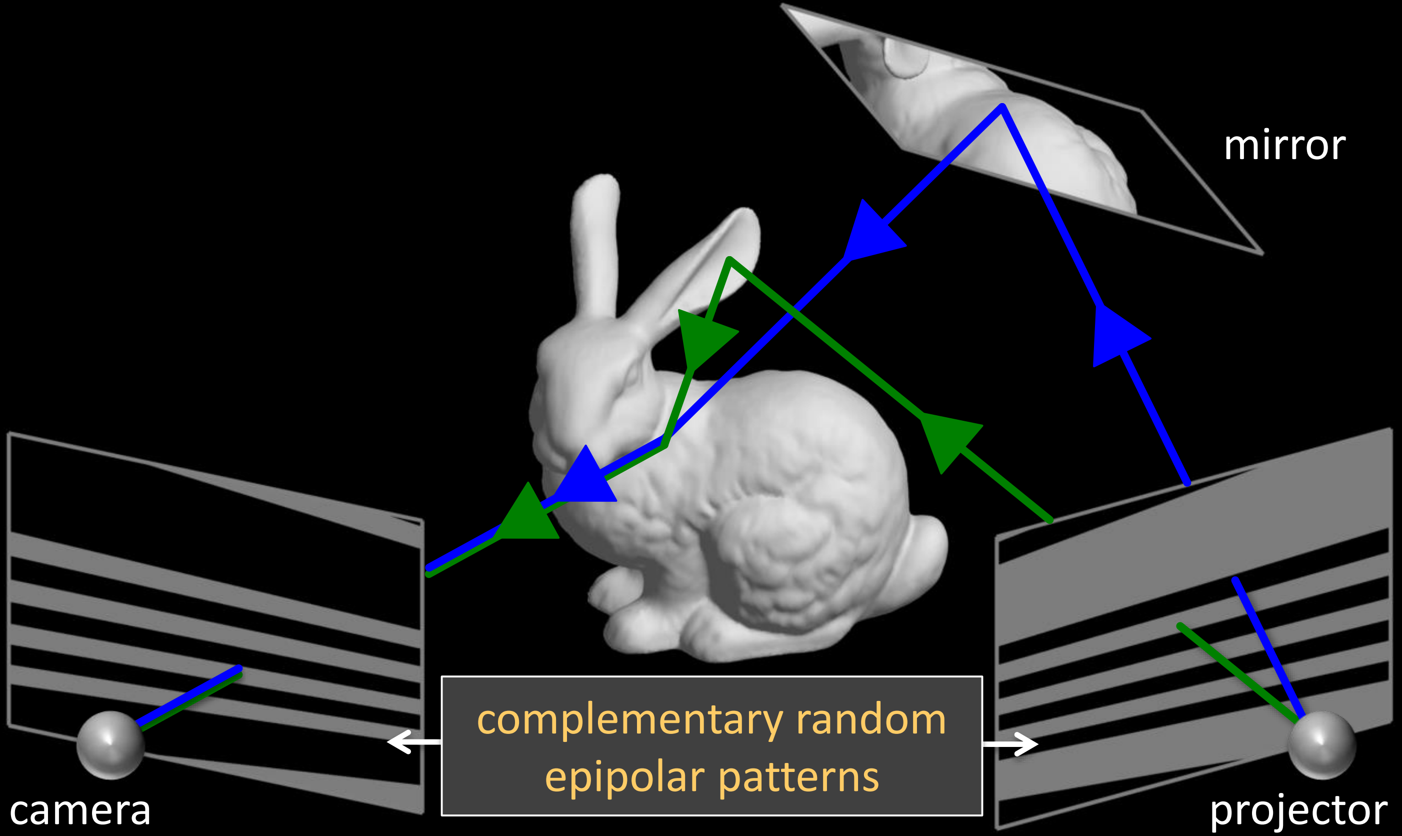

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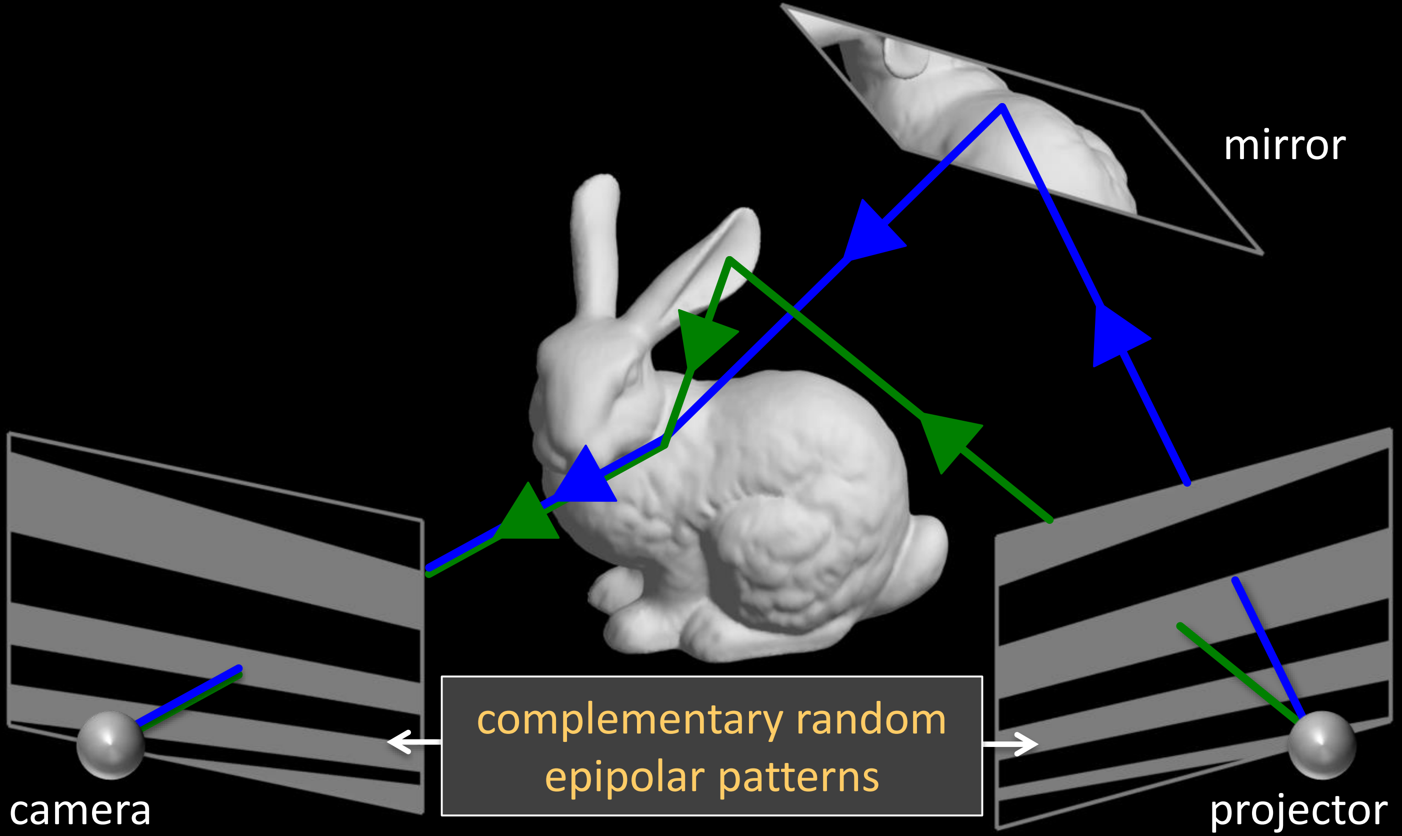
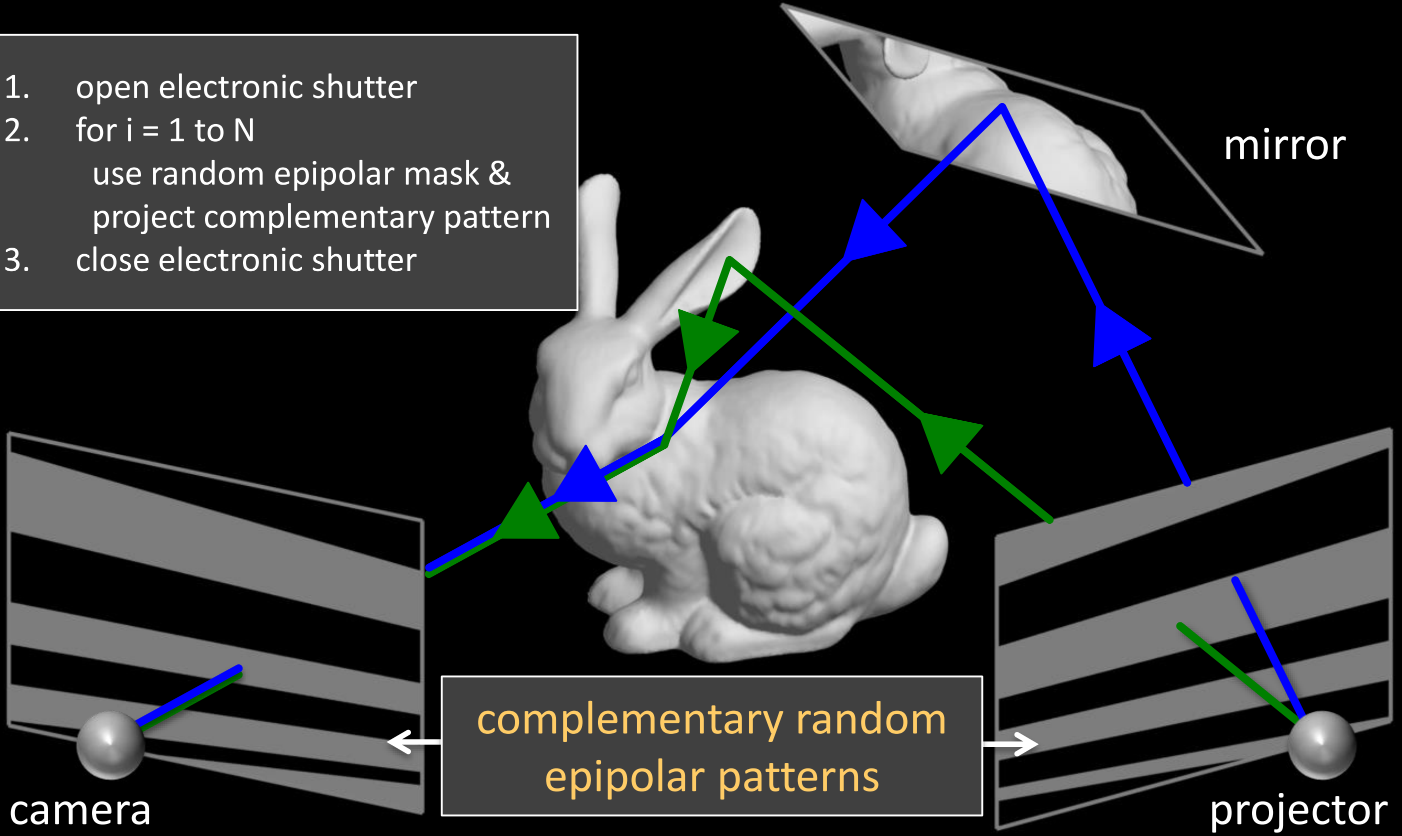


blocking epipolar paths with patterns & masks

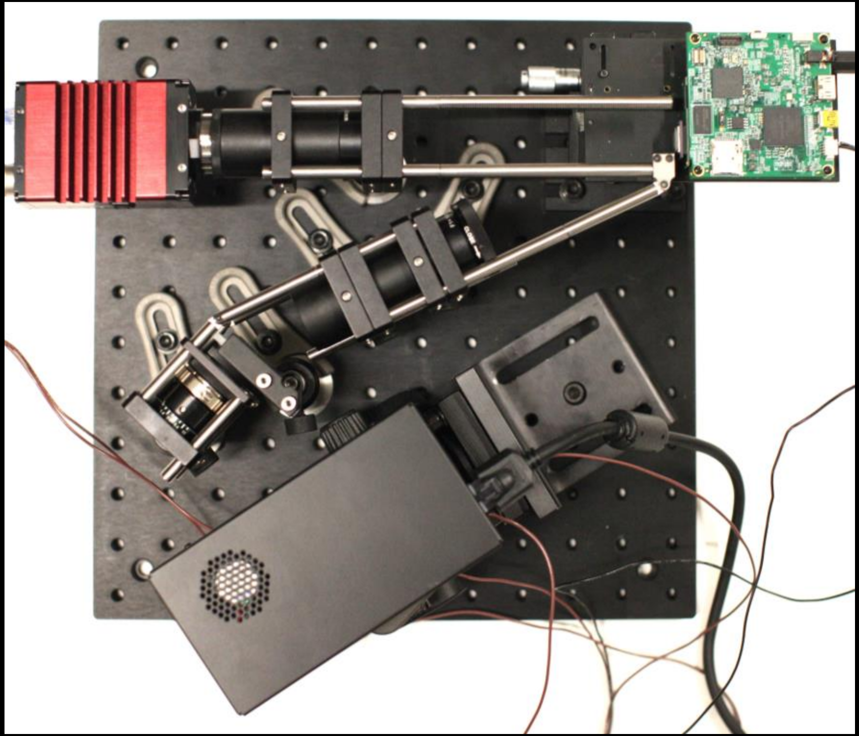
1. open electronic shutter
2. for i = 1 to N
   use random epipolar mask &
   project complementary pattern
3. close electronic shutter



probing with DMD based projection

probing prototype with DMD projector

using two 4kHz DLP kits for projection & pixel masking
(96 codes / video frame)



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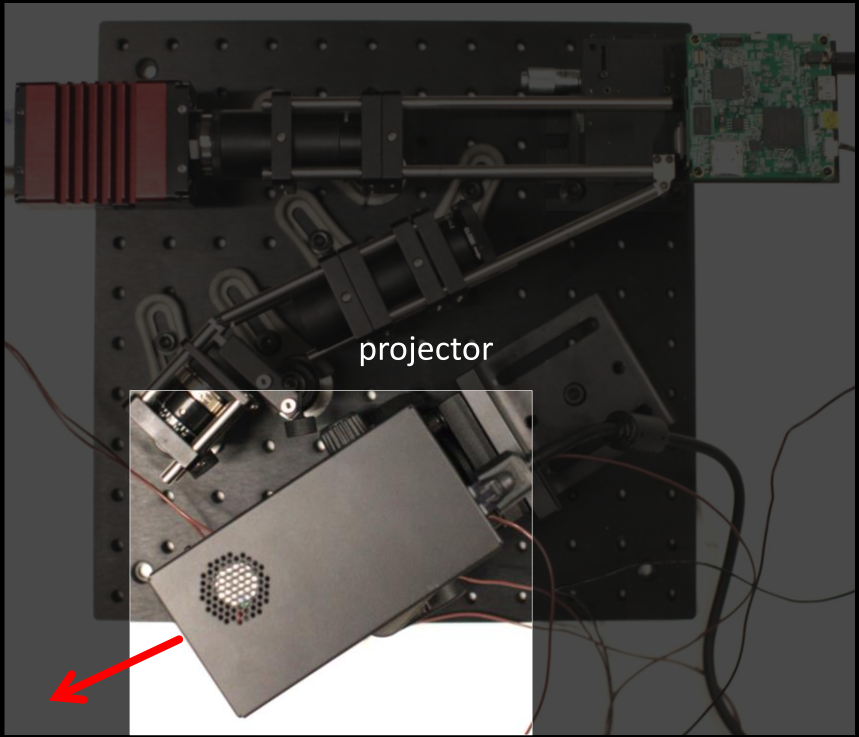

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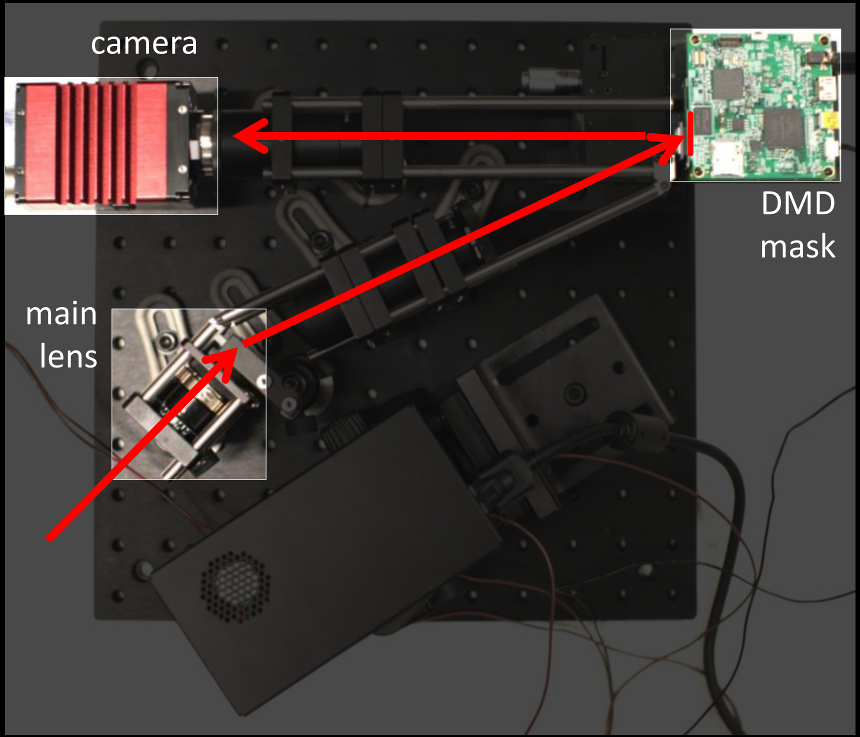
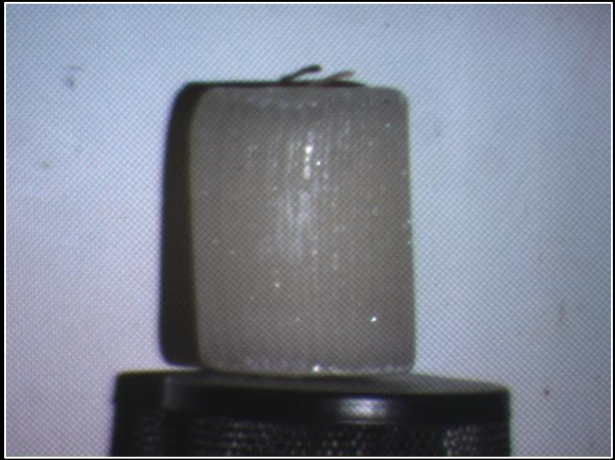


all-optical probing procedure



step 1
open shutter

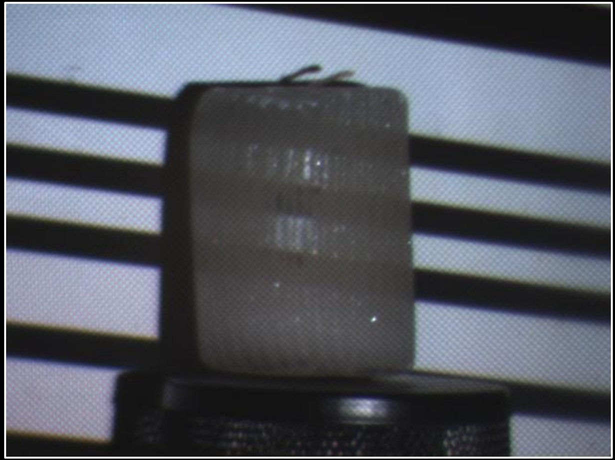
step 2
illuminate scene with vector $\mathbf{l}_i$

step 3
attenuate image with vector $\mathbf{m}_i$

step 4
repeat K times

step 5
close shutter

all-optical probing procedure



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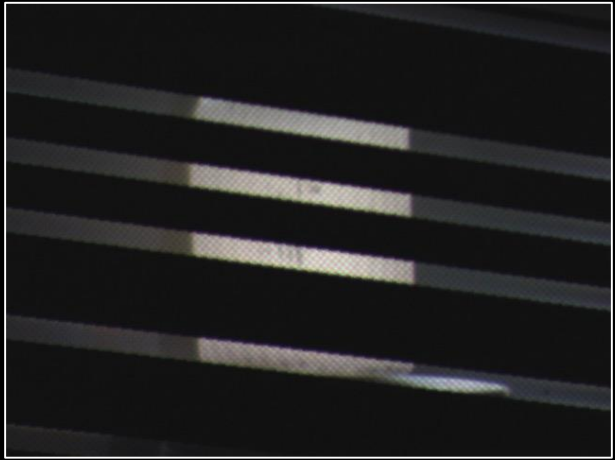

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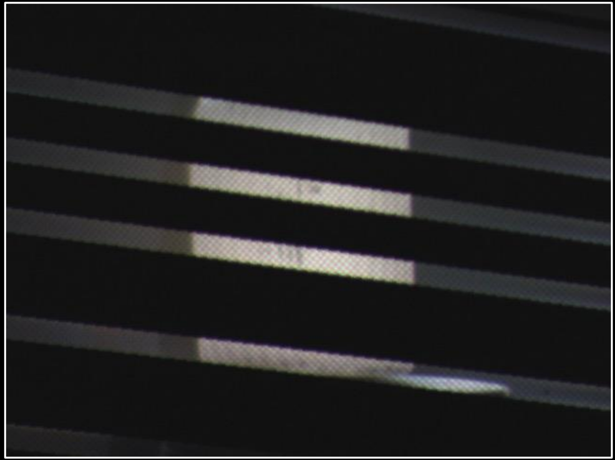
all-optical probing procedure

$$\sum_{i=1}^{K}$$



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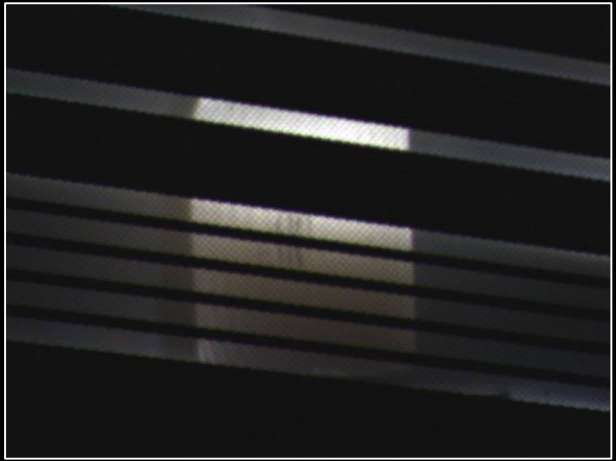

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all-optical probing procedure

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repeat K times

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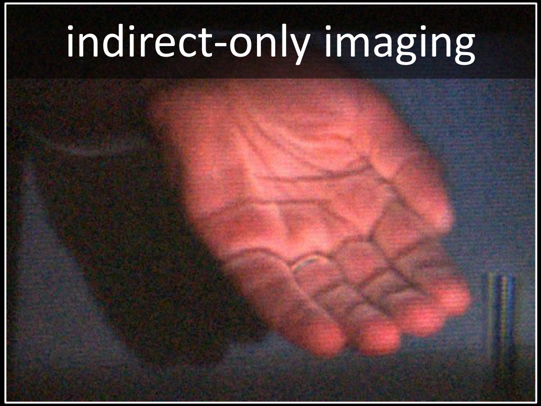
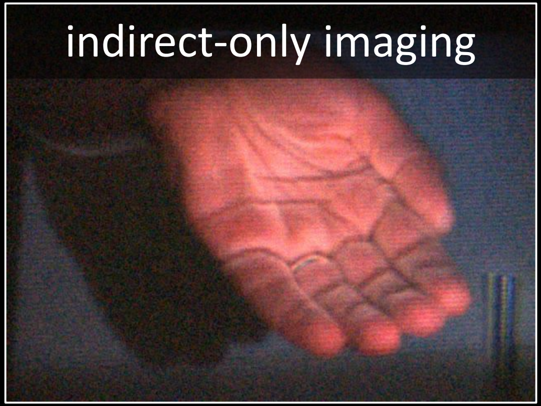
close shutter

live indirect-only and direct-only video stream

live indirect-only and direct-only video stream

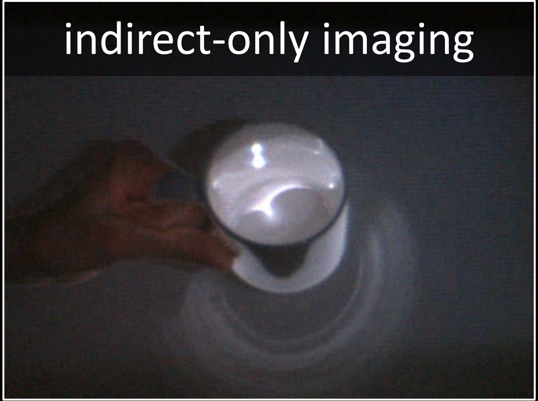


live indirect-only and direct-only video stream



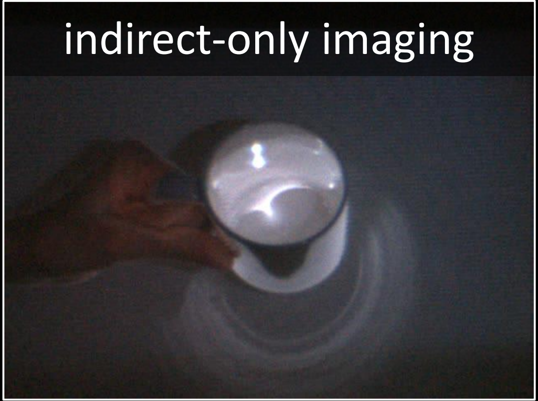
live indirect-only and direct-only video stream


conventional imaging


indirect-only imaging


direct-only imaging

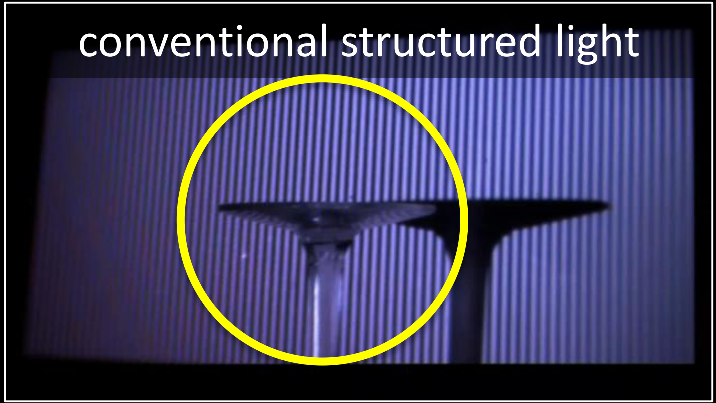
live indirect-only and direct-only video stream

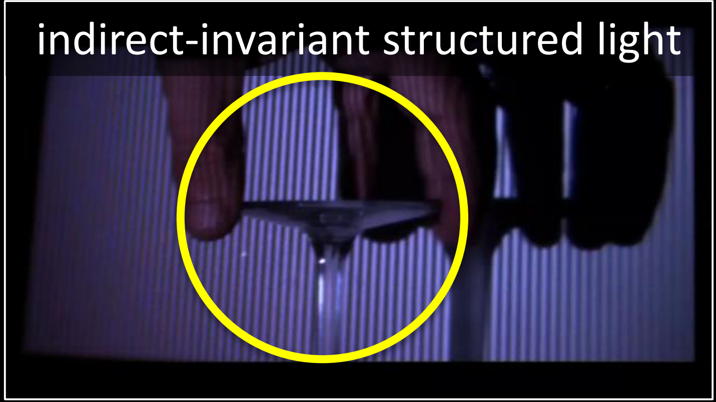


live indirect-only and direct-only video stream

indirect-invariant imaging

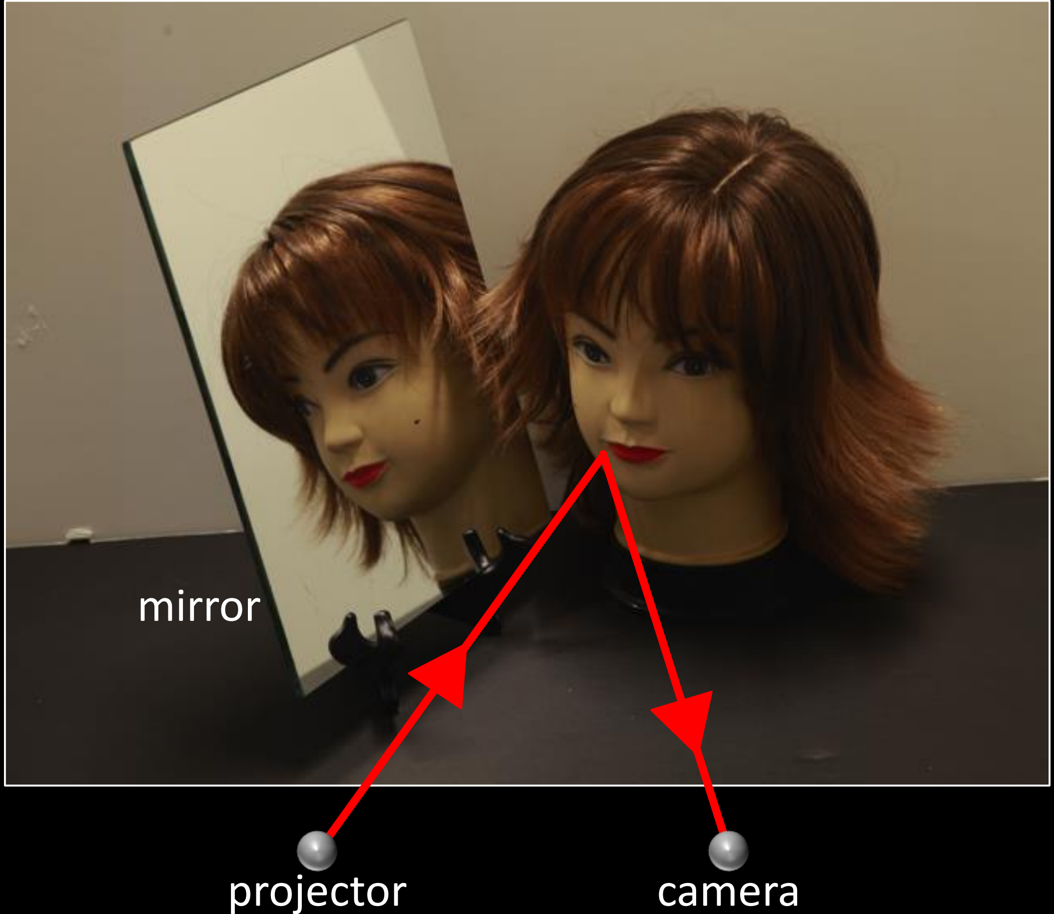
live indirect-invariant video stream



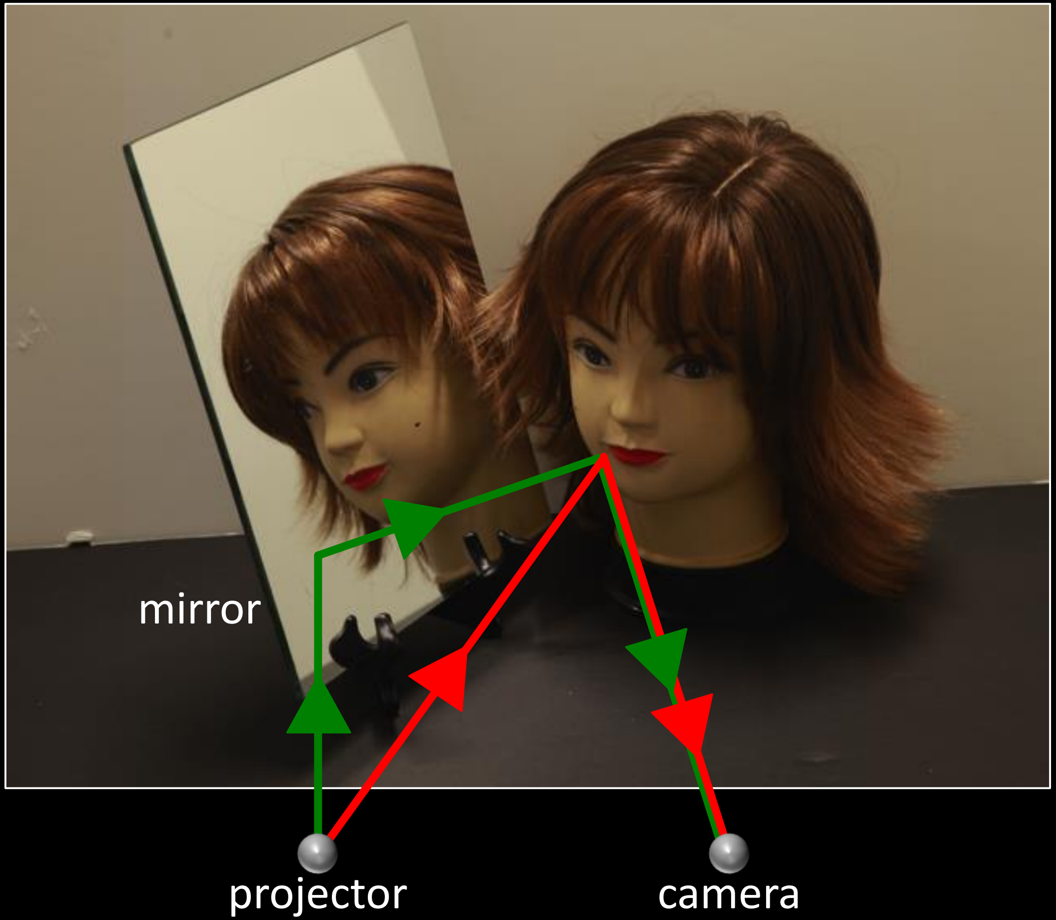


shape acquisition by structured light

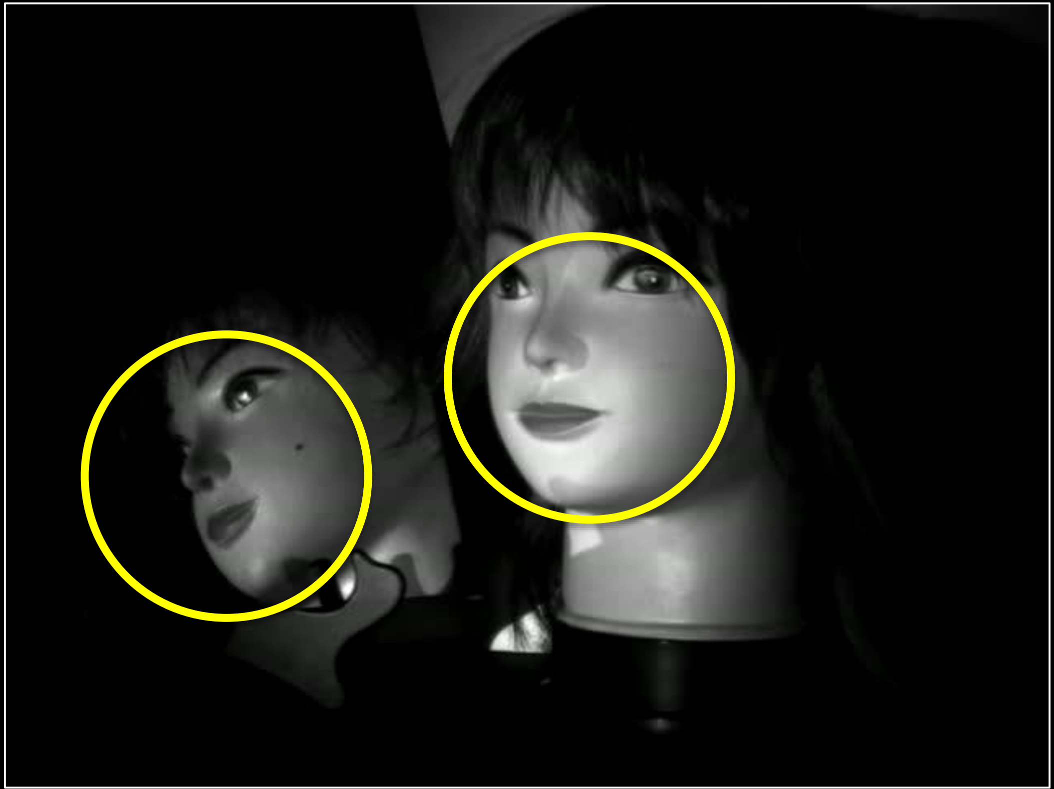
shape acquisition by structured light



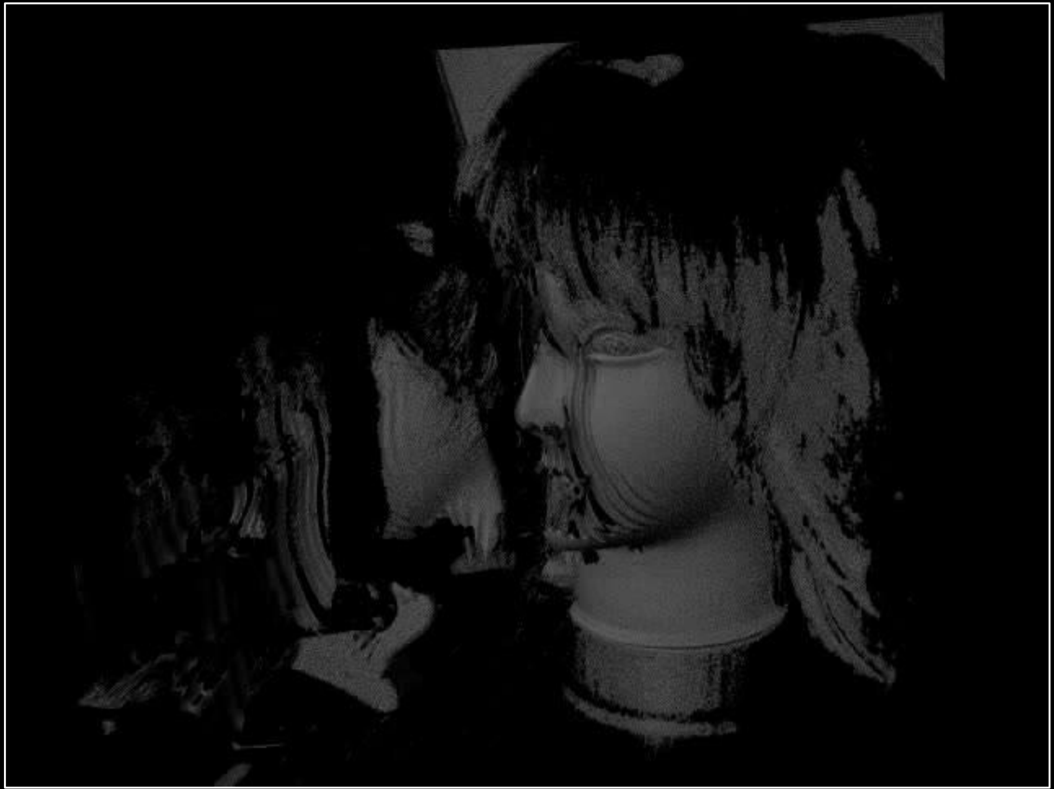
shape acquisition by structured light



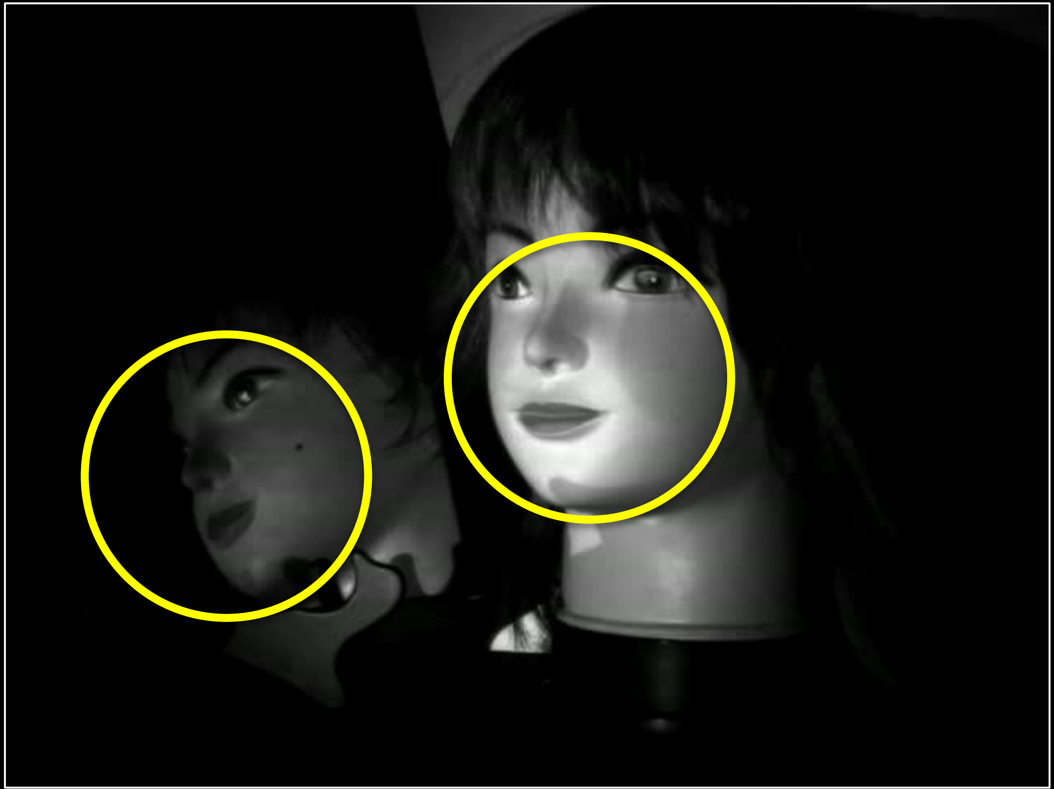
conventional structured light



reconstructed 3D shape

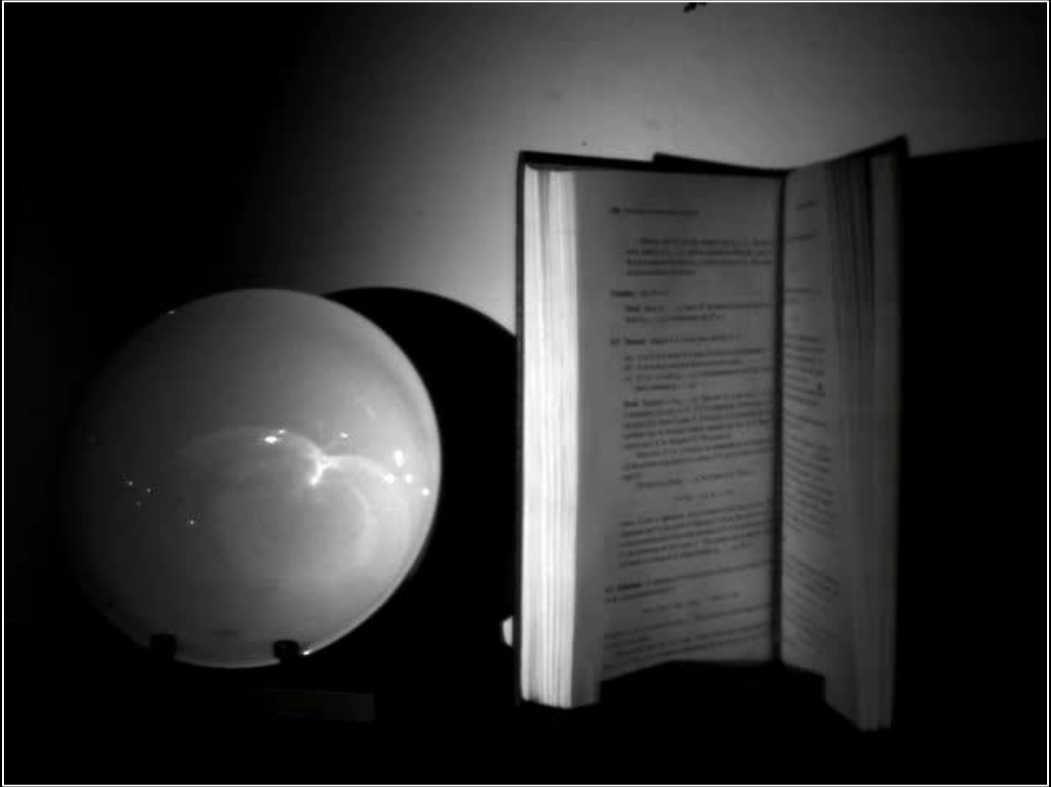


indirect-invariant structured light



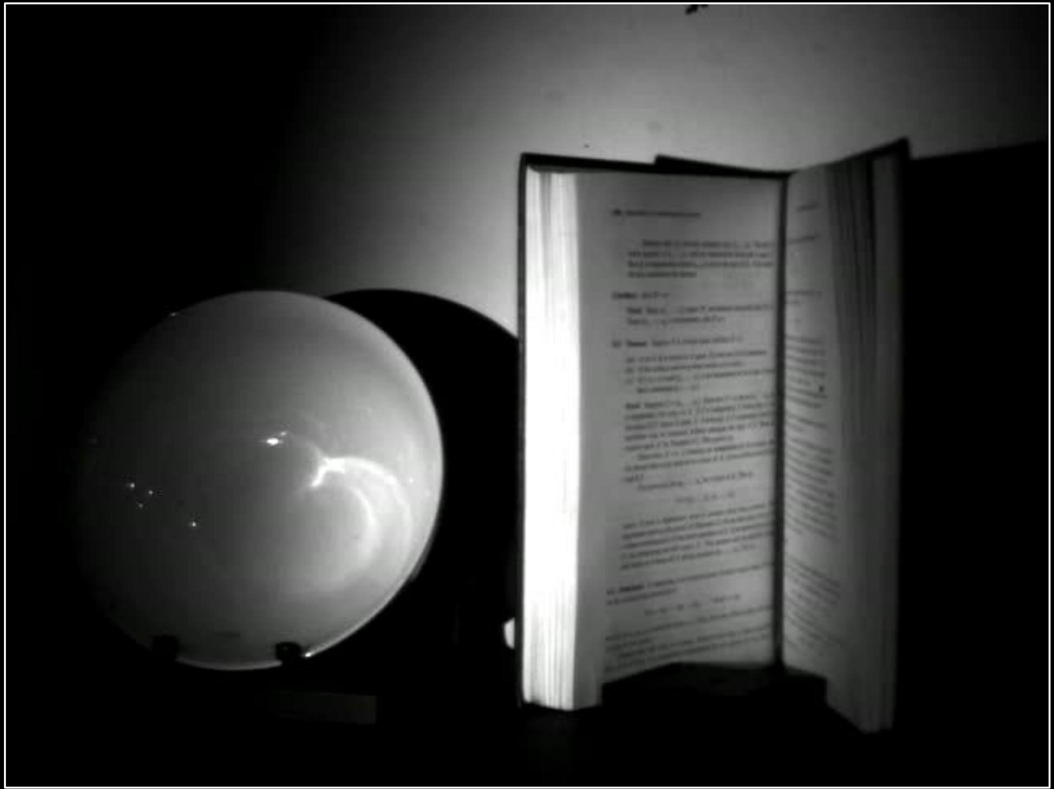
reconstructed 3D shape (same algorithm)

conventional structured light



reconstructed 3D shape

indirect-invariant structured light

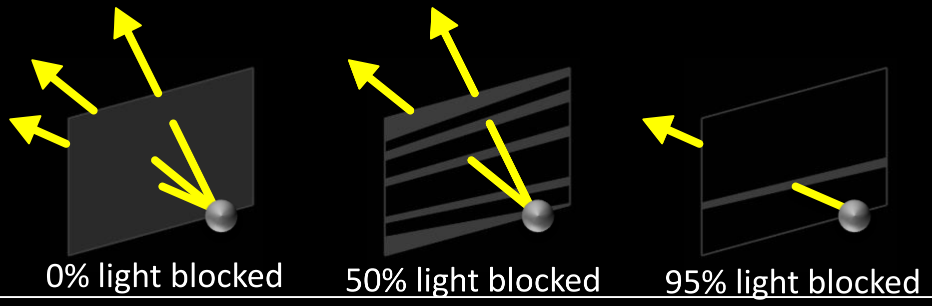


reconstructed 3D shape (same algorithm)

energy-efficient imaging

projector technologies

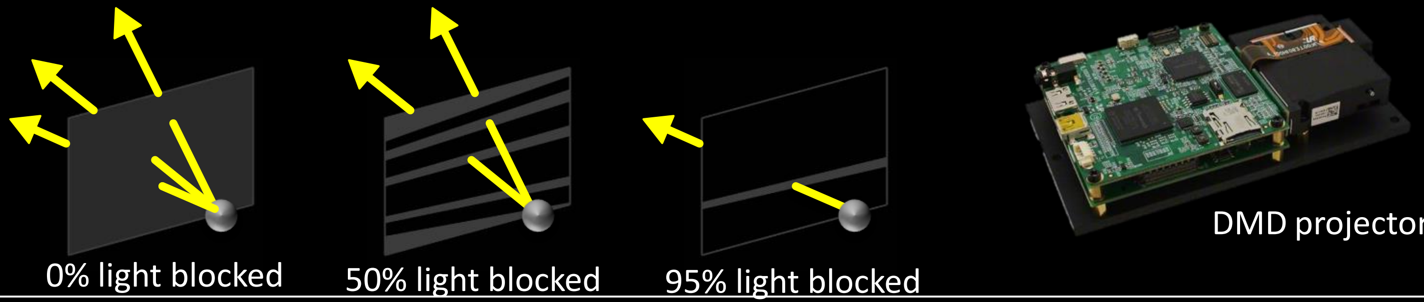
DMD or LCD projection: attenuate light at each projector pixel



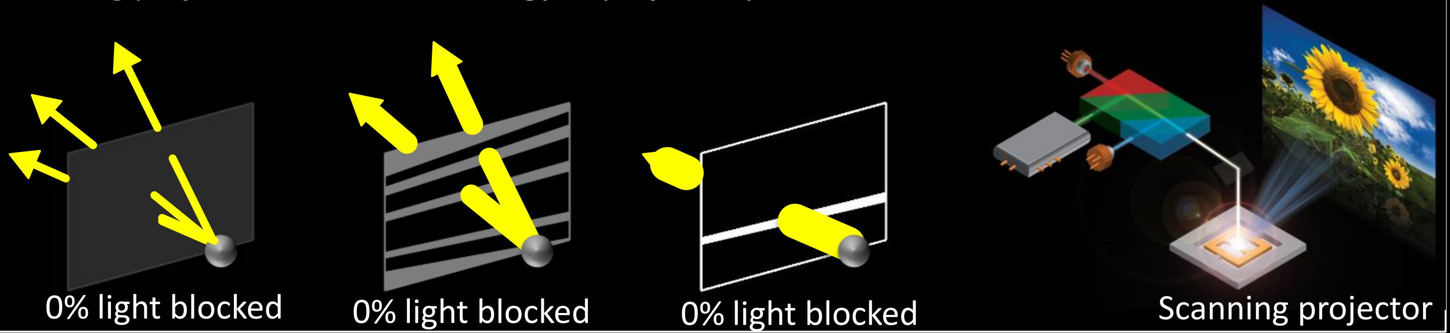
DMD projector

projector technologies

DMD or LCD projection: attenuate light at each projector pixel



MEMs scanning projection: reallocate energy of projector pixels



our scanning projector based prototype

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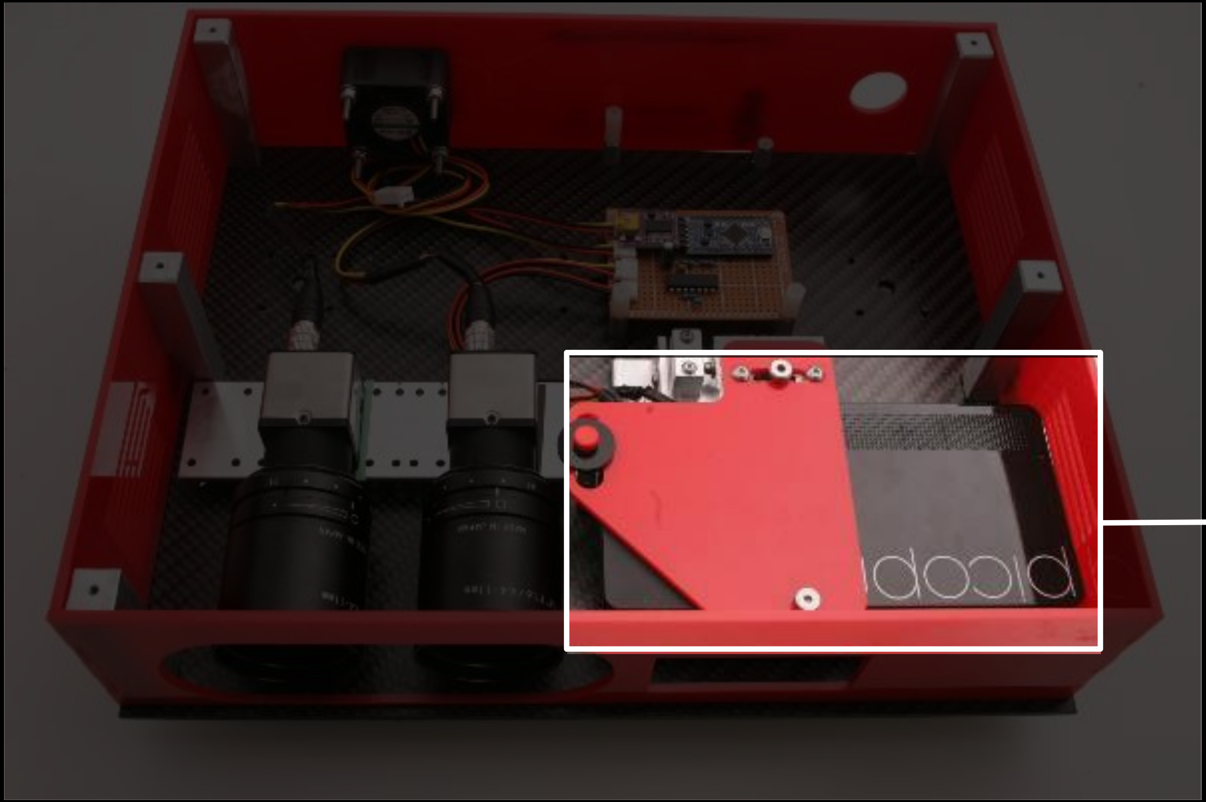
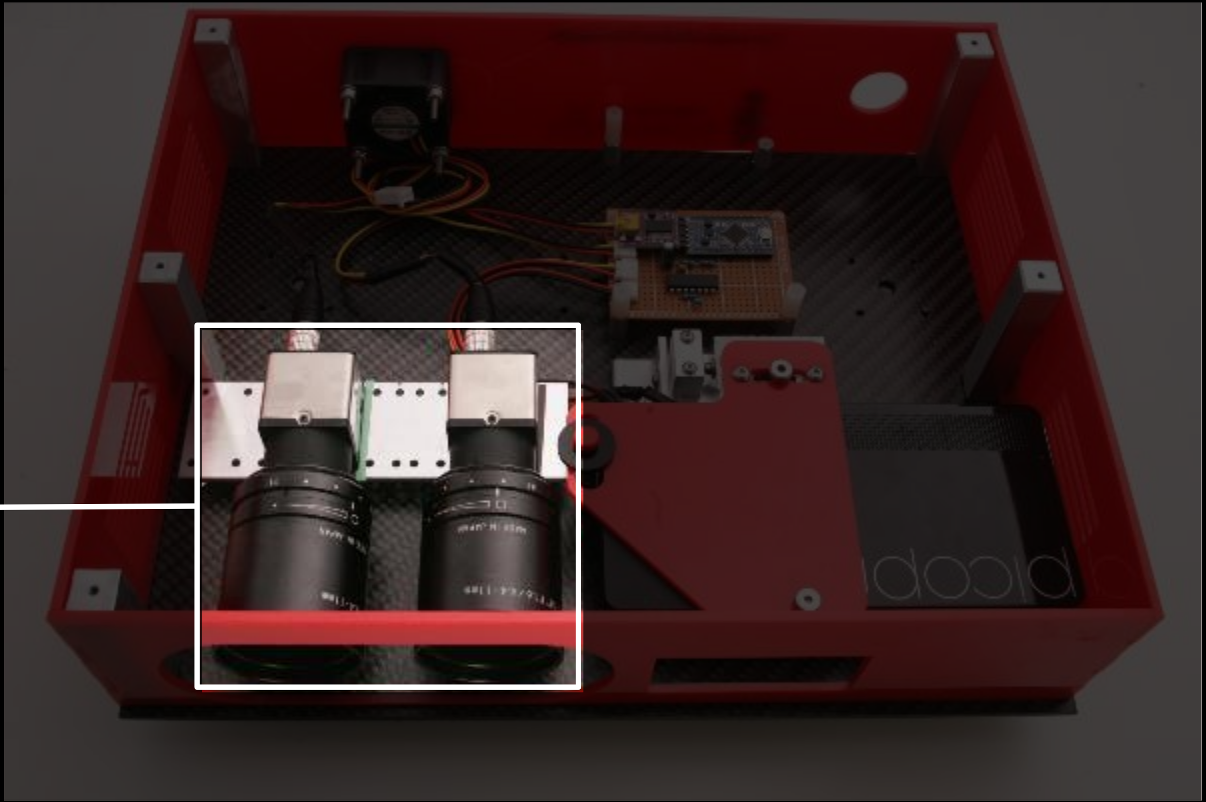


raster scanning
laser projector

30 lumens power, split between R,G and B channels

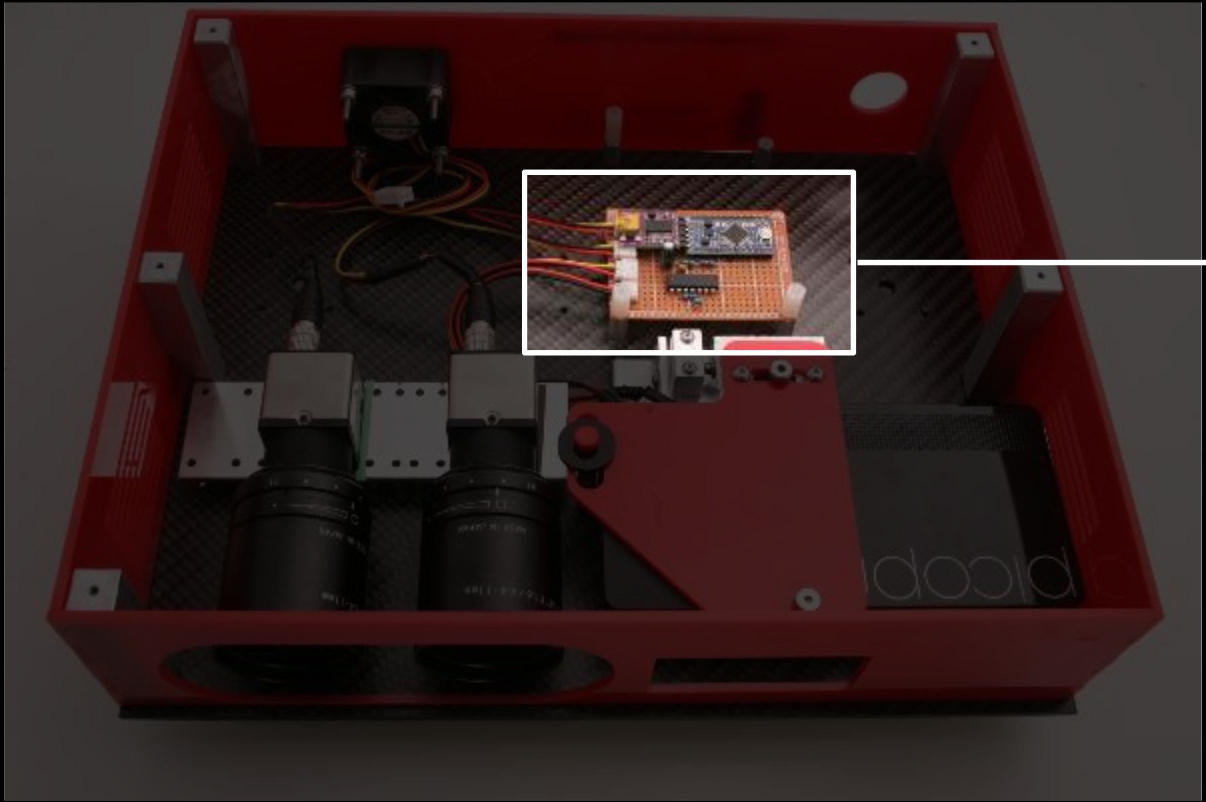
our scanning projector based prototype

rolling shutter
CMOS cameras



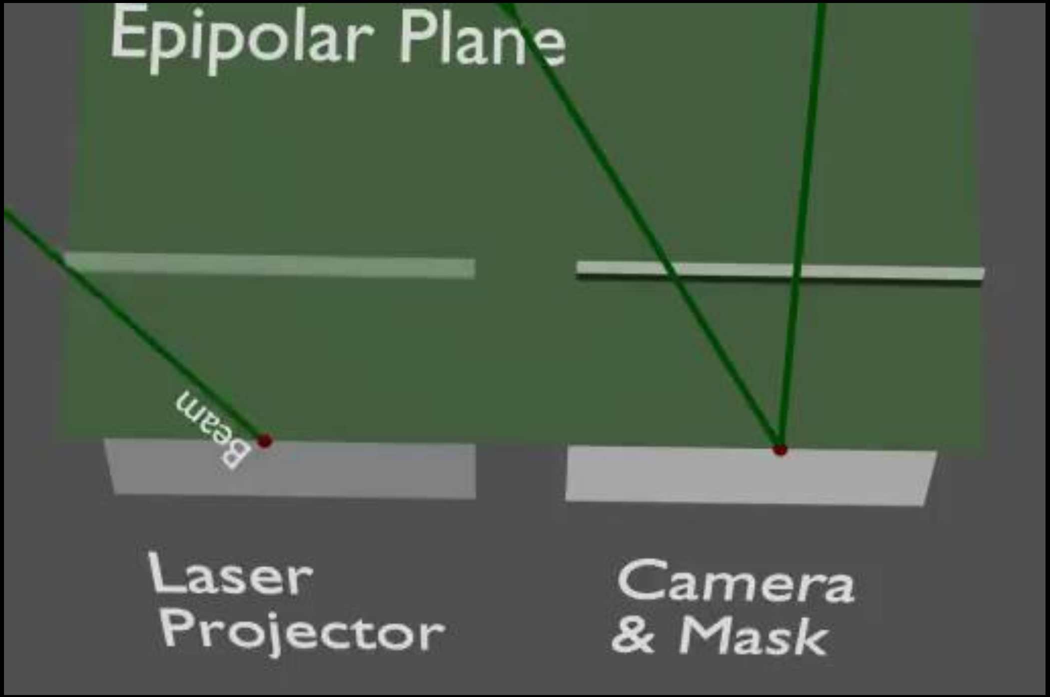
cameras fitted with red bandpass filters

our scanning projector based prototype



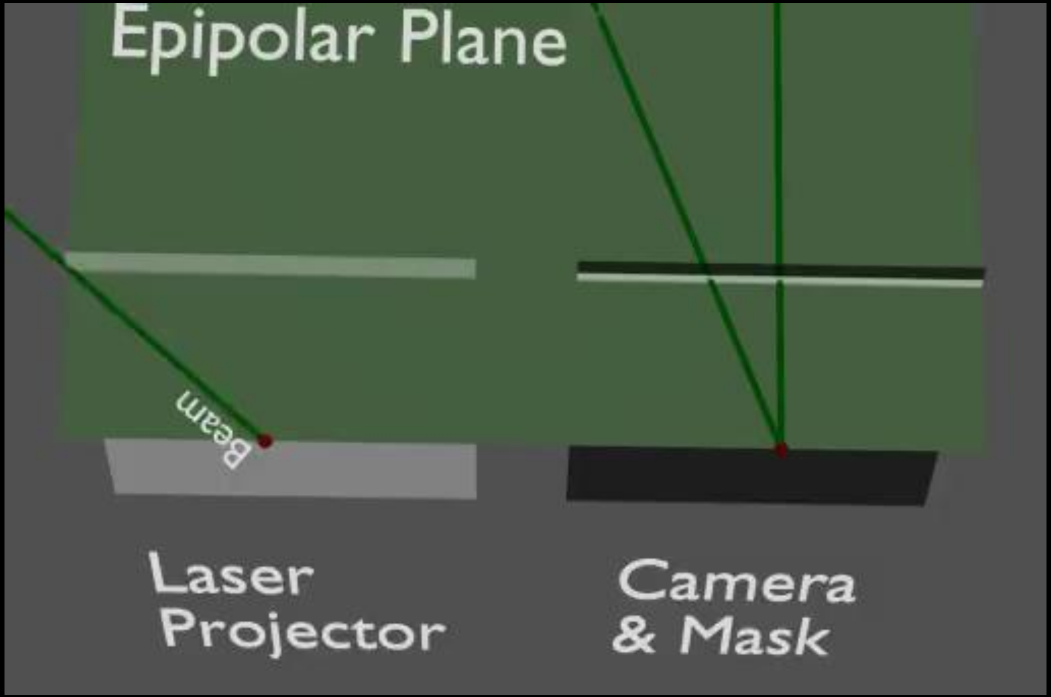
synchronization
electronics

scanning projectors - indirect probing



Exposed Pixels
Masked Pixels

scanning projectors – direct probing



Exposed Pixels
Masked Pixels

short exposure → ambient light is blocked

robustness to ambient light

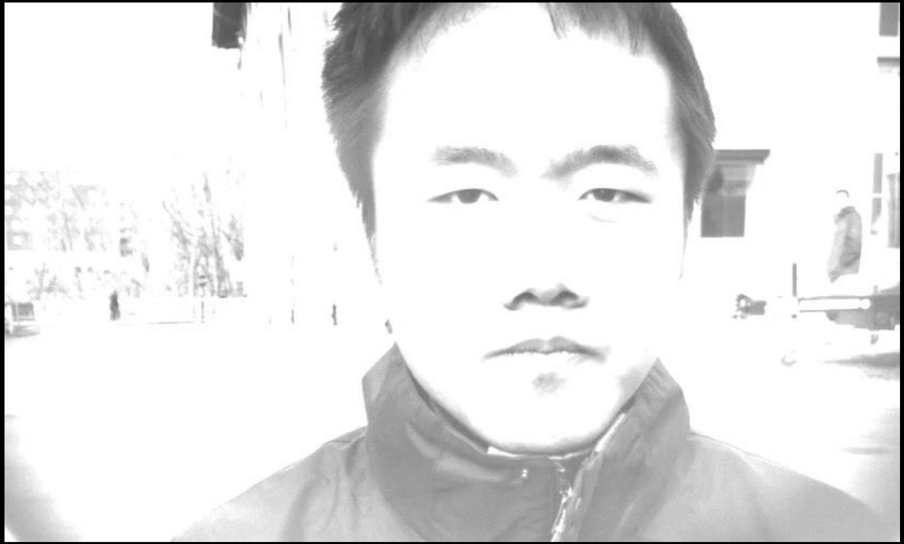
regular imaging

reducing aperture doesn't make the pattern visible

epipolar-only (direct) imaging

structured light outdoors

regular imaging



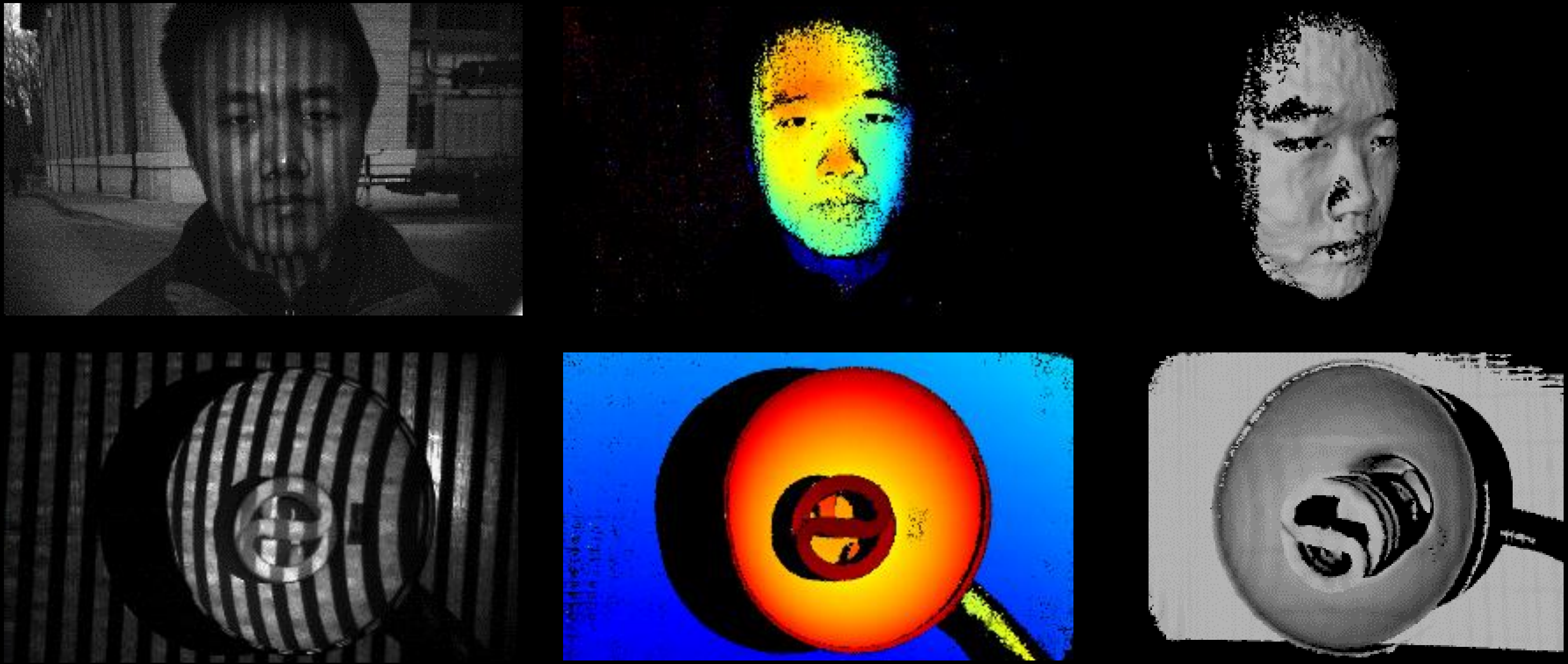
epipolar-only (direct) imaging

ambient light level ≈ 80,000 lux

recovering shape under bright ambient conditions

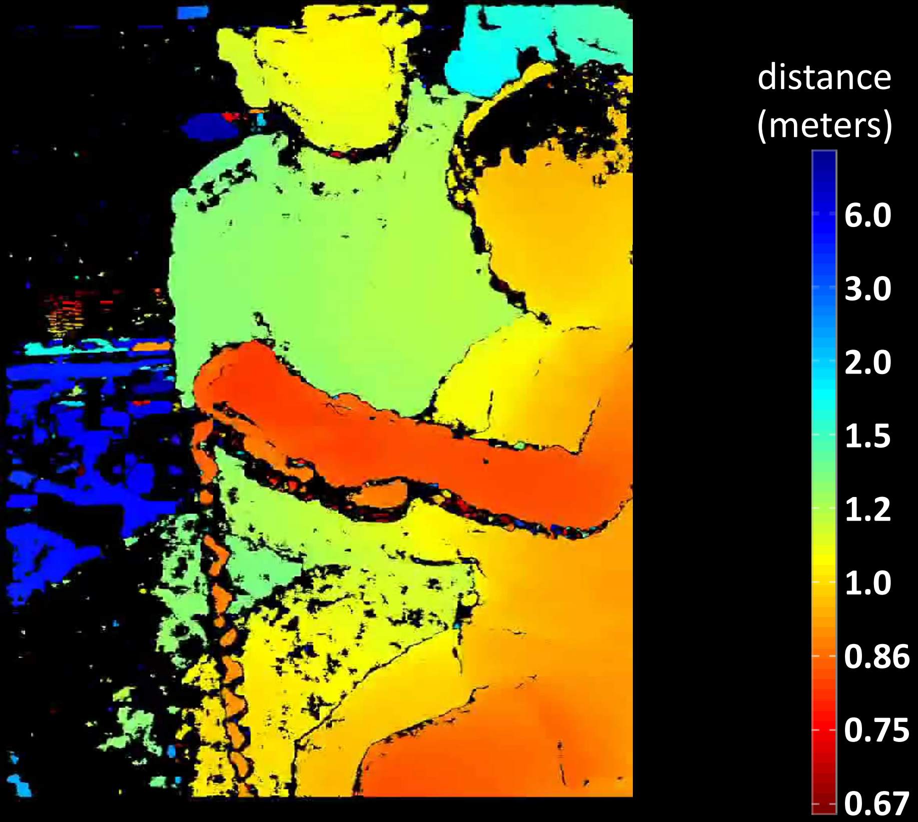
depth map

3D reconstruction



active stereo in bright sunlight

raw image (left camera)



depth map

active stereo in bright sunlight

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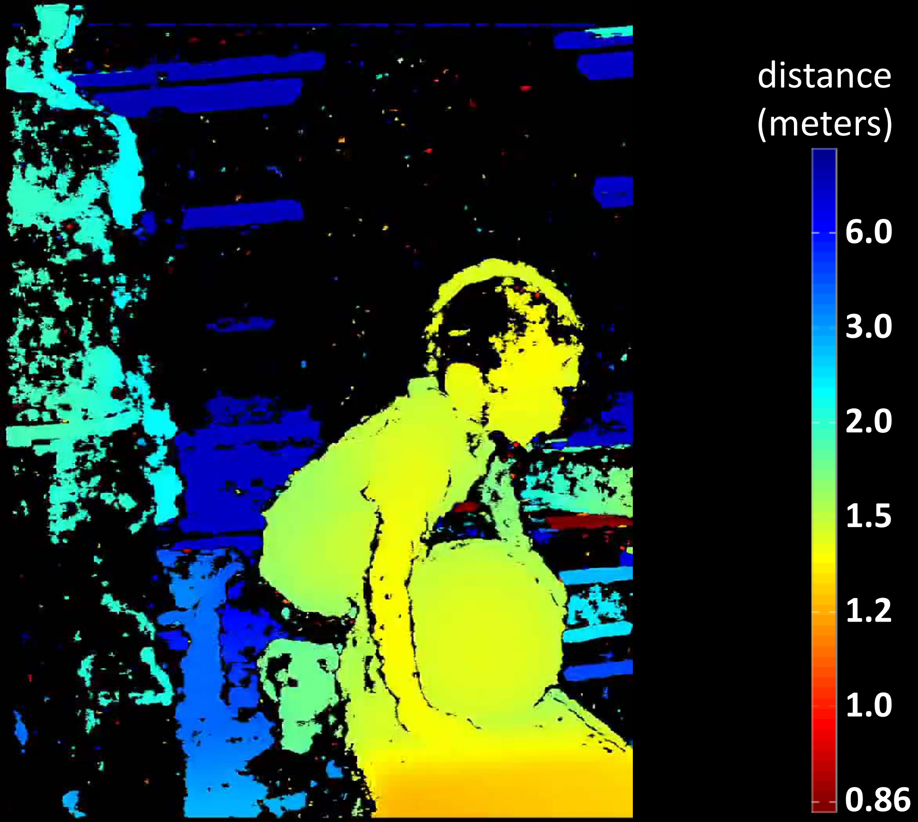
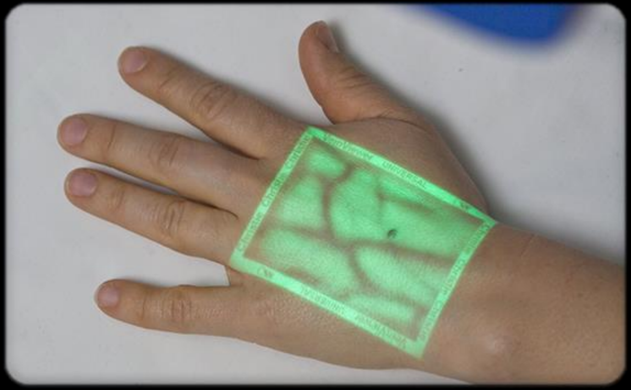
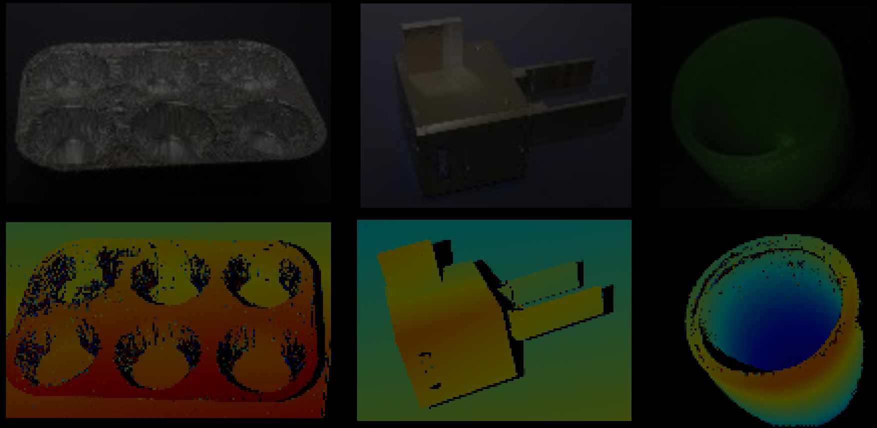


depth map

taking transport probing everywhere



Medical Imaging

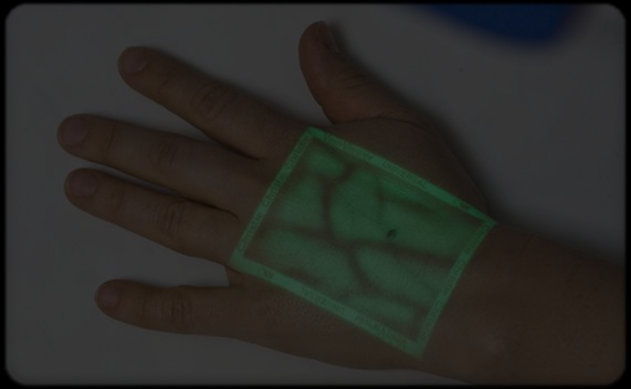


Industrial Inspection

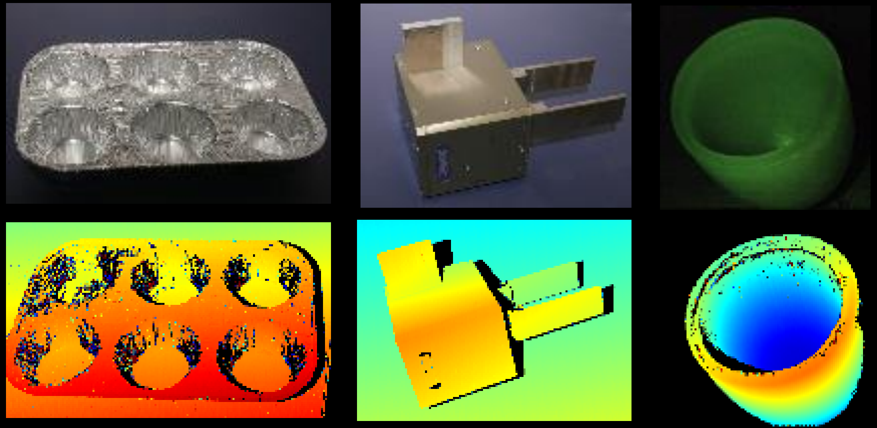
Mobile Robotics

Consumer Electronics

taking transport probing everywhere



Medical Imaging



Industrial Inspection

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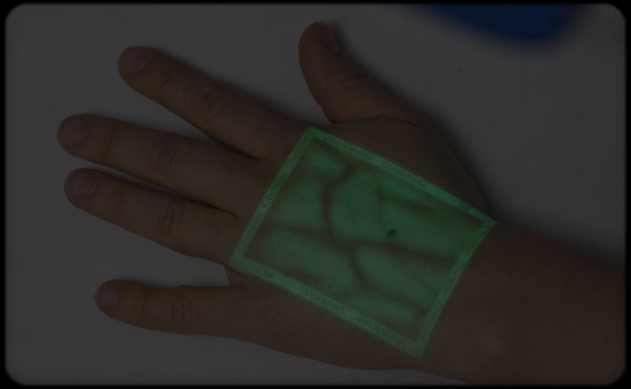
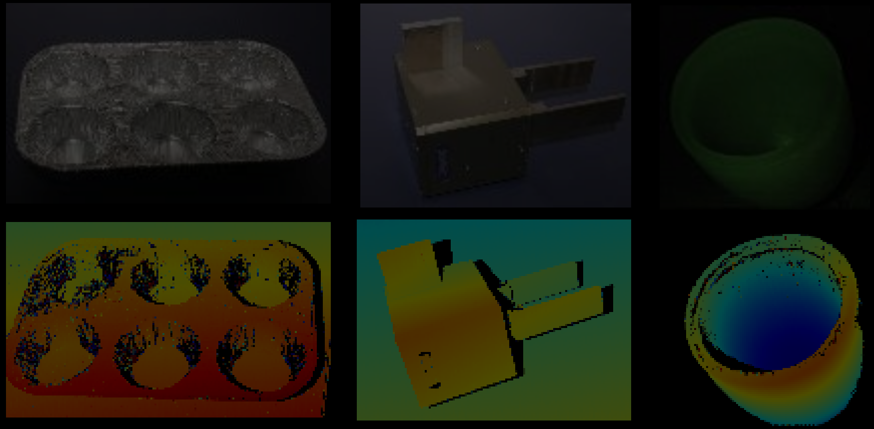
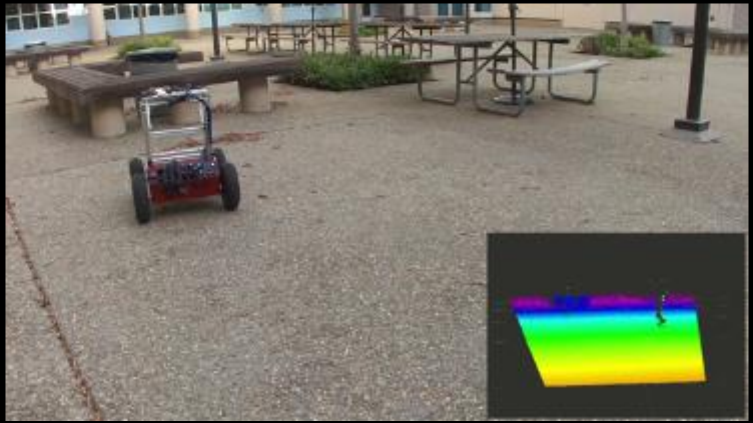


Medical Imaging



Industrial Inspection



Mobile Robotics

Consumer Electronics

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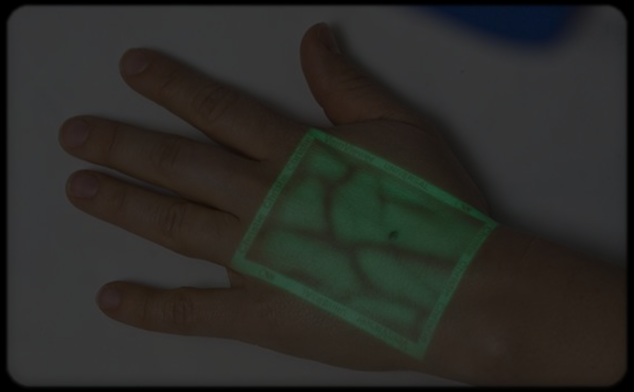
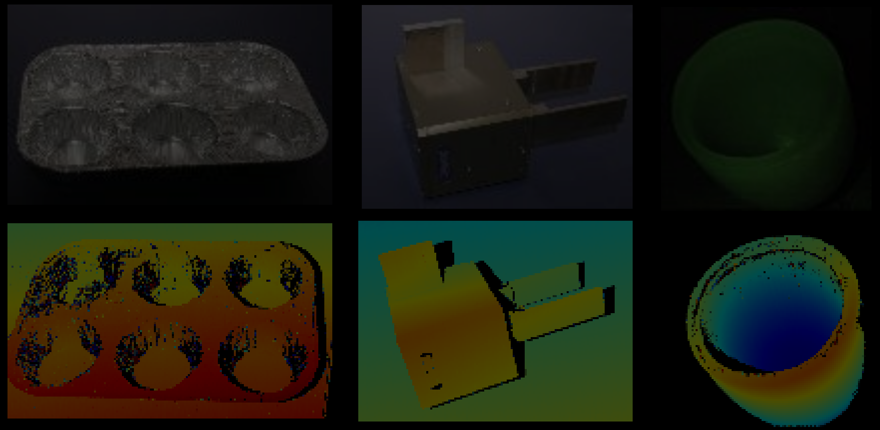


Medical Imaging



Industrial Inspection

Mobile Robotics

Consumer Electronics

Probing Light Paths for 3D Shape and Indirect Appearance

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Supreeth Achar
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Srinivas Narasimhan
CMU