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Cameras
As Computational Devices

Prof. Hank Dietz

CSU, April 8, 2013

University of Kentucky
Electrical & Computer Engineering

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Purdue ECE Dept. Newsletter 1992

The acquisition of the MasPar MP-1 started with a human form of "parallel processing" with eight professors cooperating in the preparation of the funding p to the National Science Foundation. Front: Professors Jan Allebach (kneeling), Henry Dietz (seated); from left: Jeff Gray, Leah Jamieson, H.J. Siegel, Jose Fort Dave Landgrebe and Ed Delp.

Purdue Students First in U.S. to Have Access to Fully Configured MasPar MP-1

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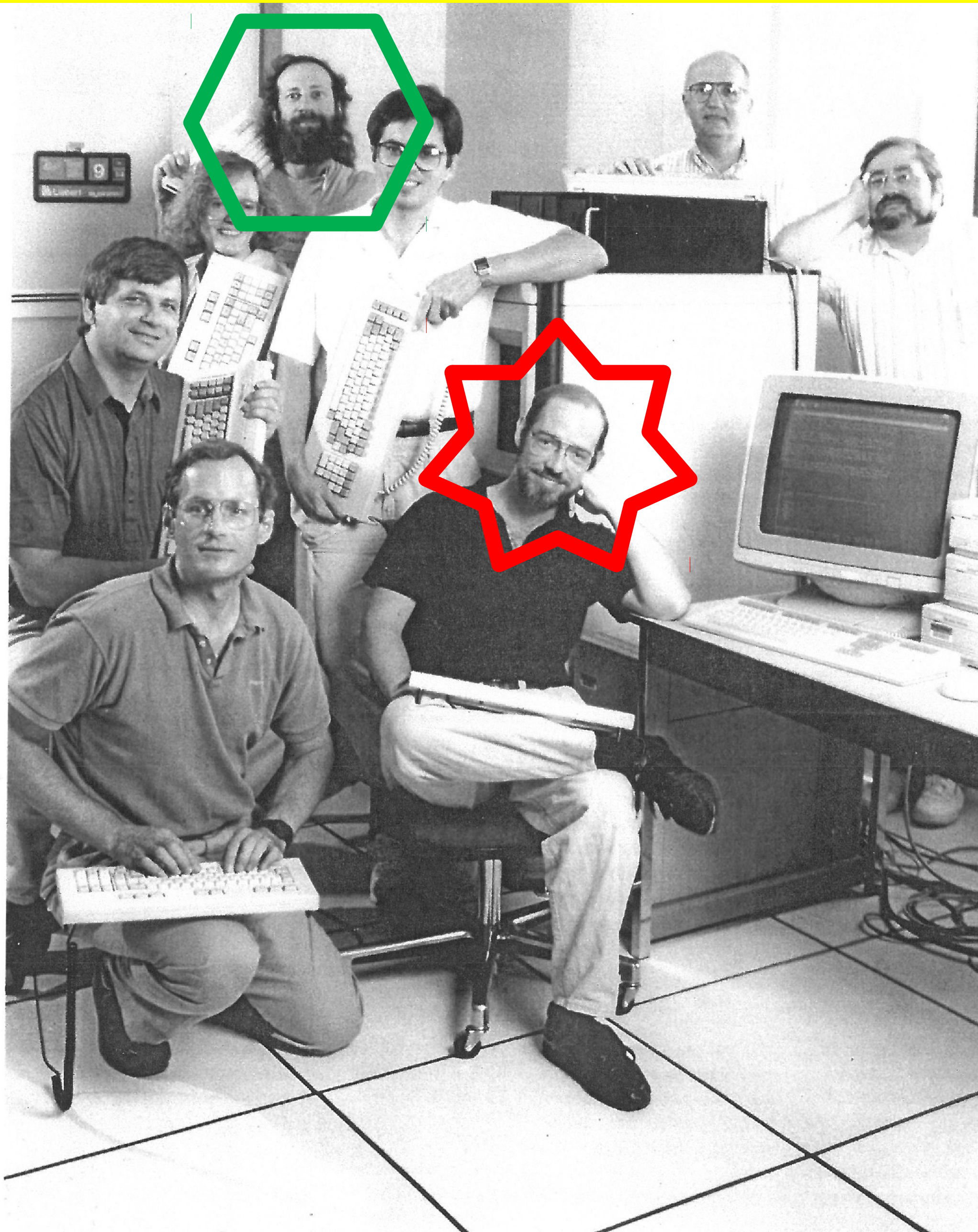

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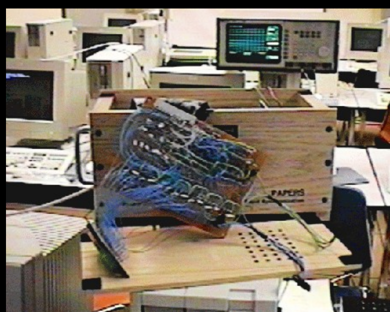
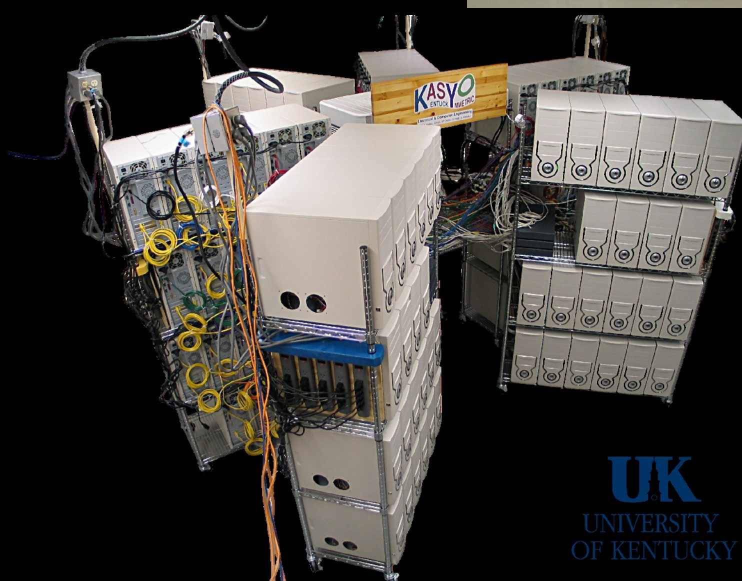
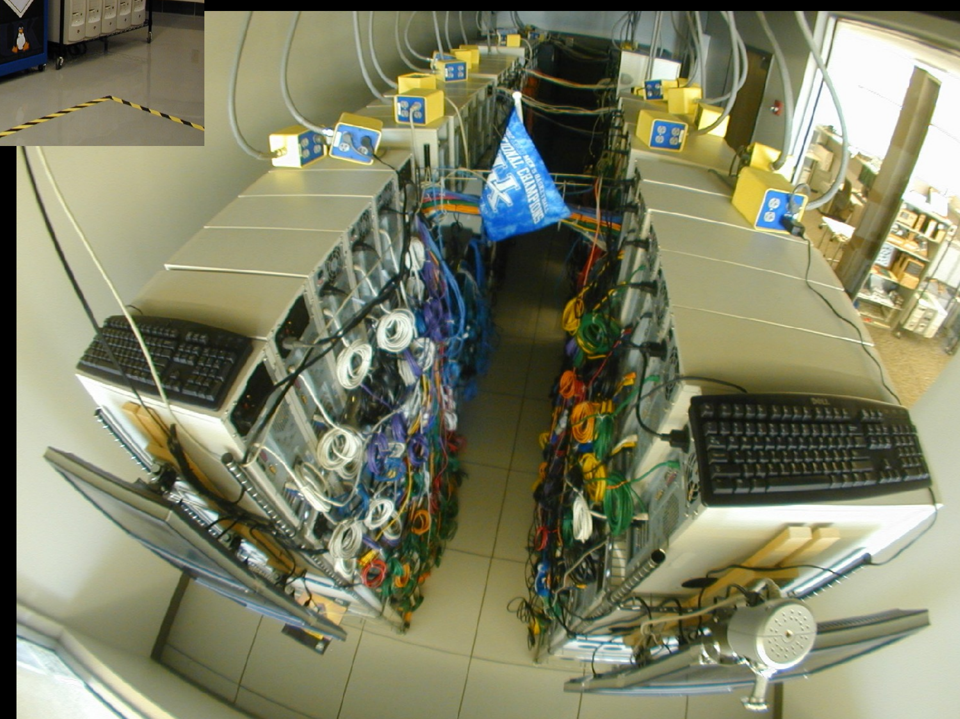
My Best-Known Toys







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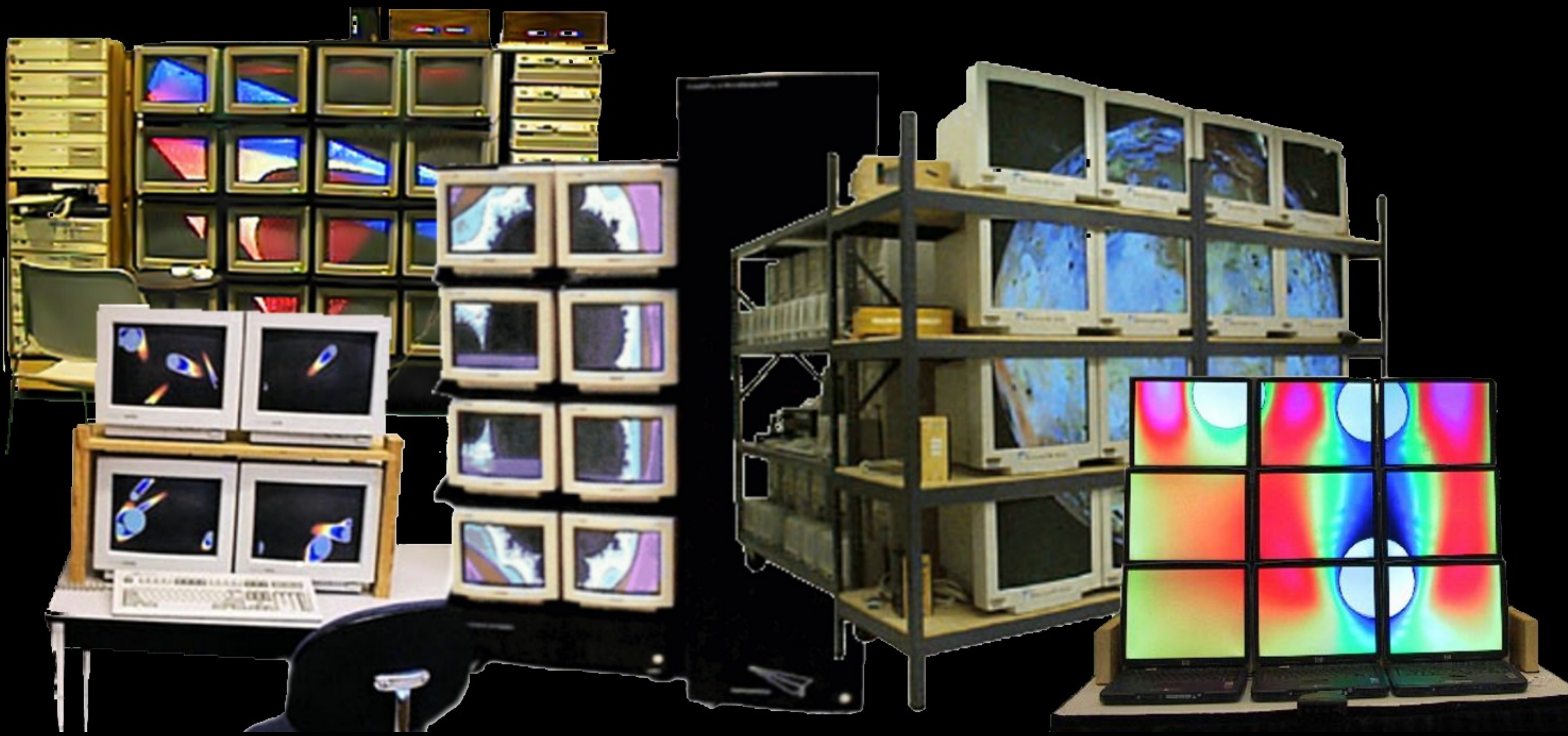
Some Of My Other Toys



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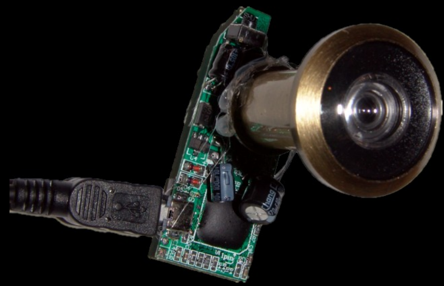
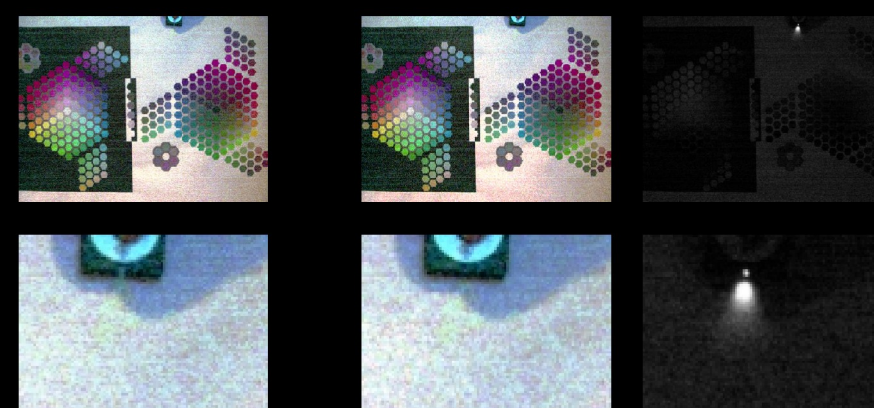


Normal processing | RGB extraction | IR extraction



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My Background

- I am a computer engineer / systems guy
  And...
- In 1970s, photo editor of various school pubs and a published professional photographer
- Digital halftoning (of X-ray images) in 1984-5
- High-quality & computer-controlled digital imaging, e.g., for 30MP video wall in 1996
- Computational photography since 1999...

Computational Photography

Cameras as computing systems;
using computation to enhance camera abilities
and / or to process the data captured.

- New camera / sensor / processing models
- Intelligent computer control of capture
- Detection / manipulation of image properties

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Canon Hack Development Kit (CHDK)

Enables running arbitrary C code in a Canon PowerShot with full access to camera

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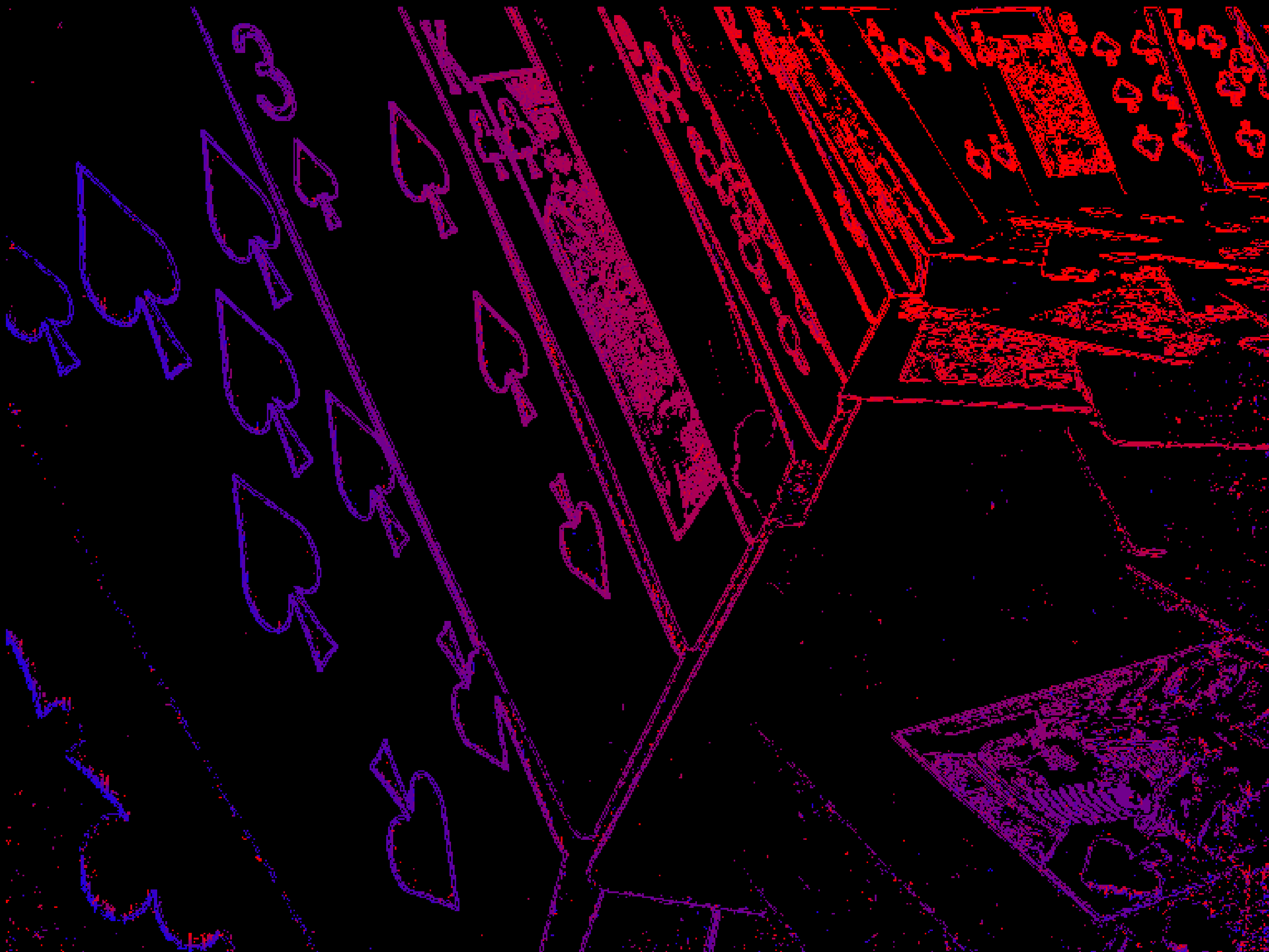
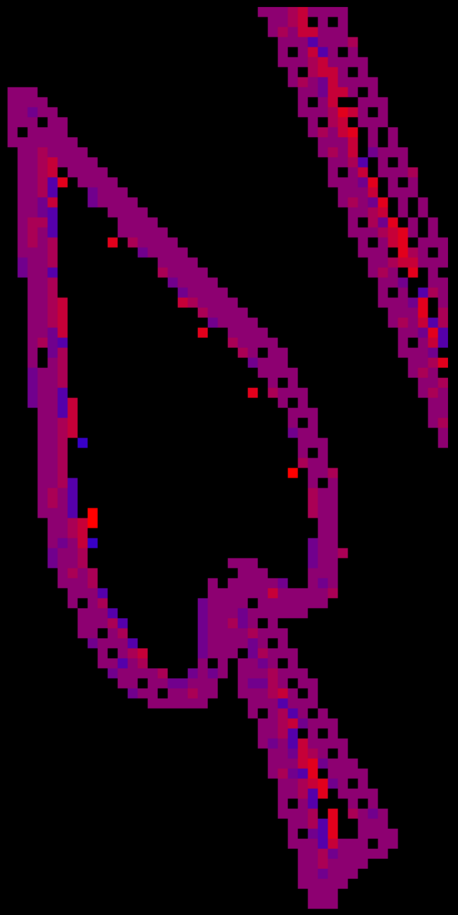
Spring 2009, EE499

- Jennifer Danhauer, Joe Lanford, Ross Levine project to capture a depthmap inside a Canon PowerShot using depth-from-focus
- CHDK scripting so a single press captures a sequence with different focus distances
- CHDK processing modified with custom C code to measure blur & combine images
- Blur measurement was fairly state-of-the-art



How Good Is The Depthmap?

- Accurate depths at edges
- No depth in featureless fields
- Wrong depths near edges!
- Wrong by a lot
- Wrong both directions
- Seems to "echo" edges...



Point Spread Function (PSF)

- Describes the response of an imaging system to a point source (impulse response)
- PSF is the spatial domain representation of the modulation transfer function (MTF)
- An image is essentially the sum of the PSFs of all points of light in the scene
- What does a typical out-of-focus (OOF) PSF look like?

What Went Wrong?

- Most image processing algorithms model OOF PSF as Gaussian blur:

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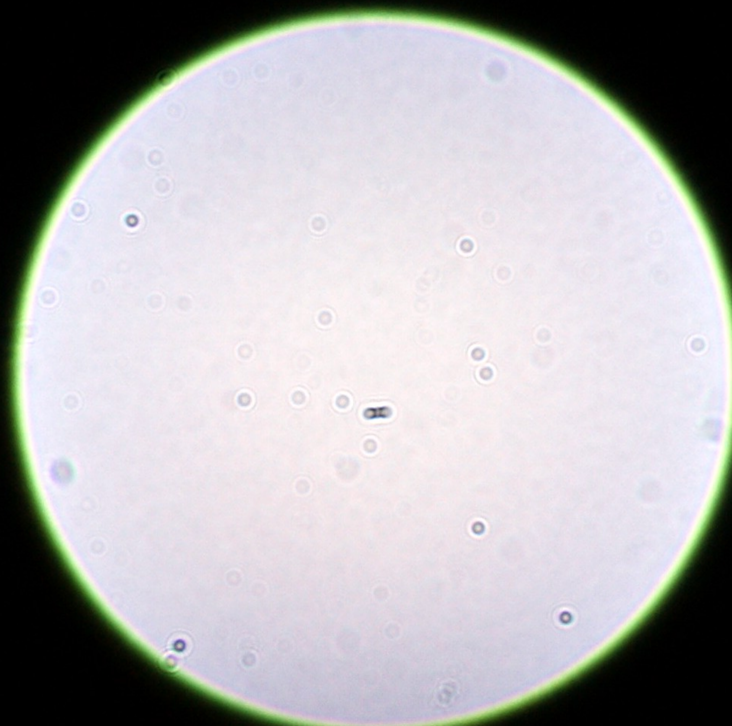
Out-Of-Focus Isn't Blurry!

- OOF PSF typically has a sharp edge!



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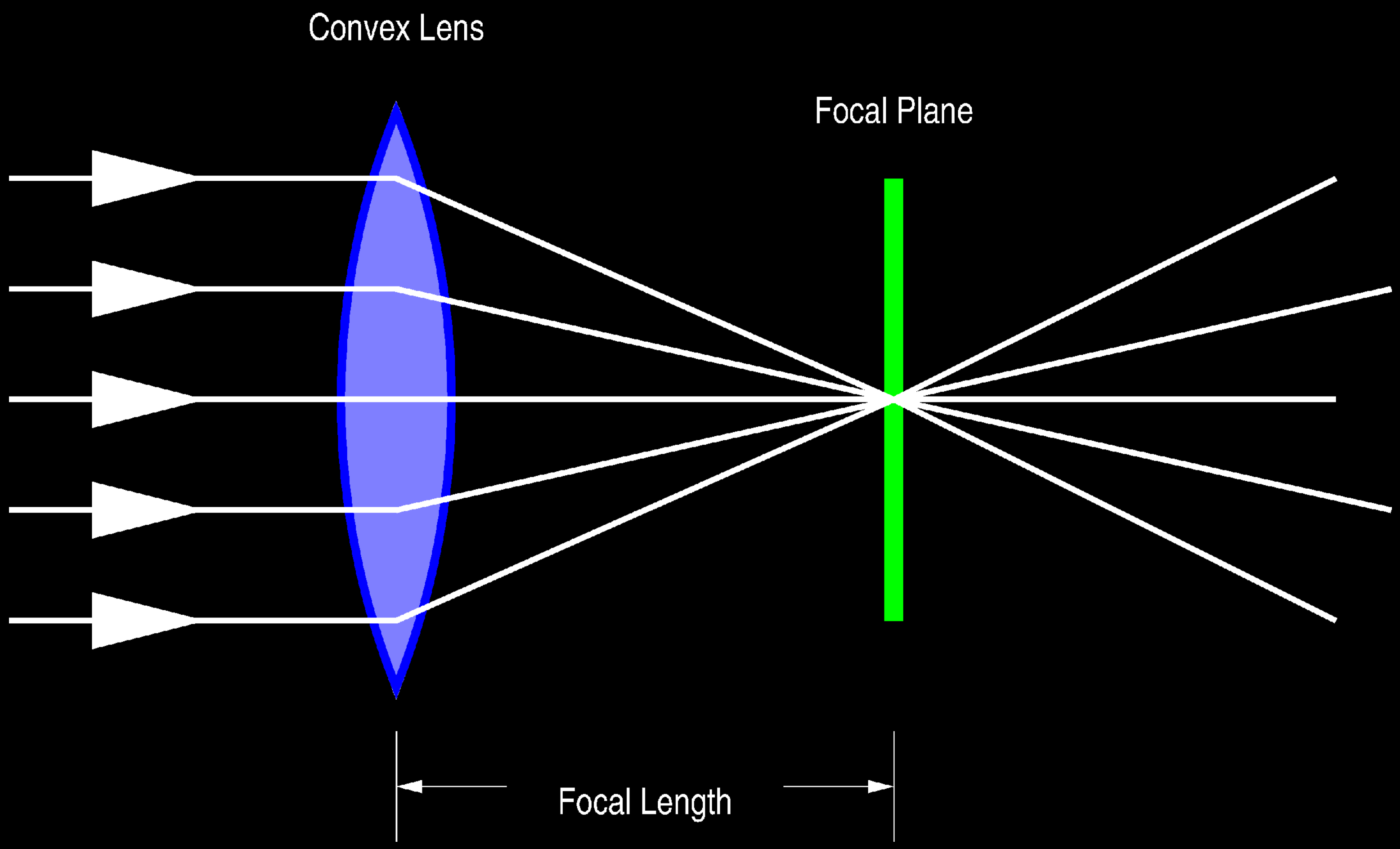
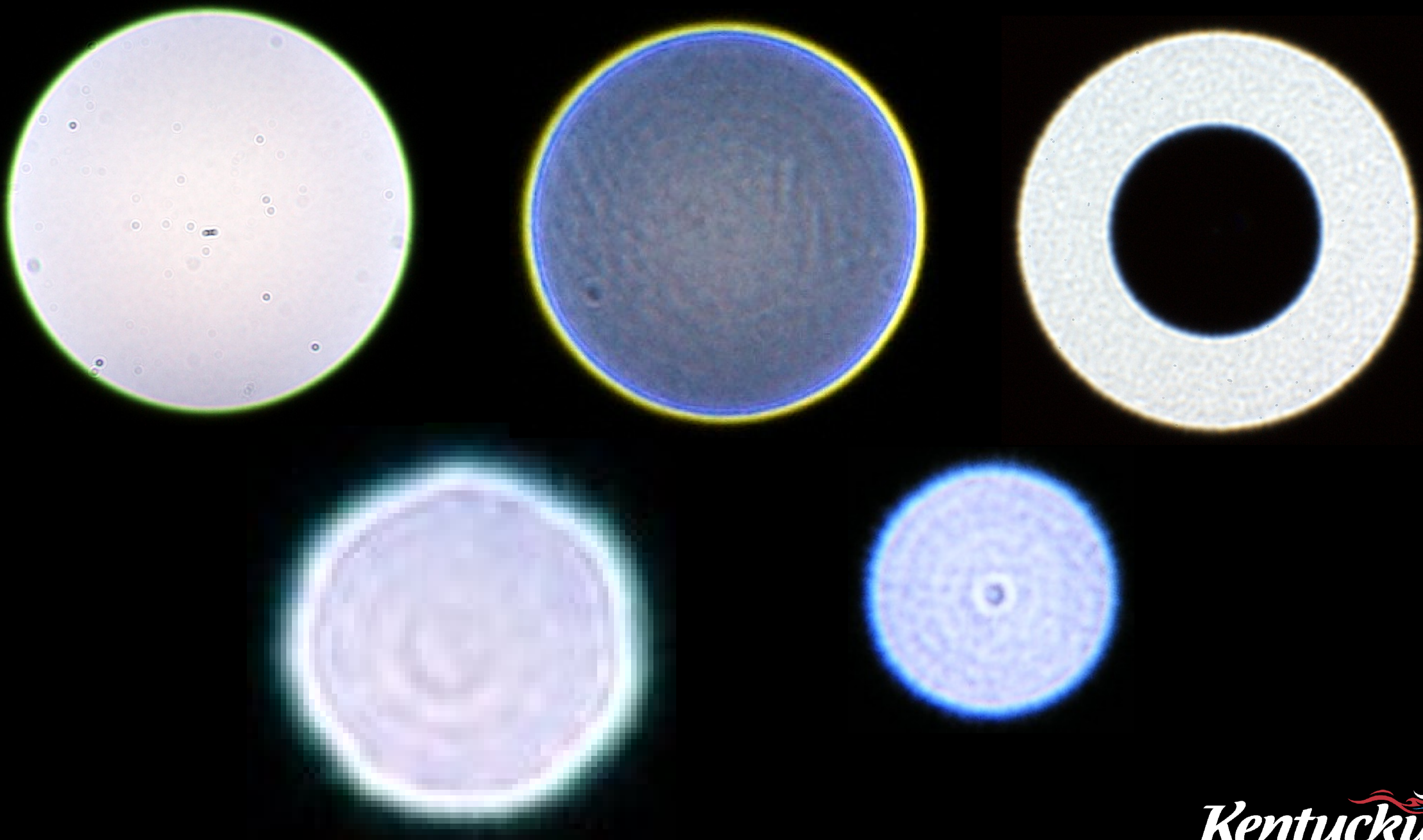
Why The Sharp Edge?



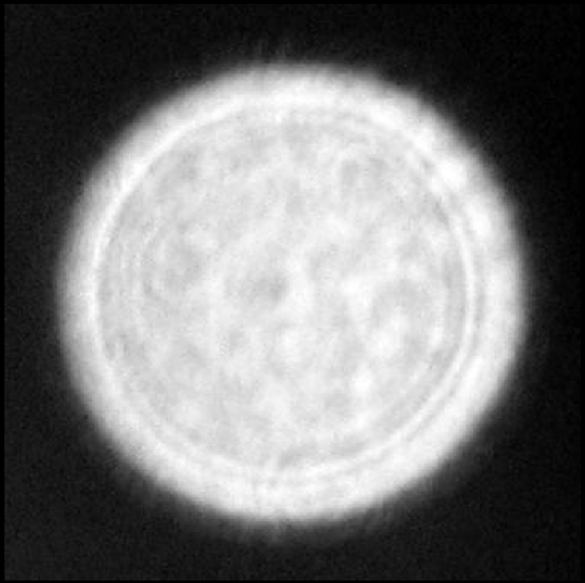
Measured OOF PSFs

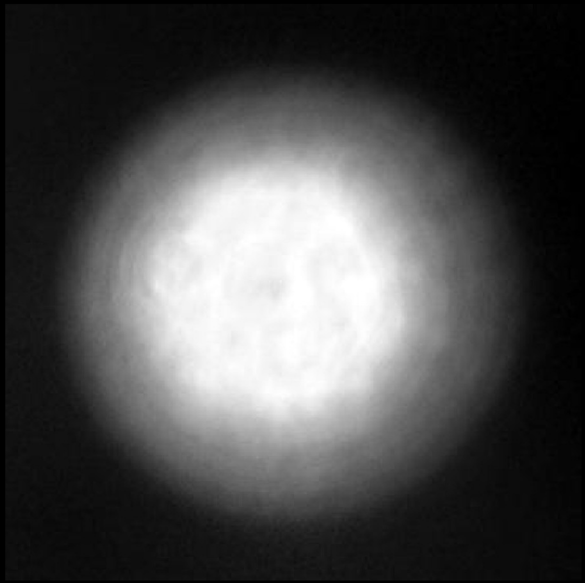


Enough science! Let`s do some engineering!

A sneaky way to make OOF PSFs Look like people think they do.

Dynamic Bokeh Apodization





- Bokeh is the collective effect of OOF PSF
- Approximate Gaussian blur by dynamically changing the aperture size using CHDK

Ok. I feel better now. Some more science….

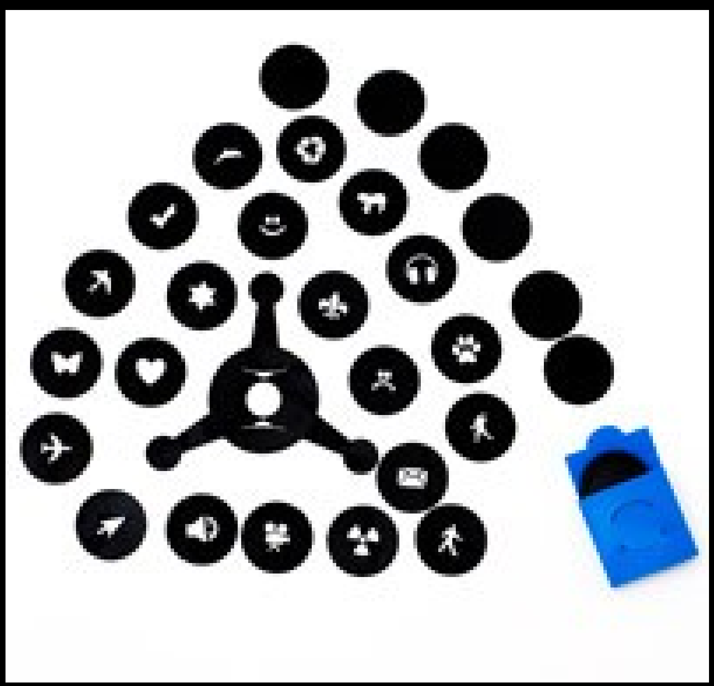
Apertures For Soft Focus

Imagon & Fujinon "Sink Strainer" apertures

(photos from mflenses.com and m42.org)

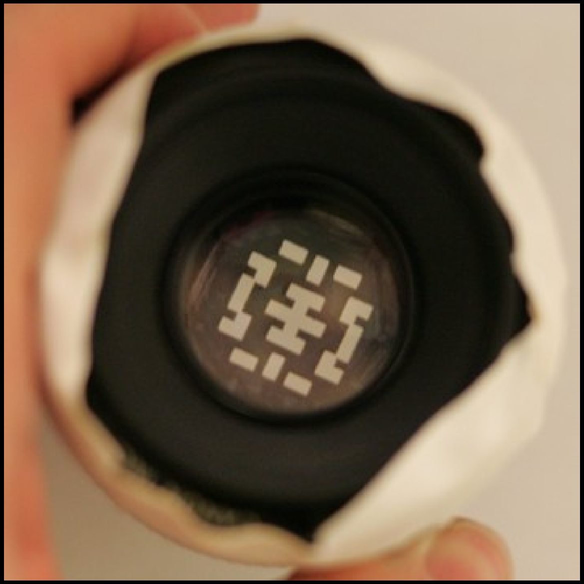
Apertures For Bokeh Effects

E.g., from `bokehmasterskit.com`



Coded To Ease Recognition

(images from MIT CSAIL)



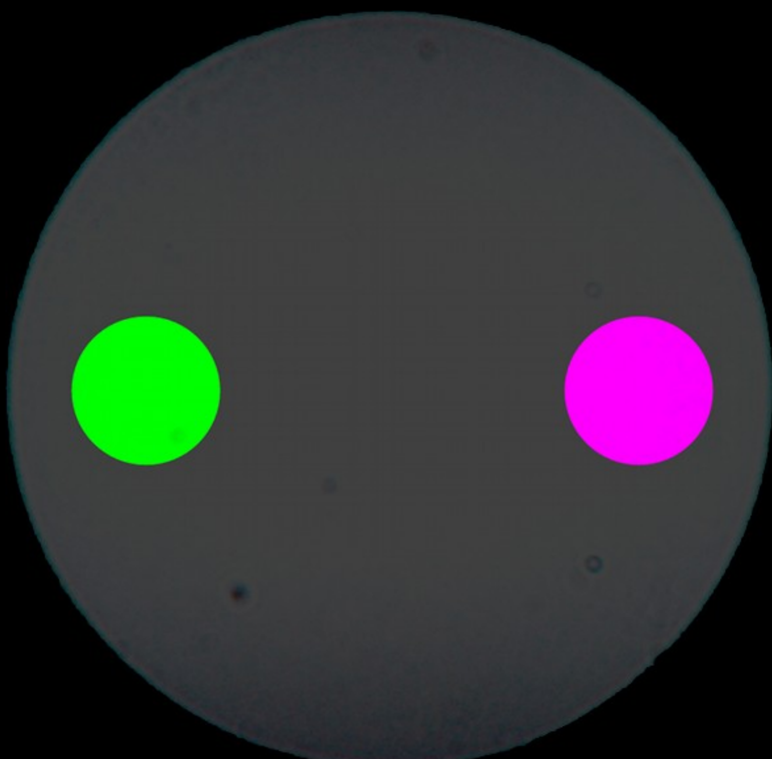
Coded Aperture Issues

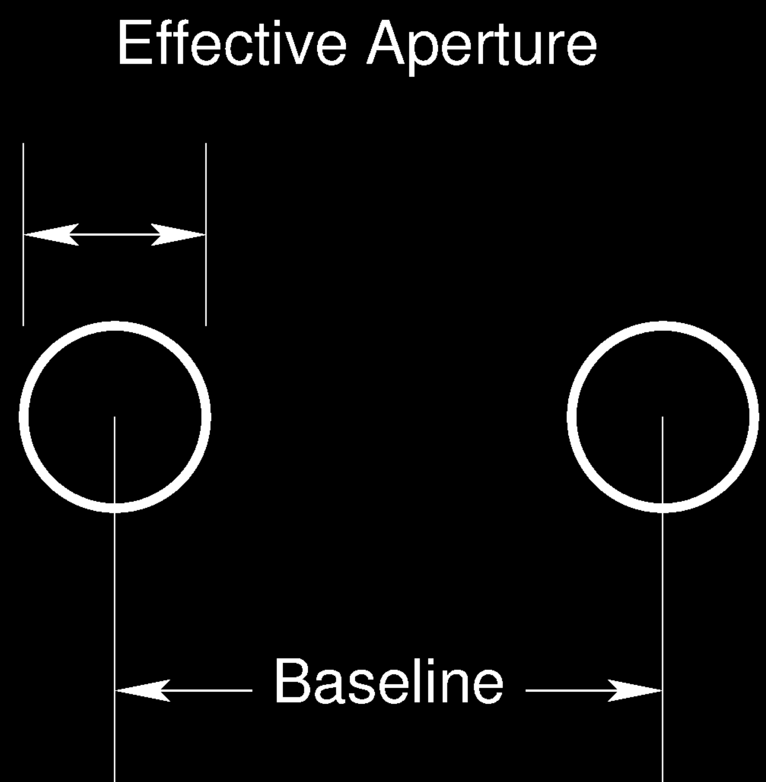
- No need to put aperture inside the lens...
- Recognize PSF by deconvolution, but...
  - Aperture corners cause diffraction
  - OOF PSFs don't actually convolve!

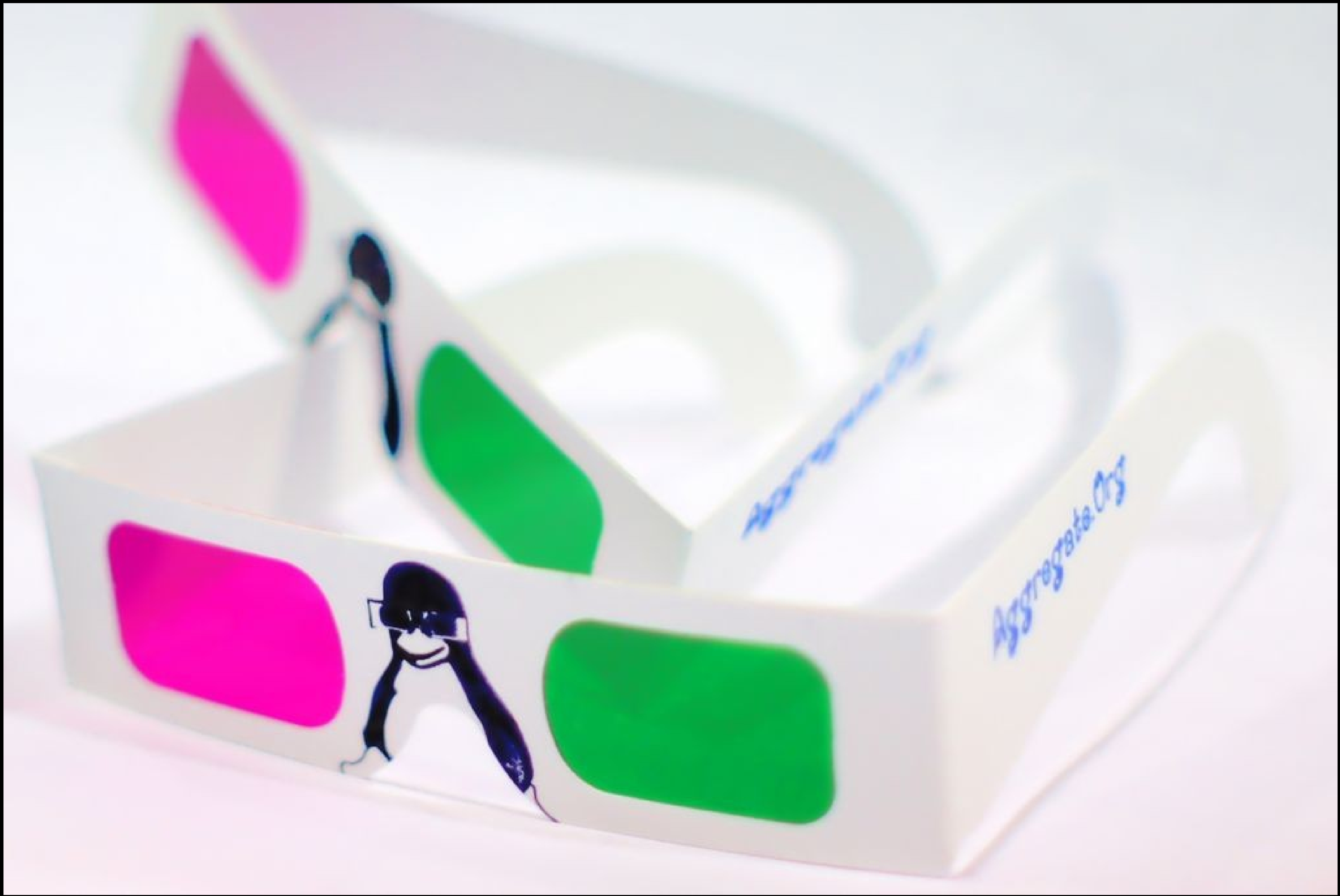
Why Not Color-Code Aperture?

- Color code views through left and right sides of the lens... to directly capture an anaglyph
- Stereo view with glasses (even live view)
- Computationally extracting the views allows:
  - Full color stereo pairs
  - After-the-fact refocus, depth capture, etc.
- Design for reprocessing, e.g., green/magenta Instead of red/cyan

Anaglyph Capture Aperture



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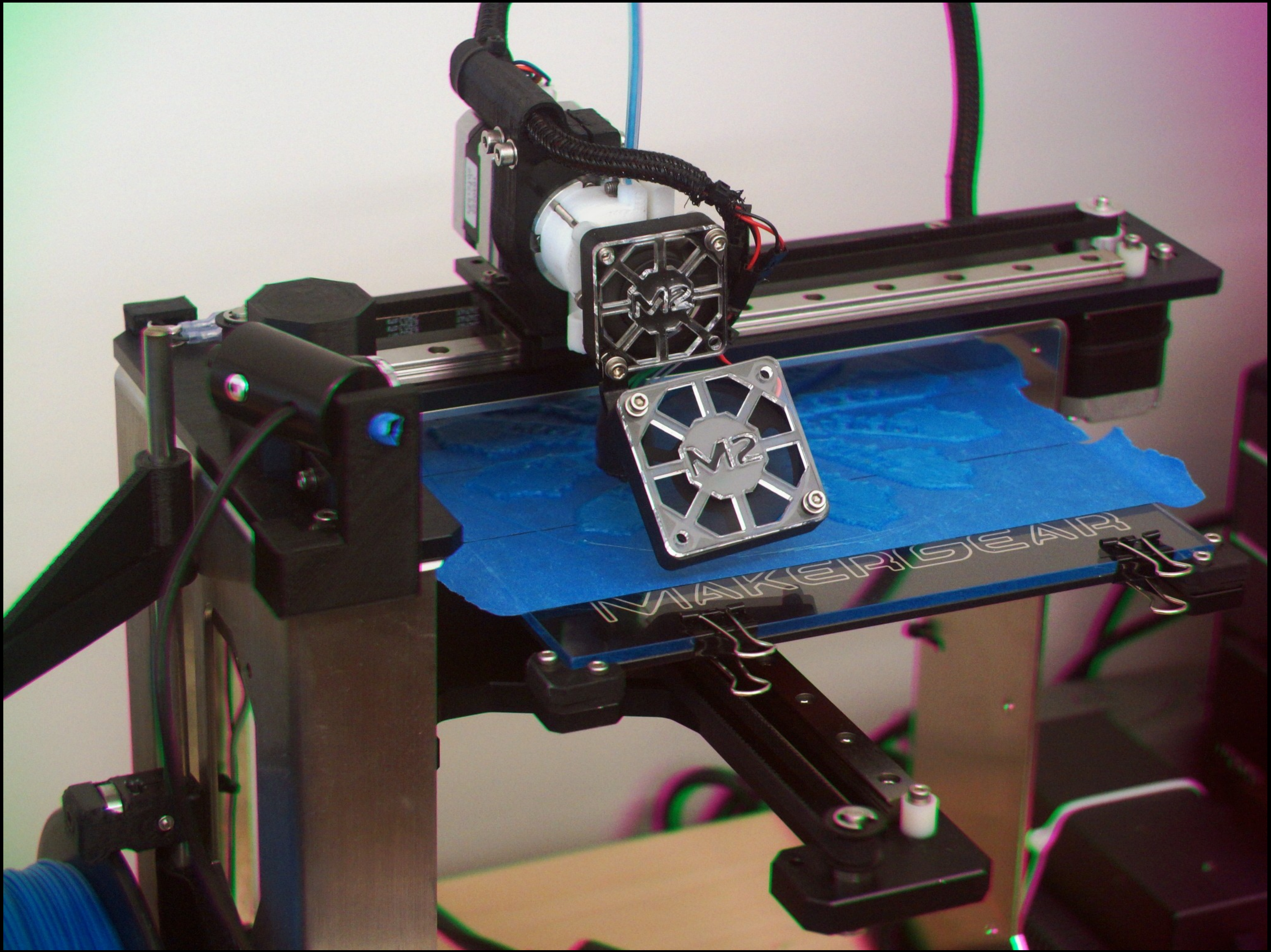
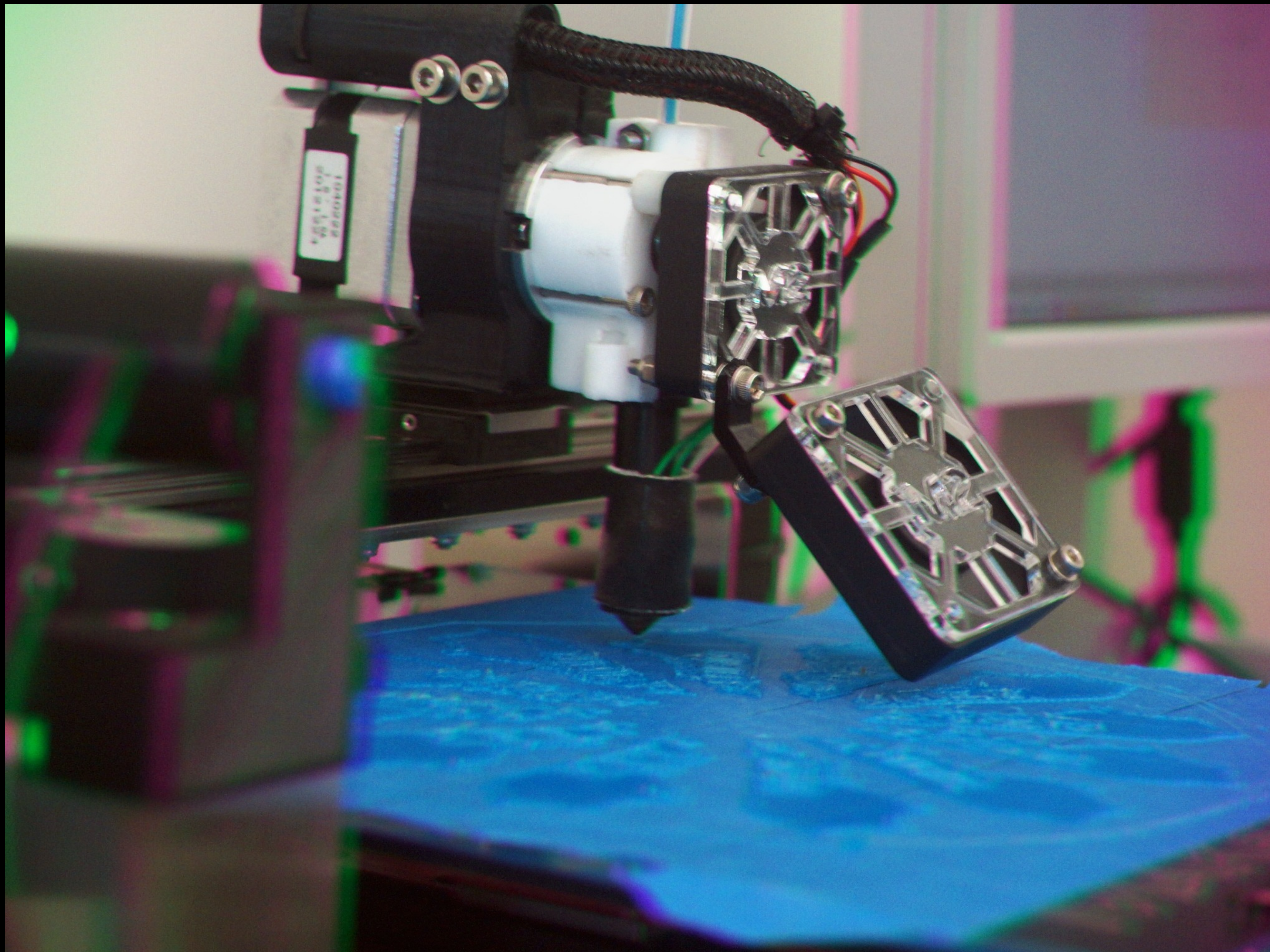


M2
M2
MAKERGEAR



Can We Computationally Create A Full-Color Stereo Pair?

- Theoretically it's impossible...

Red

Green

Blue

How To Computationally Create A Full-Color Stereo Pair

- It is really hard...
- Deconvolution fails completely, but more powerful GA PSF matching works s-l-o-w-l-y
- Blur & mask works badly
- Stereo matching has trouble finding matches
- Modified superpixel / shape matching is ok
- Color analysis currently works best...

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And now for something slightly different:

Software that replaces ugly sensor defects with pretty lies.

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FUJIFILM  White Orbs

- X10 “White Orbs” look like OOF PSFs...
- Easier to recognize and computationally Fix – which is what **`DeOrbIt`** does

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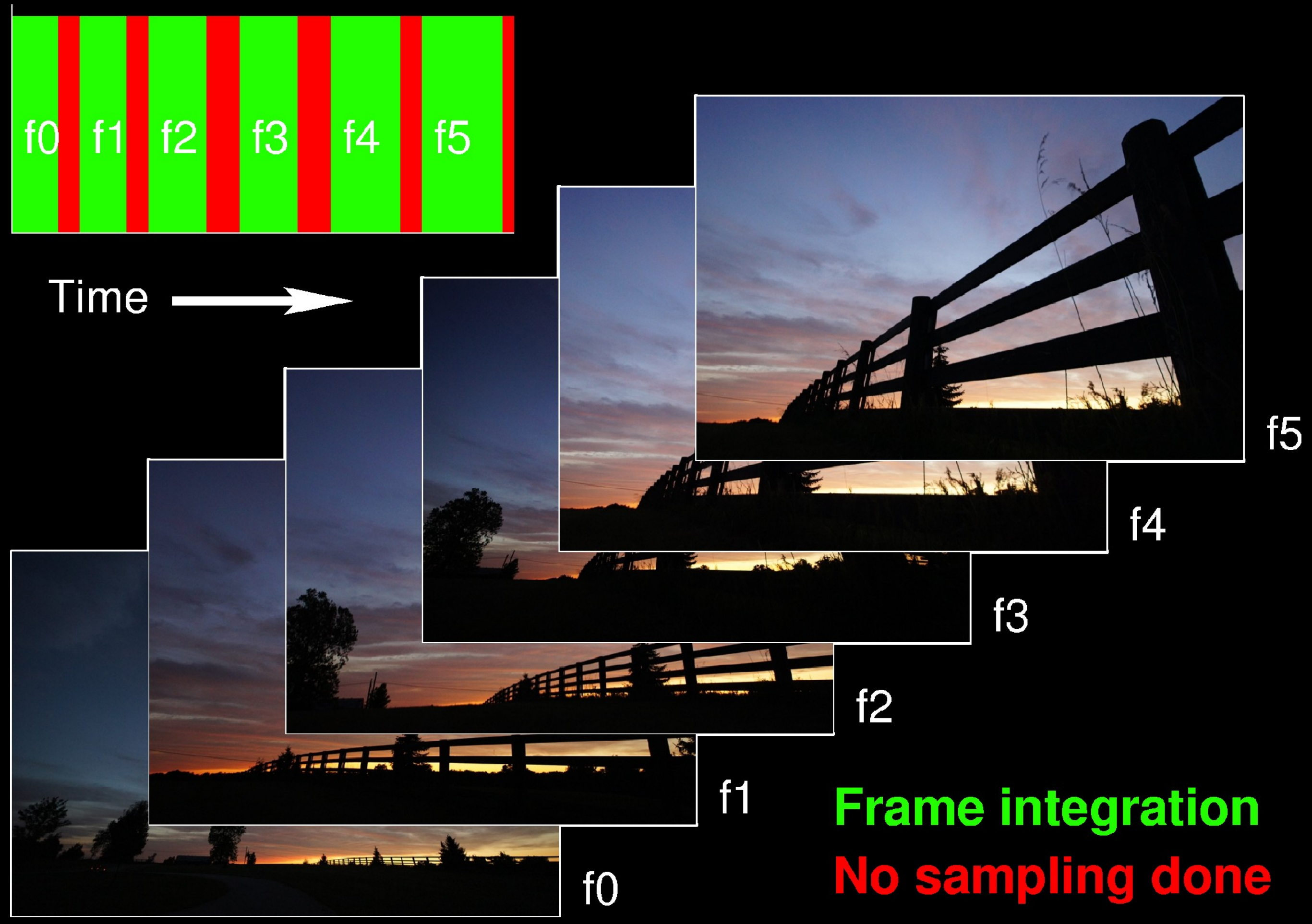
And now for something completely different:

An image sensor
that doesn't capture images.

Traditional Image Capture

- Shutter is opened
- Sensor is exposed to light; each photon adds to the accumulated analog charge (~linearly)
- Shutter is closed
- Analog charge accumulated by each sensel is read-out and digitized to form "raw" image
- Processing converts raw into JPEG, etc.

Traditional Image Capture



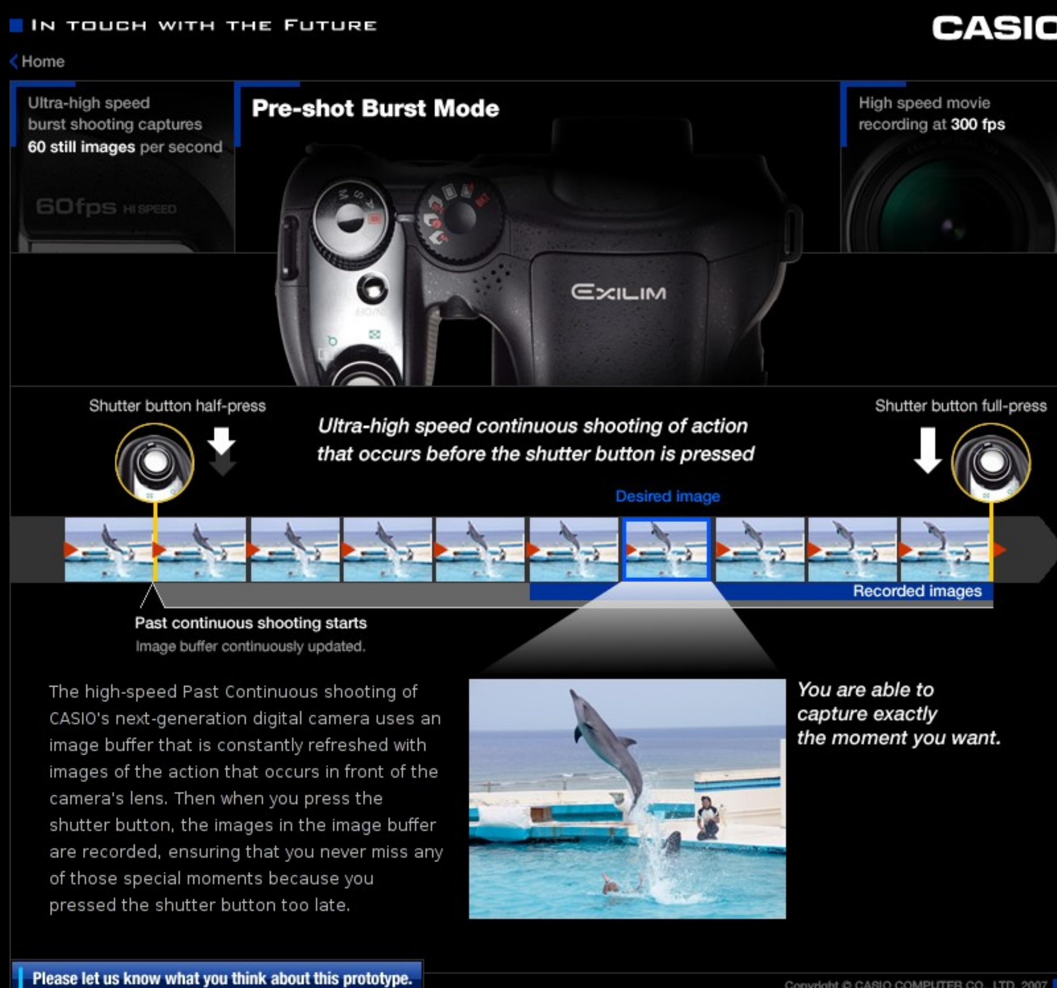
Frame integration

No sampling done

Problems: Dynamic Range

- HDR (high dynamic range) of scenes
- Linearity of sensel charge accumulation
  - Noise issues with low charge
  - Clipping/leakage at high charge
- Photon shot noise – natural statistical variation in photon emission rate; accurate sampling requires *many* photons
- Exposure interval == integration period

Problems: Shutter Lag



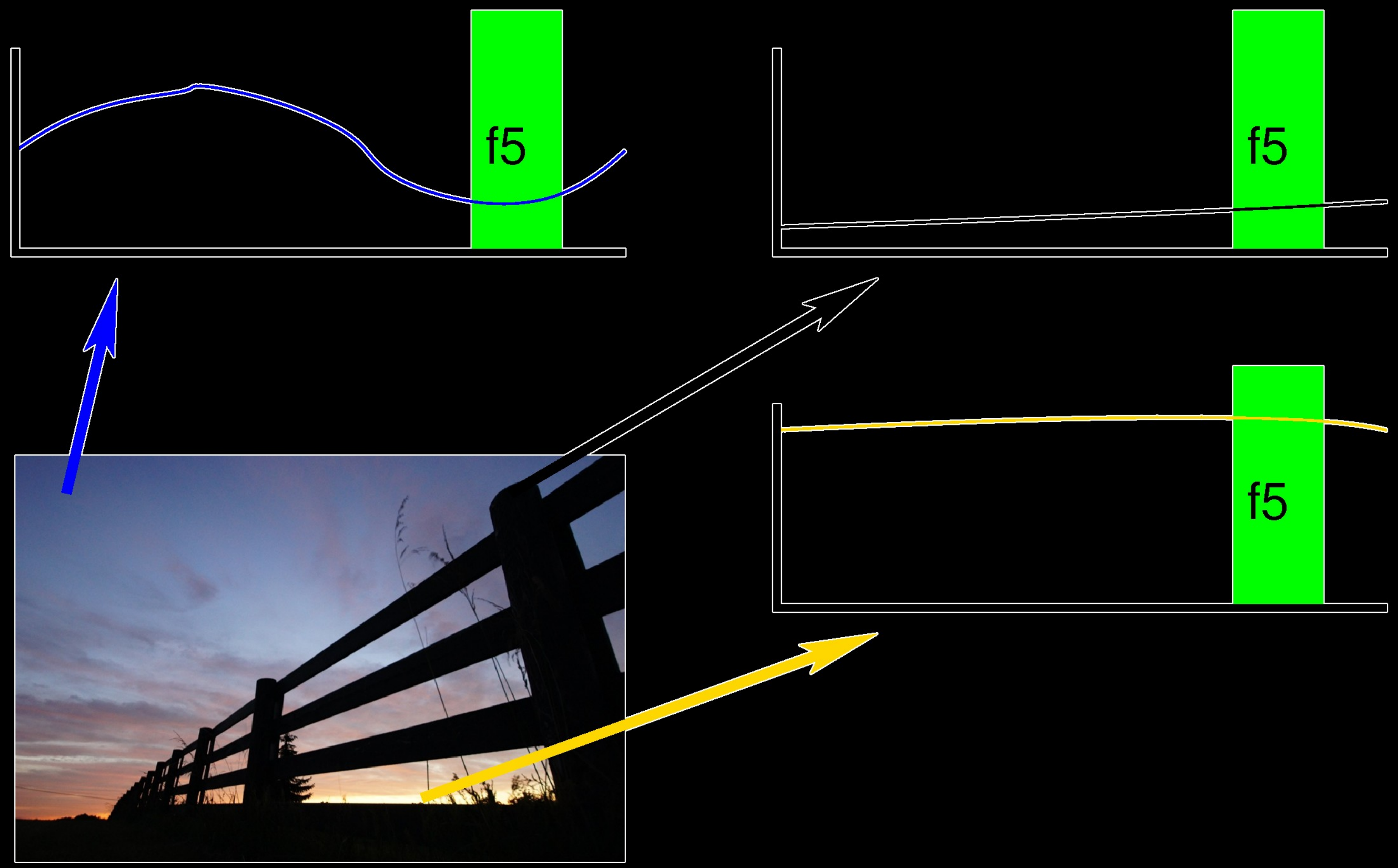
Problems: Video

- What is the framerate for movies?
  - 24 FPS 35mm film (often triple flashed)
  - 25 FPS PAL standard
  - 29.97 FPS (59.94 fields/s) NTSC
- The “jumping telephone poles” pan effect caused by time gap between frames (1/500s @ 24 FPS misses 95% of the action)

Time Domain Continuous Imaging (TDCI)

- Photon arrival rate at each sensel is measured independently at each sensel
- Raw output is the time-varying value at each sensel – a waveform per pixel, which can be efficiently compressed
- An image is formed for a given interval by computing the average value of each pixel's waveform over that interval

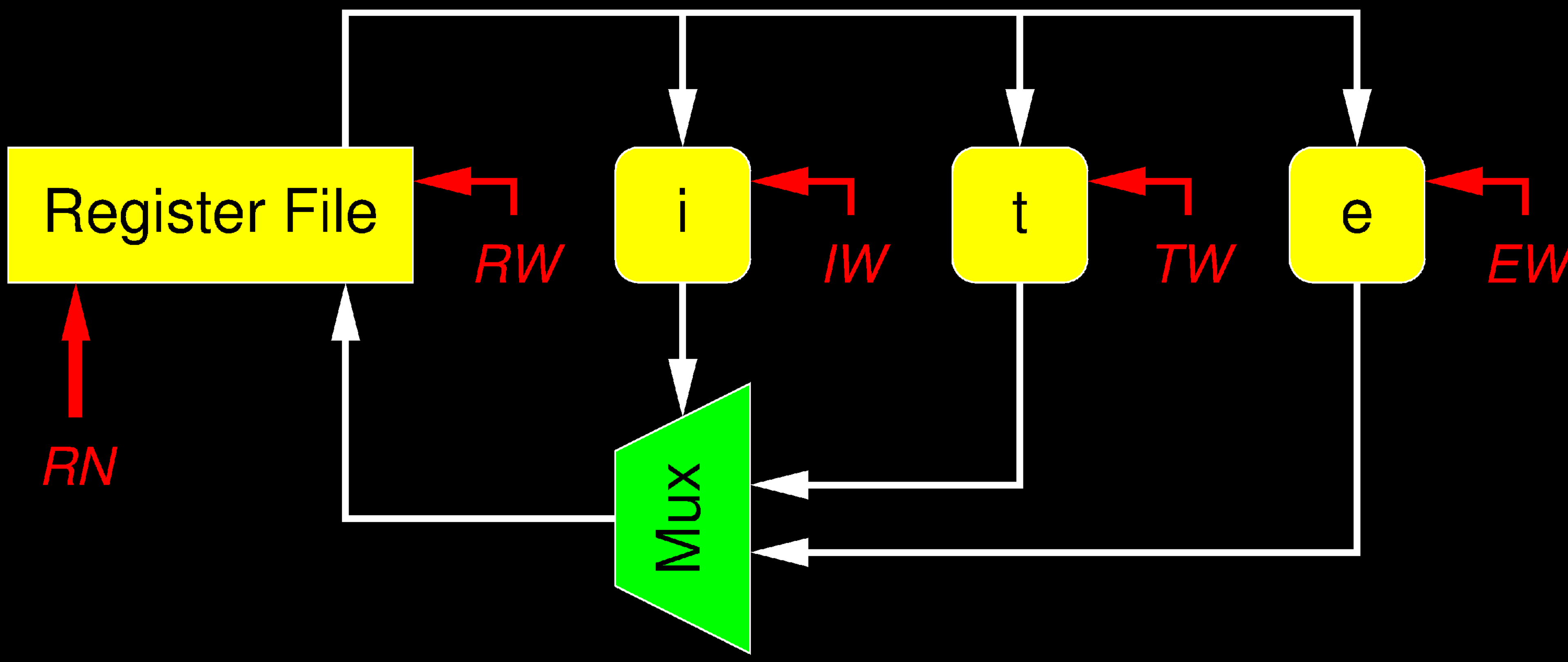
Continuous Capture



A Nanocontroller Per Sensel

- Each sensel has a tiny, programmable, nanocontroller *under* it
- Each nanocontroller counts how long its sensel takes to reach a charge threshold, then updates the encoded waveform
- The nanocontrollers together operate as a parallel computer with millions of tiny PEs, for example, reducing off-sensor bandwidth

Nanoprocessor Architecture



Nanocontroller Operation

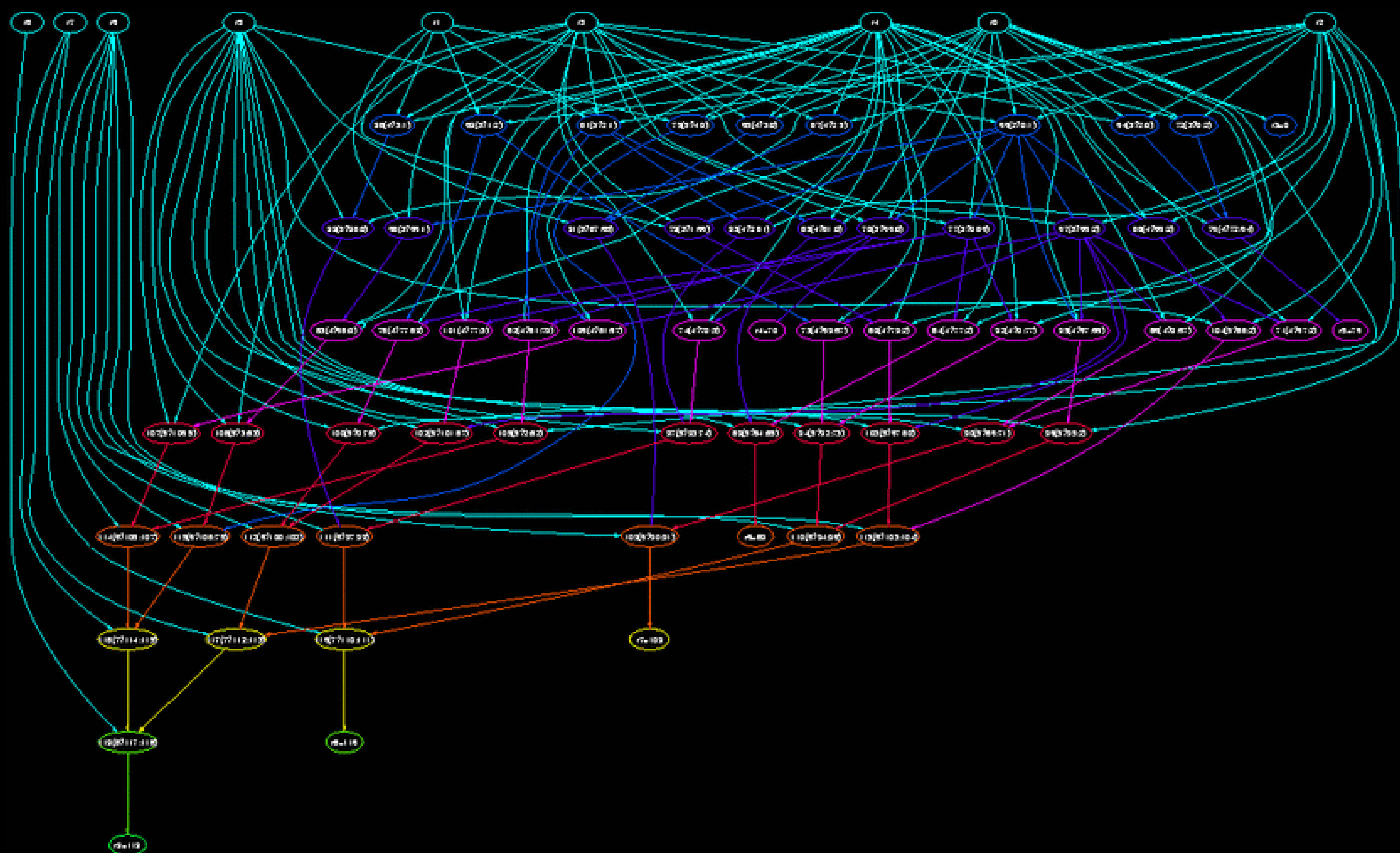
- SIMD hardware, MIMD program executed via MSC (meta-state conversion)
- Program using BitC, a small C dialect:
  - Explicit precision: `int:3 a;`
  - Mapped I/O & net: `int:1 adc@5;`
  - Adds: `?<` (min), `?>` (max), `$` (ones), etc.
- Compiled into gate-level circuit design, then serialized for just one 1-of-2 mux...

SITE (Store If-Then-Else)

- Like NAND, ITE (1-of-2 mux) is complete
- Mapping from more familiar gates:

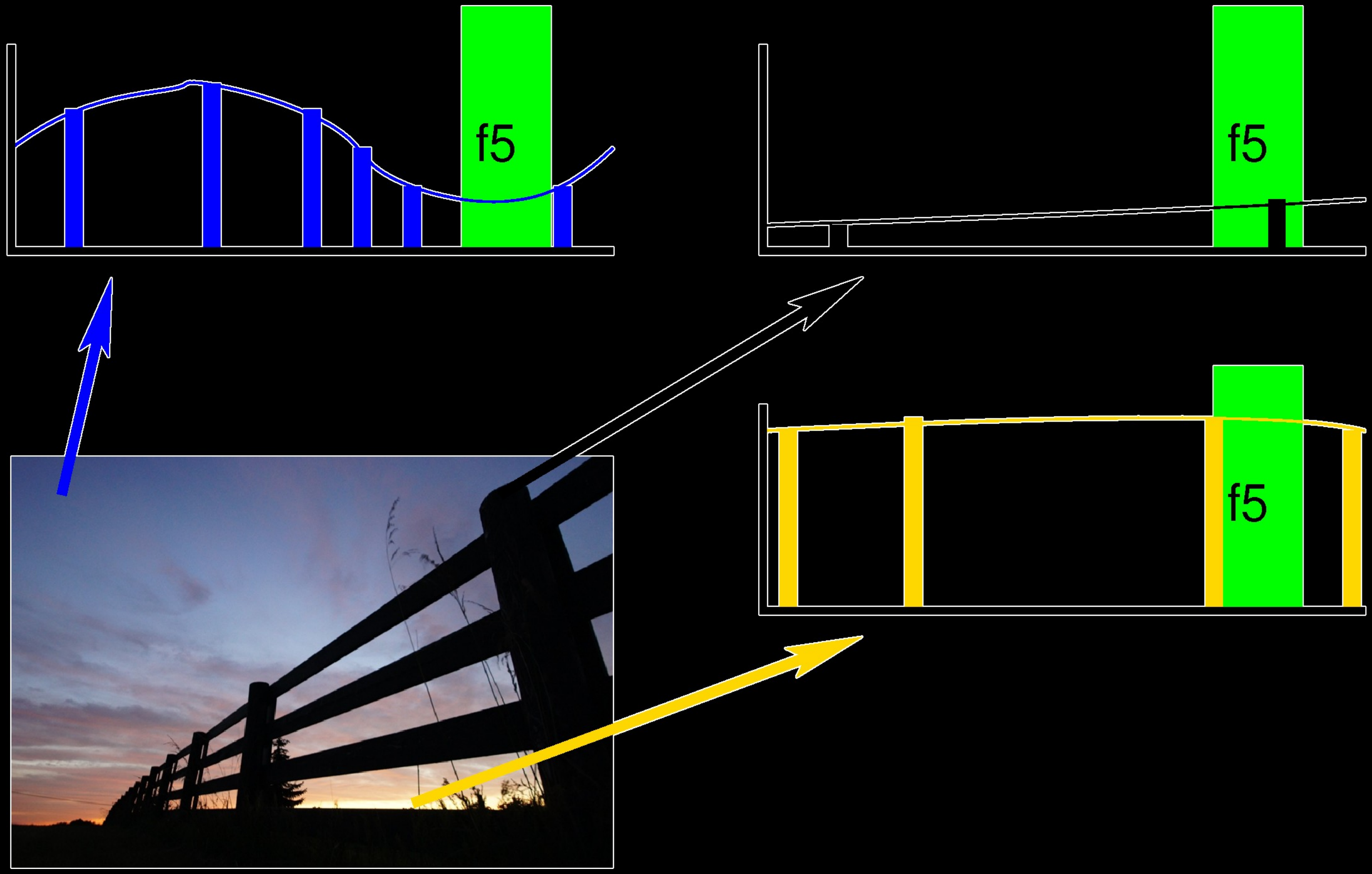
Logic Operation	Equivalent ITE Structure
(x AND y)	(x ? y : 0)
(x OR y)	(x ? 1 : y)
(NOT x)	(x ? 0 : 1)
(x XOR y)	(x ? (y ? 0 : 1) : y)
((NOT x) ? y : z)	(x ? z : y)

int:8 a; a = a * a;




Max
Pixel Value
Min
Integration Periods
Reconstructed Function
Interpolated Value
Actual Intensity
Start
Time
End

Psuedo-Random Sampling



The Camera I Want To Build

- Large format (4”x5”) solar cell based sensor
- Lens resolution → ~500MP-1.5GP
- Nanocontrollers @1GHz → ~1KFPS
- *Uncompressed ~1TB/s* HDR data stream

Conclusion

- Cameras are computing systems
- Computation controlling capture and clever post-processing are not all you can do – rethinking the entire system will enable new capabilities

Want To Know More?

Watch our research WWW site:

Aggregate.Org

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