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Frameless, time domain continuous image capture

Prof. Hank Dietz

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University of Kentucky
Electrical & Computer Engineering

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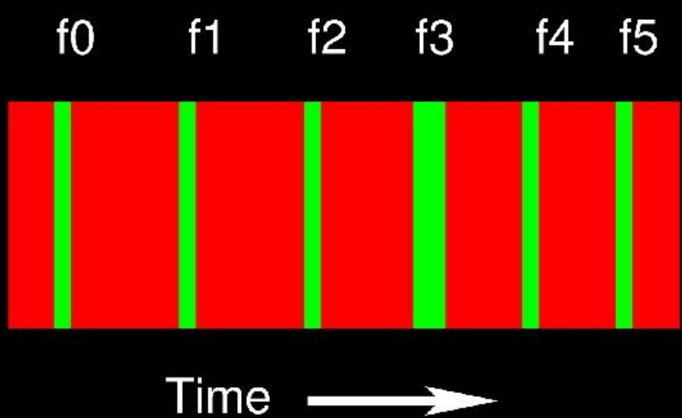
Traditional Image Capture

- 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



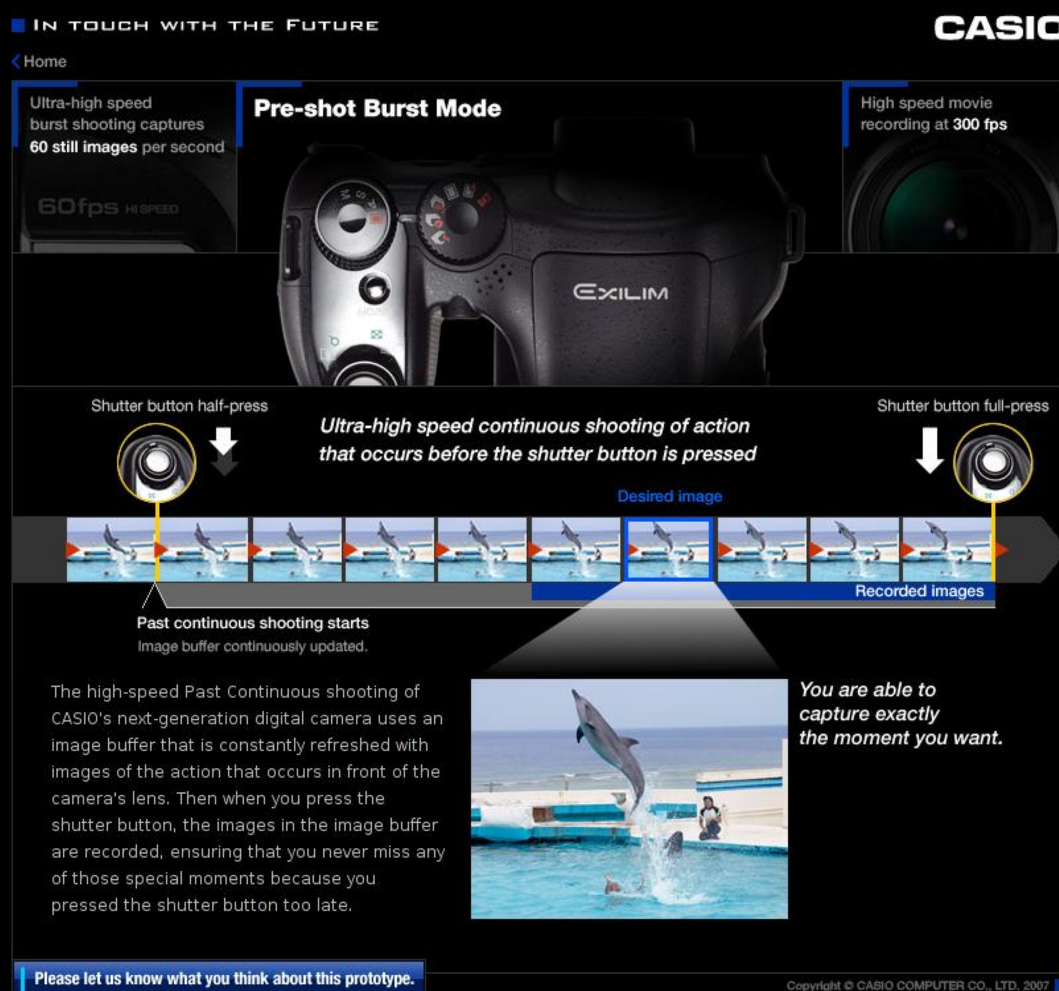
Frame integration

No sampling done

Problems: Dynamic Range

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

Problems: Exposure Interval



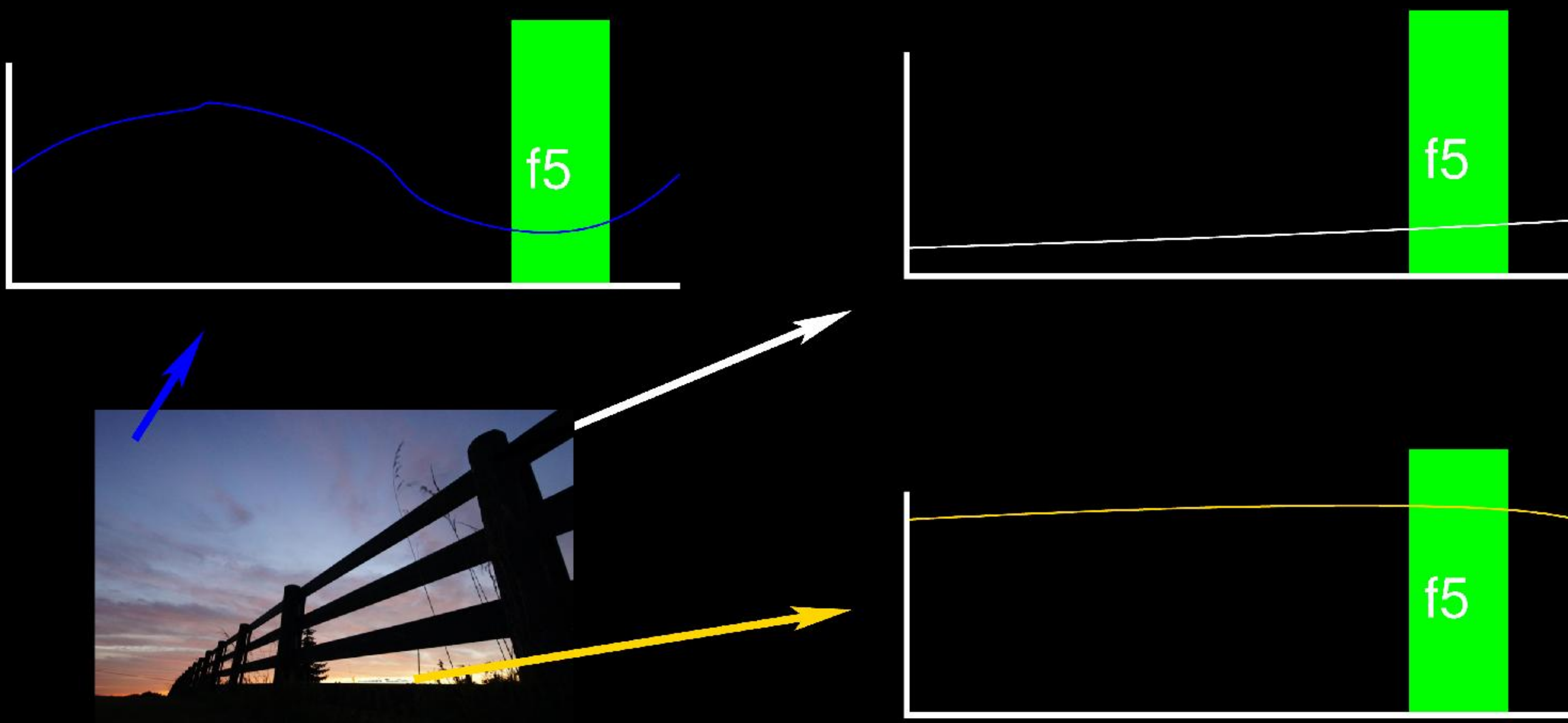
Problems: Video

- 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 on the sensor
- An image is formed for a given interval by computing the average value of each pixel's waveform over that interval

Continuous Capture



Goal: Spatial Resolution

- Fraunhofer Diffraction limit:
  2.44**wavelength*f/number*
  for 450nm @ f/1, 1.1um; @ f/5.6, 6.2um
- Line pairs per mm measurements:
  - Roughly independent of lens coverage
  - 54.3 center, 39.3 corner, average for 4x5
- Nyquist & CFA (Bayer filter) multipliers?
- 4x5 with 5um sensels is ~500MP

Goal: Spatial Resolution

~500MP confirmed using Sony NEX-5

Goal: High Dynamic Range

- Measured in units of Ev or stops
- No obvious bounds on photon arrival rate
  - Prints have tiny DR; displays <10 Ev
  - Humans instantaneously see <14 Ev
  - Consumer cameras record 9.6-14.4 Ev
  - Natural scenes often >16 Ev
- Avoid ***inherently*** limiting Ev captured...

Goal: Temporal Resolution

- Interval represented by Ev reported
- Shuttering mechanisms:
  - Leaf dynamically changes aperture
  - Focal plane temporally skews interval
  - Generally insert gaps between intervals
- Each photon has an arrival time, but one photon does not define a rate; ultimate limit on resolution is photon shot noise

Sensel Design

- Individual sensels need different integration periods for different photon arrival rates
- Possible implementations:
  - Single-pixel compressive sensing
  - Single-photon sensing
  - Threshold detection
  - Logic under a segmented solar cell

Single-Pixel Compressive Sensing

- Controversially sample below Nyquist rate, reconstruction based on sparsity
- DMD used to select random pixel areas to contribute to light falling on single sensel
- Not scalable to 500MP and beyond...

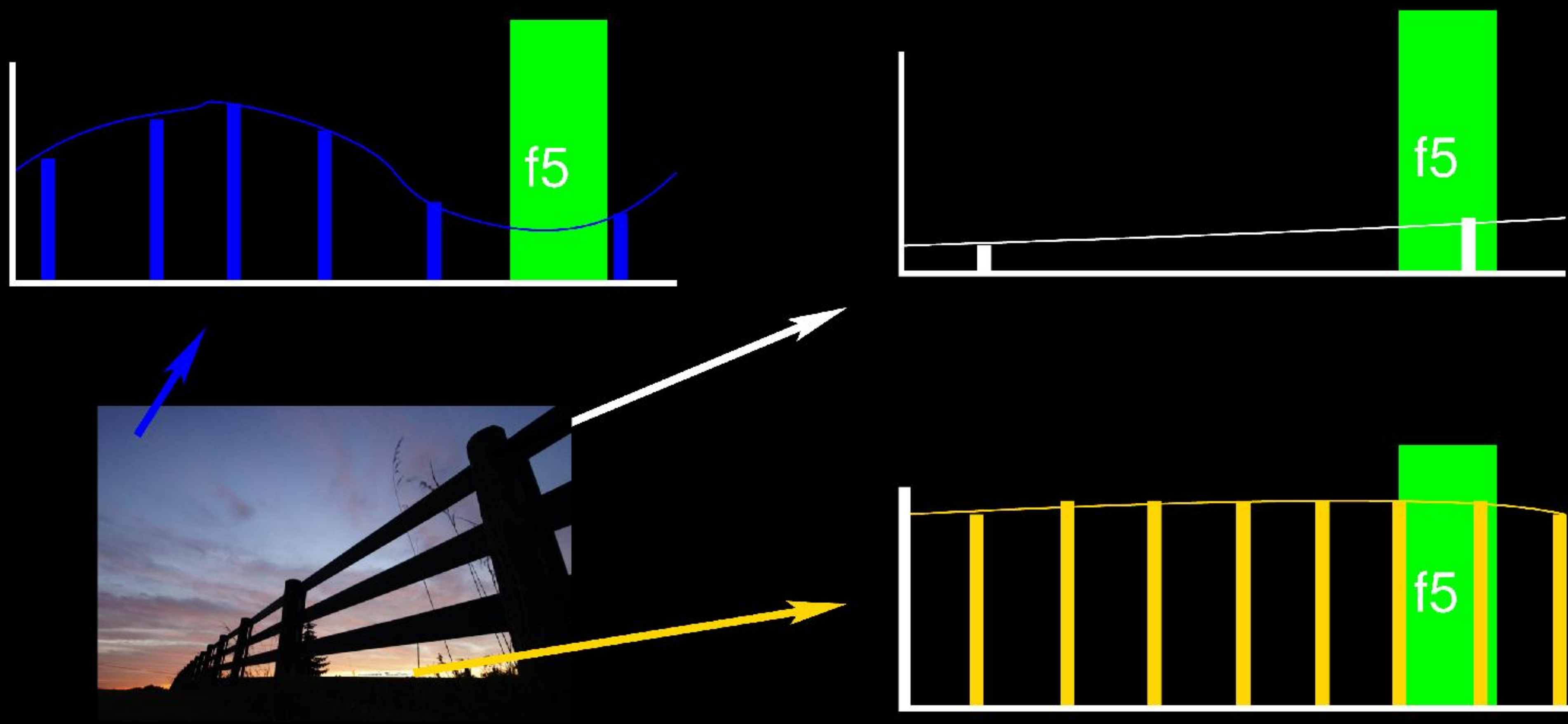
Single-Photon Sensing

- Geiger-mode avalanche photodiodes can detect single-photon events
- Intended for time-of-flight depth capture, detecting ***first*** photon to reach each sensel (with high noise reduced by many trials)
- Low spatial resolution, high I/O bandwidth
- Single photons tell more about ***the light*** than about ***the scene***... not statistically significant

Threshold Detection

- Measure time to reach set photon-count threshold at each sensel:
  - Reduce impact of noise (photon shot, etc.)
  - Ev accuracy (16 bits needs ≥ 2^{16} photons)
  - Decrease sampling frequency, data rate (single-photon 0.1ns vs. 1000ns polling)
- Many viable implementation technologies

Practical TDCI



Logic Under A Segmented Solar Cell

- Threshold detection sensor structure:
  - Digital control circuitry, passivation layer
  - Deposit solar cell film on top connecting to circuitry via diode to detect threshold
- Advantages:
  - Fab like a solar cell
  - Tunable spectrum
  - High fill factor
  - Self-powered?

Sensor System Design

- Goal of ≥500MP, ≥16-bit HDR, ≥1000 FPS conventionally would require ≥TB/s data rate
- Possible system designs:
  - Simulation using a conventional sensor (tethered UVC webcam, CHDK camera)
  - Adaptive compressive sensing
  - Nanocontrollers

Simulation Using A Webcam

- Extract frames from a UVC video feed
- For each sensel, four active counters:
  - Time (virtual) since level changed
  - # times threshold hit since then
  - Sub-threshold remainder
  - Time (virtual) since threshold last reached
- Each frame adds value, elapsed time
- TDCI output is per-sensel streams

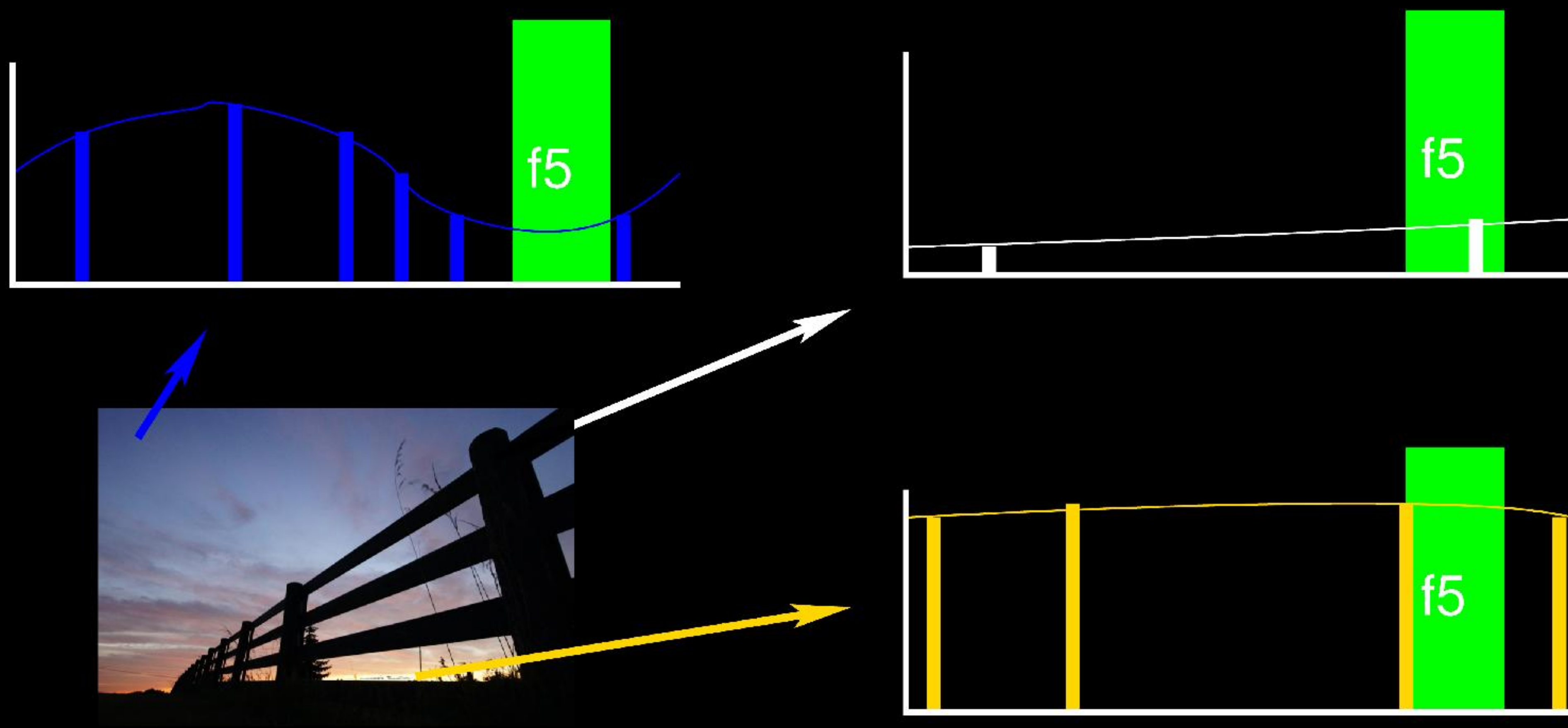
Simulation Using CHDK

- Canon Hack Development Kit allows C code to access sensor raw buffer in PowerShot
- TDCI implemented in 16MP $100 A4000:
  - Compute & save hash for each pixel block
  - Count blocks with unchanged hash
  - Output run length and changed block
- Significantly reduced data volume to write, but raw capture rate was not increased

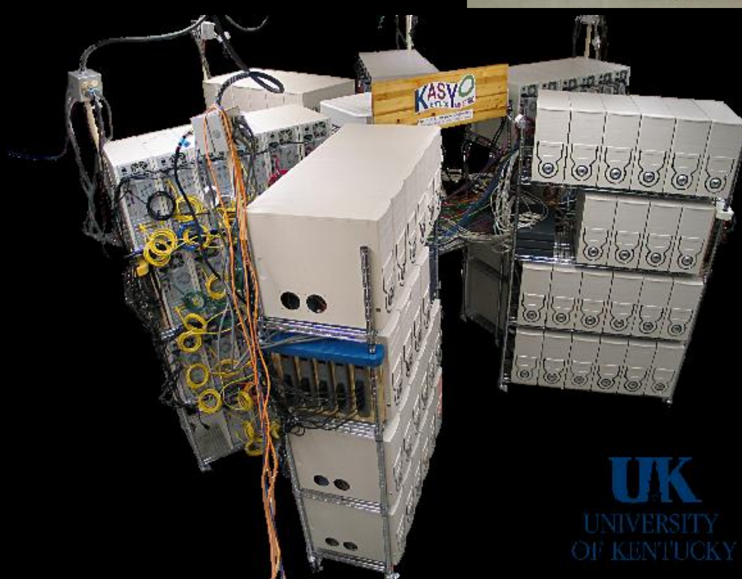
Adaptive Compressive Sensing

- Sensel is 0 until threshold, then 1 until reset
- Externally construct waveforms and track ***expected time to threshold*** per sensel
- Randomly sample sensels with ***probability proportional to uncertainty*** with which time-to-threshold may have occurred
- Can electrically sum/OR/XOR sensel 0/1 of an entire group of random sensels

Compressive Sensing TDCI

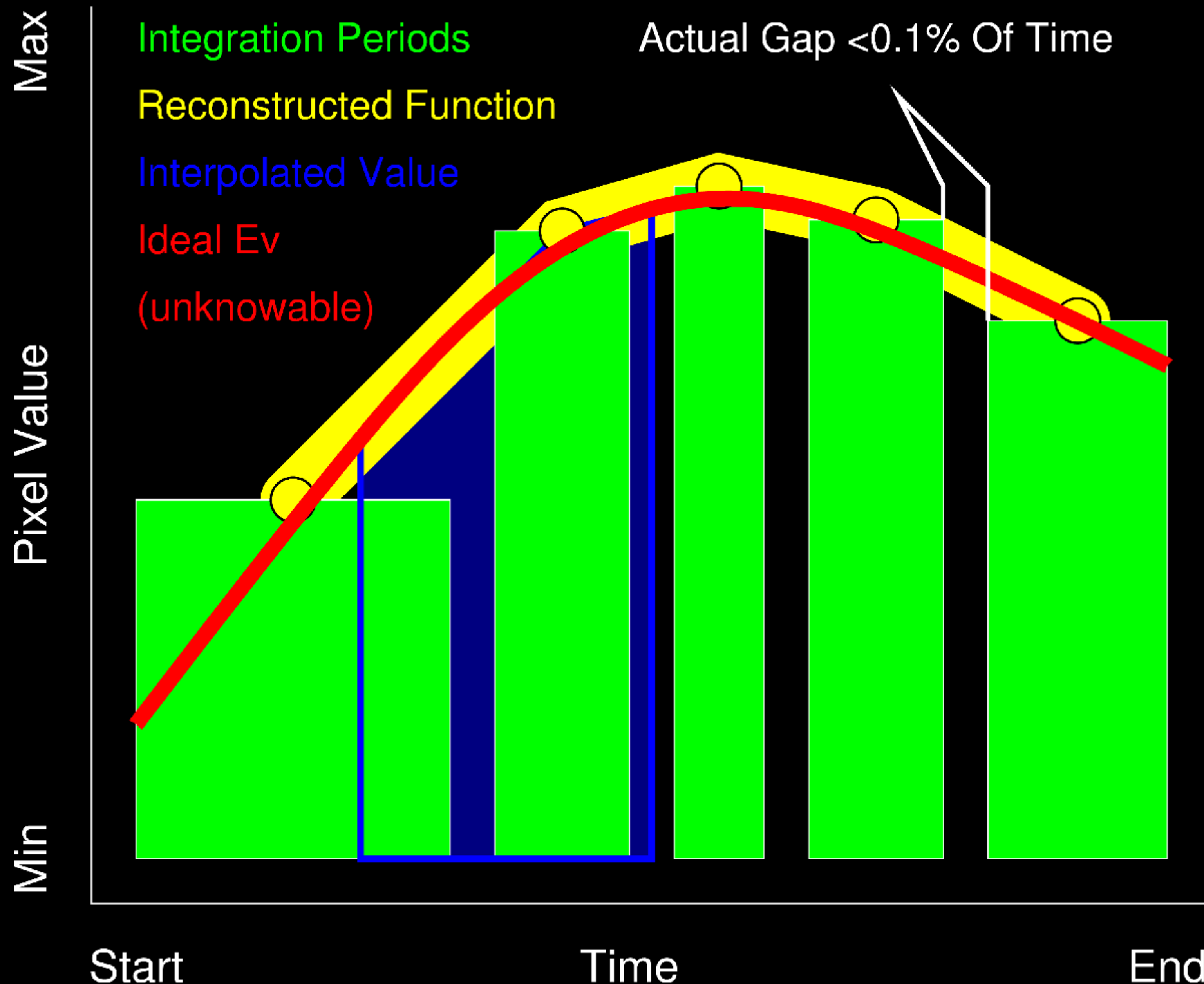


But I Like Parallel Computing...

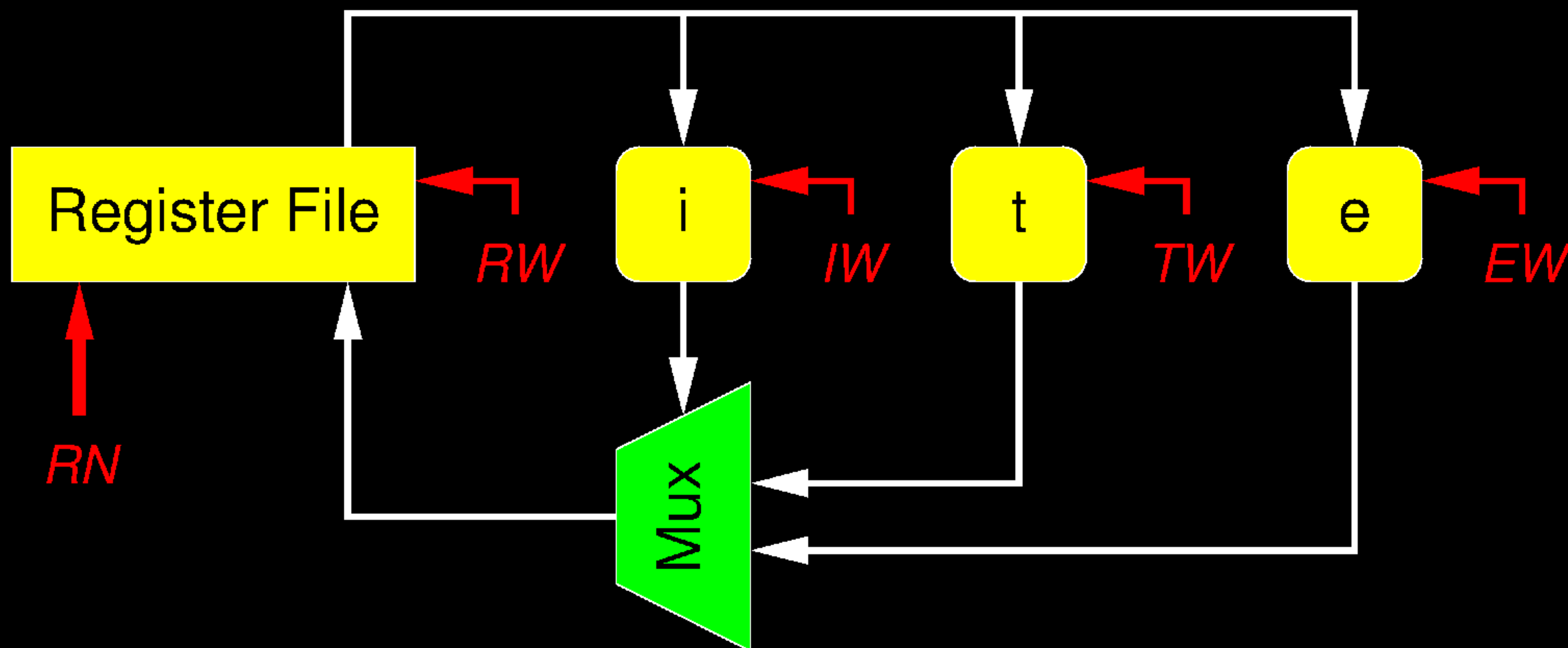


Nanocontroller Per Sensel

- 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


Max
Pixel Value
Min
Integration Periods
Reconstructed Function
Interpolated Value
Ideal Ev
(unknowable)
Actual Gap <0.1% Of Time
Start
Time
End

Nanoprocessor Architecture



Nanocontroller Operation

- SIMD parallel hardware
- Program using BitC, a small C dialect:
  - Explicit precision: `int:3 a;`
  - Mapped I/O & net: `int:1 xout@5;`
  - Adds: `?<` (min), `?>` (max), `$` (ones), etc.
- Compile into gate-level circuit design, then serialize 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)

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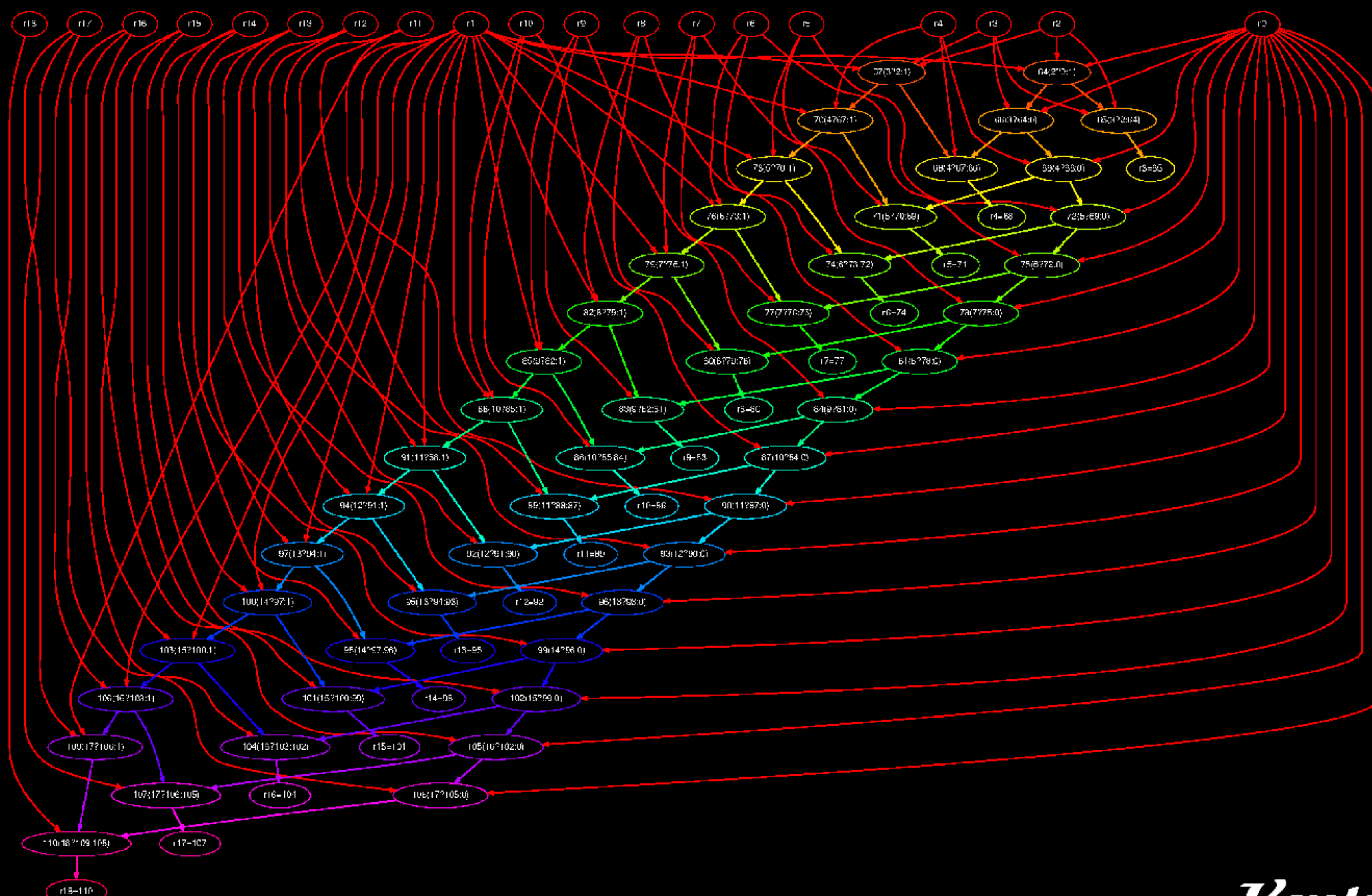
counter += !sensel;



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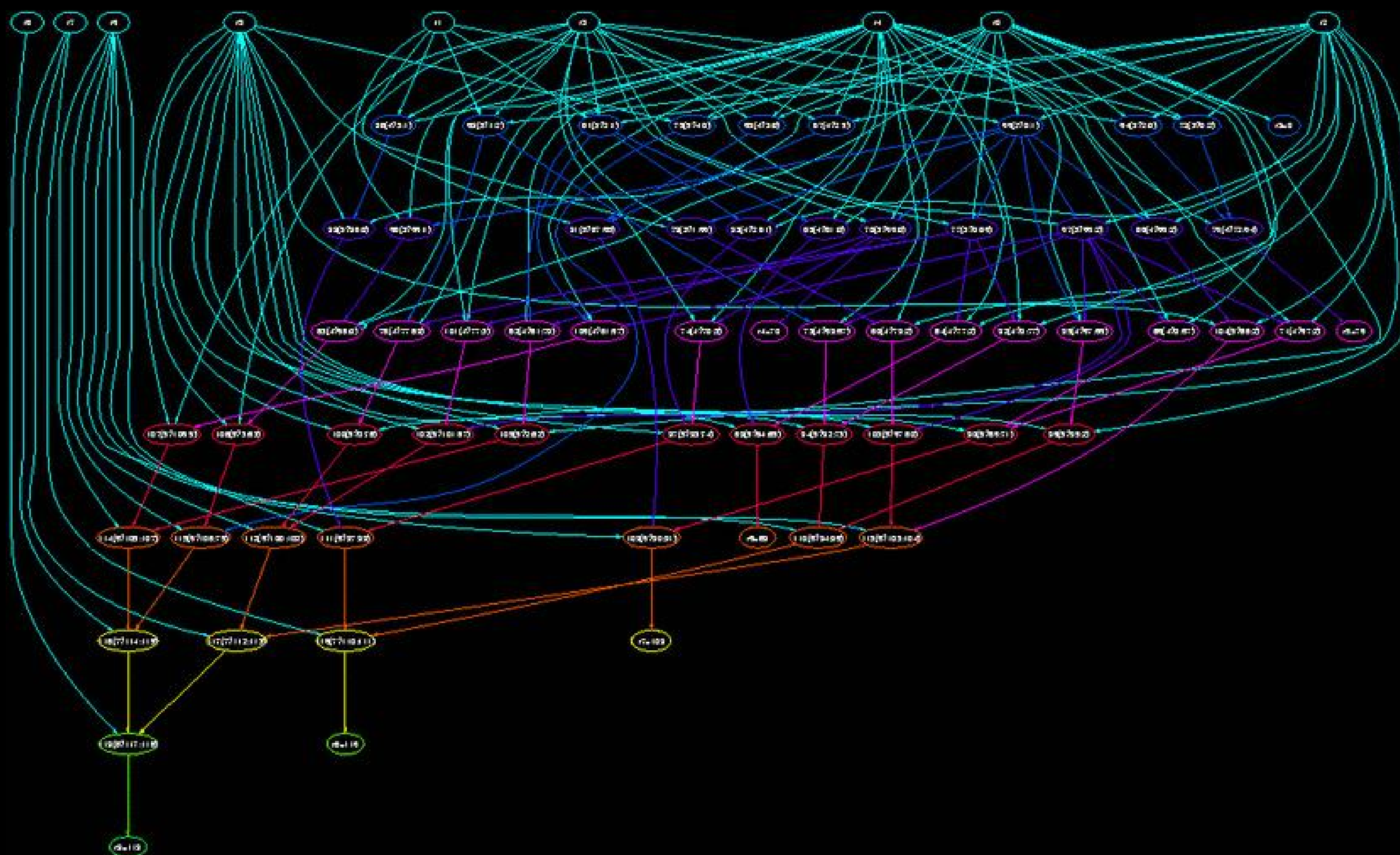
int:8 a; a = a * a;



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
- Lots of work to do on TDCI...
  - No solar-cell-based prototypes yet
  - Immature data formats & algorithms

Want To Know More?

Watch our research WWW site:

Aggregate.Org
UNBRIDLED COMPUTING