Lecture 5: A Single-Pixel Compressive Camera

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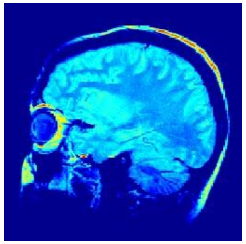
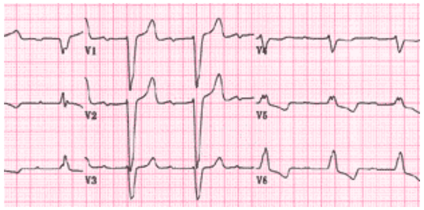
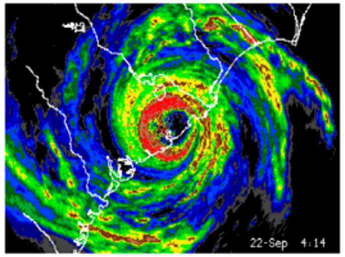
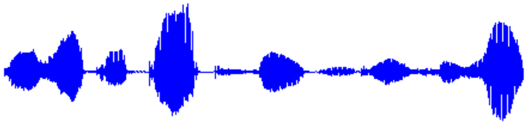
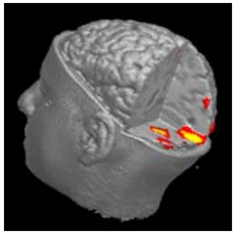





Digital Revolution

Pressure is on DSP

- Success of digital data acquisition is placing increasing pressure on signal/image processing hardware and software to support

higher resolution / denser sampling

» still cameras, video cameras, imaging systems, ...

+

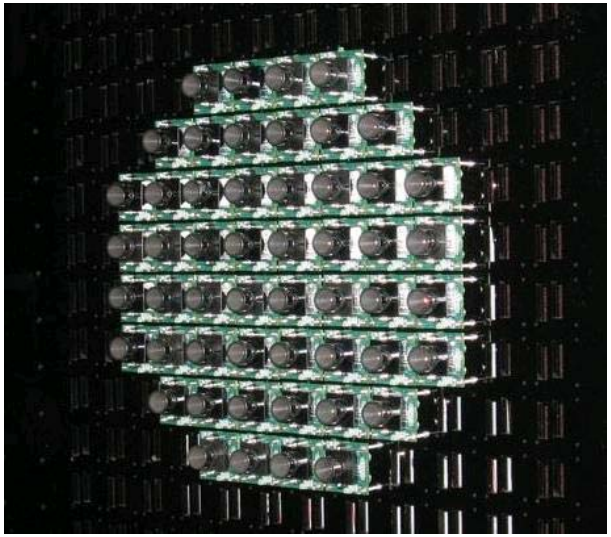
large numbers of sensors

» multi-view image data bases, camera arrays and networks, pattern recognition systems,

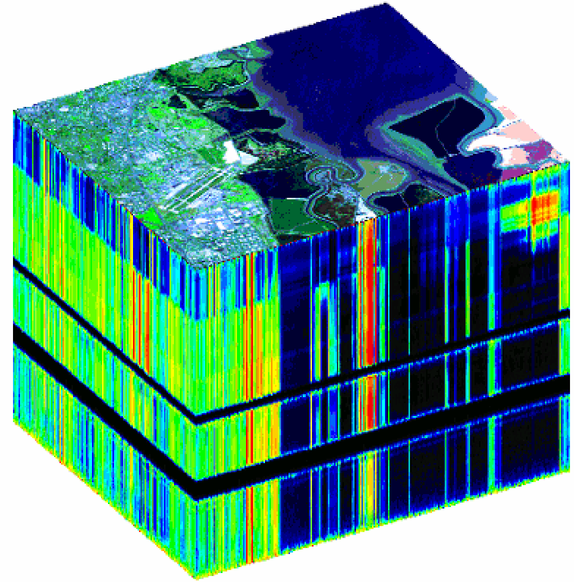
+

increasing numbers of modalities

» visual, IR, UV, SAR, ...



camera arrays



hyperspectral cameras

distributed camera networks

Pressure is on DSP

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+

increasing numbers of modalities

» visual, IR, UV, SAR, ...

=

deluge of data

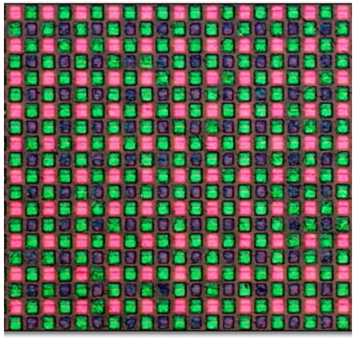
» how to acquire, store, fuse, process efficiently?

Sensing by *Sampling*

Data Acquisition

- Time: A/D converters, receivers, ...
- Space: cameras, imaging systems, ...

- Foundation: ***Shannon sampling theorem***
  - *Nyquist rate*: must sample at 2x highest frequency in signal/image



N periodic samples via CCD/CMOS array

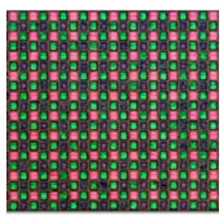
- higher resolution X more modalities X more sensors = ***deluge of data***

Sensing by *Sampling*

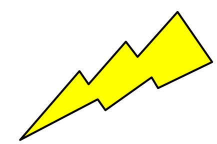
- **Step 1:** ***sample*** data (A/D converter, digital camera, ...)
- **Step 2:** ***compress*** data

$N \gg K$

$x \longrightarrow$ sample $\xrightarrow{N}$ **compress** $\xrightarrow{K}$ transmit/store



JPEG
JPEG2000



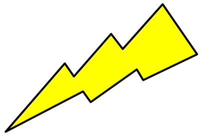
receive $\xrightarrow{K}$ decompress $\xrightarrow{N}$ $\widehat{x}$

Compressive Sampling (CS)

- Directly acquire a “compressed” image
- Replace samples by more general “measurements”

$$K < \underline{M} \ll N$$

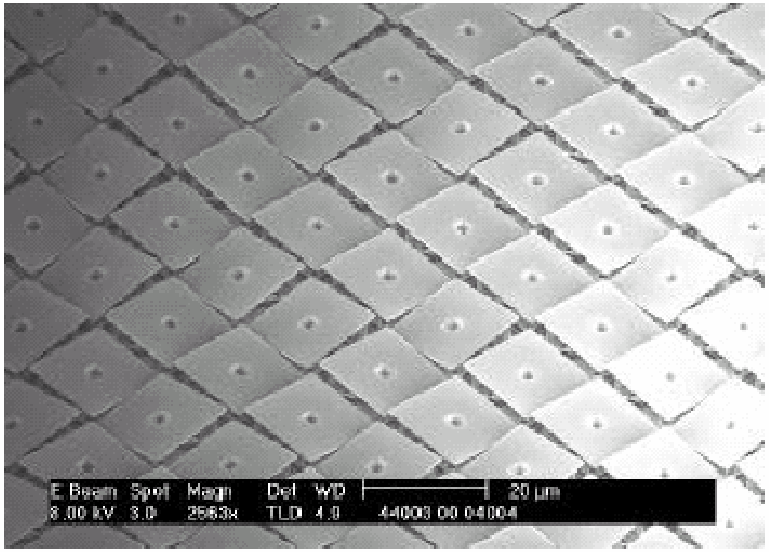
$x \rightarrow$ **compressive sampling** $\xrightarrow{M}$ transmit/store

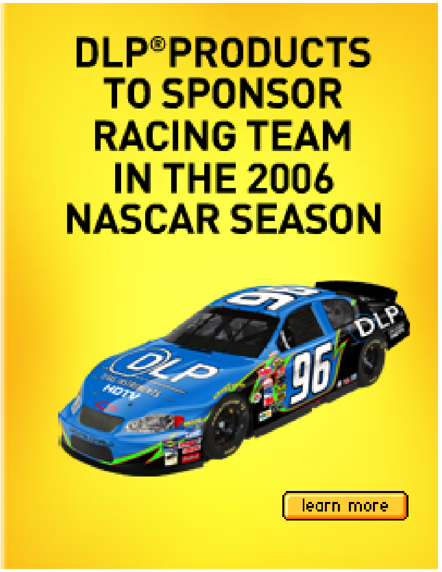


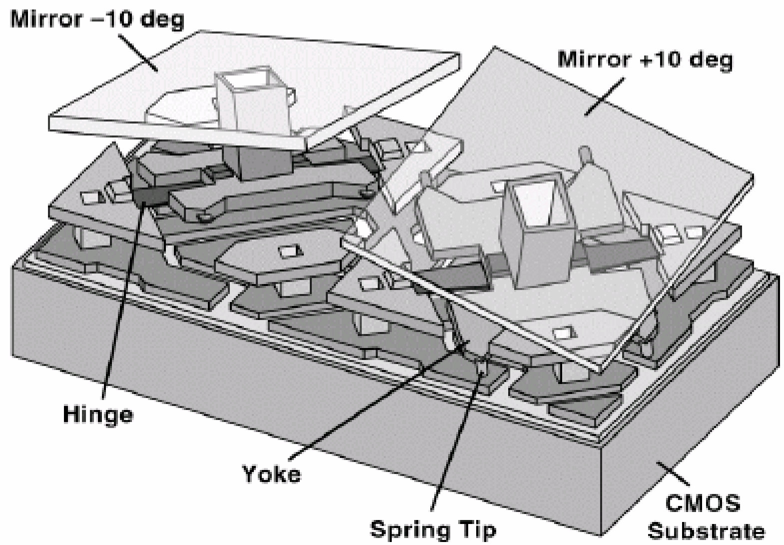
receive $\xrightarrow{M}$ reconstruct $\xrightarrow{N} \widehat{x}$

Compressive Sampling in Action

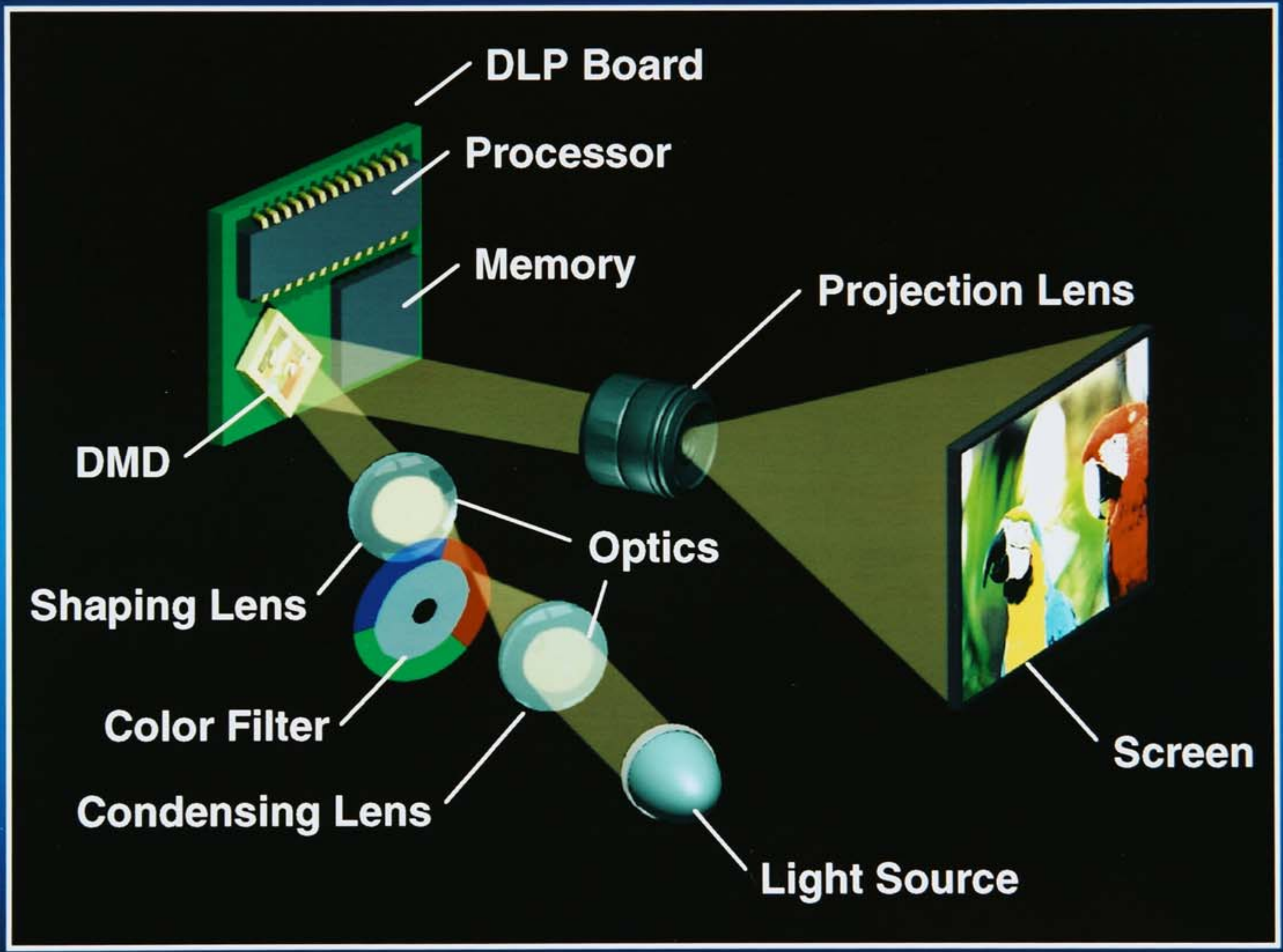
“It’s All Done with Mirrors”



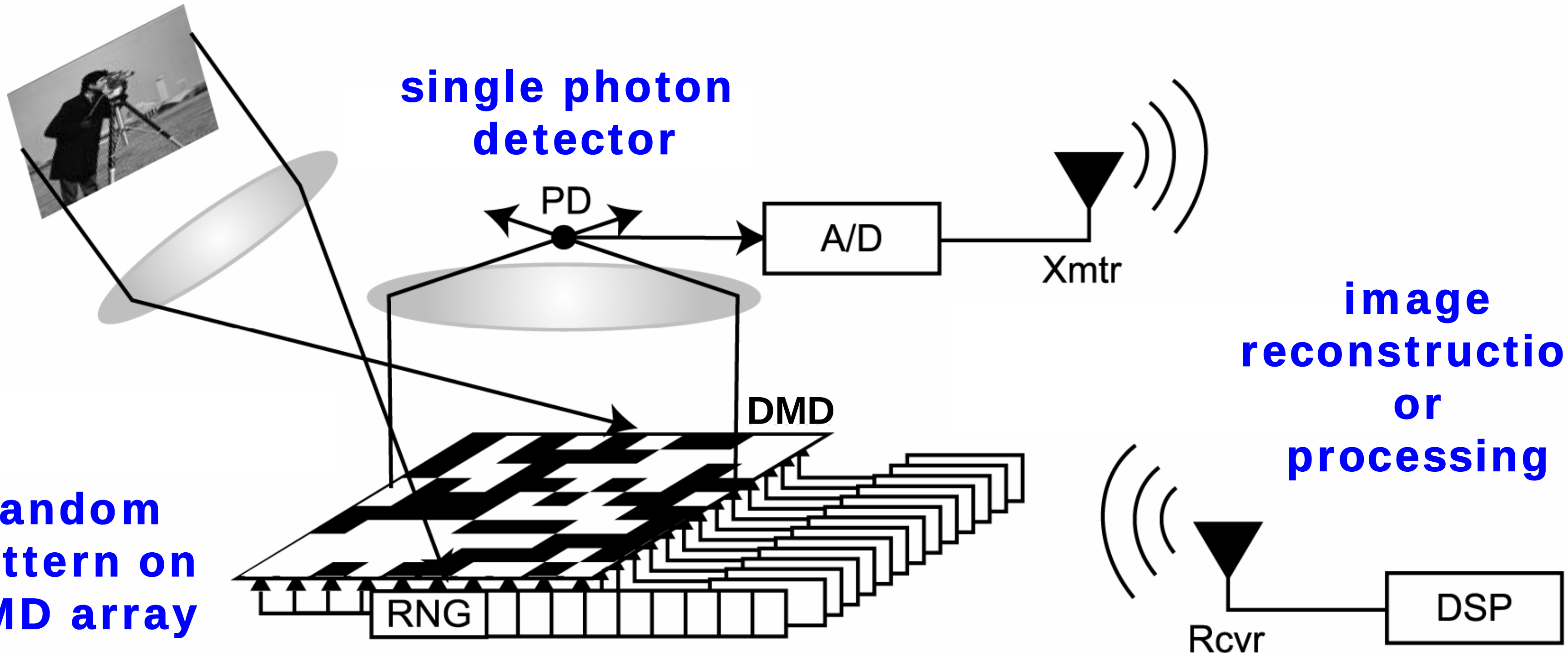


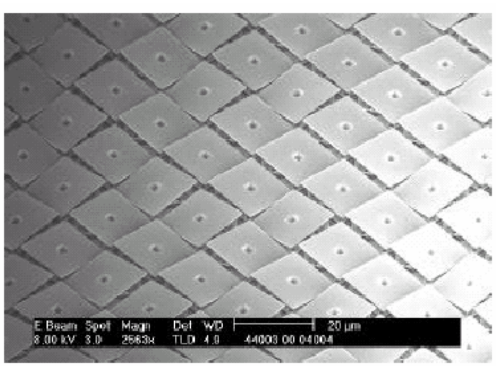


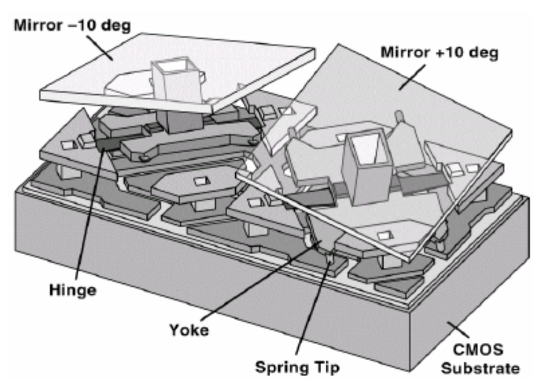
1 Chip DLP™ Projection



“Single-Pixel” CS Camera

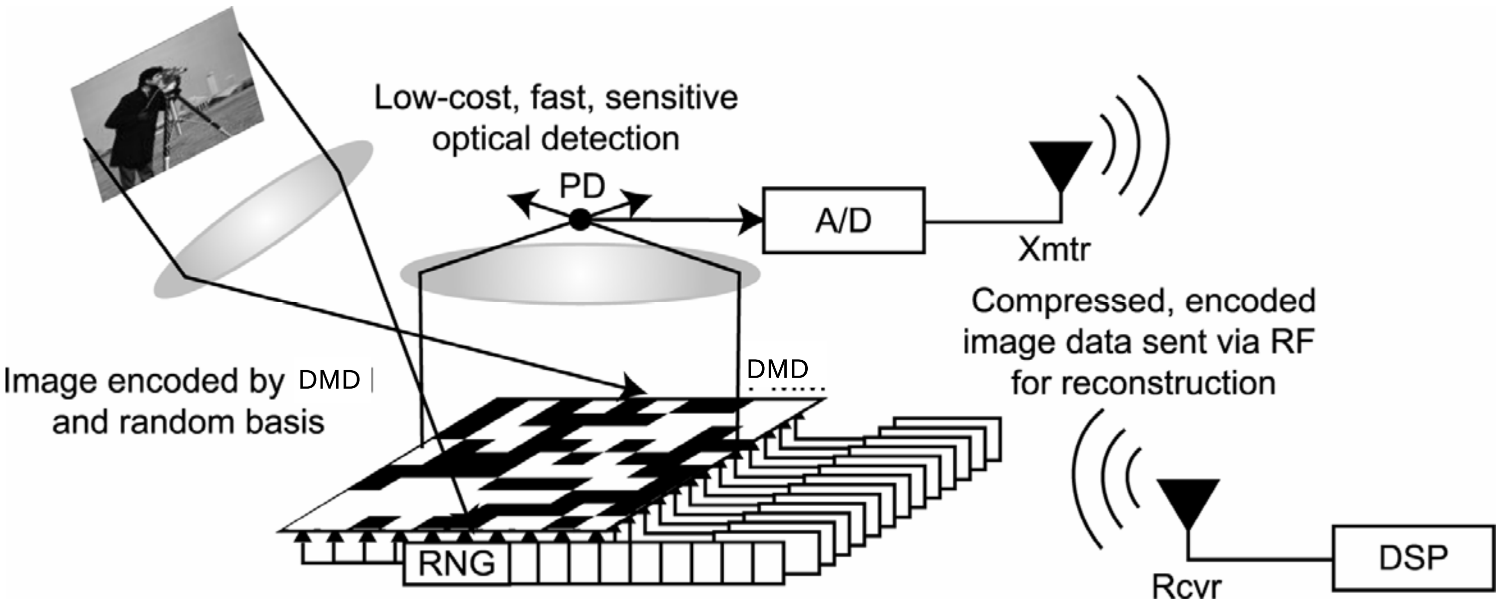






w/ Kevin Kelly and students

Single Pixel Camera



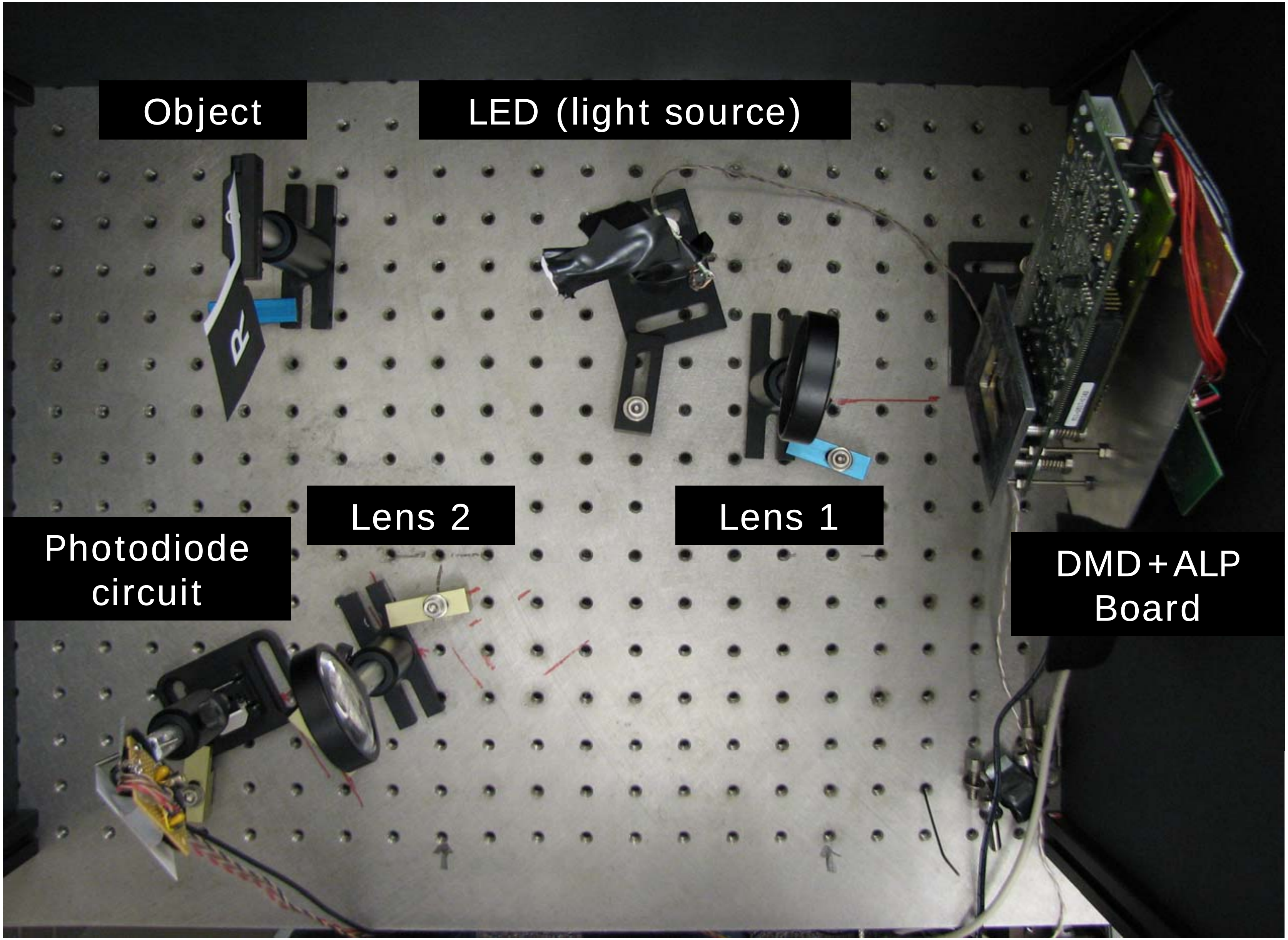
1

2

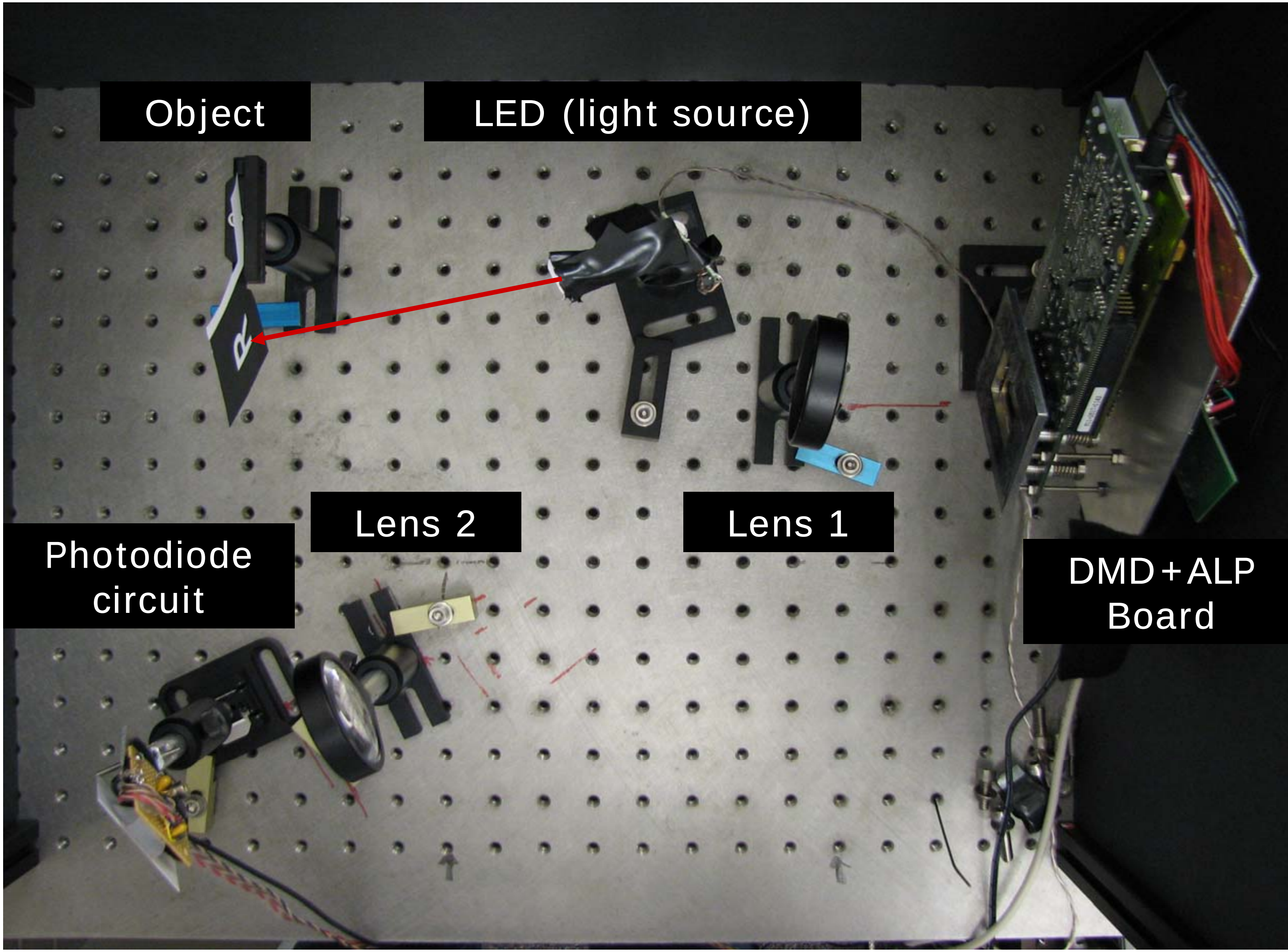
...

M

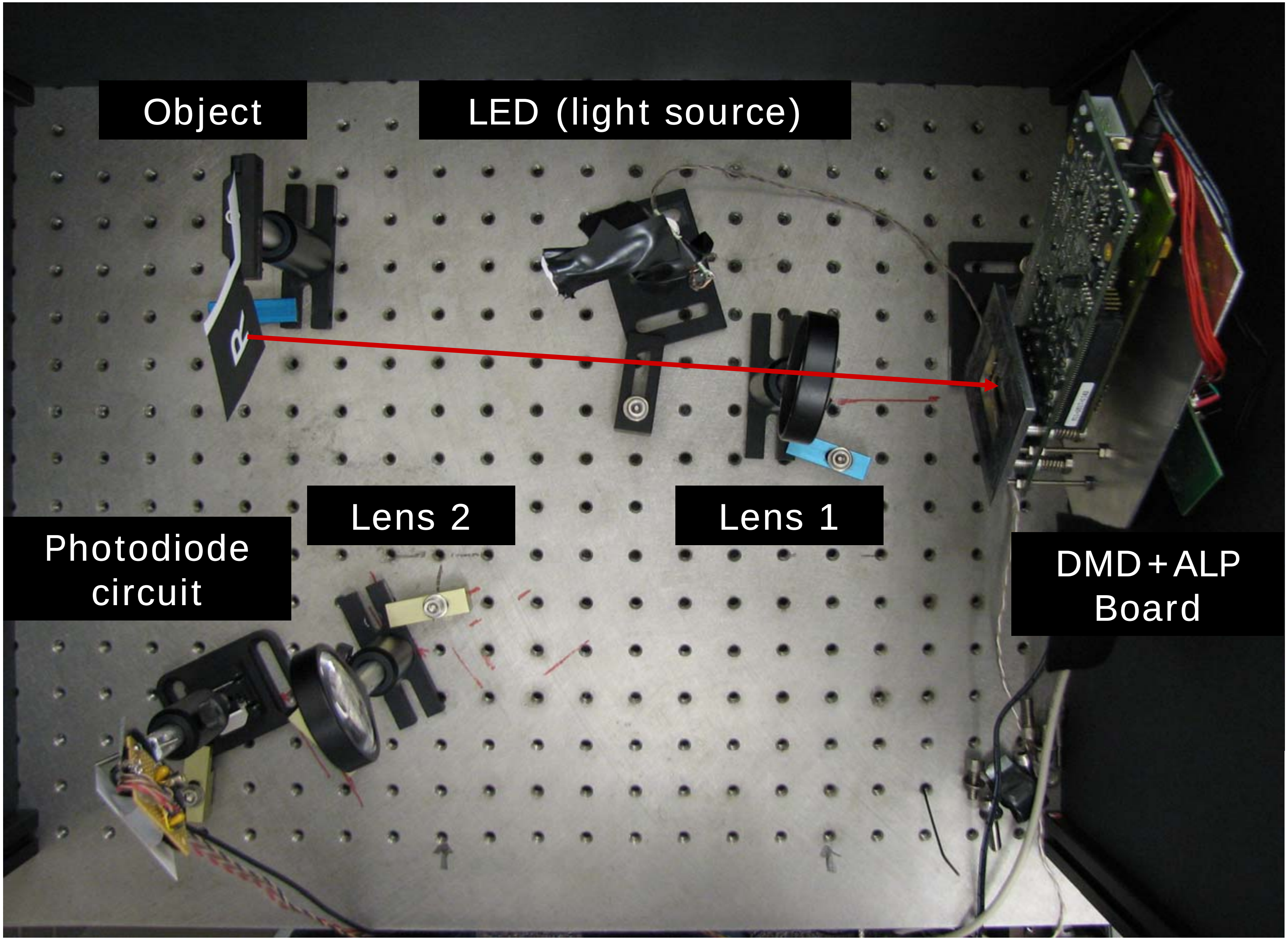
Single Pixel Camera



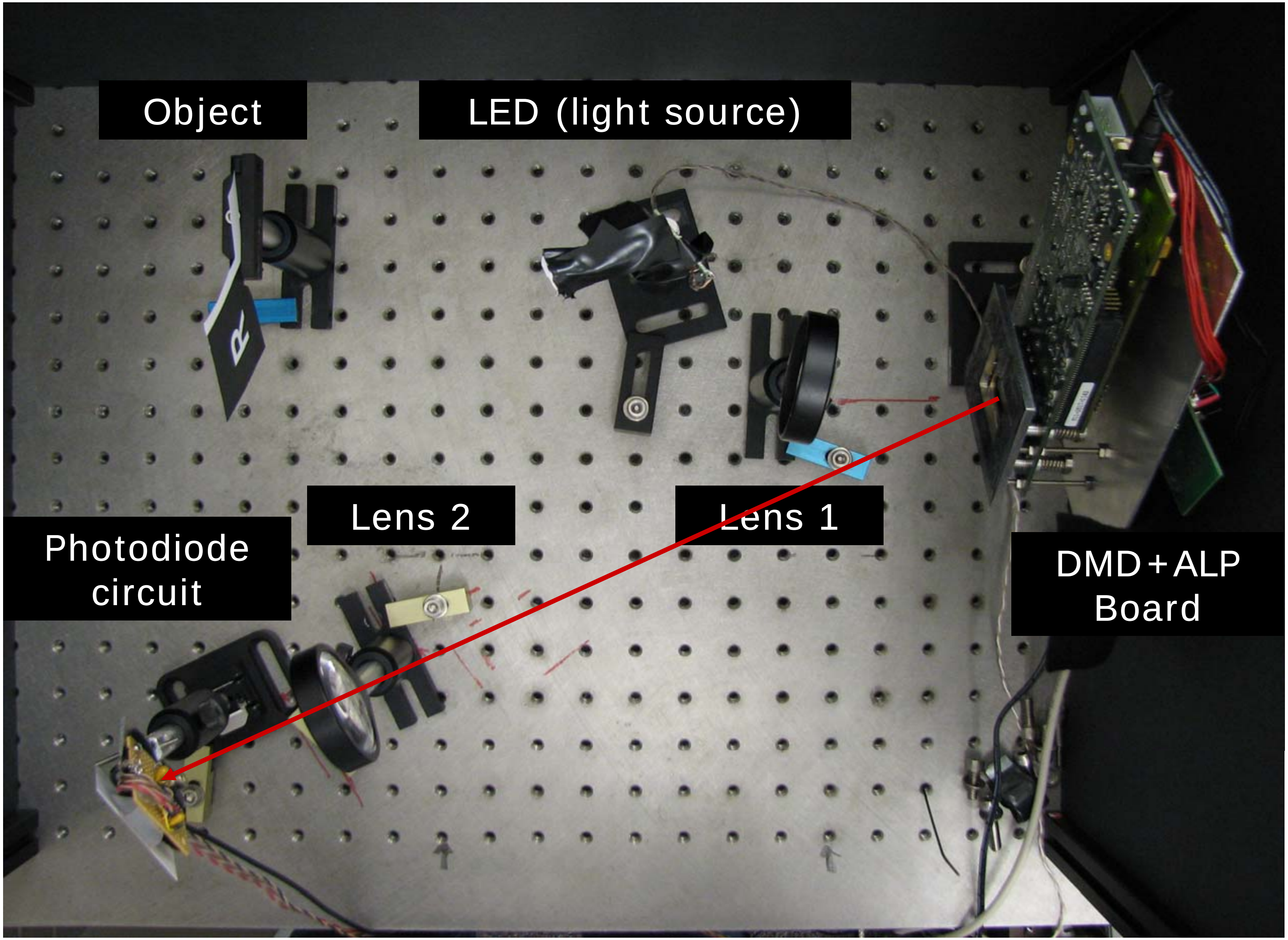
Single Pixel Camera



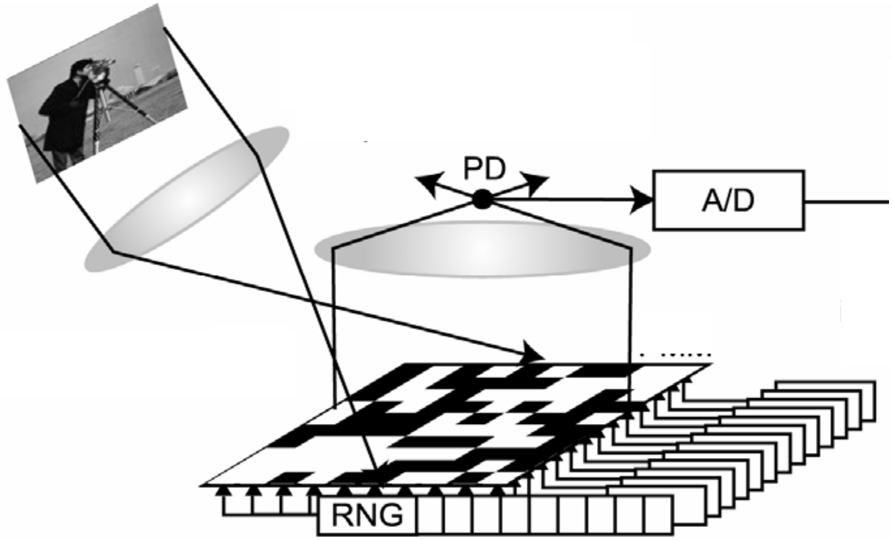
Single Pixel Camera



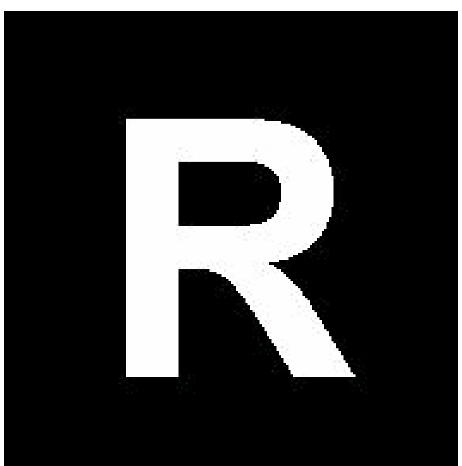
Single Pixel Camera



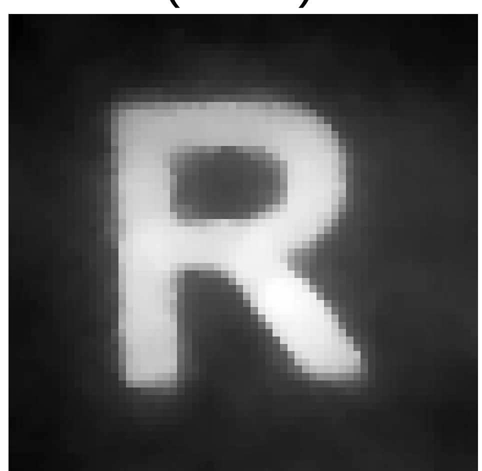
First Image Acquisition



target
65536 pixels



11000 measurements
(16%)



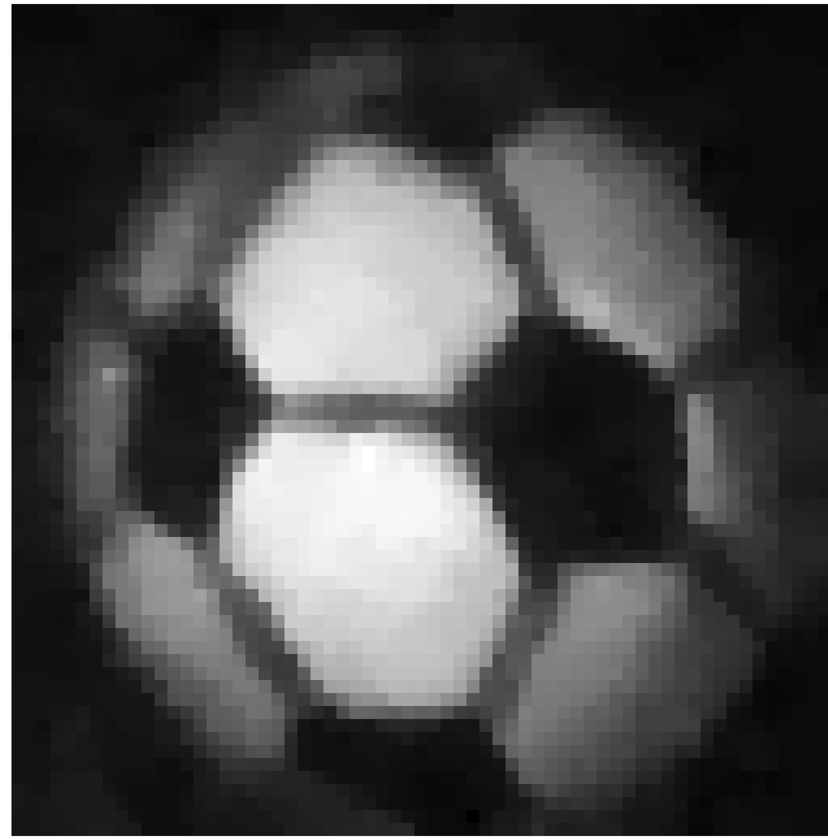
1300 measurements
(2%)

World’s First Photograph

- 1826, Joseph Niepce
- Farm buildings and sky
- 8 hour exposure
- On display at UT-Austin

Second Image Acquisition

4096
pixels

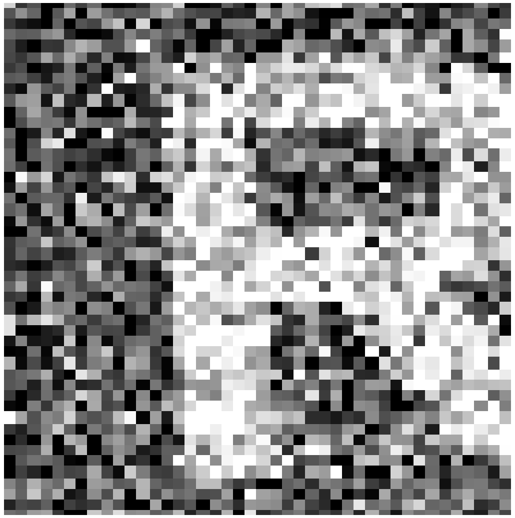


500
random measurements

CS vs. Raster Scan

- Raster scan: $1/N$ of total light per measurement
- CS measurements: ½ of total light per measurement

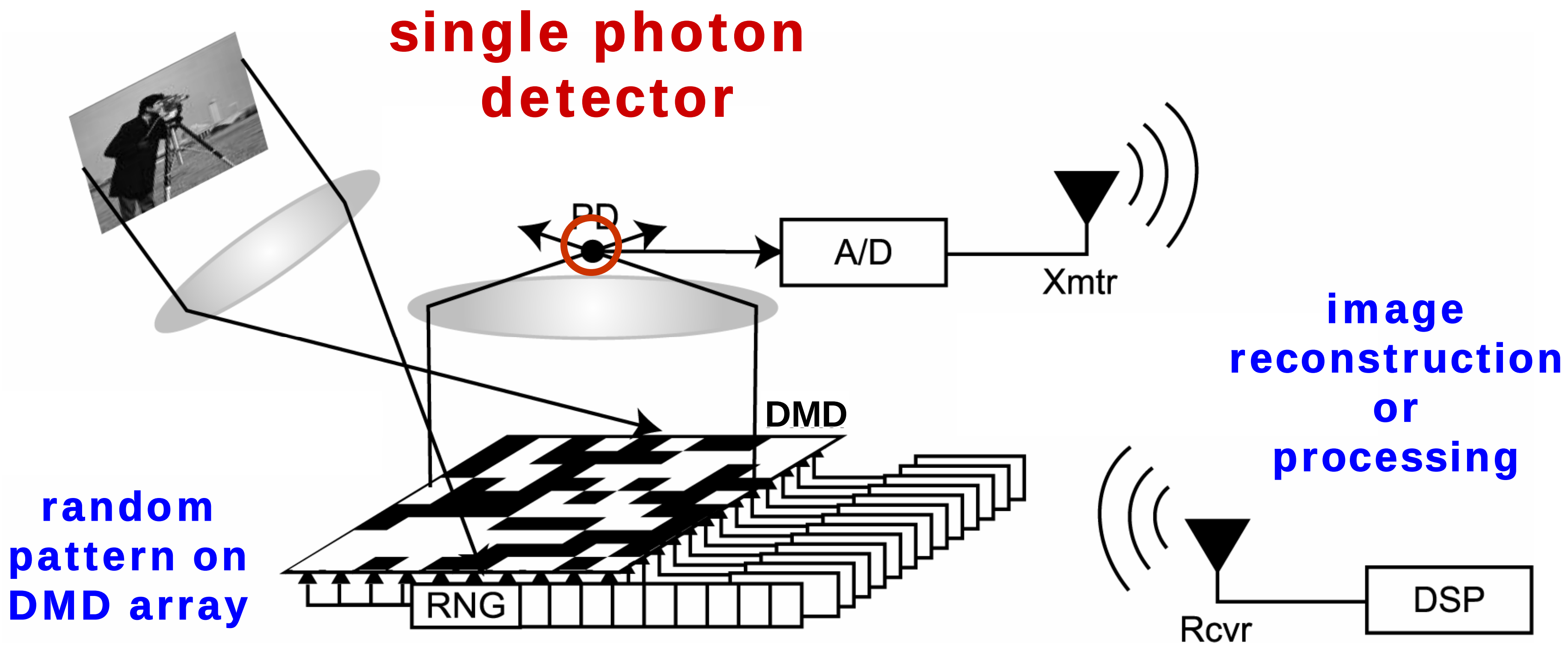
20 measurements/s



64x64 raster
w/ M=4096

64x64 CS
w/ M=2700

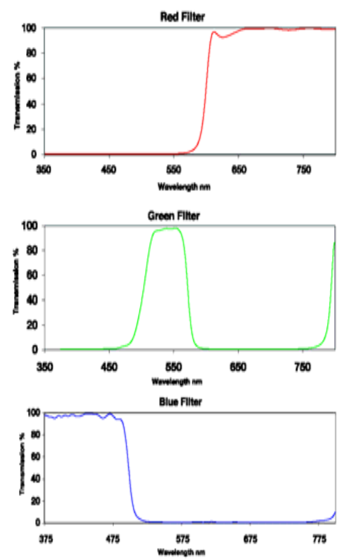
Single-Pixel Camera

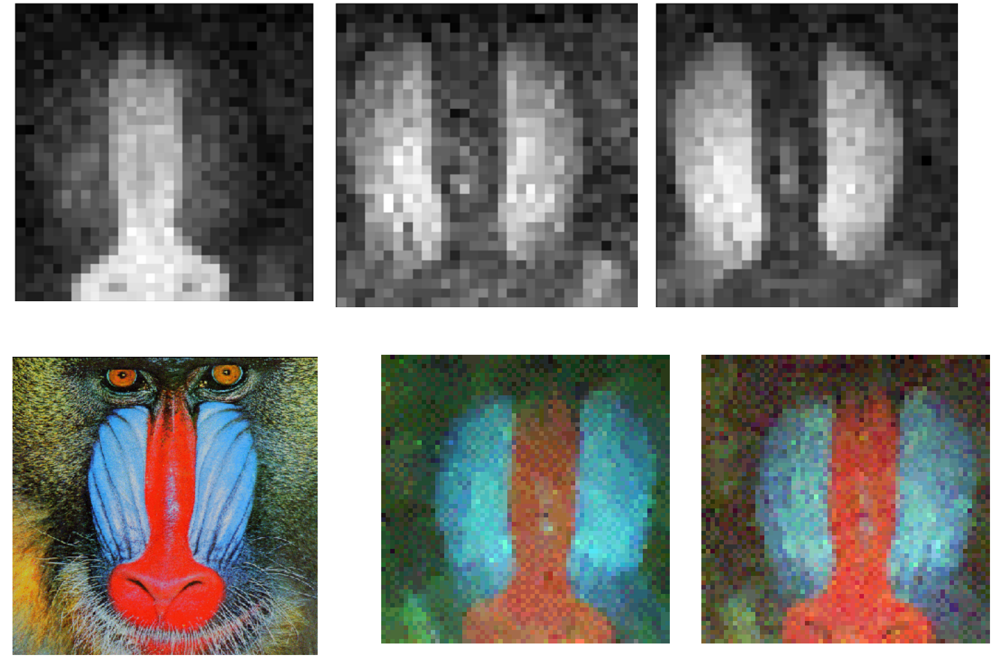


Color Imaging

Merging RGB channels

Color Filter Wheel



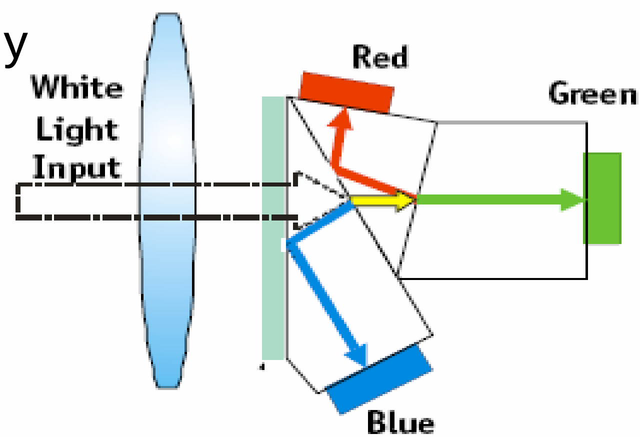


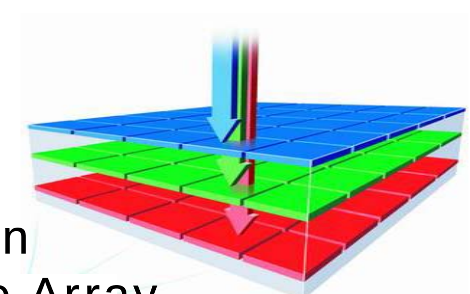
4096 Pixels
800 (20%)
measurements

4096 Pixels
1600 (40%)
measurements

Two strategies:

1. Prism assembly
2. Layered sensors
   (a la Foveon)



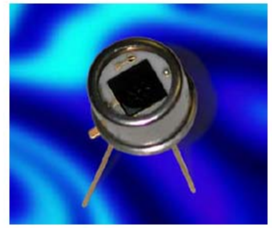


Foveon
Image Array

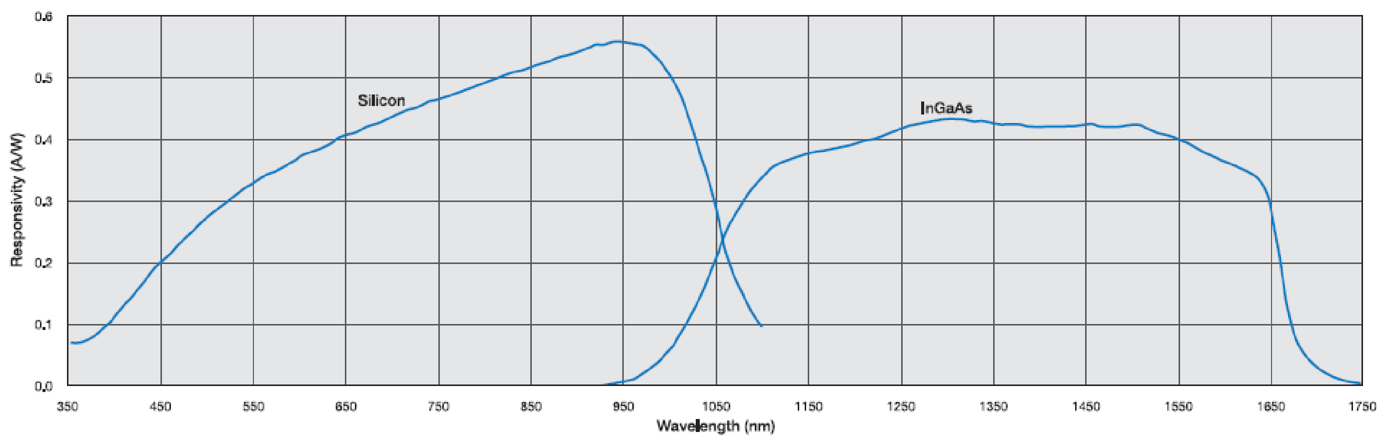
Dual Visible and Infrared Imaging

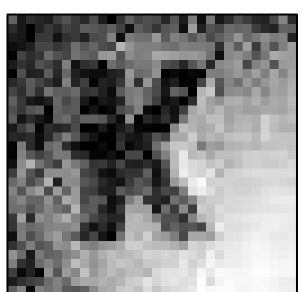
ADVANCED PHOTONIX, INC.®

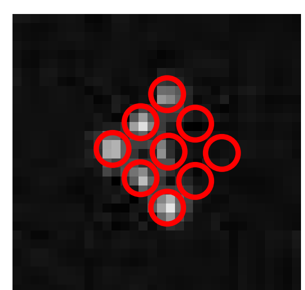
SD138-11-31-211
Silicon PIN Photodiode Sandwich Detector



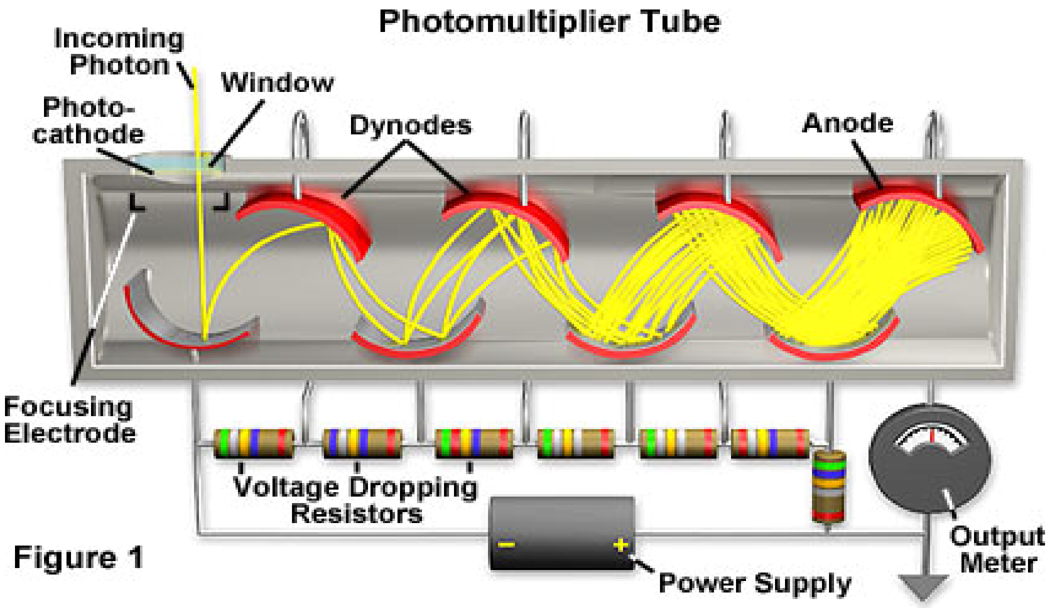
dual photodiode sandwich







CS Low-Light Imaging with PMT



true color low-light imaging

256 x 256 image with 10:1 compression

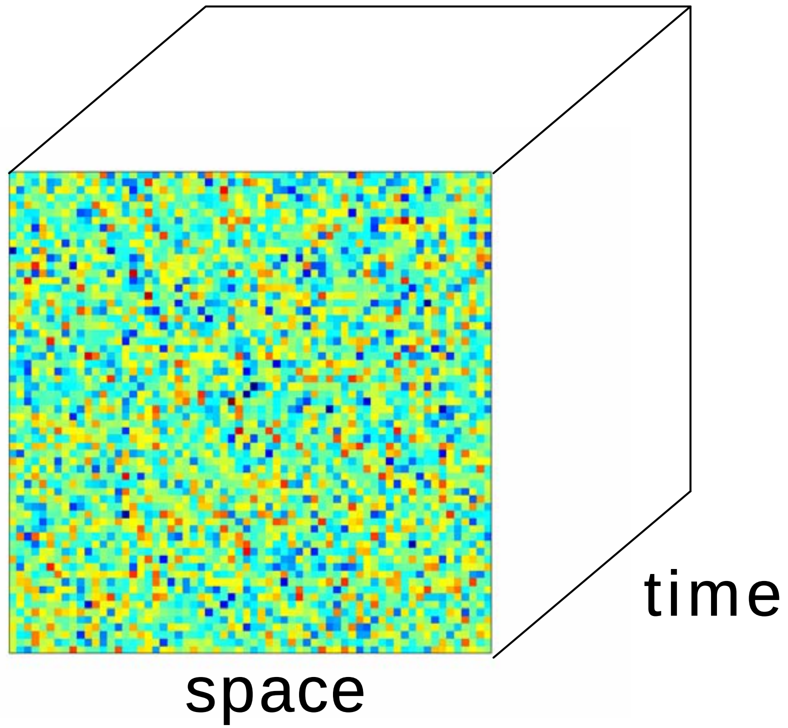
Low-Light Color Imaging w/ PMT

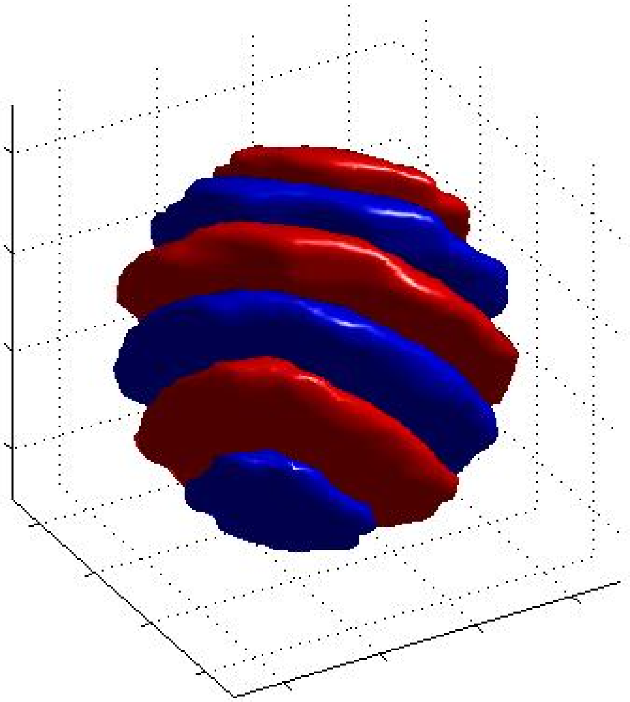
Mandrill 256x256

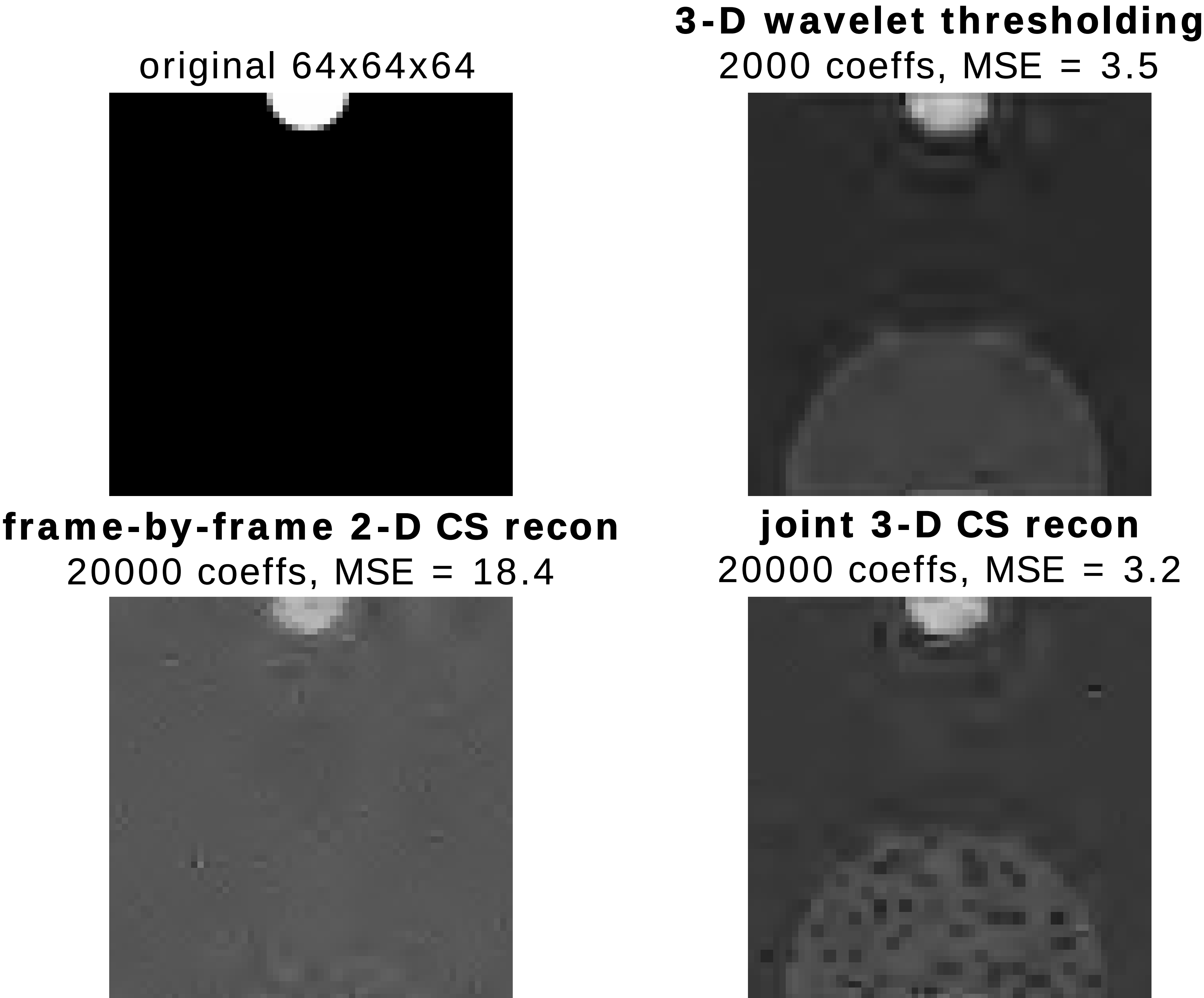
Mandrill 10x sub-Nyquist

CS Video Imaging

- Incoherent projections in space-time (random)
- Reconstruct using 3-D wavelets (localized in space-time)






original 64x64x64
3-D wavelet thresholding
2000 coeffs, MSE = 3.5
frame-by-frame 2-D CS recon
20000 coeffs, MSE = 18.4
joint 3-D CS recon
20000 coeffs, MSE = 3.2

An Attentive Video Camera

- Detect activity from random measurements
- Detection requires far fewer measurements than reconstruction
  - 320x240 pixels x 24 bits/pixel x 20 frames per second
    = **36,864,000 bits per second**
  - *detect activity* from statistics of
    6 CS measurements/second x 4 bits/measurement
    = **24 bits/second**

red = rate throttled back

Slashdot

News for Nerds. Stuff that matters.

Oops, crash, seven million years of bad luck!?!

This is me skydiving

.

This is me swimming with dolphins

.

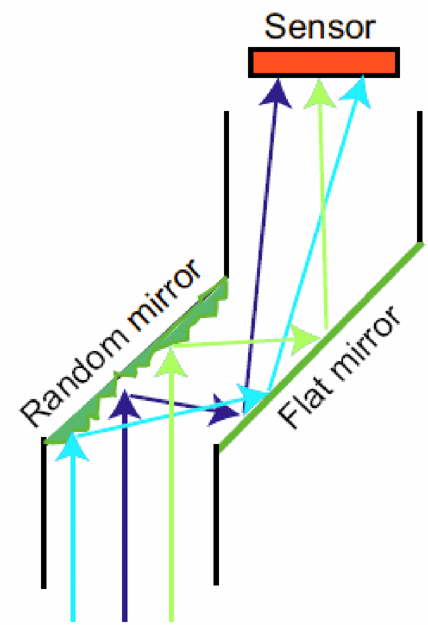
This is me at the grand canyon

.

Other Compressive Sampling Cameras

Random Lens Camera

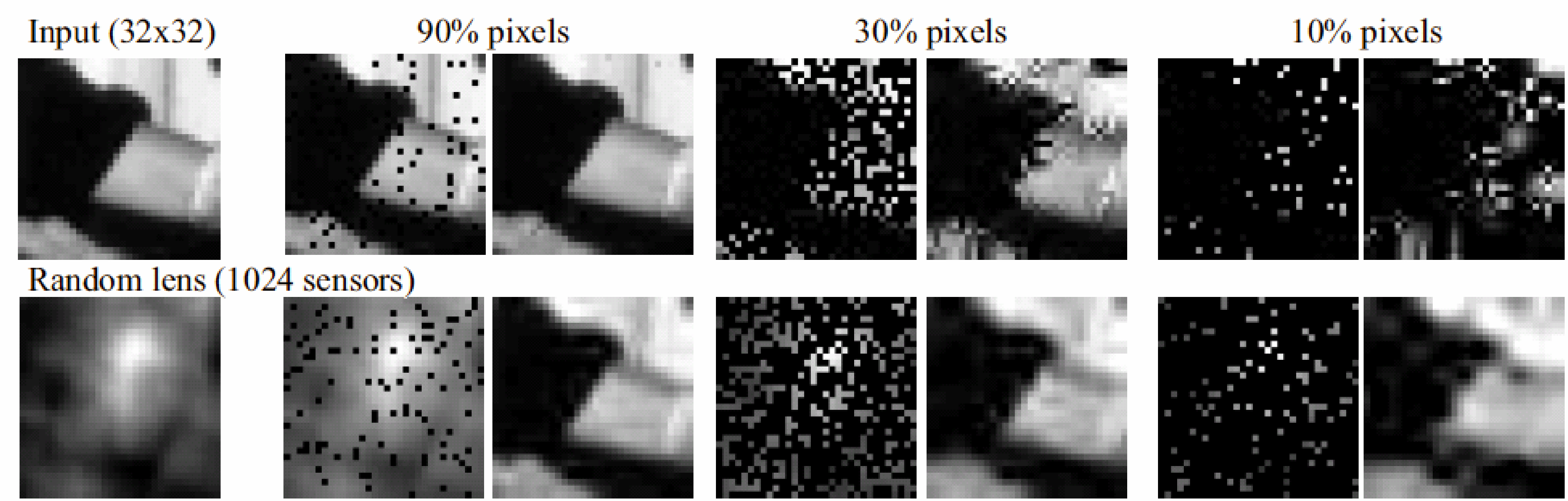
- Computes random sums using random mirror
- Use regular CCD array to acquire many random sums at once
- CS reconstruction



[Rob Fergus, Antonio Torralba, Bill Freeman @ MIT]

CS vs. Super-Res

super-resolution using subset of CCD

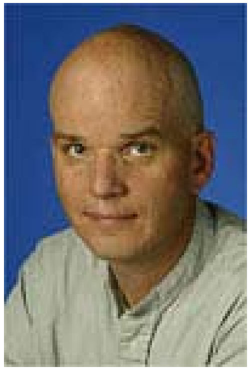


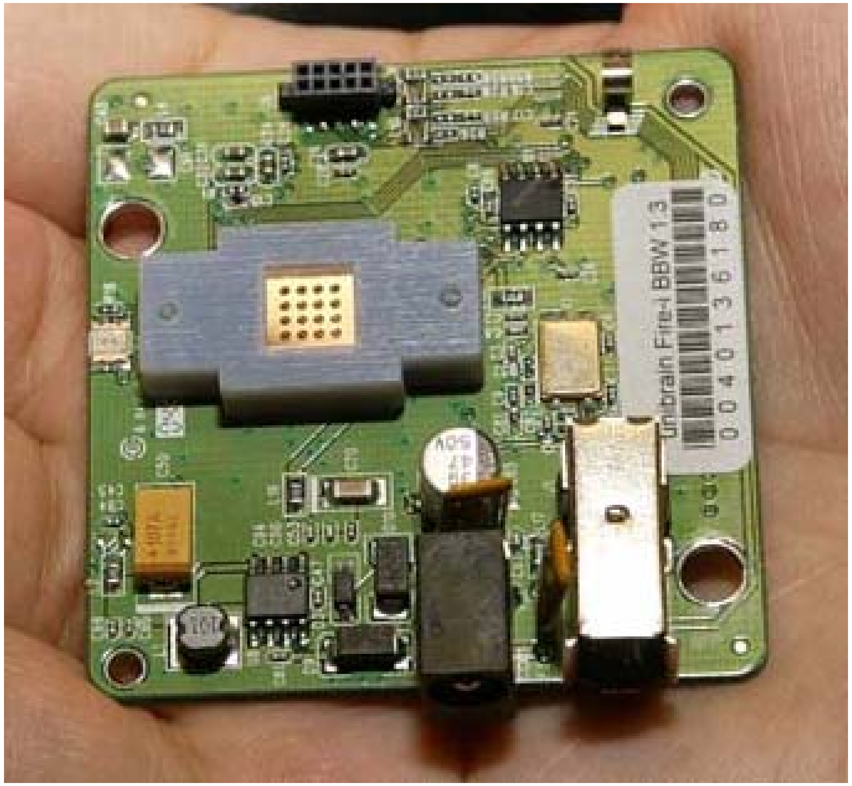
reconstruction using random mirror
and same subset of CCD pixels

[Rob Fergus, Antonio Torralba, Bill Freeman @ MIT]

Thin Cameras

- Dave Brady @ Duke
- Thin cameras < 2.5mm
- Based on coded aperture, lenslets





Summary

- **Compressive sampling camera**
  - exploits image sparsity/compressibility
  - integrates sensing, compression, processing
  - single photon detector enables new modalities

- Near/Medium-term **applications**
  - cameras and imagers where CCDs and CMOS imagers are blind (science, military)
  - security applications (potential for low cost / low power)
  - large camera arrays (compressibility gain with multiple cameras – distributed compressive sensing)
  - advanced algorithms for today's cameras (eg: deblurring)

Some References

- Michael Wakin, Jason Laska, Marco Duarte, Dror Baron, Shriram Sarvotham, Dharmpal Takhar, Kevin Kelly, and Richard Baraniuk, “Compressive Imaging for Video Representation and Coding,” Proc. Picture Coding Symposium — PCS 2006, Beijing, China, Apr. 2006.

- Dharmpal Takhar, Jason Laska, Michael Wakin, Marco Duarte, Dror Baron, Shriram Sarvotham, Kevin Kelly and Richard Baraniuk, “A New Compressive Imaging Camera Architecture using Optical-Domain Compression,” Proc. of Computational Imaging IV at SPIE Electronic Imaging, San Jose, CA, Jan. 2006.

for more, see **dsp.rice.edu/cs**