SIGGRAPH2008

Computational Photography: Advanced Topics

Paul Debevec
Ramesh Raskar
Jack Tumblin

Class: Computational Photography, Advanced Topics

Debevec, Raskar and Tumblin

Module 1: 105 minutes

1:45:	A.1	Introduction and Overview	(Raskar, 15 minutes)
2:00:	A.2	Concepts in Computational Photography	(Tumblin, 15 minutes)
2:15:	A.3	Optics: Computable Extensions	(Raskar, 30 minutes)
2:45:	A.4	Sensor Innovations	(Tumblin, 30 minutes)
3:15:	Q & A		(15 minutes)

3:30: Break: 15 minutes

Module 2: 105 minutes

3:45:	B.1	Illumination As Computing	(Debevec, 25 minutes)
4:10:	B.2	Scene and Performance Capture	(Debevec, 20 minutes)
4:30:	B.3	Image Aggregation & Sensible Extensions	(Tumblin, 20 minutes)
4:50:	B.4	Community and Social Impact	(Raskar, 20 minutes)
5:10:	B.4	Panel discussion	(All, 20 minutes)

Class Page : http://ComputationalPhotography.org

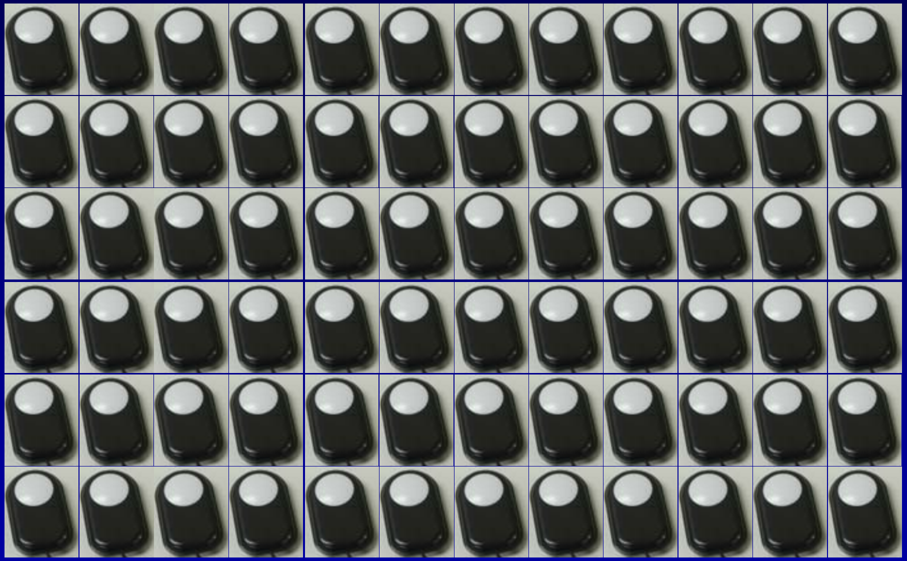
Computational Photography: Advanced Topics

A4: Sensor Innovations
(30 minutes)

Jack Tumblin

Northwestern University

Film-Like Sensor: Array of Light Meters



Film-like Goals:

- ***Instantaneous*** measurement
- ***Infinite*** resolution; arc-min, λ
- ***Infinite*** sensitivity, Dyn. Range
- ***Zero*** noise visible

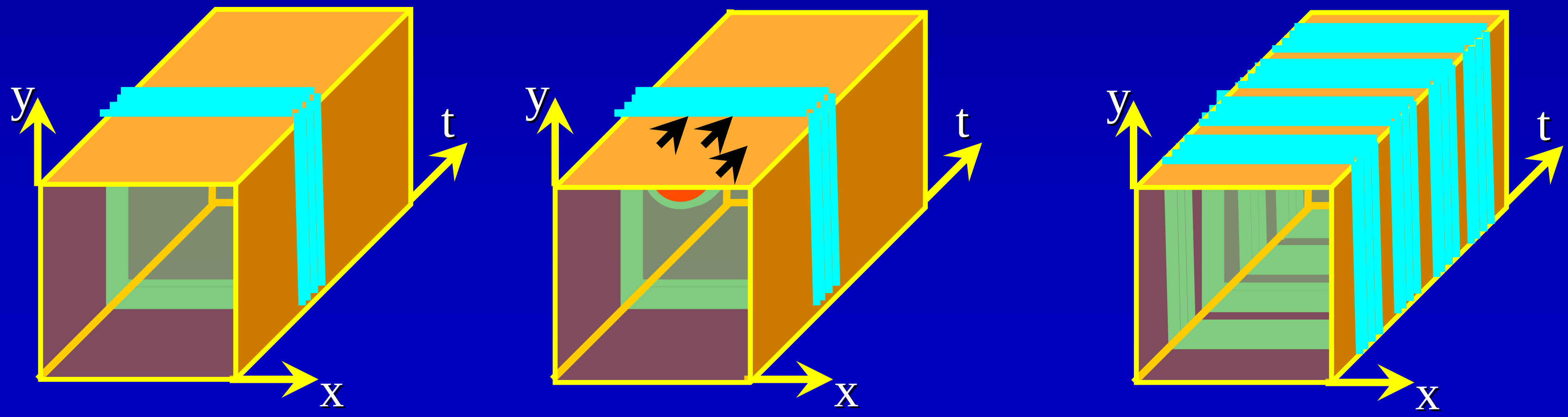
Film-Like Photo: Photon Arrival Record

- Snapshot: ‘flattened’ volume of space time
- More volume→ more photons→ “less noise”
- Movie: Repeated snapshots

Ordinary Snapshot

Snapshot with Motion-Blur

‘Motion Picture’ (missing time!)



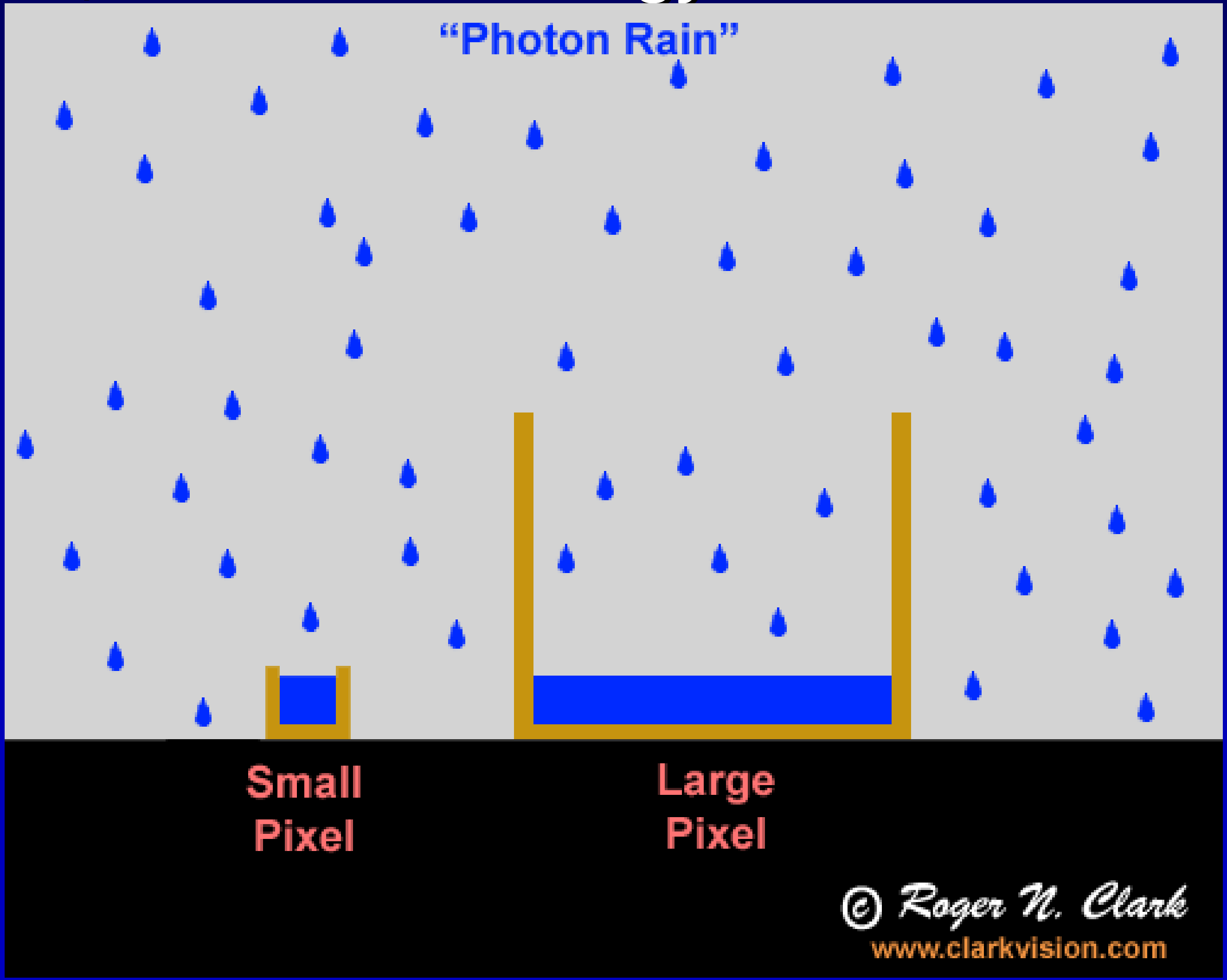
6 Megapixel 3µm Always Best?

http://www.6mpixel.org/en/

- Independent Lab & Photo Enthusiasts site:
  "The more pixels, the worse the image!"

Noise In Camera Systems

accurate, beautiful analogy:



Sensor Noise Sources

- Quantum Noise: ‘Photon Rain’ (signal dependent)
- Thermal-dependent noise in semiconductors:
  Schott (‘shot’) noise (electron-hole pairs)
  Imperfect materials; insulator flaws
  (temp, voltage, current dependent)
- Thermal-dependent noise in electronics:
  insulator leakage, phonon effects
  (temp dependent)
- RFI/EMI noise in electronics: ‘crosstalk’
  (signal dependent)

Good tutorial: http://www.ph.tn.tudelft.nl/Courses/FIP/noframes/fip-Photon.html

Sensor Noise Sources

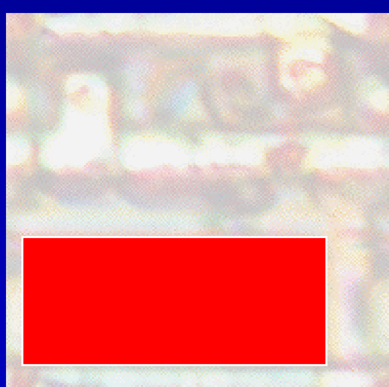
- Quantum Noise: 'Photon Rain' (si… …nt)
- Thermal-dependent nois… …rs:
  - Schott ('shot') noi…
  - Imperfec…
  - …dependent)
- T… …electronics:
  - …phonon effects
  - (temp dependent)
- R… …oise in electronics: 'crosstalk'
  - (signal dependent)

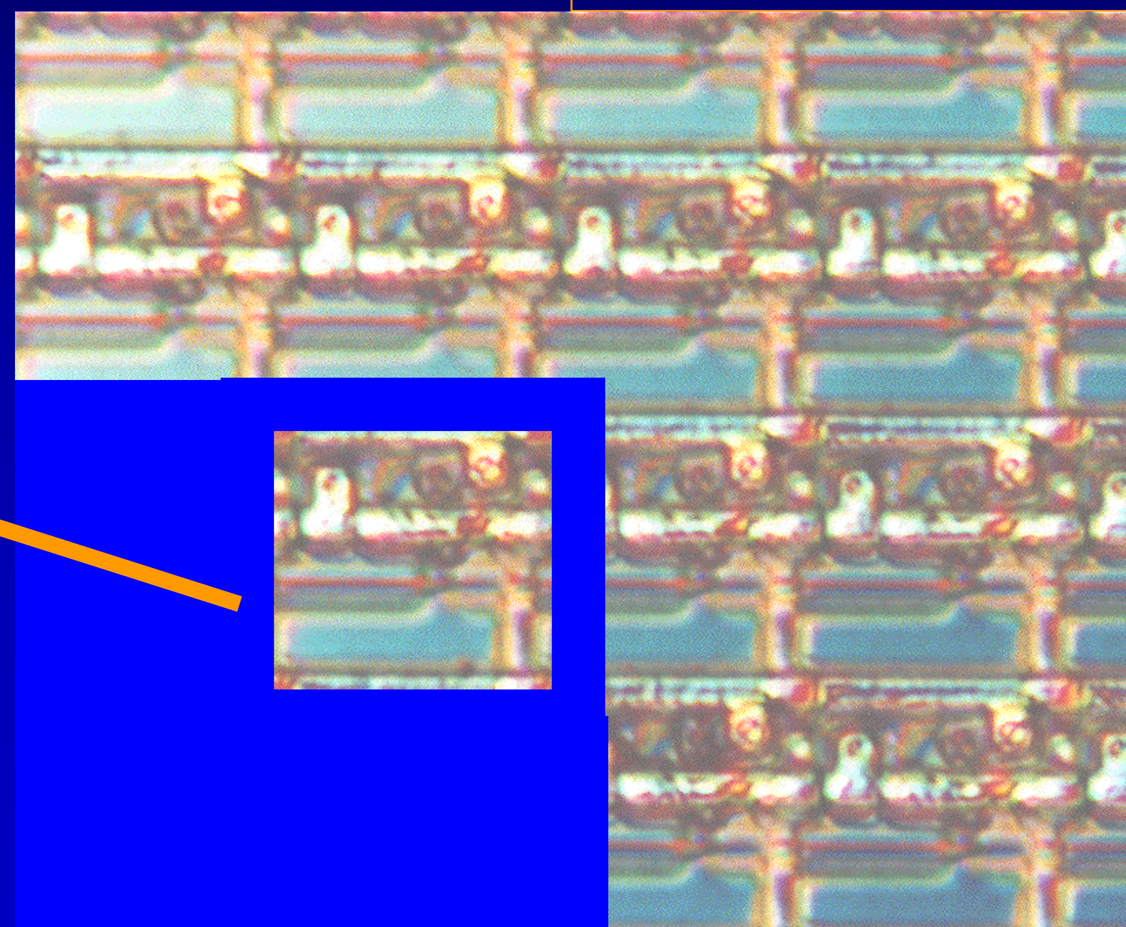
"Additive (fixed-strength) vs. Signal Dependent"

Fill Factor

- (Sensing Area / total Area)%age
- Interconnects, readout transistors
- As low as 20-30%
- Micro-Lenses help

Aptnia (Micron Technologies)

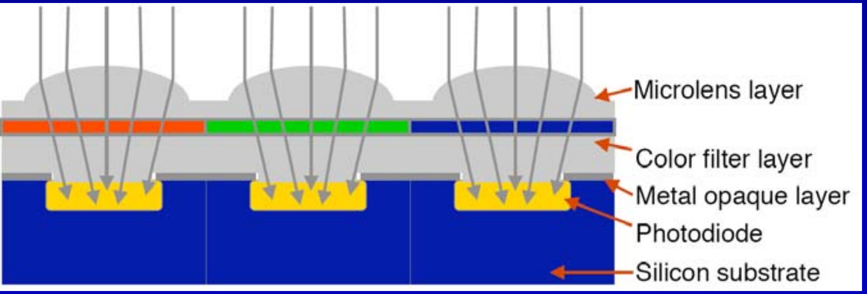


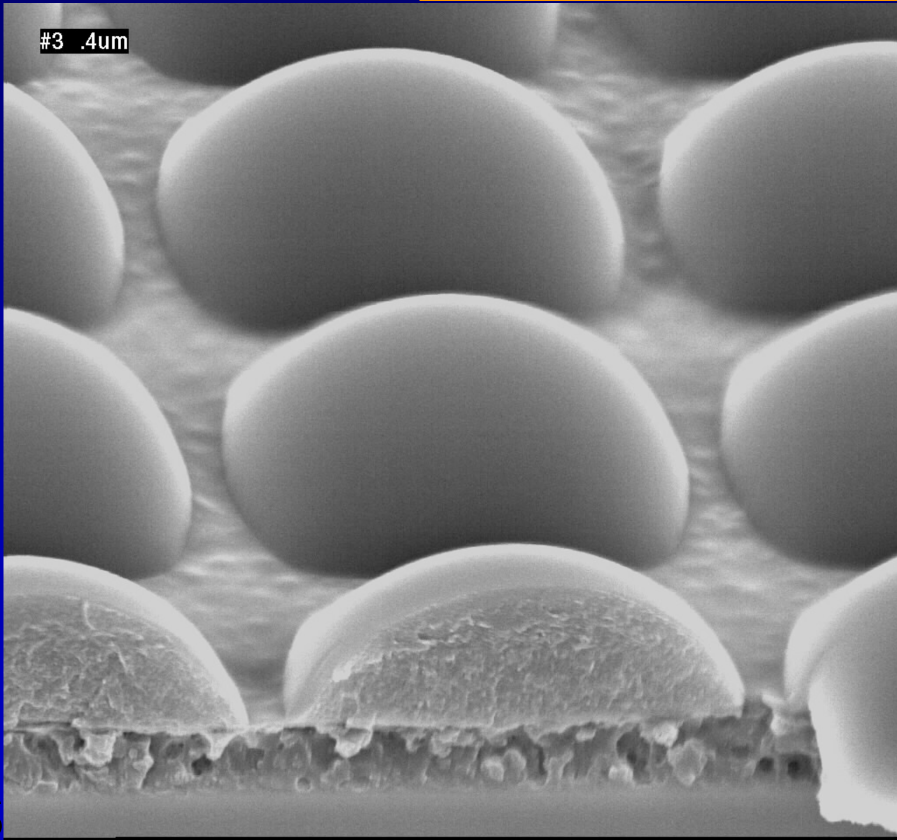


Light-Gathering Microlenses

- Counteracts low fill-factor
- Improved light gathering
- Less Aliasing

Micron Technologies, Inc



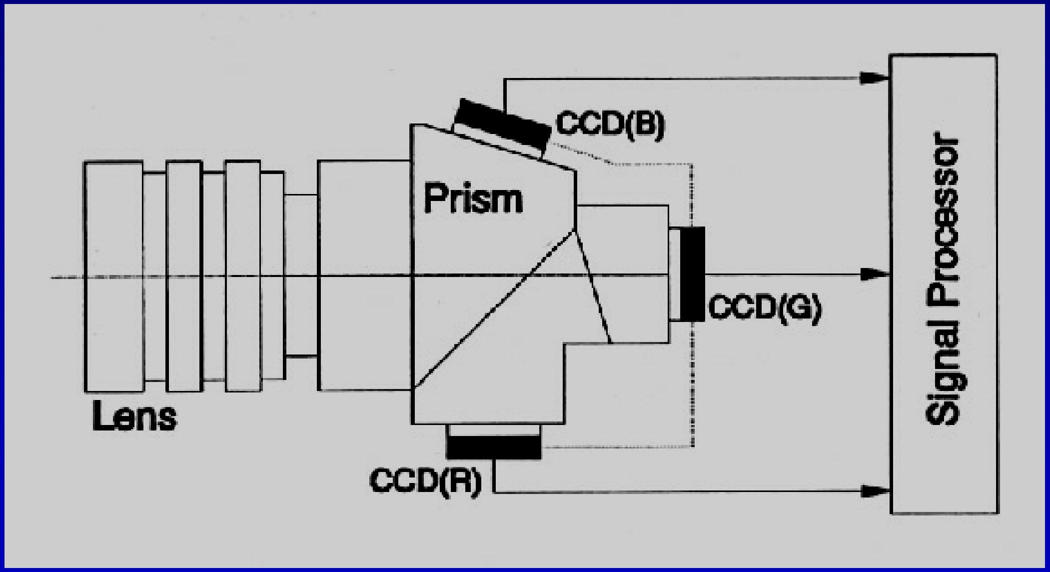


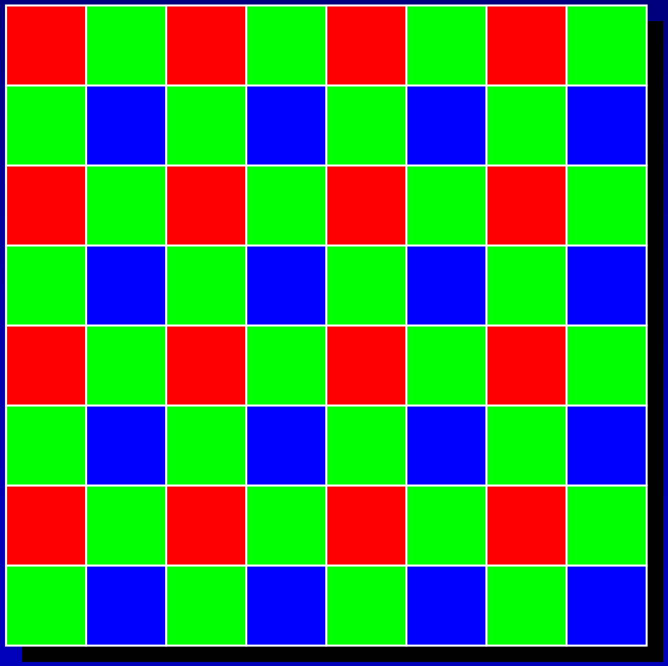
- Suitable for color filters

FAB4Y

Color Sensing

- 3-chip: vs. 1-chip: quality vs. cost



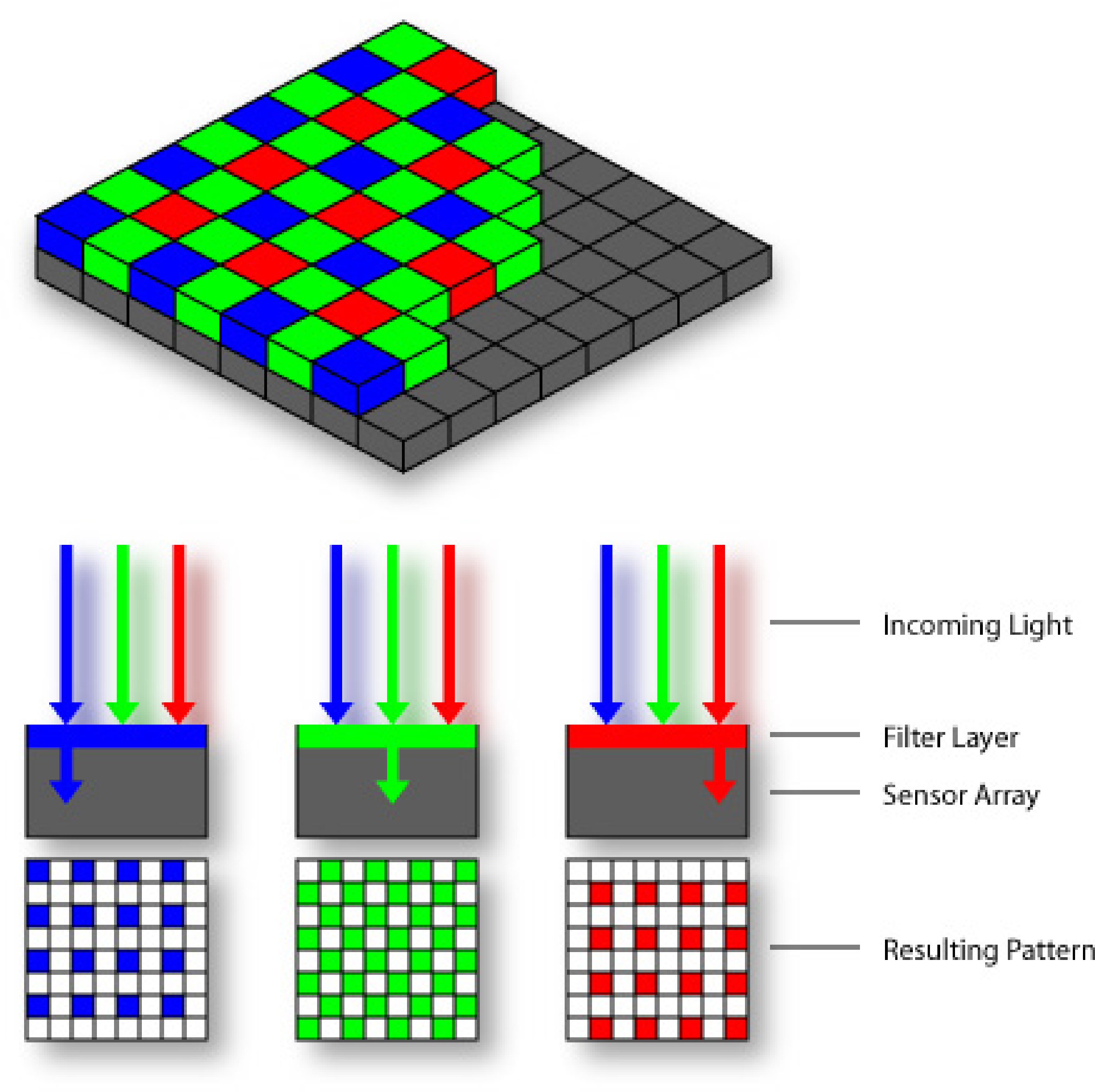


http://www.cooldictionary.com/words/Bayer-filter.wikipedia

1-Chip Color Sensing: Bayer Grid, De-Mosaicing

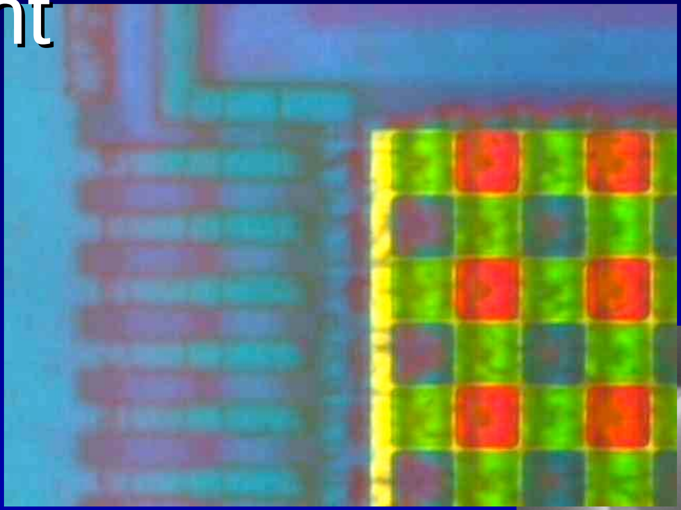
- Estimate RGB at ‘G’ cels from neighboring values

http://www.cooldictionary.com/words/Bayer-filter.wikipedia

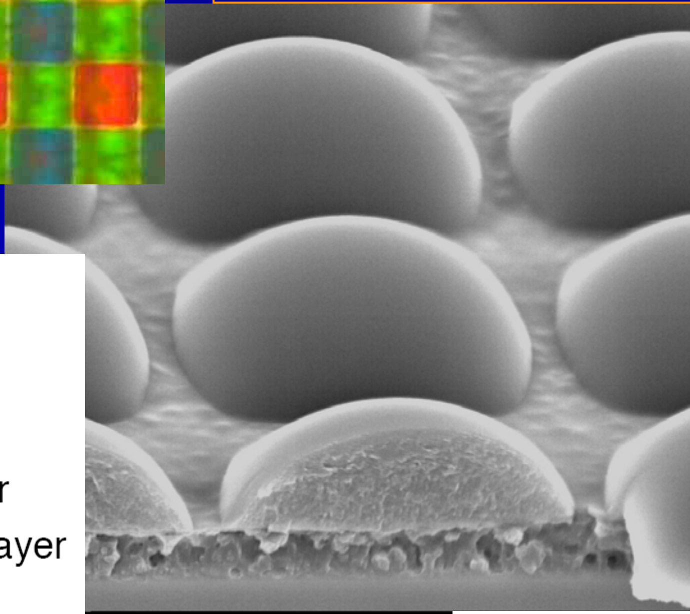


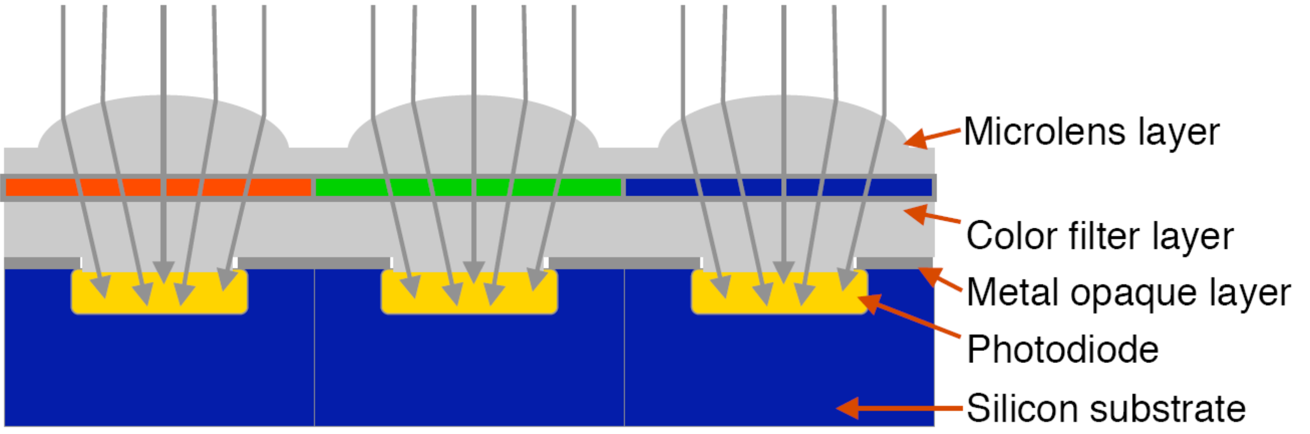
Microlenses + Color Filters

- Improved light gathering
- Fixed Alignment
- Less Aliasing



Micron Technologies, Inc





Backside Illumination

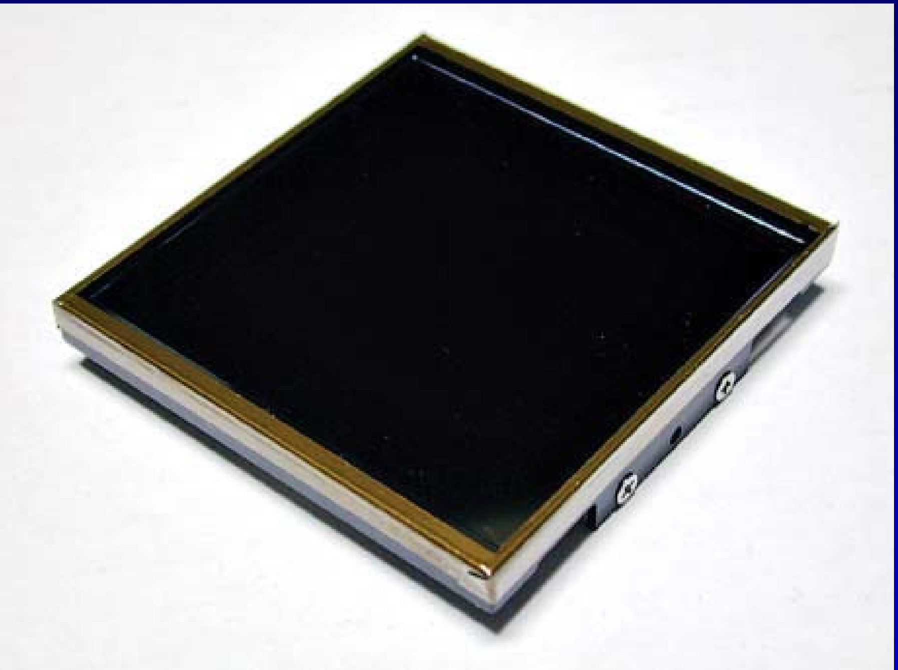
Advantages:

- Better fill-factor → larger pixel sensors
- Less-cramped circuitry (more of it?)
- Seamless Surface → less glare, aliasing

Difficulties:

- Fragile: tough to create, mount, connect
- Opacity, Noise, sub-surface scatter

Back-Illuminated CCD



Started ~2000 (micron tech),

Now High-Performance

Fairchild 4k x 4k CCD486:

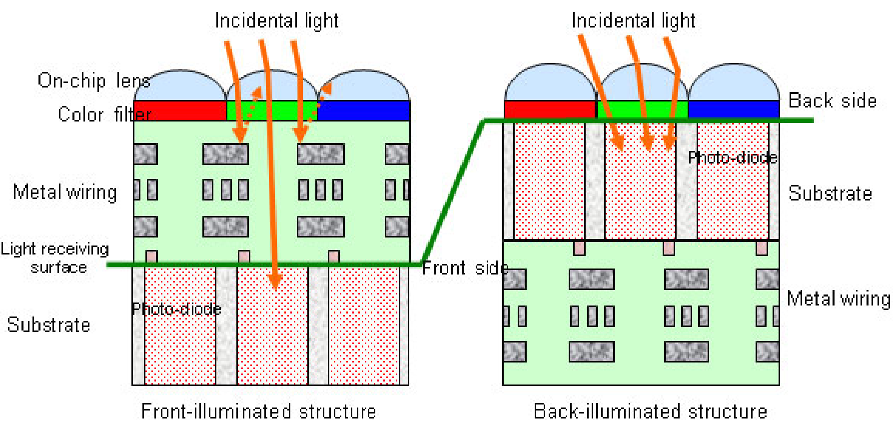
- Thinned to 18microns
  + anti-reflective coating
- 100% fill factor, 15um pixels,
- 61.4 x 61.4mm sensor area

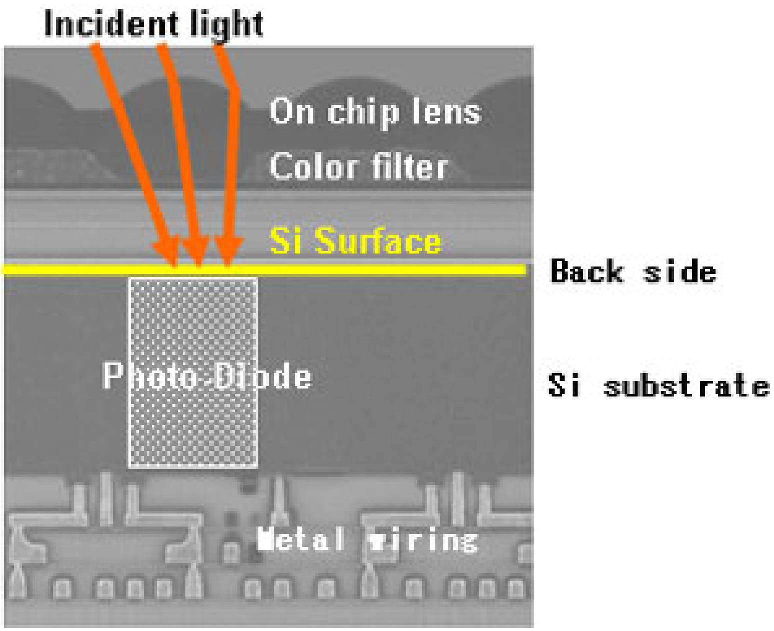
Back OR Front illumination

Practical Back-Illuminated CMOS

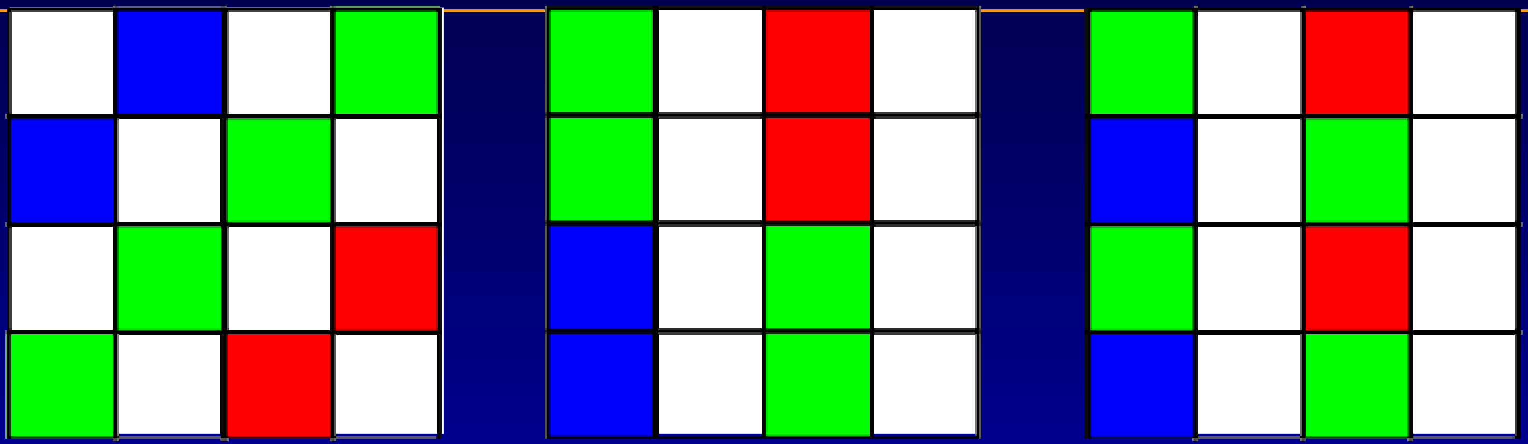
- Difficult 'Thinning' --bulk substrate removal
- Promising preliminary results: 1.75µm pixels now → 0.9 µm expected
- (+6dB) sensitivity (~2x)
- (-2db) noise

Sony Corp. Prototype





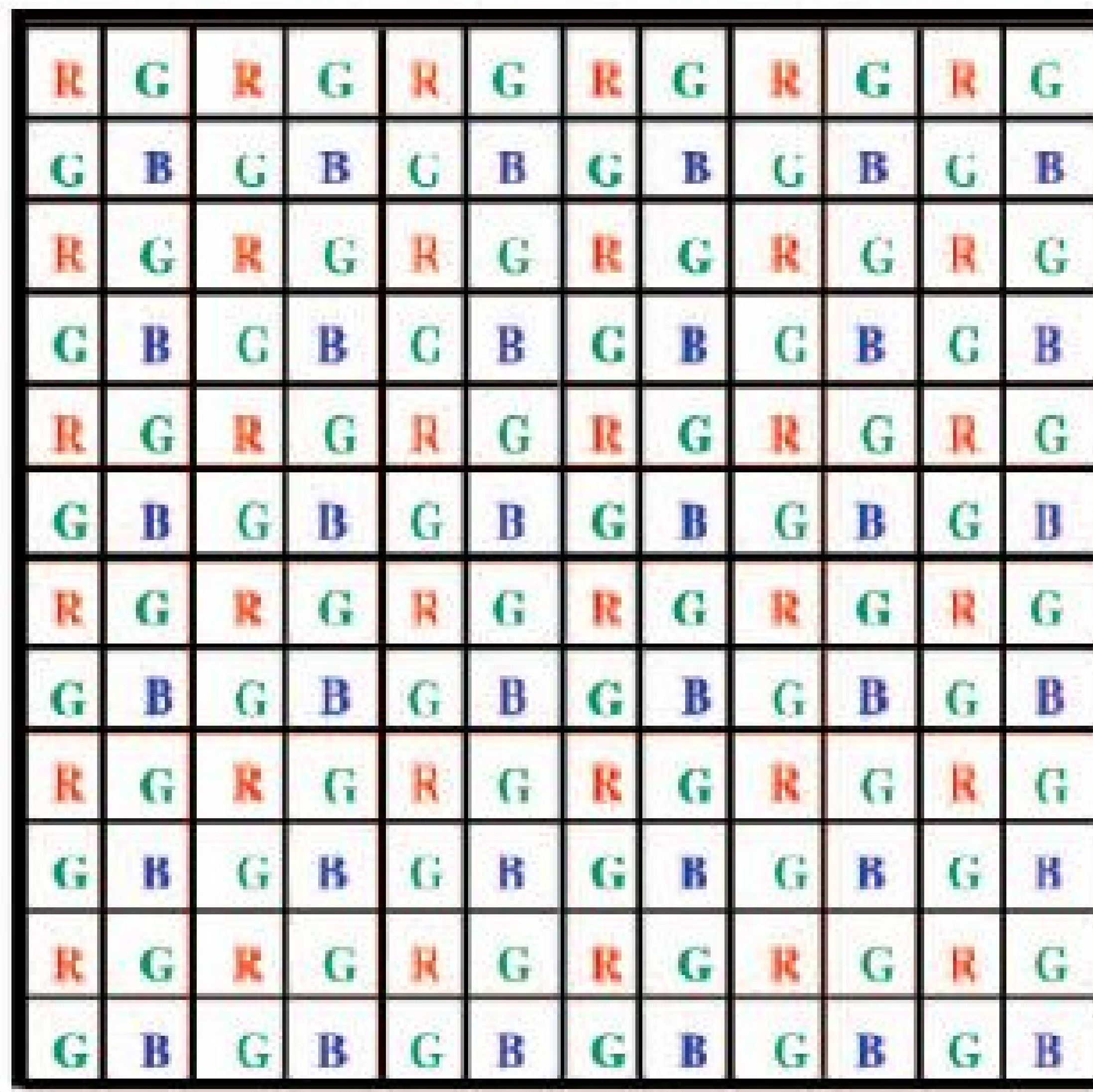
Color Estimation: RGBW Method



- 2007: Kodak ‘Panchromatic’ Pixels
- Outperforms Bayer Grid
  - 2X-4X sensitivity (W: no filter loss)
  - May improve dynamic range (W >> RGB sensitivity)
  - Colorimetry: Direct luminance, not computed
- Drawbacks? de-mosaicing more difficult; earlier 4-color systems (JVC: CMYW, Canon: CMGY) earned shrugs

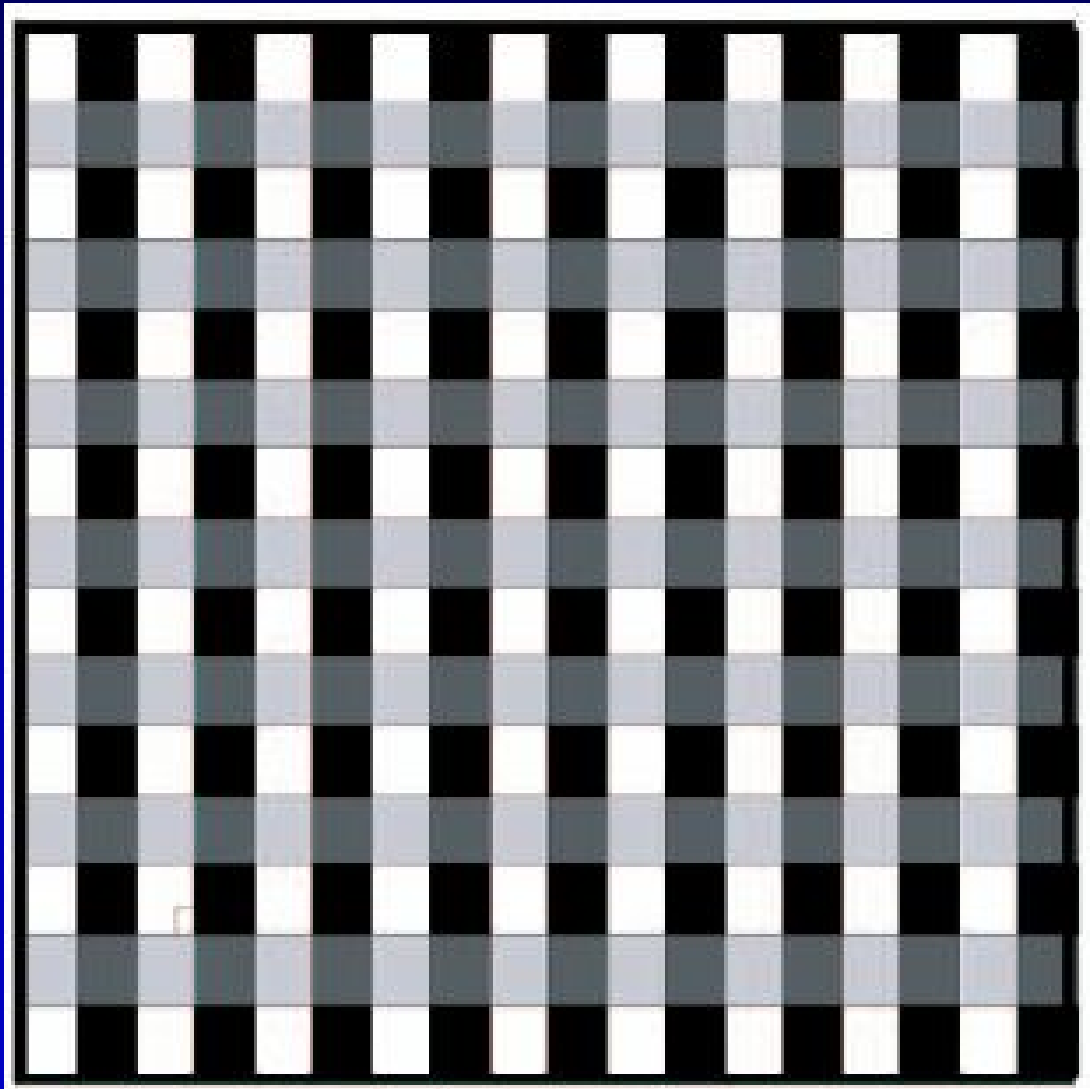
Assorted Pixels (Nayar et al.)

- Color mosaic:



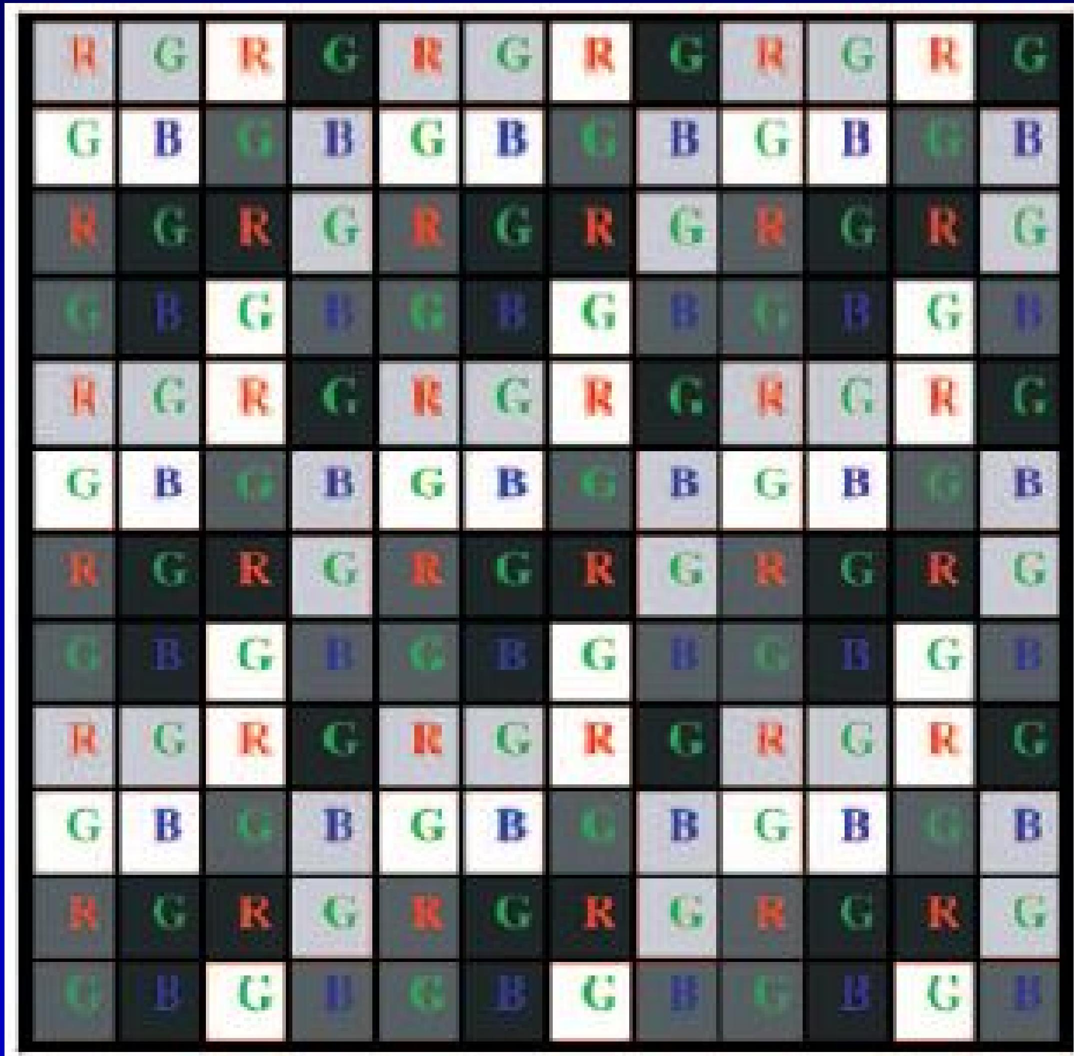
Assorted Pixels (Nayar et al.)

- Intensity mosaic:



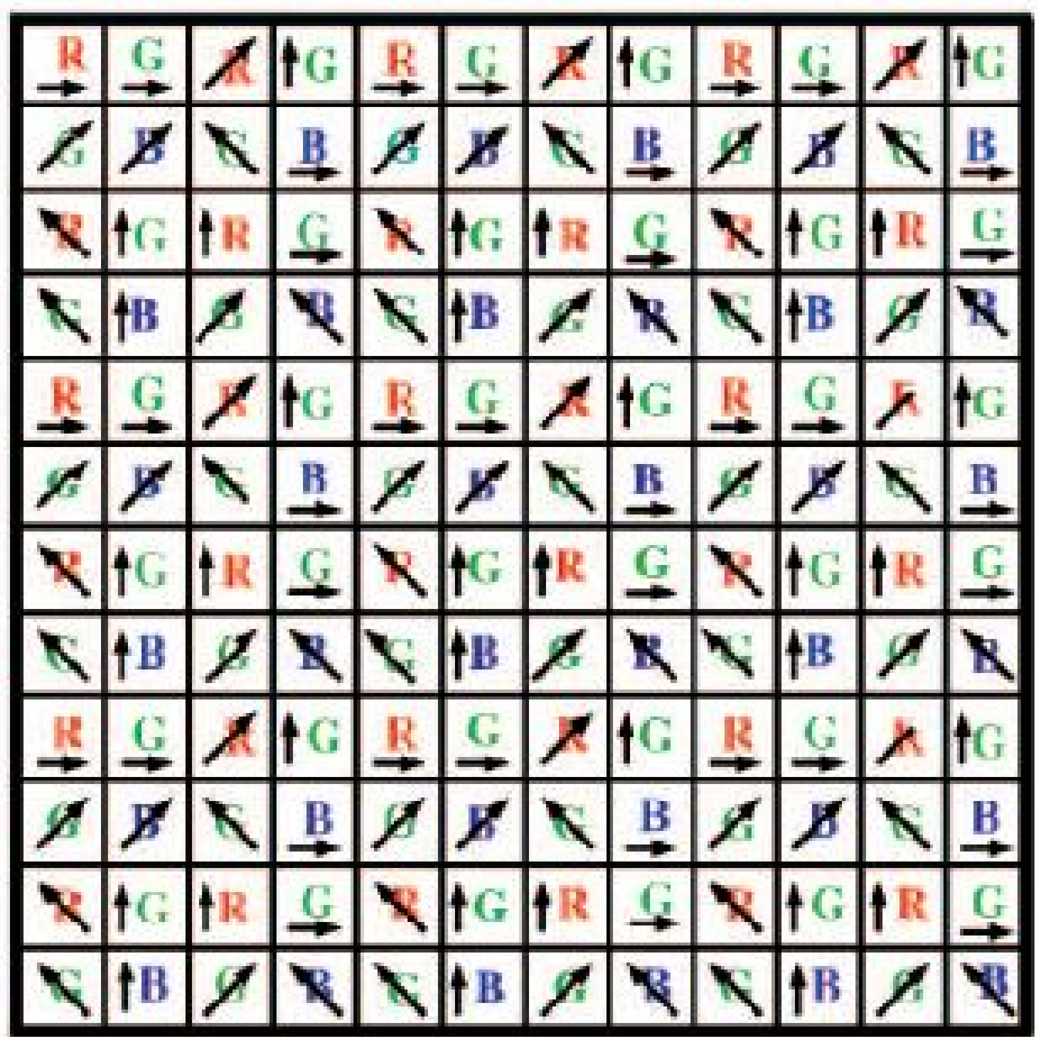
Assorted Pixels (Nayar et al.)

- Intensity-and-color mosaic:



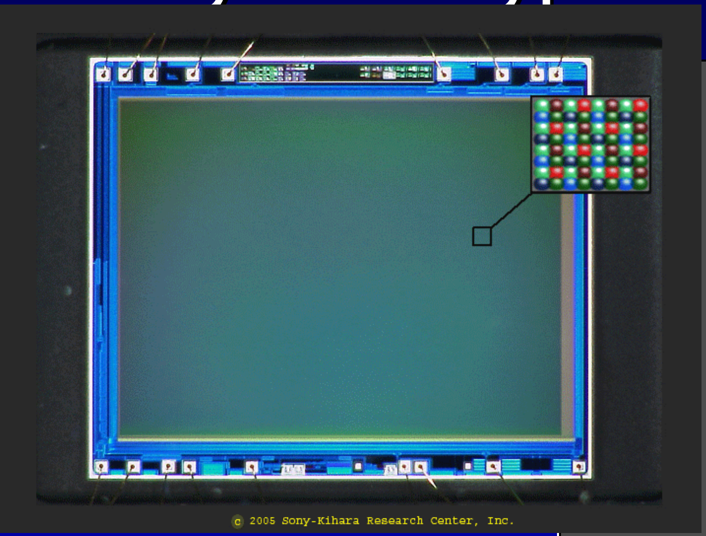
Assorted Pixels (Nayar et al.)

- Intensity-and-color-and-polarization mosaic:
- Other dimensions:
  - IR? UV?
  - Temporal? (frameless rendering)
  - Viewpoint? (camera arrays, epipolar imaging)



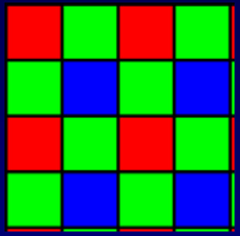
Assorted Pixels (Nayar et al.)

Sony Prototype…



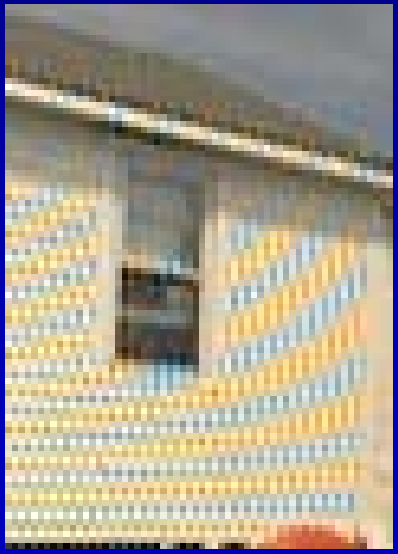
Demosaicking Difficulties

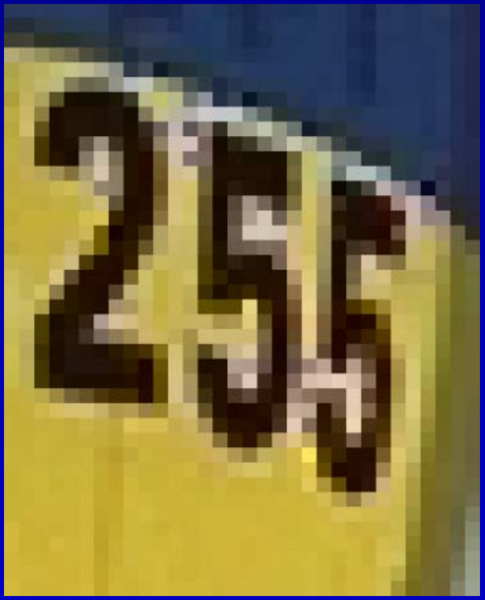
- Under-sampling, esp. in red, blue → Loss of detail, aliasing, zippering:



- Many good methods, no perfect answer

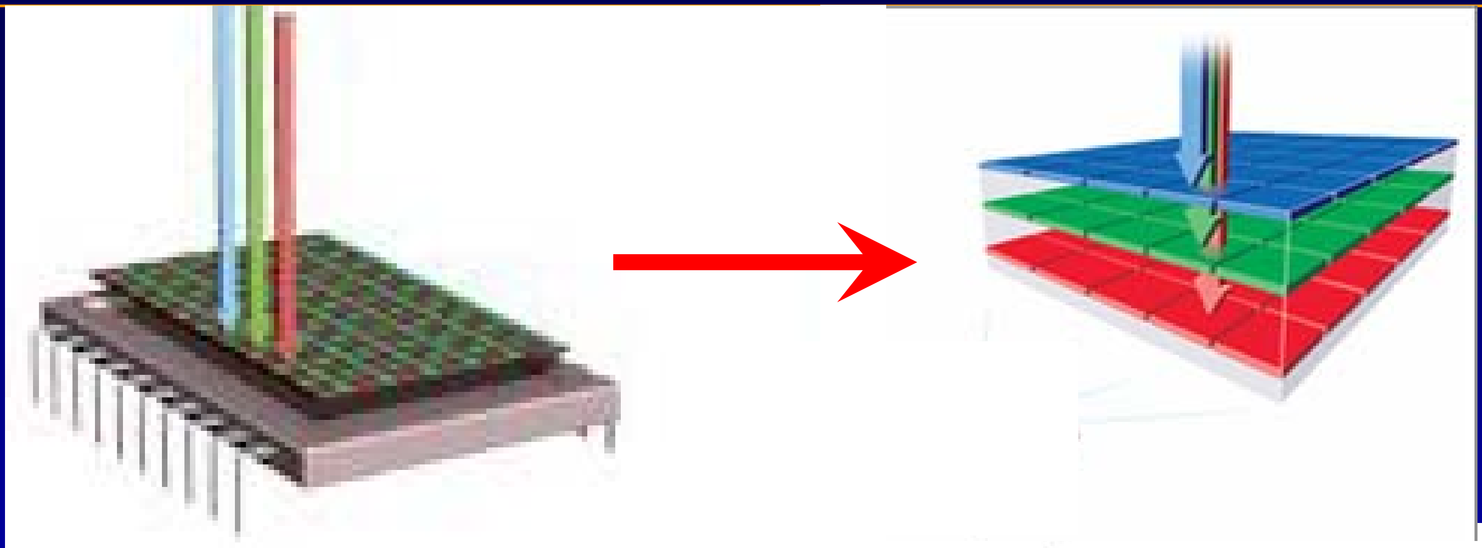
"Demosaicing by Smoothing along 1D Features", Ajdin et al., CVPR 2008



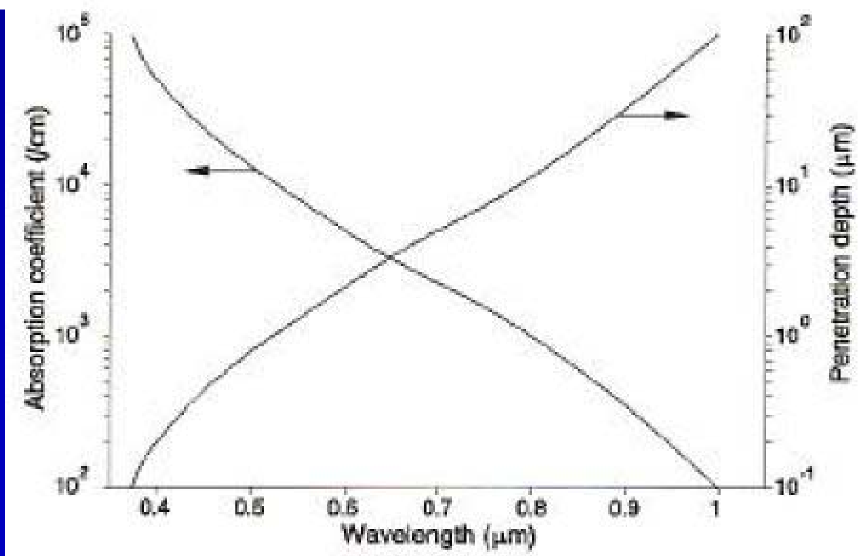


http://scien.stanford.edu/class/psych221/projects/07/Dargahi&Deshpande.pdf

FOVEON Sensor



- Multi-layer sensor, no color filter mosaic
- Senses wavelength by absorption depth

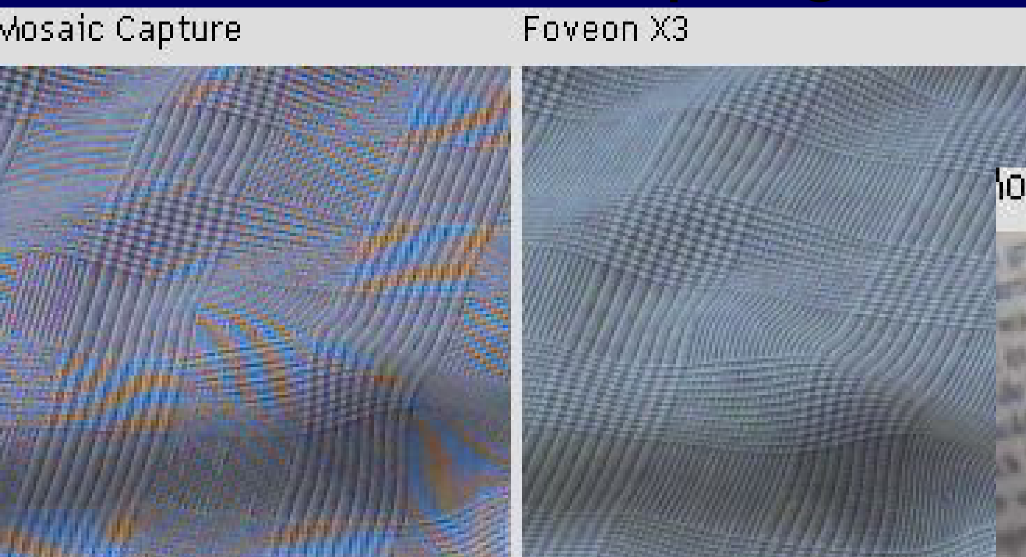


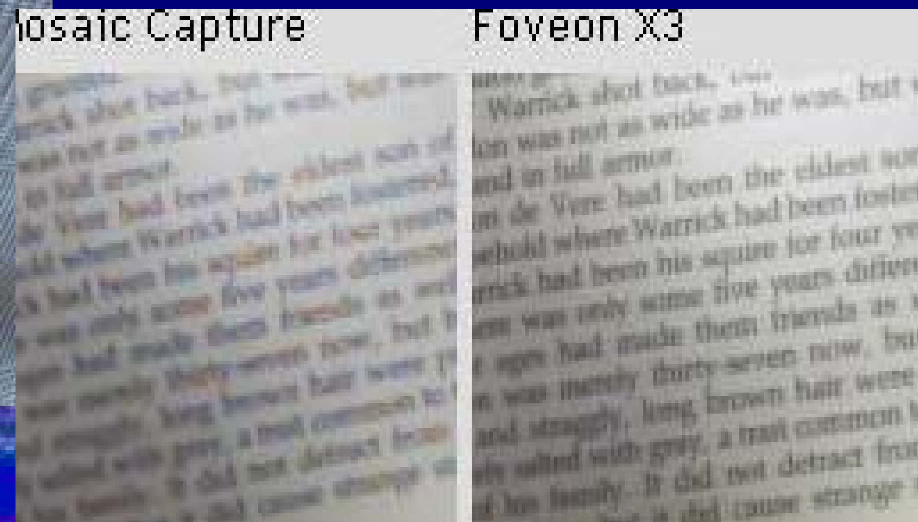
http://www.foveon.com/files/CIC13_Hubel_Final.pdf

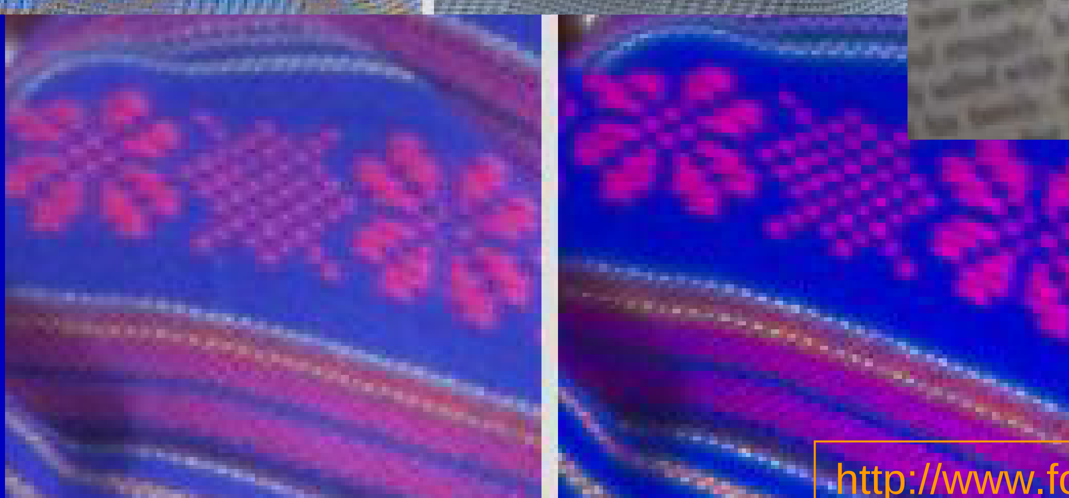
FOVEON Sensor

- No under-sampling for any color,

No de-mosaicking





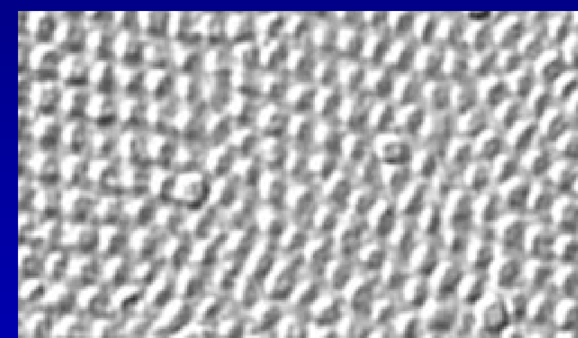


http://www.foveon.com/files/CIC13_Hubel_Final.pdf

Hyper-Acuity Hints & SuperResolution

Human Eye:

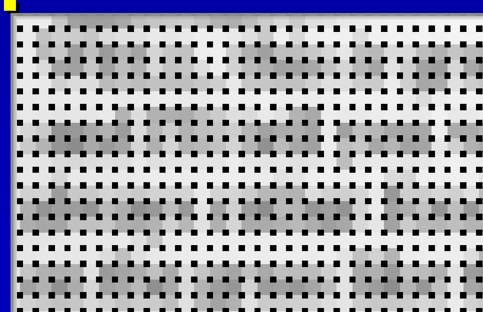
- Foveal receptors: 2.5 μm, ~28 arc-sec (Curcio et al, 1990)
- “Hyper-Acuity” can detect ~1arc-sec displacement
- Ocular tremor contributes…



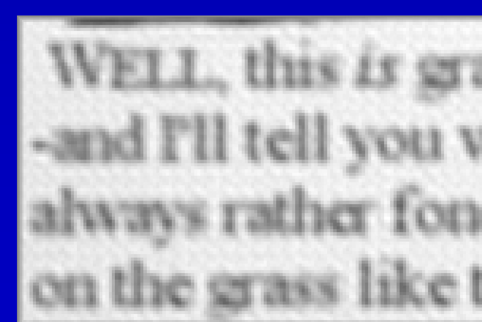
Photoreceptors in Fovea

Superresolution:

- Multiple photos subpixel shifts:

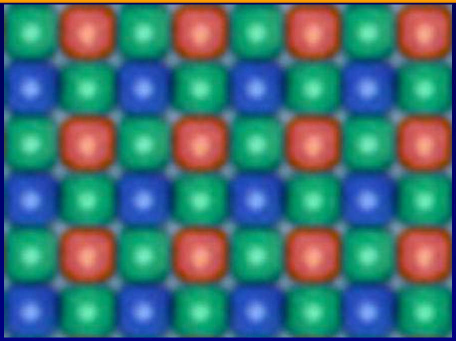


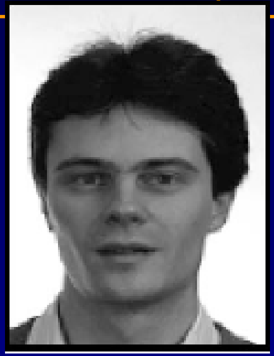
- Assemble dense sample grid:

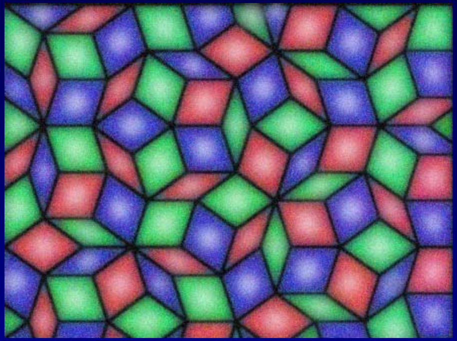


Penrose Pixels for SuperResolution

ICCV 2007, Ben-Ezra et al., "Penrose Pixels: Super-Resolution in the Detector Layout Domain"

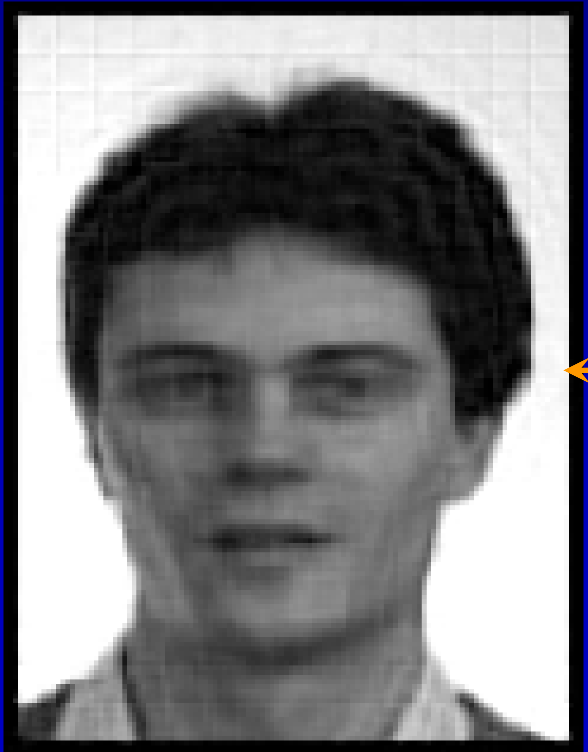






Periodic: sub-pixel shifts

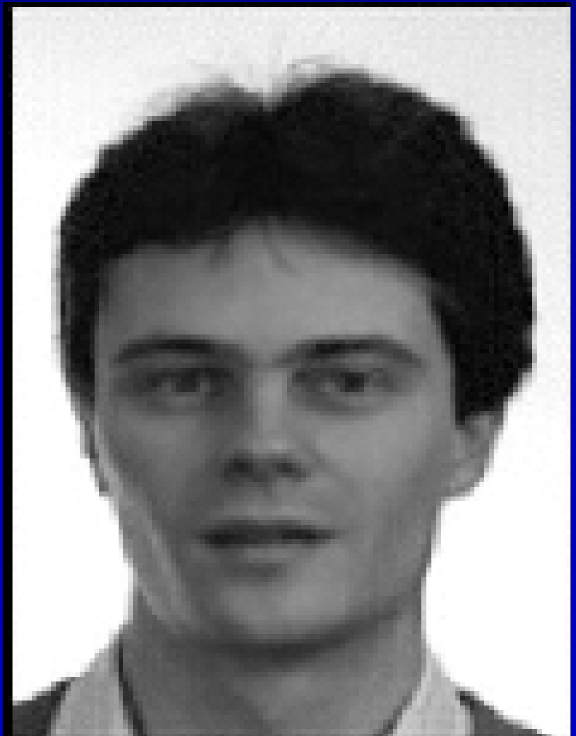
Non-Periodic: any shift ok



8X super-res;
same Back-Projection
Reconstruction Method;

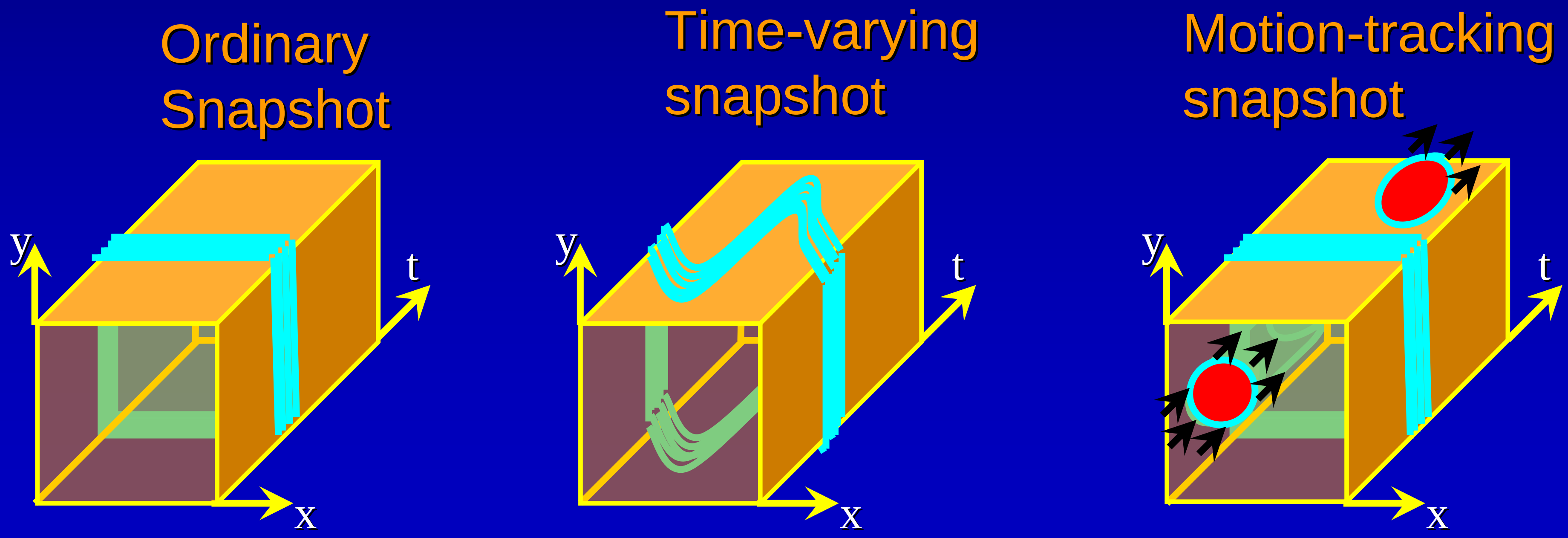
5.78 RMS error

2.78 RMS error



How can we *choose* What Matters?

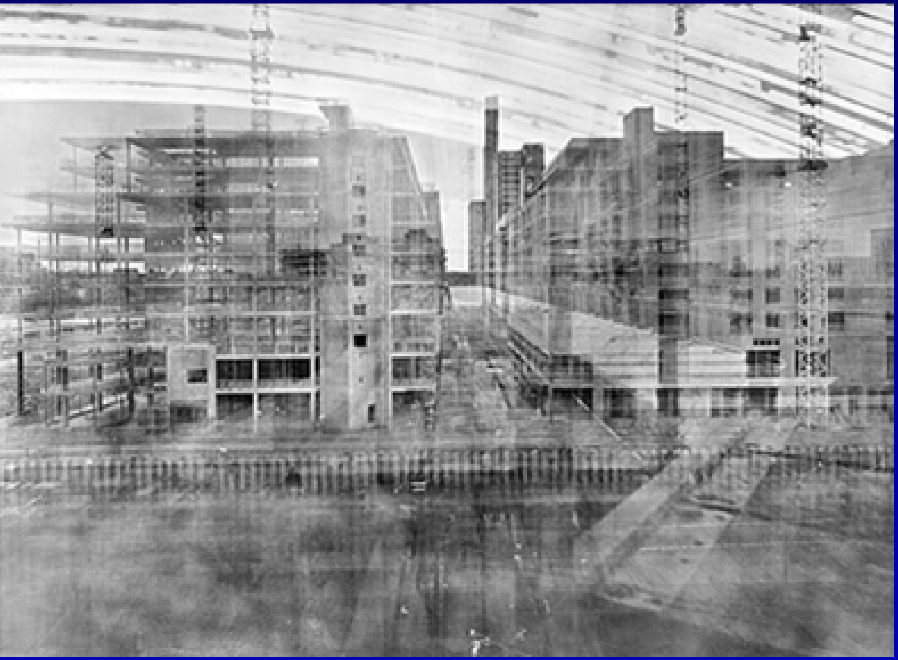
- Image== ‘flattened’ spatio-temporal volume
- Choose Integration limits to fit the task
- More volume→less noise? Not always…



Take it all: Very Long Exposure

18 Months

Postdamer Platz, Berlin

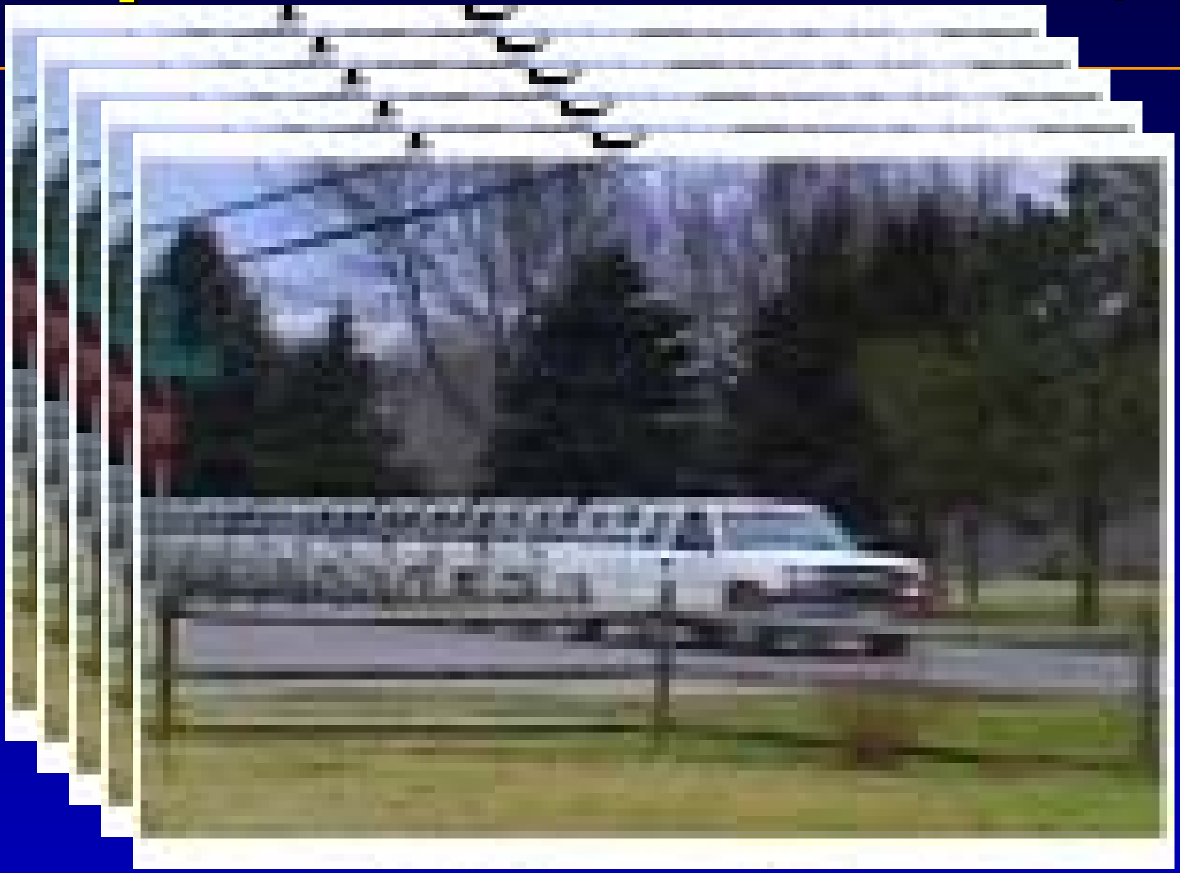


26 Months

Note sun track breaks, ‘ghost’ buildings

Michael Wesely: “Open Shutter” Exhibition, MOMA Museum of Modern Art, NY 2005 **http://www.wesely.org/wesely/index.php**

Time-Lapse without Ghosts, Jumps

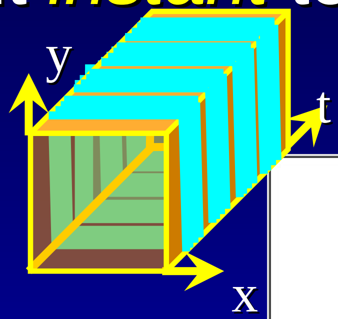


Computational Time-Lapse Video (SIGGRAPH 2007)

Eric P. Bennett, Leonard McMillan
(University of North Carolina at Chapel Hill)

Perfect Timing: Casio EXLIM Pro EX F-1

- Sports: the right *instant* to click the shutter?



Time bracketing:

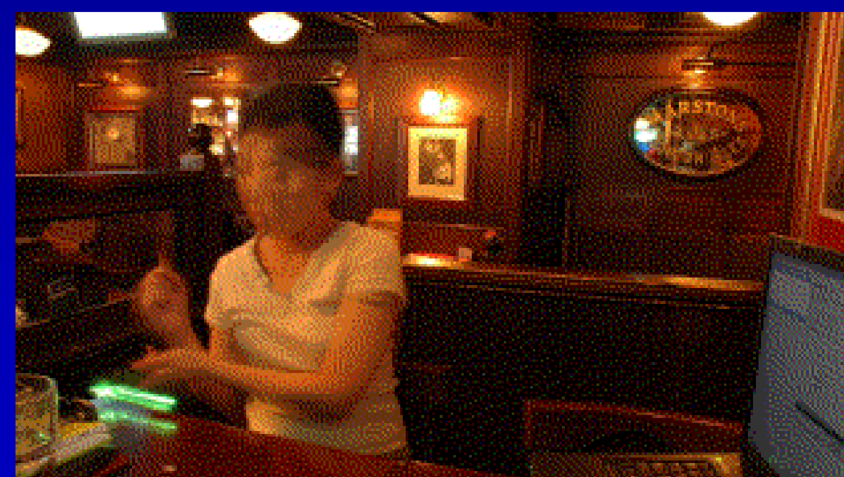
- burst buffer:
  6Mpix x 60 frames
  up to 60 Hz
- Data-rate limited:
  at 336 × 96 res
  up to **1,200 Hz**

Flash + Light-Source Blur

- Lighting Integration Tricks:
  - Draw light paths in darkness
  - Flash captures one instant

"Lighting Doodle Projects"

1949 AP: Pablo Picasso, Time Magazine 'Top 100 Artists'
See also: http://www.vpphotogallery.com/photog_mili_picasso.htm



http://tochka.jp/pikapika/2006/06/report_pikapika_in_kitijoji.html

Factored Time-Lapse Video

Factor Whole-Day Video Seq. into:

Sky-only lighting, and

Users may edit Lighting, Shadows, Reflectance, NPR

SIGGRAPH 2007 “Factored Time Lapse Video” Sunkavalli et al.

Factored Time-Lapse Video

Factor Whole-Day Video Seq. into:

Sky-only lighting, and

Whole-Day, Sun-only lighting

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SIGGRAPH 2007 “Factored Time Lapse Video” Sunkavalli et al.

Factored Time-Lapse Video

Factor Whole-Day Video Seq. into:

Sky-only lighting, and

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Shadow Amount vs time

Users may edit Lighting, Shadows, Reflectance, NPR

Factored Time-Lapse Video

Factor Whole-Day Video Seq. into:

Sky-only lighting, and

Whole-Day, Sun-only lighting

Shadow Amount vs time

Edit Scene Lighting

Users may edit Lighting, Shadows, Reflectance, NPR

Factored Time-Lapse Video

Factor Whole-Day Video Seq. into:

Sky-only lighting, and

Whole-Day, Sun-only lighting

Shadow Amount vs time

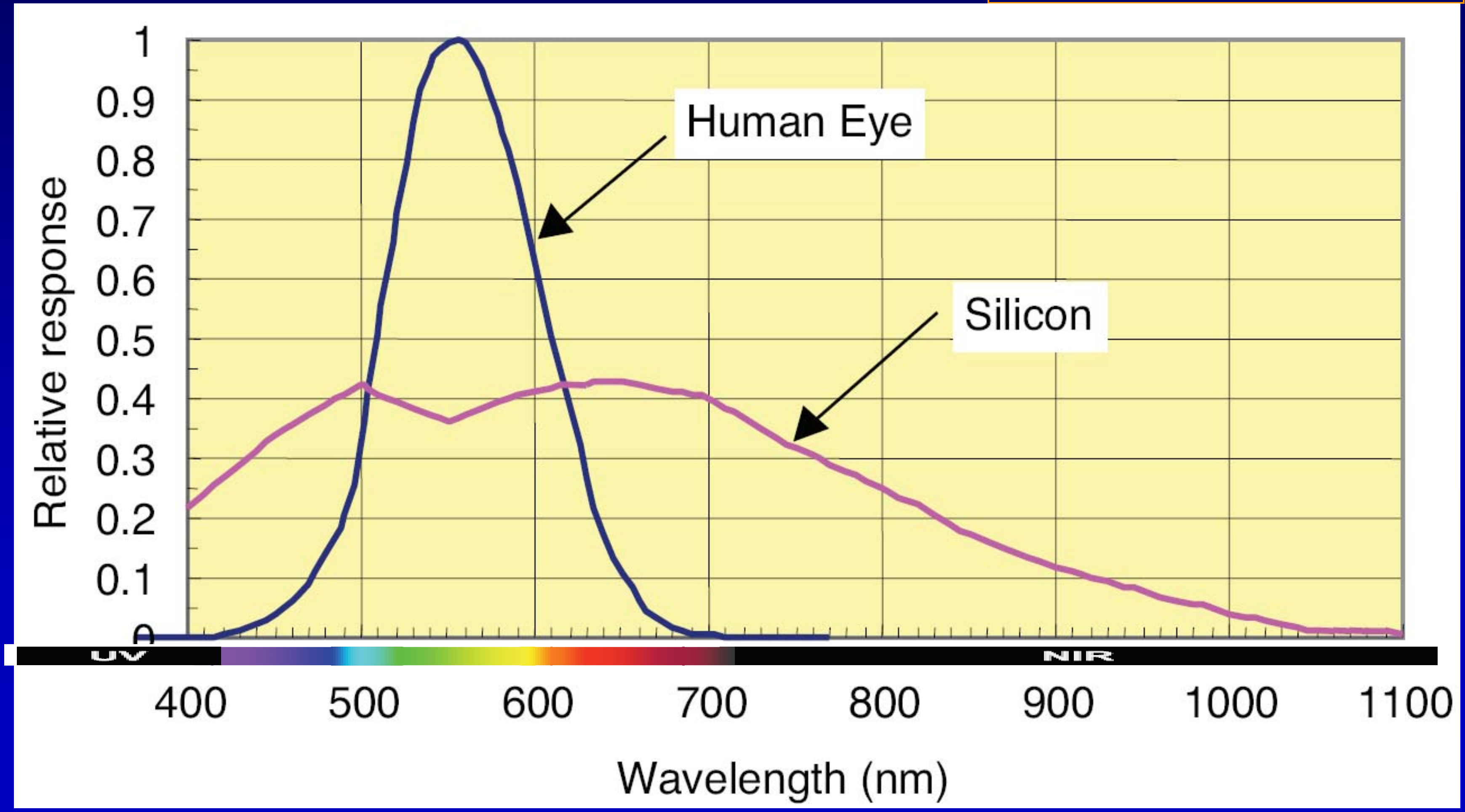
Edit Scene Lighting

NPR efx and more …

Users may edit Lighting, Shadows, Reflectance, NPR

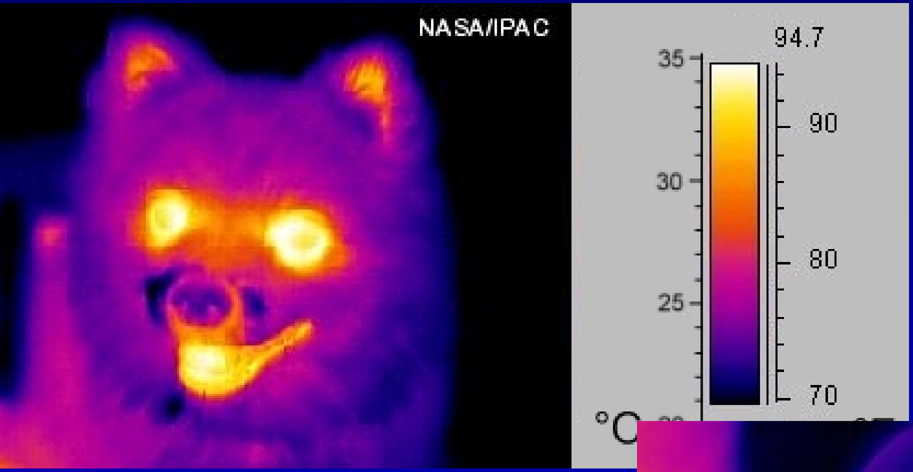
Spectral Range: Silicon >> Eye

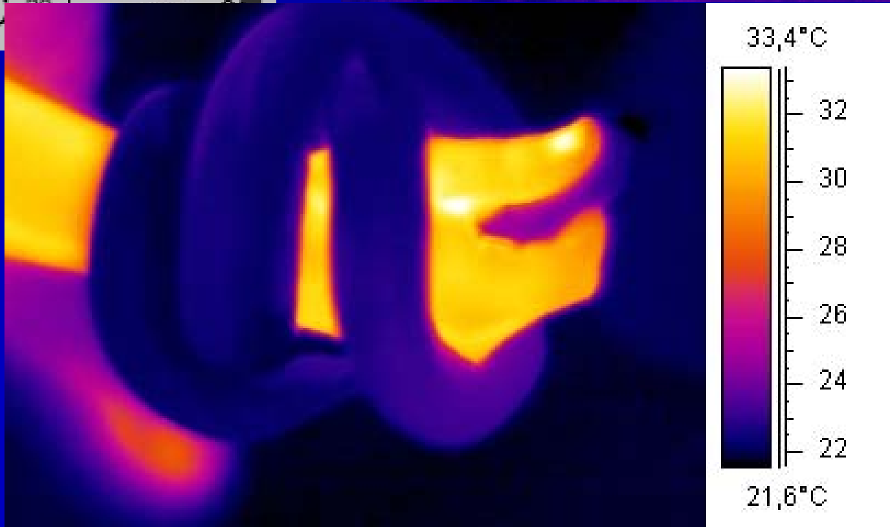
Aptnia (Micron Technologies)



Thermographic Cameras

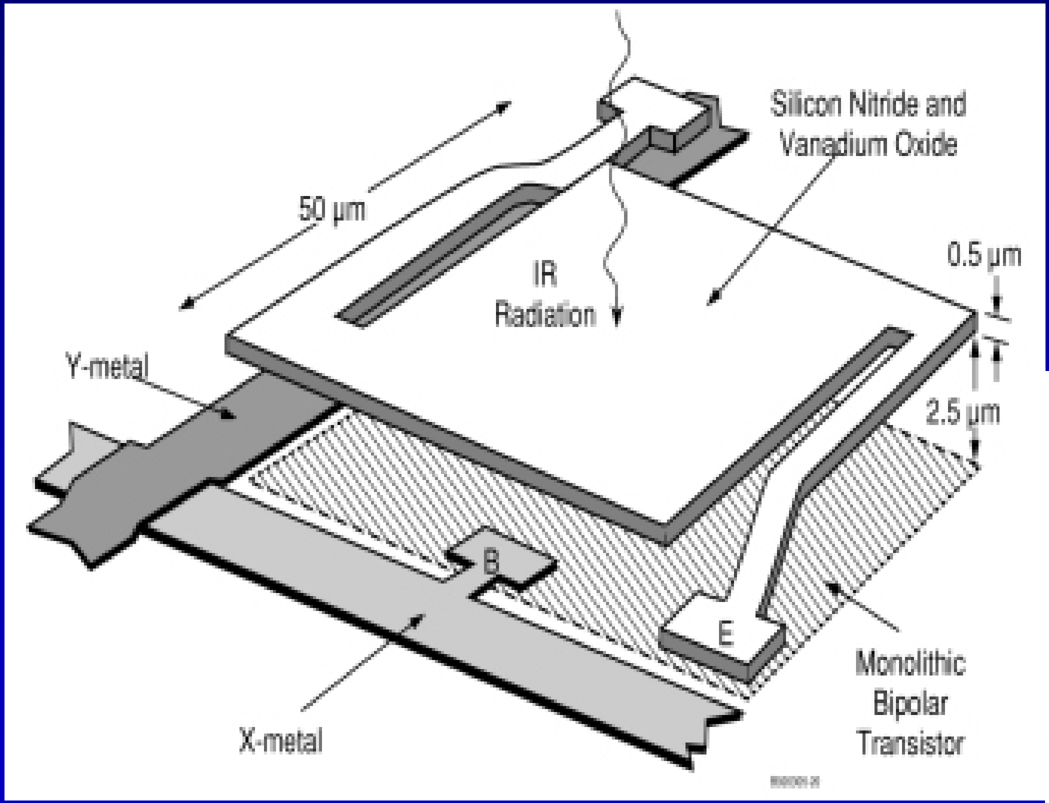
Two classes: Near-IR and Bolometer





Thermal IR Camera

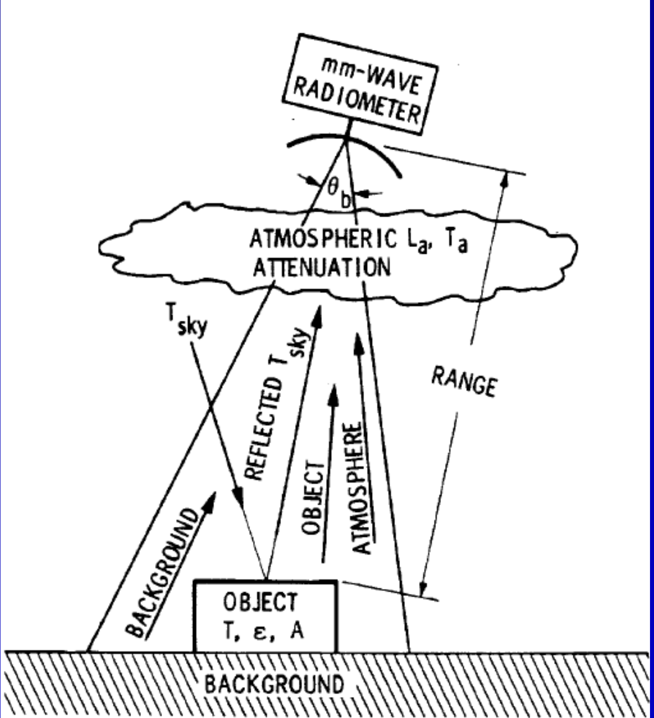
Uncooled Bolometer Arrays:
Temperature-Dependent Conductance

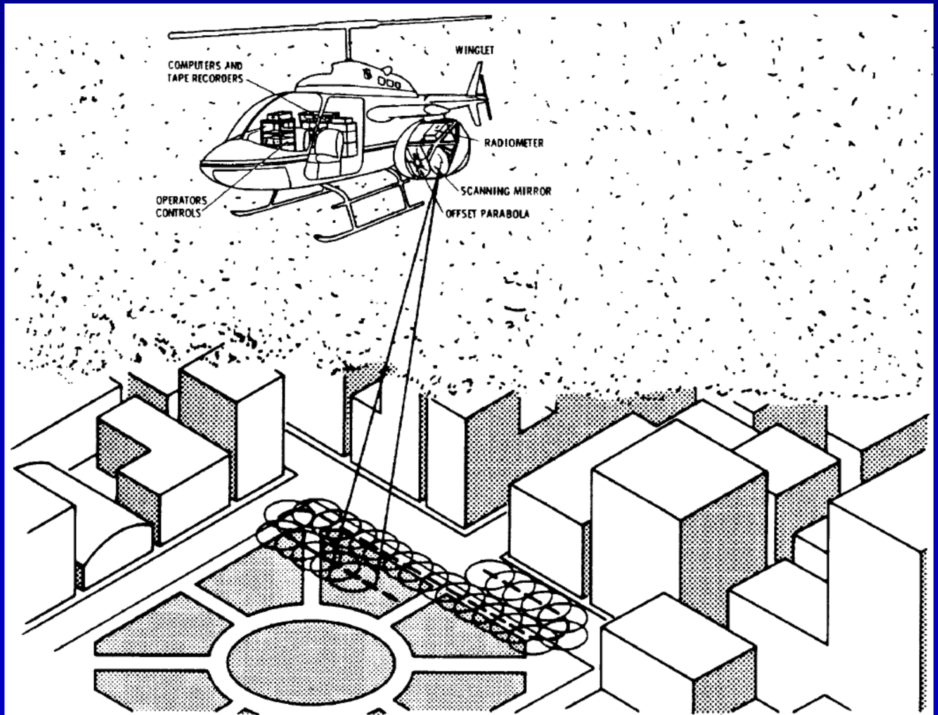


320 x 240pixels typical
Slow Temporal Response
Often Shutter-free

Millimeter Wave Imaging (Radiometry)

- Sensitive to Temperature *AND* material's reflectance
- High reflectance from water, metals, etc.
- See thru clouds and weather at some wavelengths
- High sensitivity, phase-sensitive (optical? RF? (1/r, not $1/r^2$))



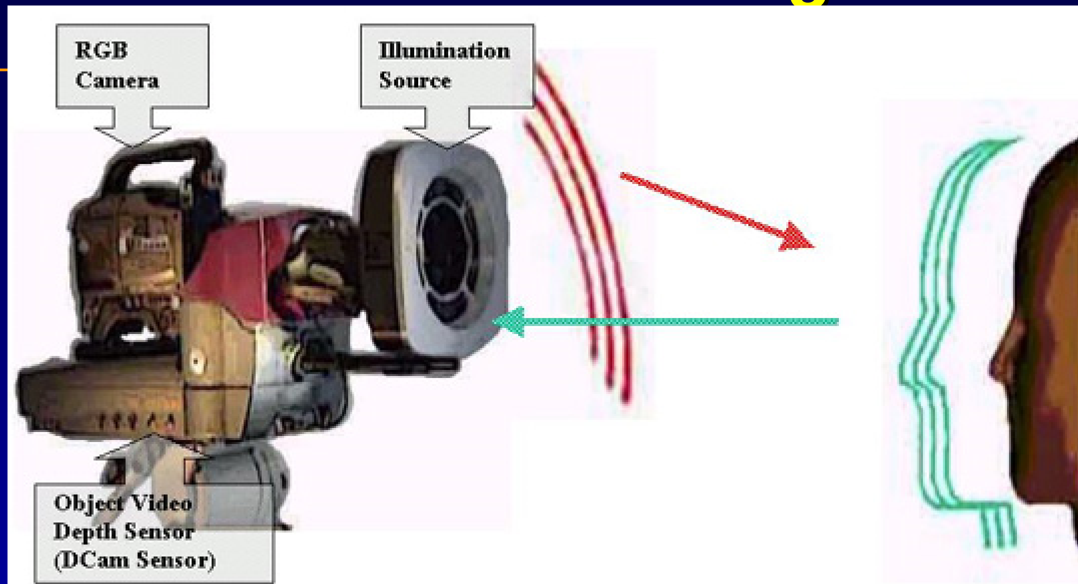


1-2mm Imaging Radiometry: Security

Millivision Systems, Inc;

- At 1-2mm humans ‘glow’ *very* faintly (10^{-14} joule)
- Metals, conductors, occlude; but clothes don’t
- Passive-only imaging: 40-60 ft camera range
- Weapons: Strong Silhouettes

ZCam (3Dvsystems),
Shuttered Light Pulse



Resolution :
1cm for 2-7 meters

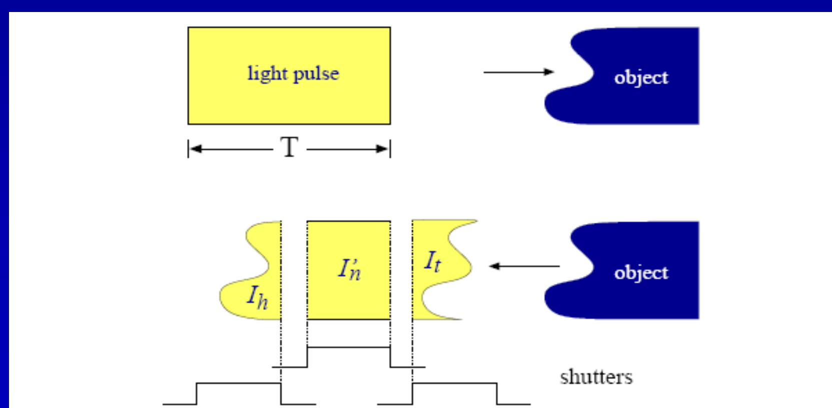
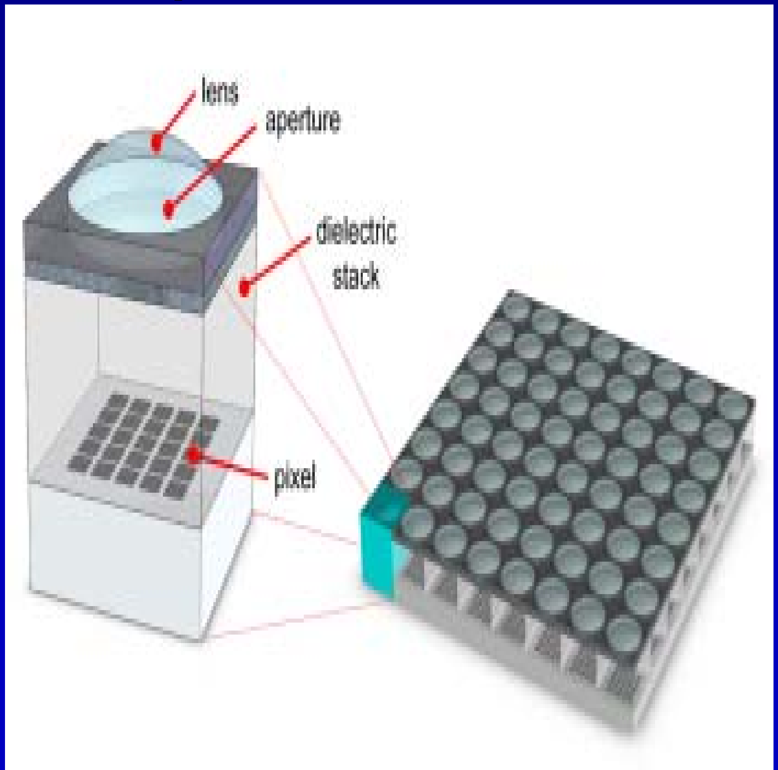
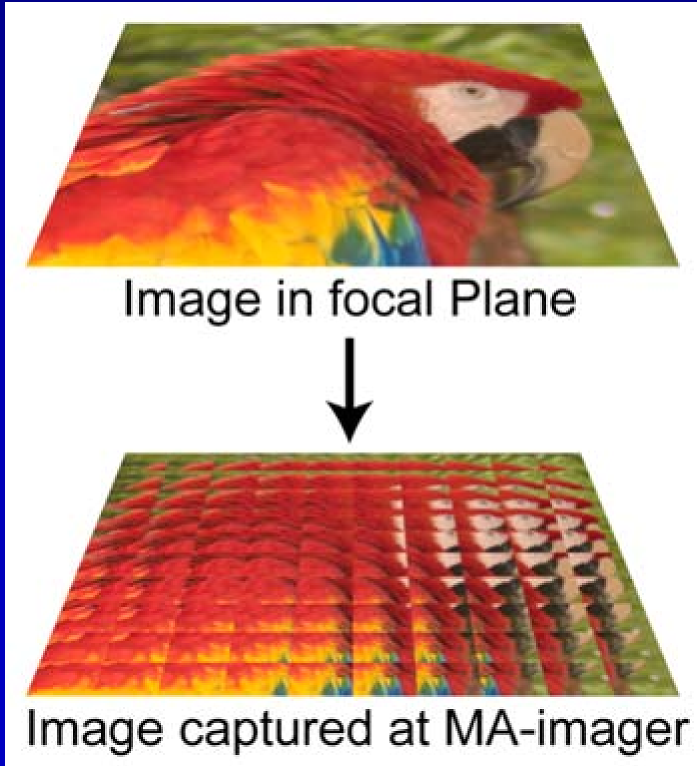


Figure 1: A light pulse of duration T radiates an object and is reflected back to the sensor. The signal is shuttered at the head, center and tail of the signal. The measured intensities I_h and I_t are functions of the distance travelled by the pulse, while the intensity I'_n is a constant fraction of the unshuttered value I_n.

Fife (2008) Multi-Aperture Imager

- 16x16 pixel overlapped sub-images
- Disjoint apertures, uniform spacing
- Many correspondences → 3D depth

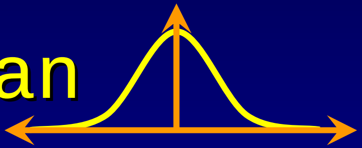




A Bit of Metrology History

How do I weigh many small parts accurately?

random error ε, zero mean

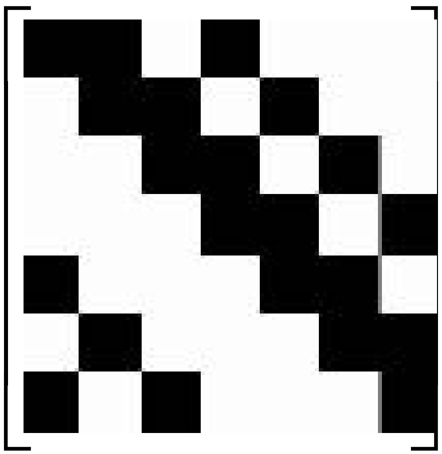


- Tedious:
  Measure N items, one-at-a-time: σ

- Extra-Tedious:
  Measure N items, M times. $\sigma / \sqrt{M}$

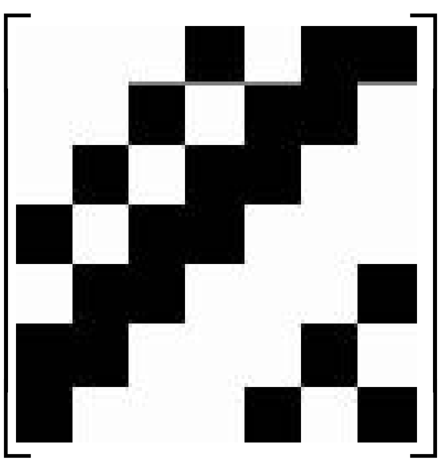
- Tolerable:
  Measure N SETS of (~N/2) items. $2\sigma / \sqrt{N}$

OLD: Hadamard Transform Imaging



$$\begin{bmatrix} L_0 \\ L_1 \\ L_2 \\ L_3 \end{bmatrix} = \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix}$$

- N sensors, N pixels, but
- Sensors get
  unique SUMS of pixels
- Each pixel is part of
  ~N/2 measurements

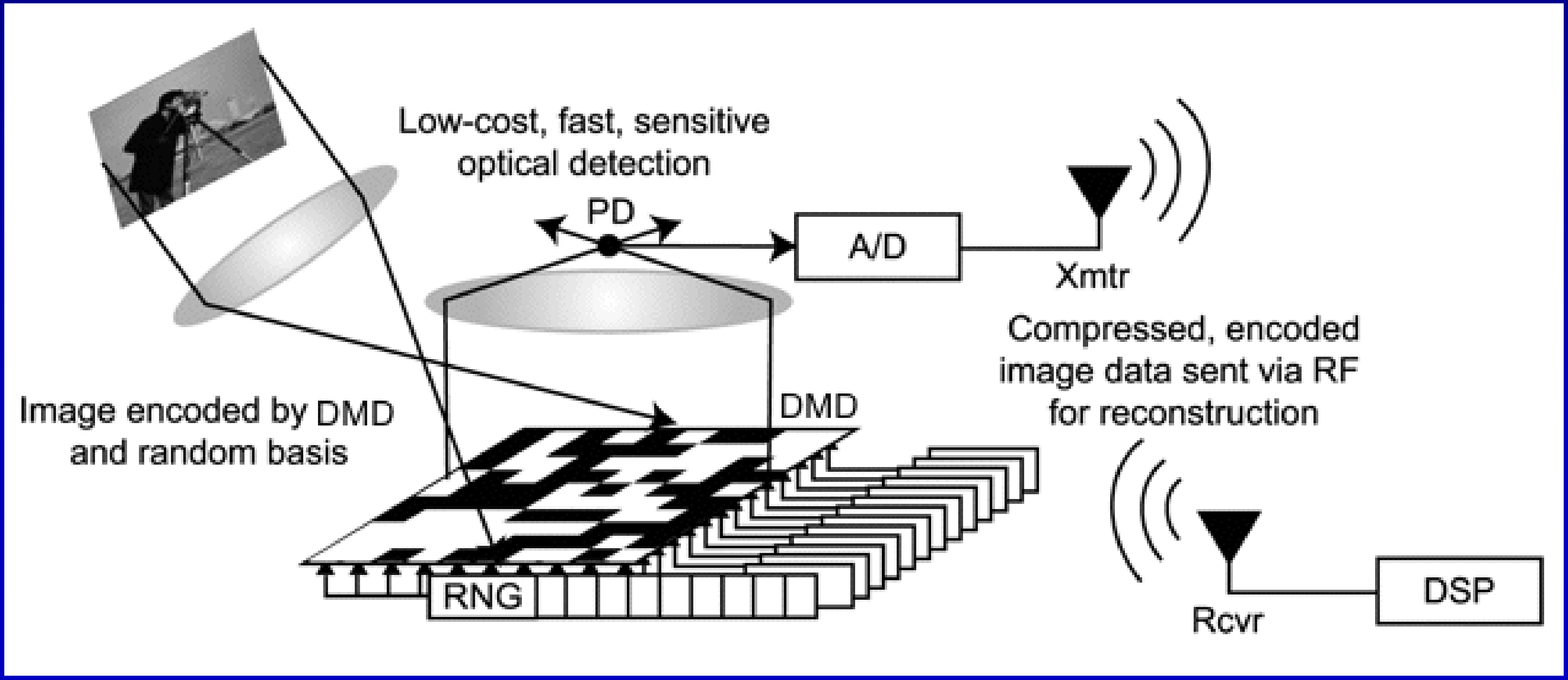


$$\begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} = \begin{bmatrix} p_0 \\ p_1 \\ p_2 \\ p_2 \end{bmatrix}$$

- Compute pixels
  using *inverse* matrix;

Compressive Sensing: "Single Pixel Cam"

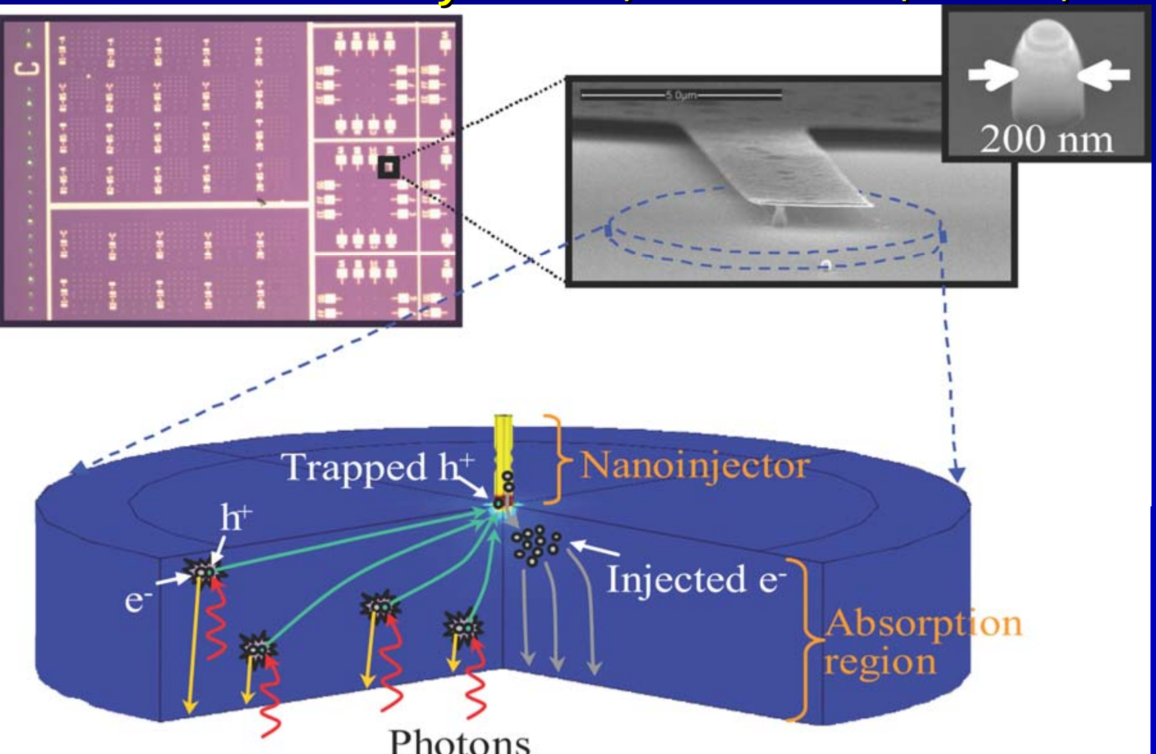
- Sense large sums of pixels, not N pixels
- Key notion: number of pixel sums << N
- Support: several ground-breaking proofs

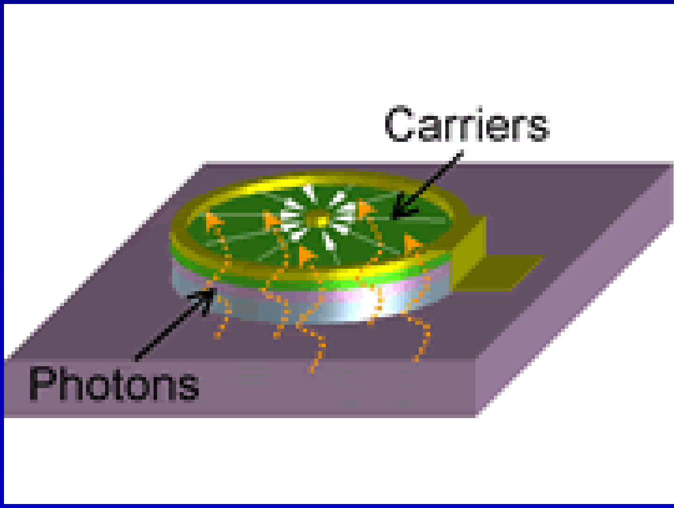


Bio-Inspired Single-Photon Detectors

http://www.eecs.northwestern.edu/hmohseni

- Mohseni,Memis: Bio-Inspired sensor
  - Large photon-absorption region (rhodopsin)
  - Nano-scale hole detection (1-electron injector)
  - Extremely small, low noise, HDR, no cooling req’d





http://spie.org/x19173.xml

Single-Photon Detectors

- Quantum Wells / Quantum Dots
  - ‘traps’ 1 electron/hole pair, from 1 absorbed photon
  - No noisy ‘avalanche’ effect
- Applications:
  - Medical imaging
  - ‘Ghost Imaging’ ?
  - Secure Quantum communications?

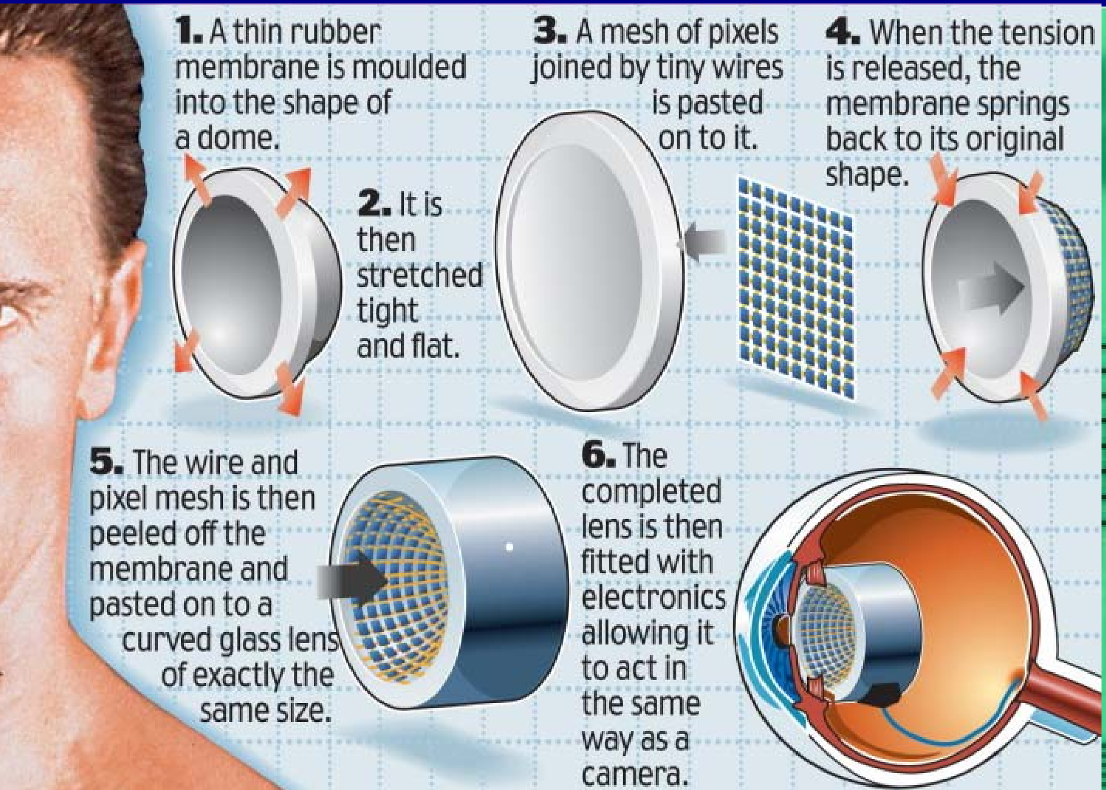
Single-Photon 'Ghost' Imaging

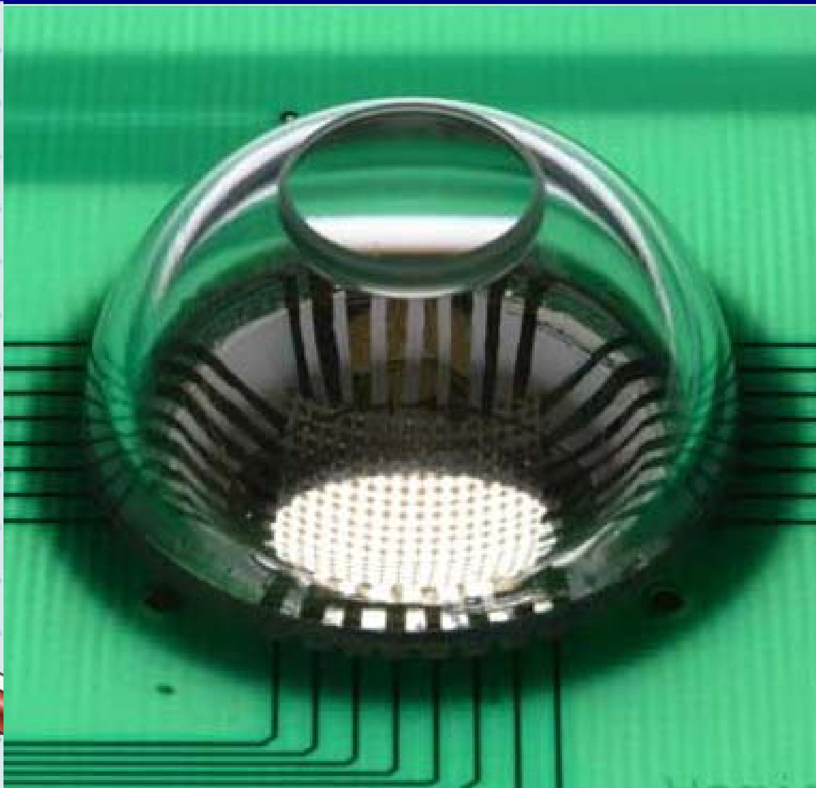
- Create two entangled photons: one to keep, one for scanning
- Kept photon tells direction, scanned photon: reflectance
- Covert Sensing: Interceptor can't identify entangled photon

Shih, Y., Univ Maryland: Physical Review A (DOI: 10.1103/PhysRevA.77.041801)

Flexible-Array Sensor

- John Rogers et al. (Beckman Institute, U of Illinois) (EECS, Northwestern Univ.)





Sensor Fabrics?

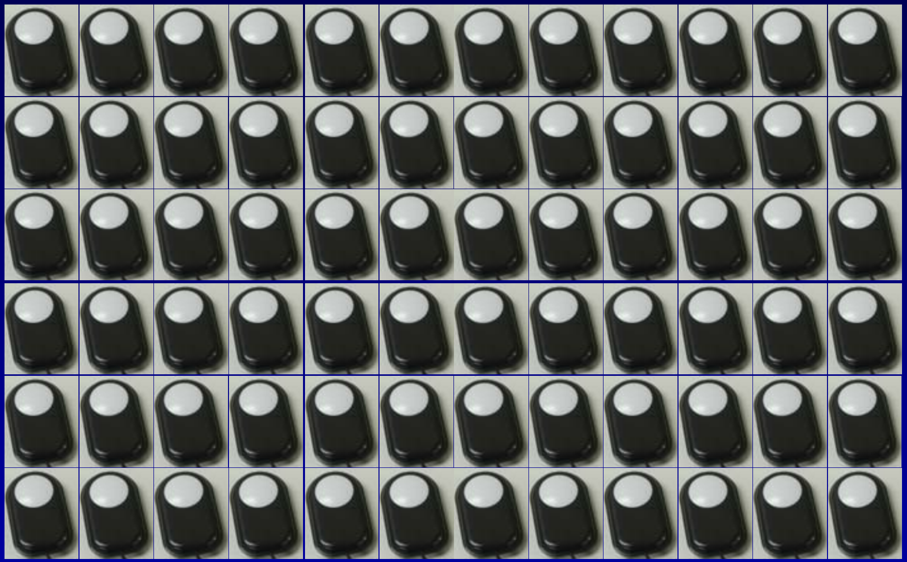
- Camera-Scale projects in that direction:

"Scene Collages and Flexible Camera Arrays," Y. Nomura, L. Zhang and S.K. Nayar, EGSR 2007.

Other Free-Form Choices?

Andrew Davidhazy, RIT: http://www.rit.edu/~andpph/

Digital Sensor: Array of Light Meters



What is <u>ABSOLUTELY MANDATORY</u> here?

- **One** sample-time? Spatial, Temporal Uniformity?
  Why not many? [Flutter Shutter, 2005 Raskar])? …
- Perfect Sync, Non-adaptive, all at once?
  rolling shutter? Adaptive Frameless Render[2005 Dayal]?   ...
- No Spatial Overlap?
  Why not sinusoids? Wavelets? Gabor functions?   …

Common Thread:

Existing Film-like Camera quality is
VERY HIGH, despite low cost.

Existing sensors and cameras are
just now escaping film-like assumptions,

?what can we compute with them?

SIGGRAPH2008