KEK Seminar
9 December 2013,
Tsukuba

CMOS Image Sensors at the Rutherford Appleton Laboratory and … a bit more

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Outline

- Introduction. STFC and some of its detector activities
- CMOS image sensors for science
  - Large area CMOS image sensor
    - Achilles
    - Lassena
    - Percival
  - Ultra-high speed CMOS image sensors
    - PImMS
    - Kirana
  - Conclusion

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UK Astronomy Technology Centre
Edinburgh

Polaris House
Swindon, Wiltshire

Chilbolton Observatory
Stockbridge, Hampshire

Daresbury Laboratory
Daresbury Science and Innovation Campus
Warrington, Cheshire

Rutherford Appleton Laboratory
Harwell Oxford Science and Innovation Campus

Isaac Newton Group of Telescopes
La Palma

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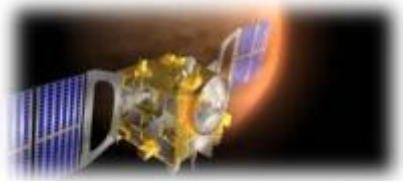
STFC in the world

STFC manage the UK contribution to large scale facilities in the world

- CERN

- European Southern Observatory ESO



- European Space Agency ESA

- European Synchrotron Radiation Facility ESRF

- Institute Laue-Langevin ILL

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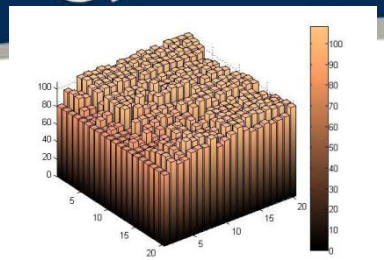

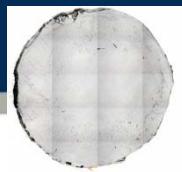

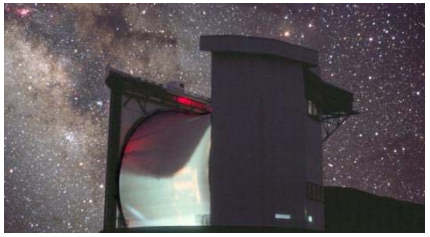

HEIS

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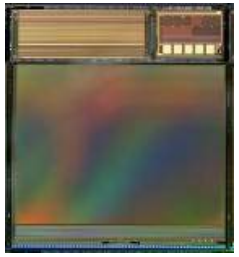
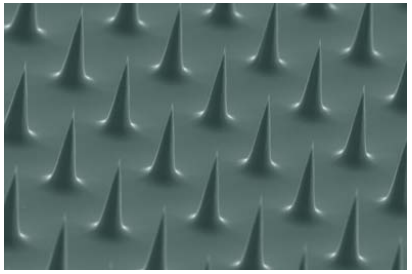
Solutions

Transfer

STFC





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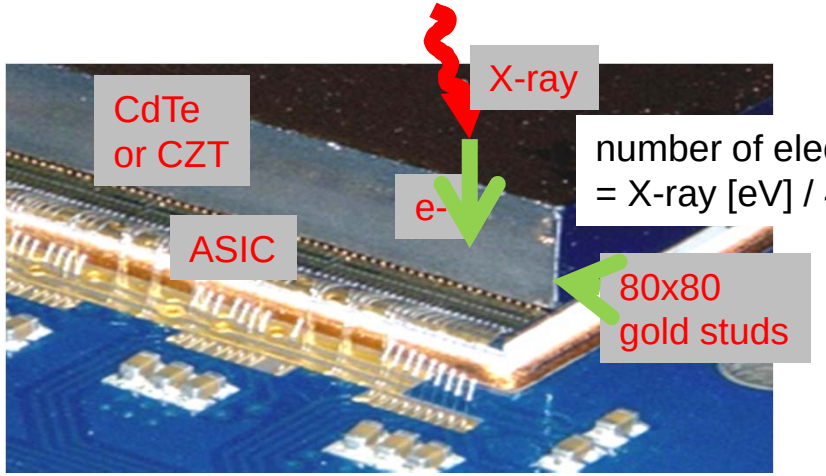
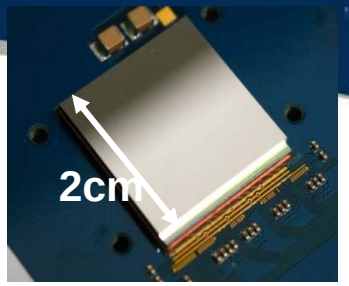
Hexitec.

Energy resolving, pixel detector

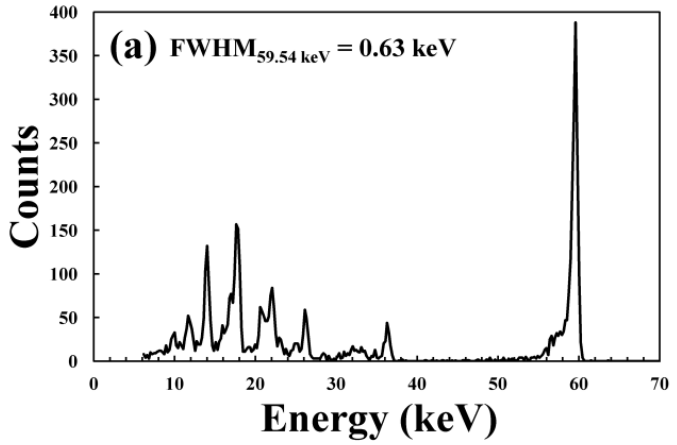


number of electrons
= X-ray [eV] / 4.2



Hexitec ASIC

- **80x80 pixels**
- **Energy Range: 4-200 keV**
- **1mm CdTe - 500V Bias**
- **$FWHM_{@60keV}$ = 0.8 +/- 0.2 keV**
- **(second range 12-600keV)**



10,000 fps @ rolling shutter

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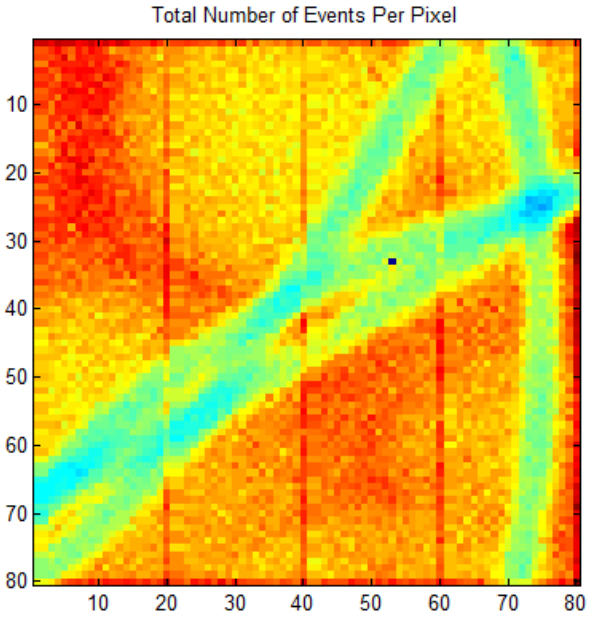
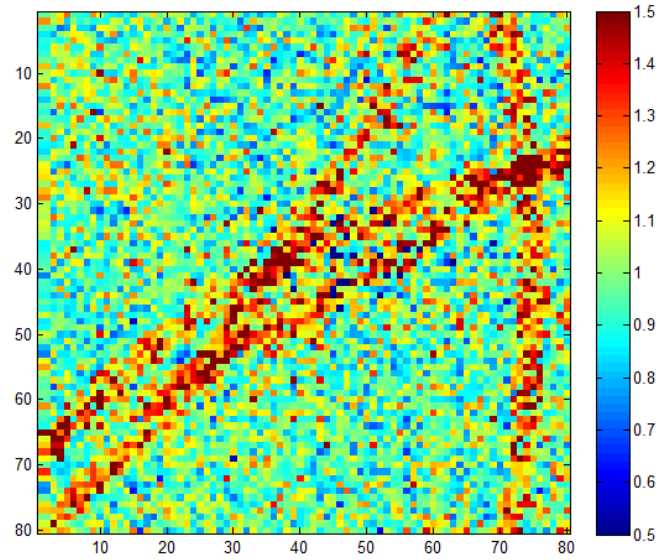
Hexitec. Next.

Hexitec: K-edge Transmission Imaging

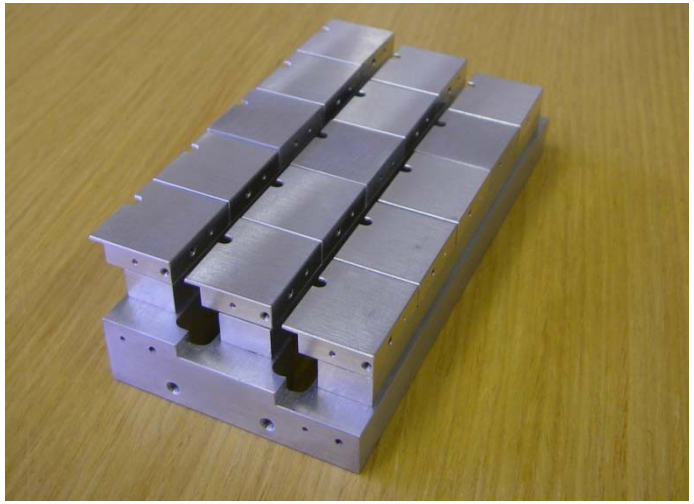


Absorption of the I in the tubing and noise of the non-uniform background.

Subtraction to remove background and leave I detail



Multi-module, large area sensor



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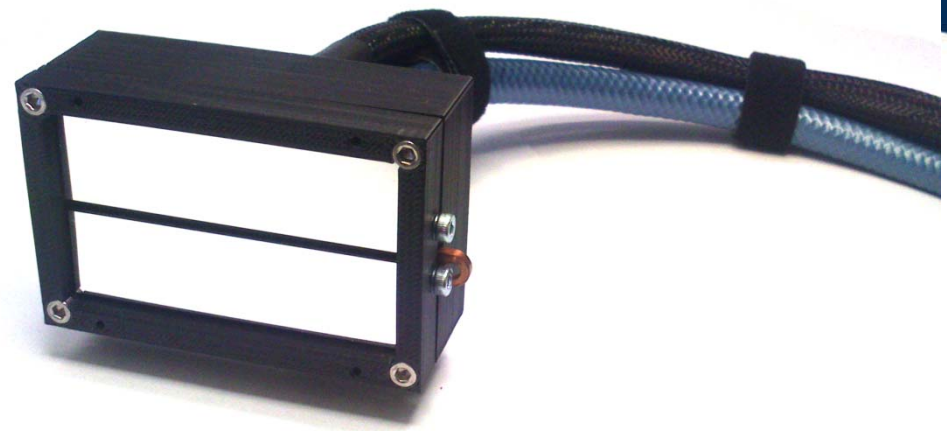
LPD.
Large Pixelated Detector

LPD is a high speed (4.5MHz) and high dynamic range (10^5 @ 12keV) integrating camera system.

Scalable system



Optimum Energy Range	5 keV – 20 keV
Sensor Thickness	500 µm
Pixel Size	500 x 500 µm
Dynamic Range at 12 keV	10^5
Inactive area	13%
Max. Frame Rate	4.5 MHz
Min. Frame Rate	10 KHz
Gain Factors	1x, 10x, 100x
Storage Capacity	512 x 3
Data Output Rate (Mpix)	10GBs

European XFEL

UCL

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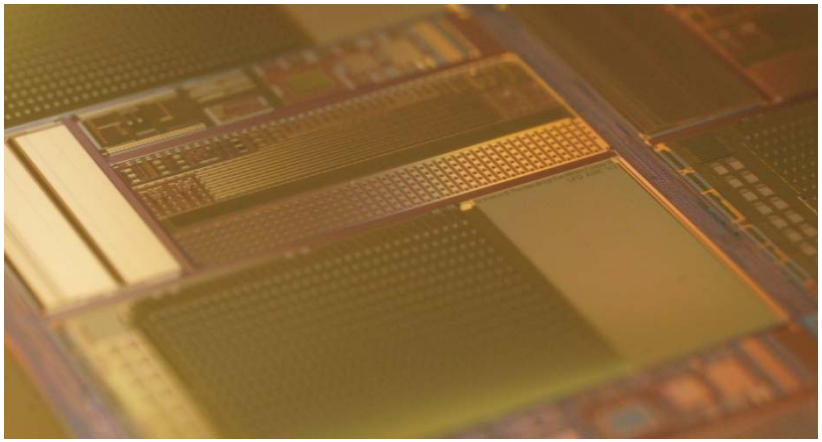
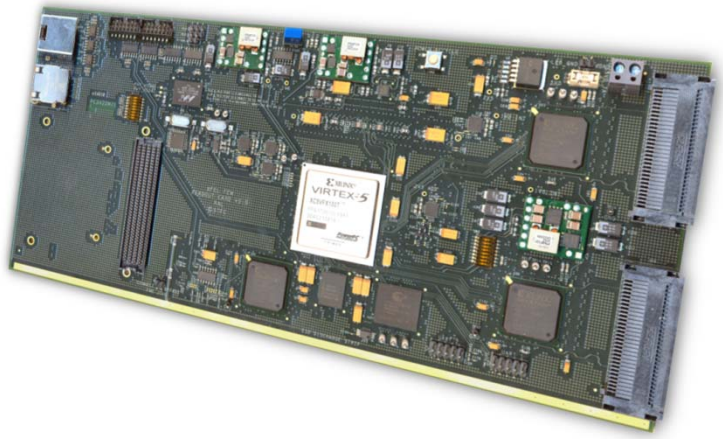
LPD.
Large Pixelated Detector

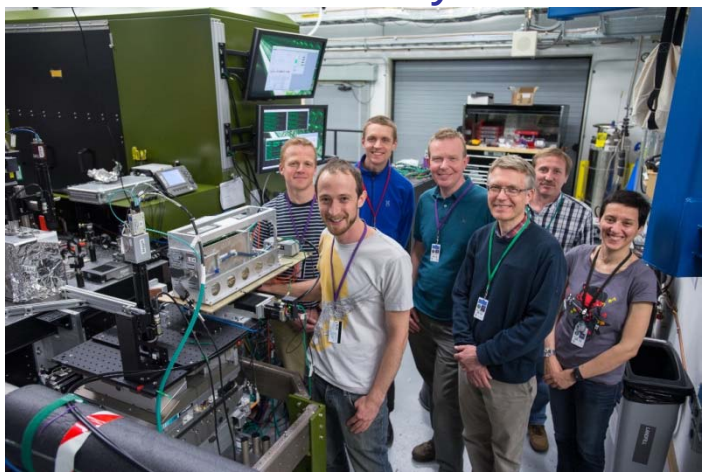
Custom ASIC in 130 nm CMOS



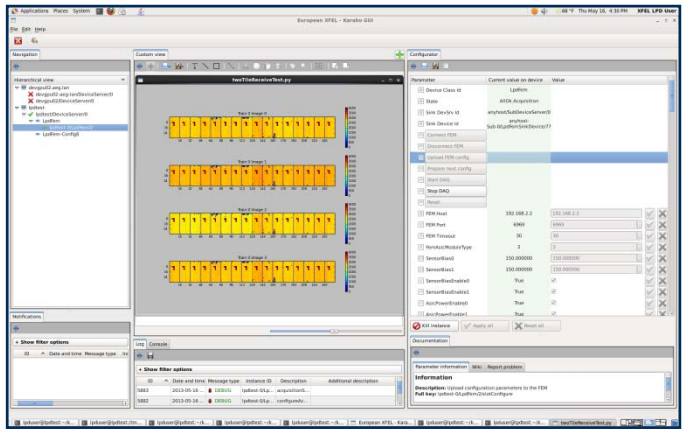
Custom DAQ. 10Gbit links



The LPD team during the beam test at LCLS this year



Custom S/W integrated with machine S/W



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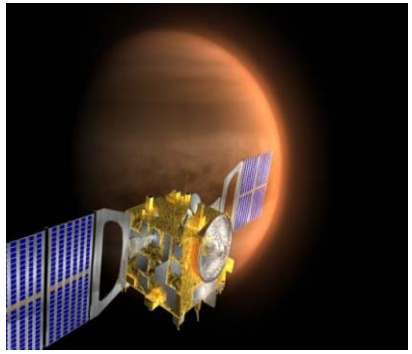
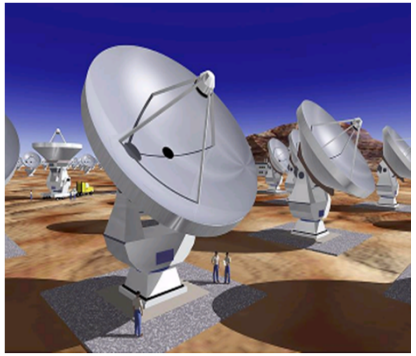
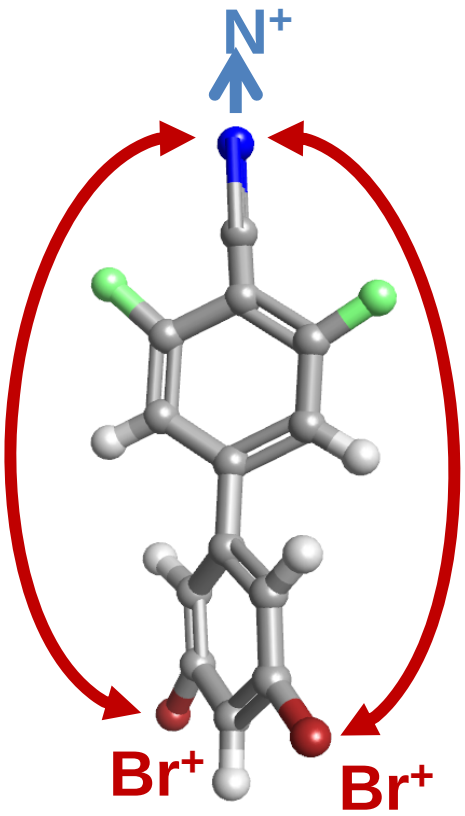
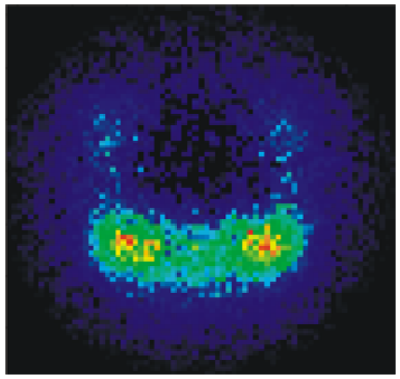
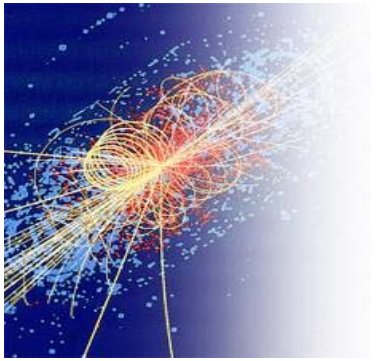
CMOS Image Sensor at RAL

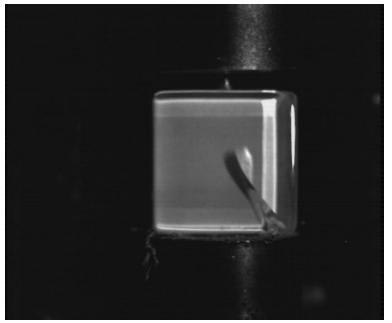


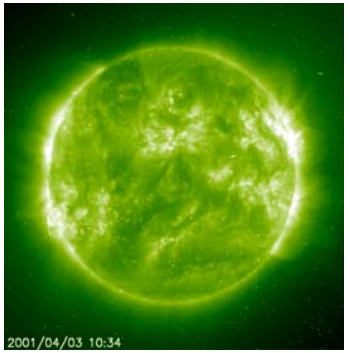












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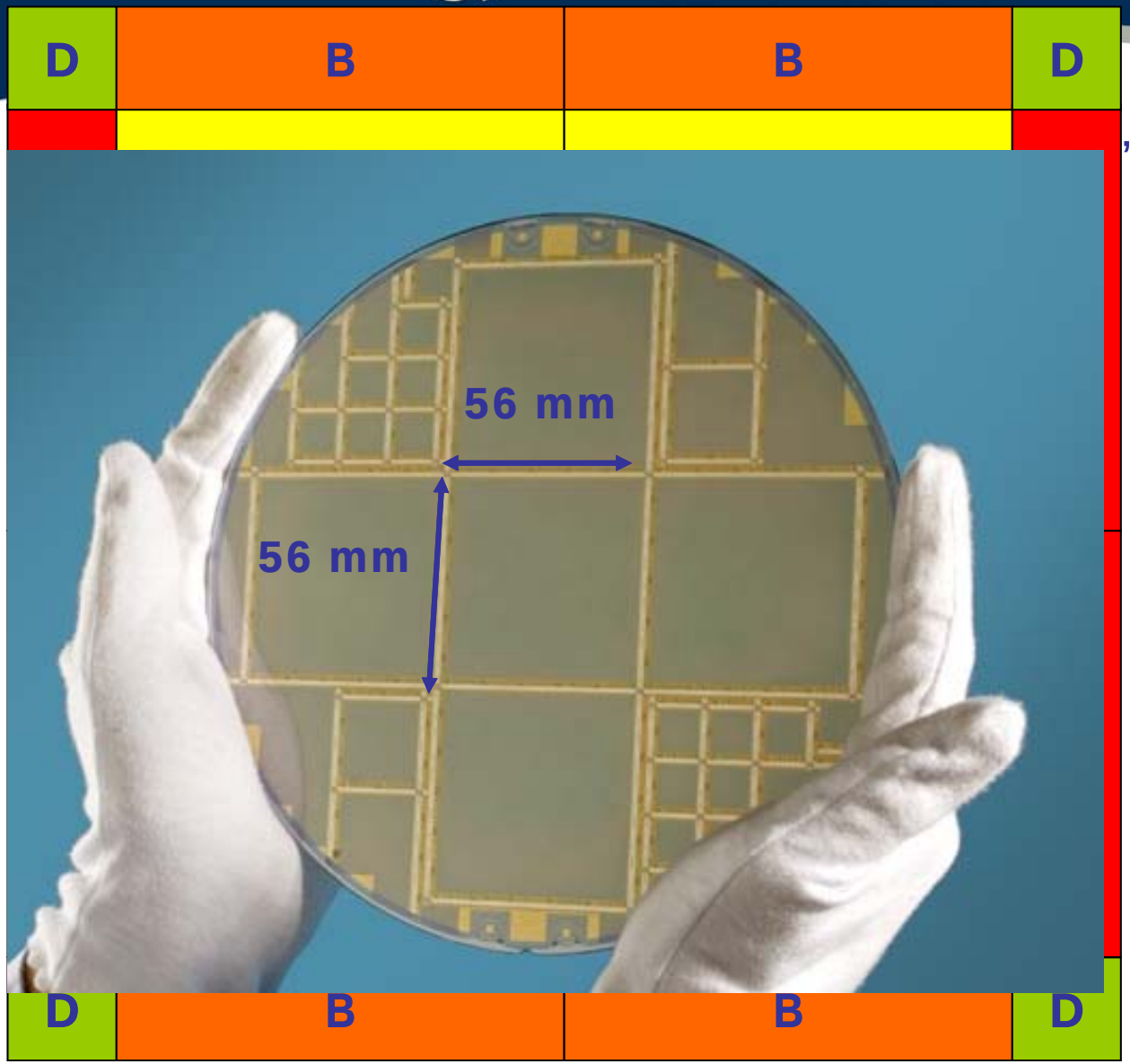
Large area sensor. Stitching.



Sensor size freed from reticle limitation → up to single sensor per wafer

Sensors of different sizes can be manufactured

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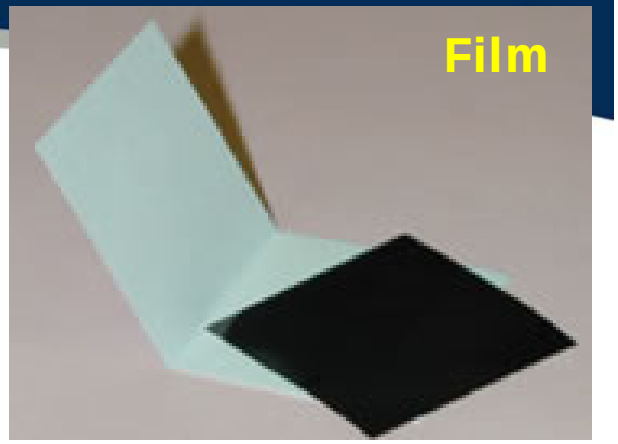
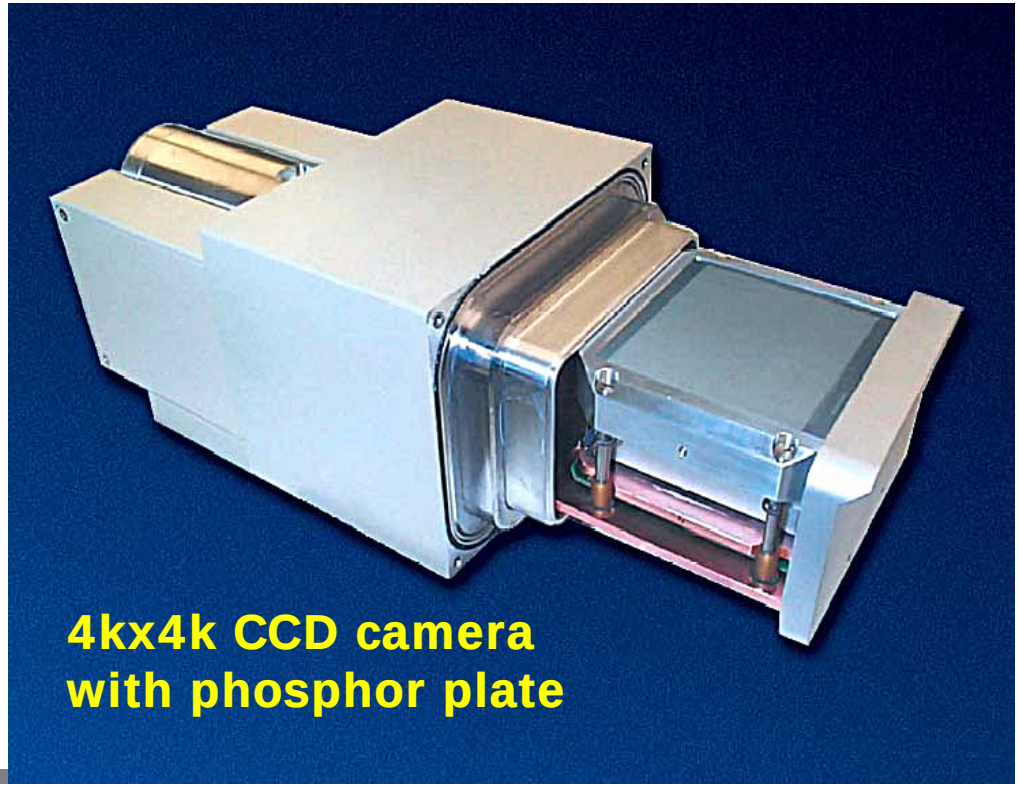
Transmission Electron Microscopy (TEM). Prior art.



- Film: direct detection, very good resolution, non digital, poor S/N for weak exposure
- CCD with phosphor: indirect detection (radiation hardness), phosphor ruins spatial resolution, good for tomography



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CMOS Sensor for TEM

- Direct detection
- Good single electron sensitivity
- Good MTF and DQE
- Radiation resistant
- 4Kx4K array
- 16 million pixels

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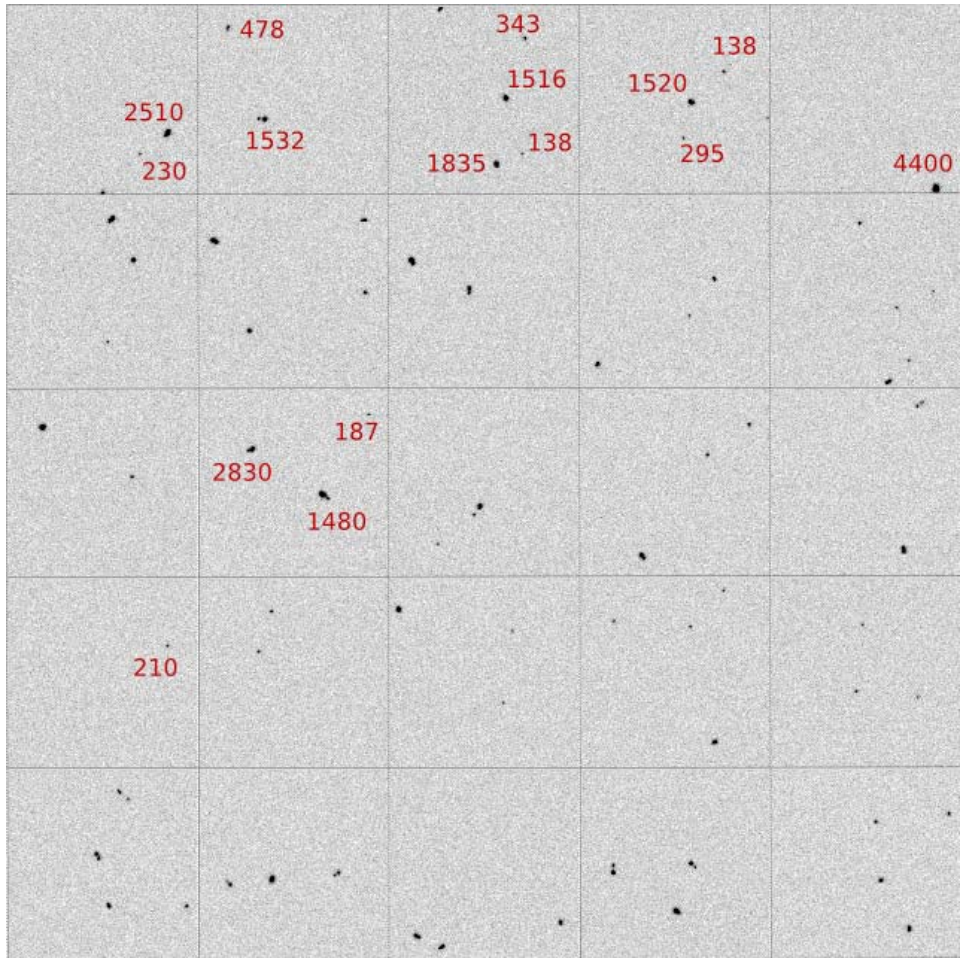
Detection of electrons in CMOS



MRC Laboratory of Molecular Biology

MAX-PLANCK-GESELLSCHAFT

FEI COMPANY
TOOLS FOR NANOTECH

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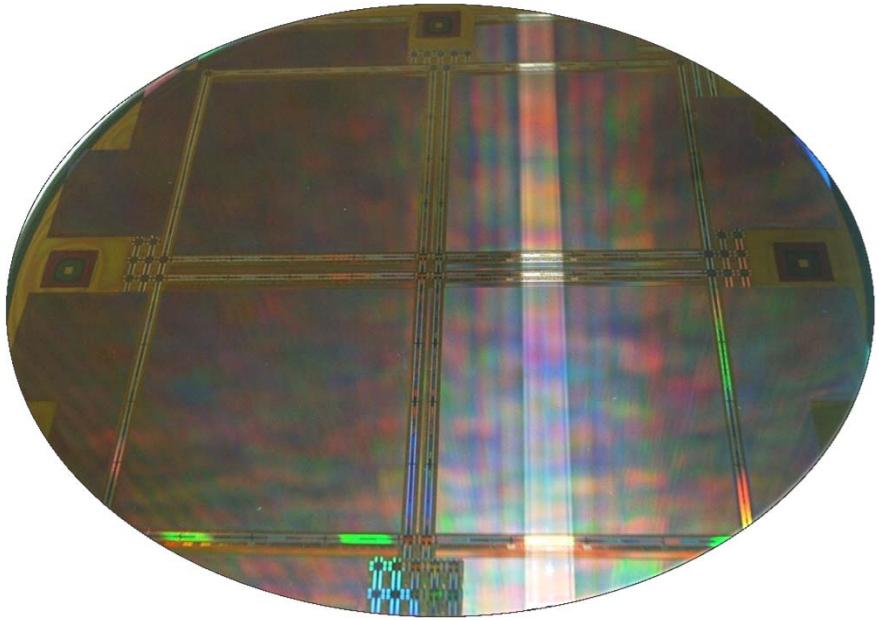
Achilles.
A 16Mpixel sensor for TEM

- 61x63 mm^2 silicon area (4 dies per wafer)
- 0.35μm CMOS
- 16 million pixels, 4Kx4K array
- 14 μm pixels
- 32 analogue outputs
- 40 fps
- Pixel binning 1X, 2X and 4X
- ROI readout
- 83 e- rms noise
- Full well 120ke-
- Radiation hardness of >500 million of primary electrons/pixel (>20 Mrad)
- 20% QE for visible light



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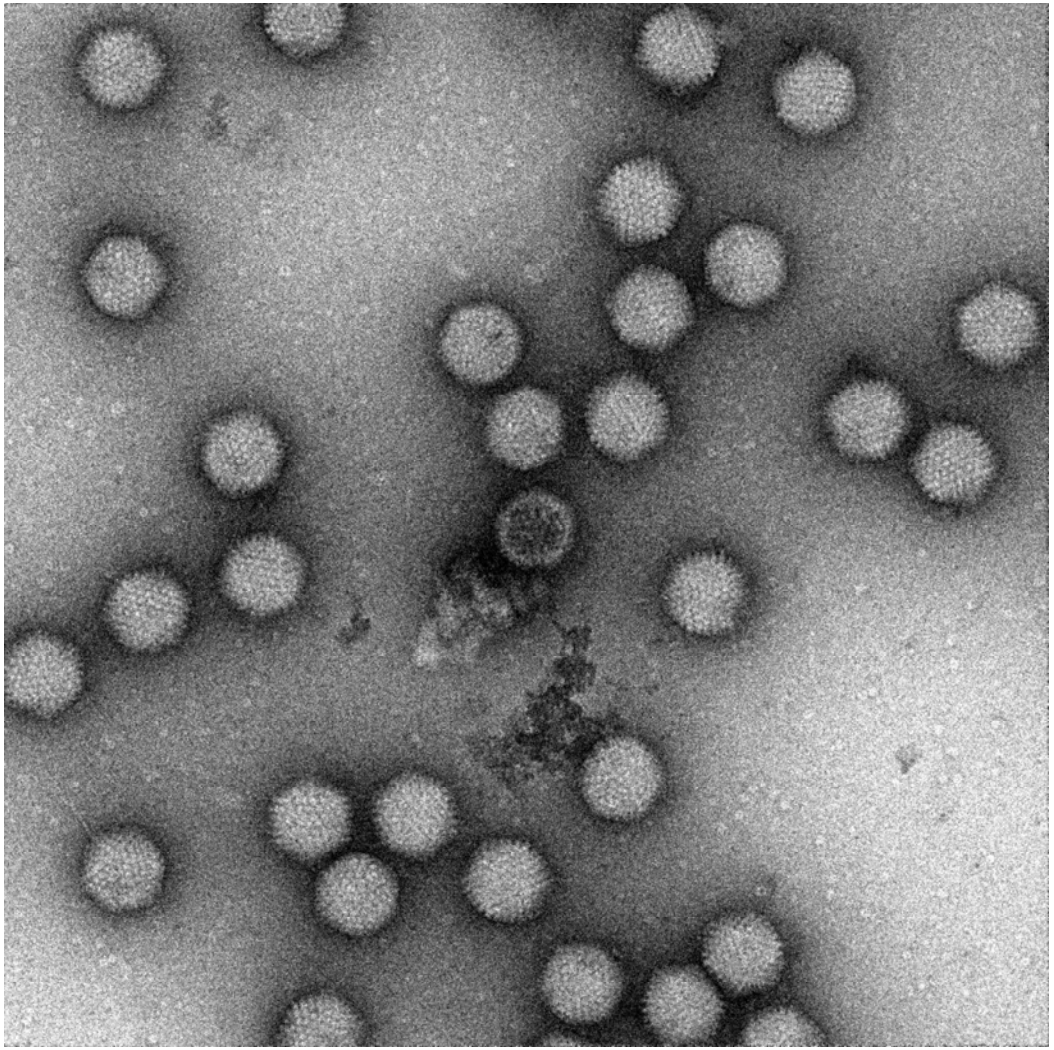
Adenovirus



Courtesy of G. McMullan (LMB, Cambridge, UK)

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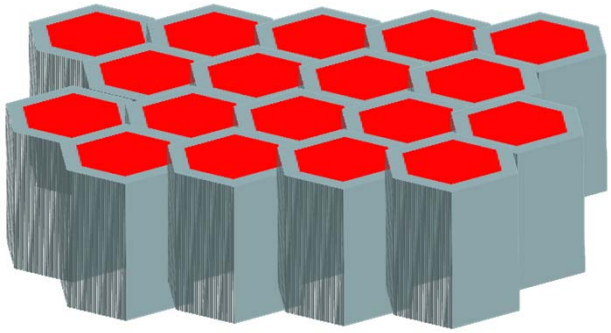
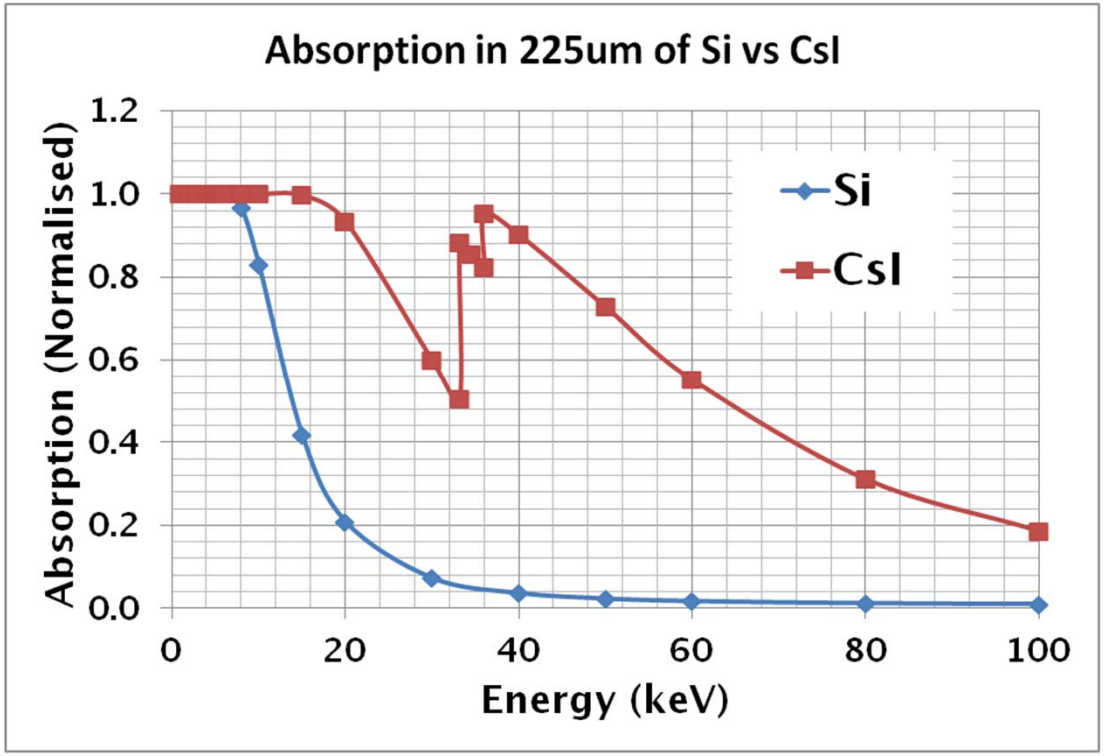
Structured scintillators

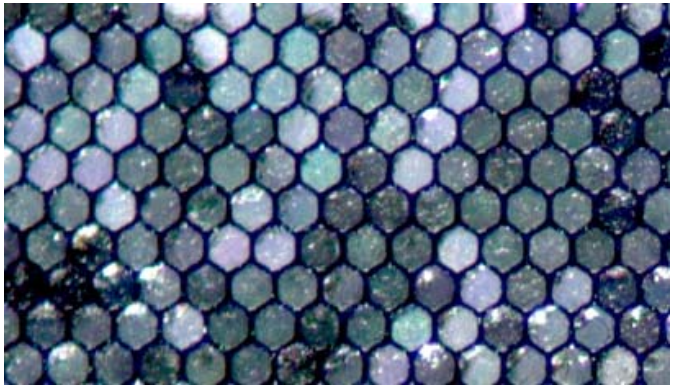
Mesh in a silicon wafer filled with CsI



'Artist view'



Photograph



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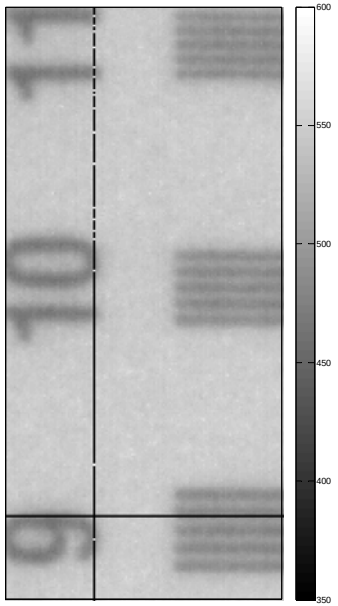
Contrast

Scintillator	CTF at 10LP/mm
Standard A	18%
New Bv1 25um pore	70±10%
New Bv2 30.8um pore	55±5%

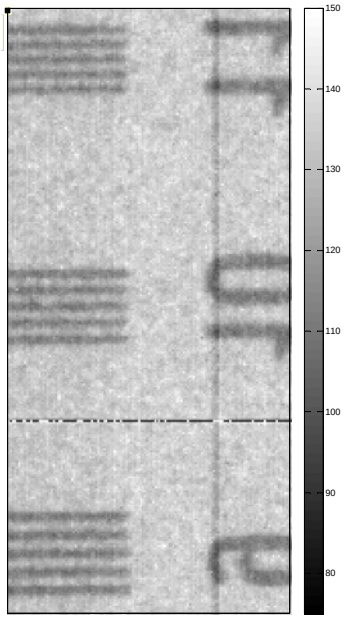
17 lpm @ 10%

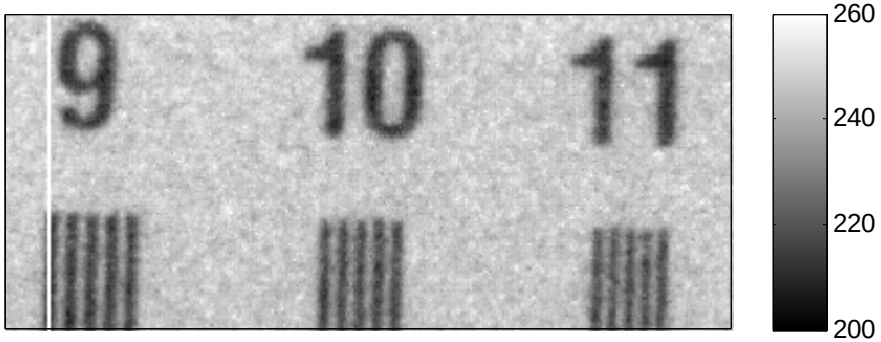
All at 120kV and 3W – noise gives uncertainty to CTF (Contrast Transfer Function) values.

Scint A



Scint B





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Wafer-scale sensor for X-ray medical imaging

Motivations

- Extra-oral dental
- with tiling:
  - Mammography
  - Chest imaging
  - Security
  - ...

Guidelines

- Wafer-scale sensor
- One sensor per 200 mm wafer
- 3-side buttable → 2xN tiling
- Radiation hard design
- Design for yield

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Main features

- High resolution. 50 µm pixel.
- High-speed. Over 30 frames per second at full resolution.
- Low noise. 68 e- rms in full frame to give very high sensitivity.
- 139mmx120mm and 3-side buttable for large area coverage.
- High dynamic range. Multiple programmable integration times
- Binning x2, x4 and Region-Of-Interest (ROI) readout
- Manufactured in 180 nm CMOS Image Sensor process from TowerJazz Semiconductor

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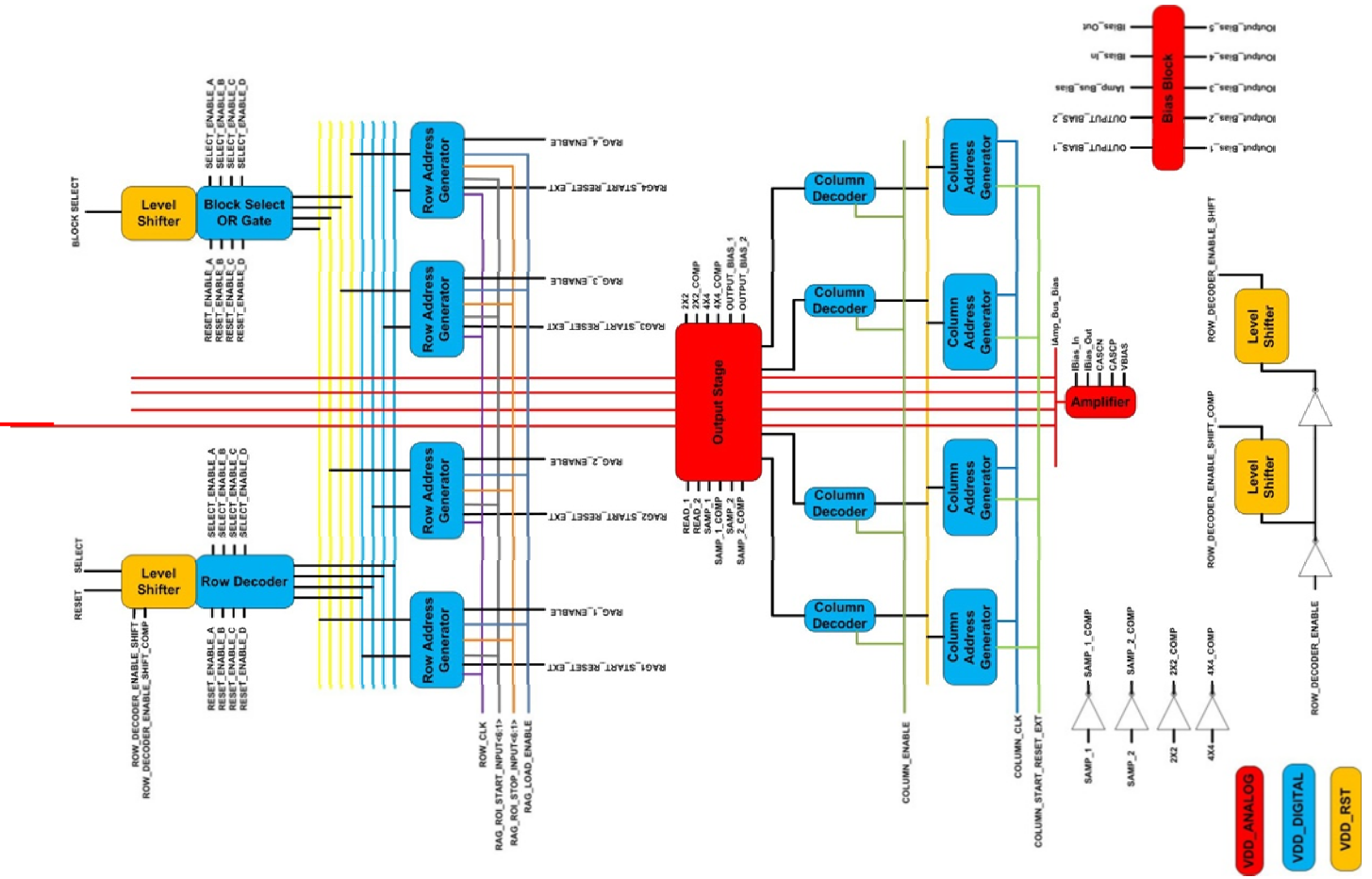
Lassena. Floorplan

To the pixel:

3T pixel base with

Low noise, large partially pinned diode

Binning capability



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Lassena. A 6.7Mpixel, wafer-scale sensor

Optical performance			
Rms electronic noise	e- rms	68	Full resolution mode (i.e. no binning)
		335	Bin 2x2 mode
		608	Bin 4x4 mode
Linear full well	e-	112,000	Full resolution mode (i.e. no binning)
		1,253,000	Bin 2x2 mode
		5,012,000	Bin 4x4 mode
Maximum full well	e-	144,000	Full resolution mode (i.e. no binning)
		1,374,000	Bin 2x2 mode
		5,496,000	Bin 4x4 mode
Dynamic range (Linear)	bits	10.7	Full resolution mode (i.e. no binning)
		11.9	Bin 2x2 mode
		13.0	Bin 4x4 mode
Dynamic range (Maximum)	bits	11.0	Full resolution mode (i.e. no binning)
		12.0	Bin 2x2 mode
		13.1	Bin 4x4 mode
Readout speed	frames per second	35	Full resolution mode (i.e. no binning)
		70	Bin 2x2 mode
		140	Bin 4x4 mode
Quantum efficiency	Measured @ 540nm	50%	
Lag		Negligible	
Other			
Power supply	V	3.3	
Number of pads	480	All on one side	
Power Consumption (mW)	W	<2.5	CMOS only

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Percival

Pixelated Energy Resolving CMOS Imager, Versatile and Large

DESY

elettra

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Percival target specifications

- Low energy X-ray detection <~ 2,000 eV
- High efficiency → back-side illuminated and direct detection
- High resolution → 4kx4k on a 25µm pitch
- Good single photon sensitivity → low noise
- High dynamic range, i.e. up to ~ $2*10^5$ photons @ 250 eV → high dynamic range (HDR) pixel --> ~120dB or full well >10 Me-
- High frame rate → 120 fps
- Fully digital

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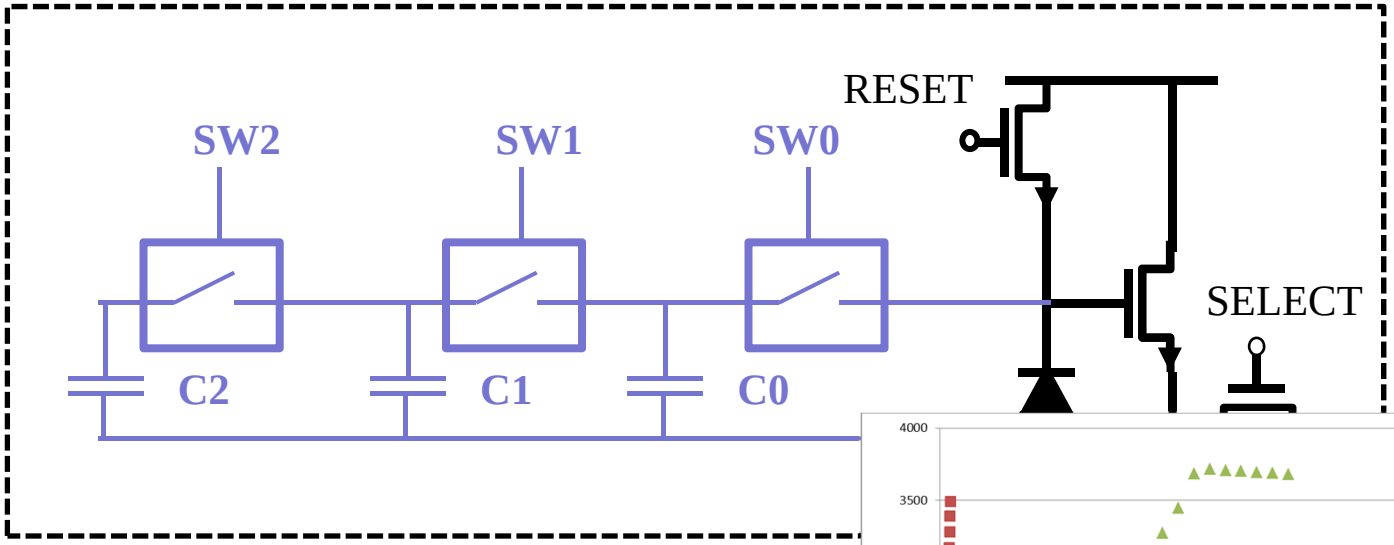
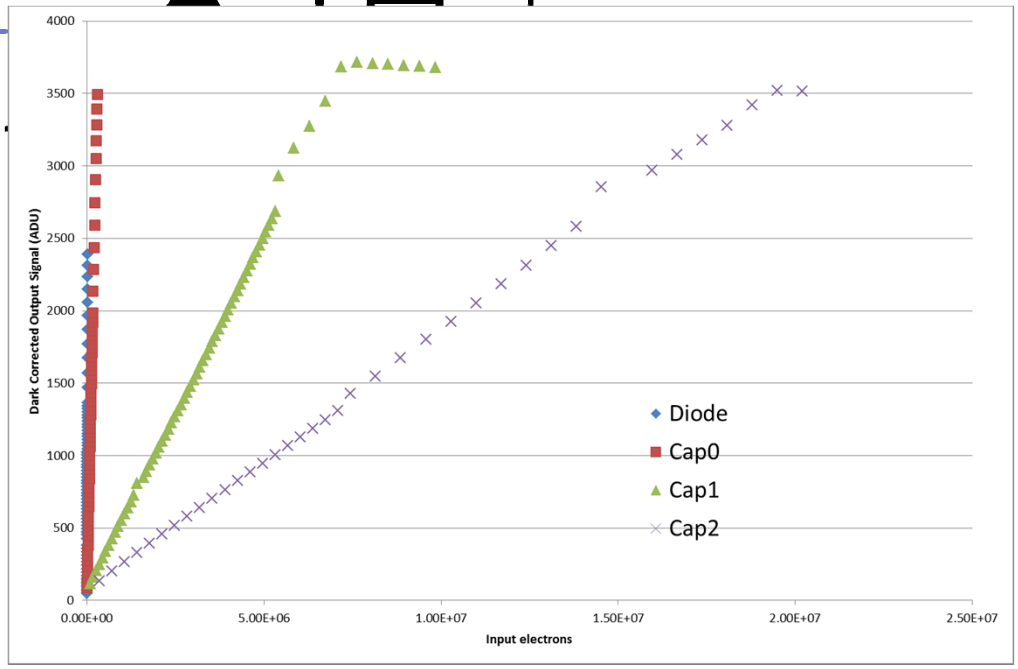
HDR pixel





- Based on overflow capacitors.
- Switches SW0, 1 and 2 are held ‘almost open’ during integration

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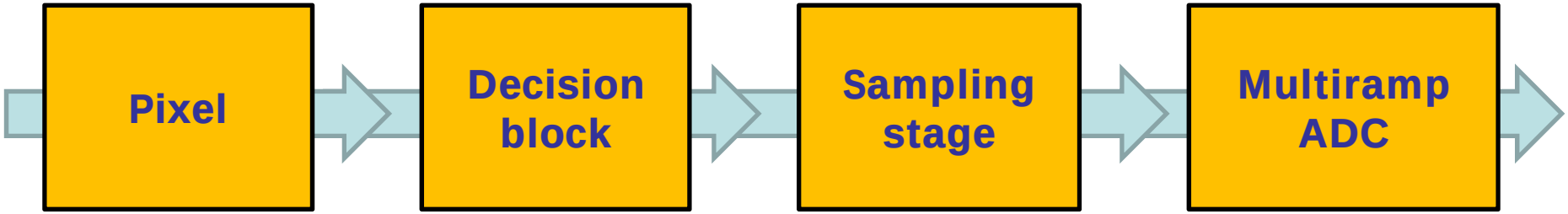
Signal path



The diode is read first, then the three capacitors

It selects the lowest non saturated value

This value is sampled, as well as the reset value

Both sampled value and reset are converted

ADC conversion over 12 bits. 5 coarse plus 7 fine (plus 1 for over-range)
2 bits for gain, as selected by the decision block

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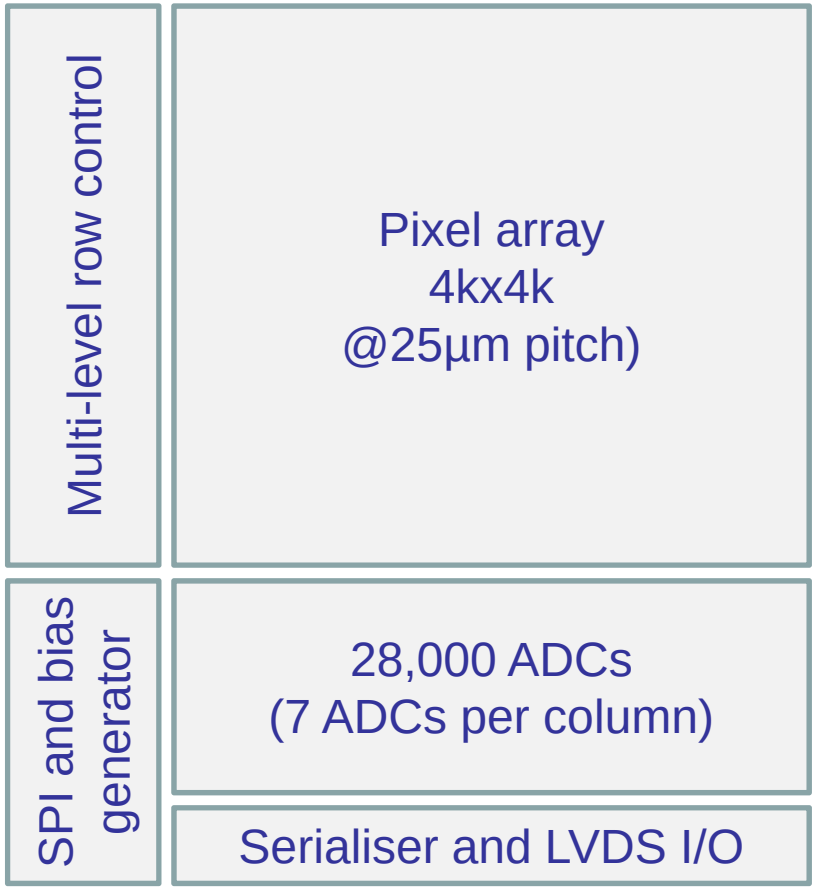
Percival sensor floorplan

Preliminary specifications

- 16 MPix resolution
- 120 fps (digital CDS)
- High dynamic range (4 gains per pixel)
- 12+1bit ADC
- 15 bits per pixel (2 gain bits + 13 bits)
- Digital I/O (LVDS)
- 60 Gbit/sec continuous data rate



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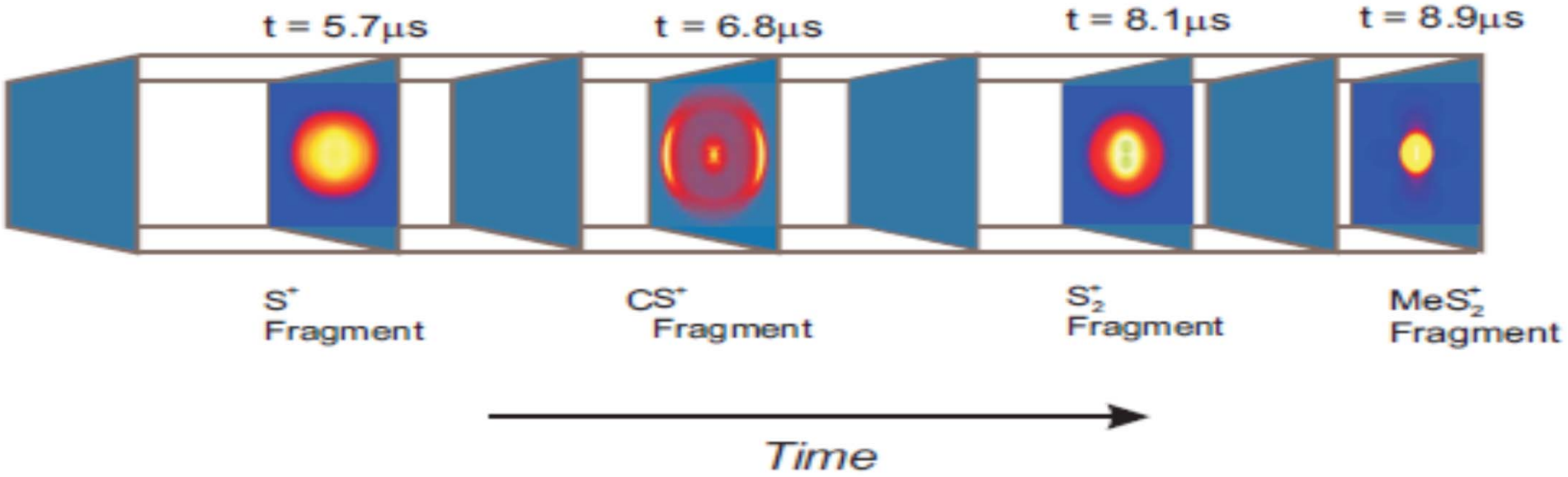
Time-Of-Flight Mass Spectroscopy

Requirements

- Spatial information
- Timing information



Courtesy of M. Brouard, C. Vaillance, R. Nickerson et al., Oxford University

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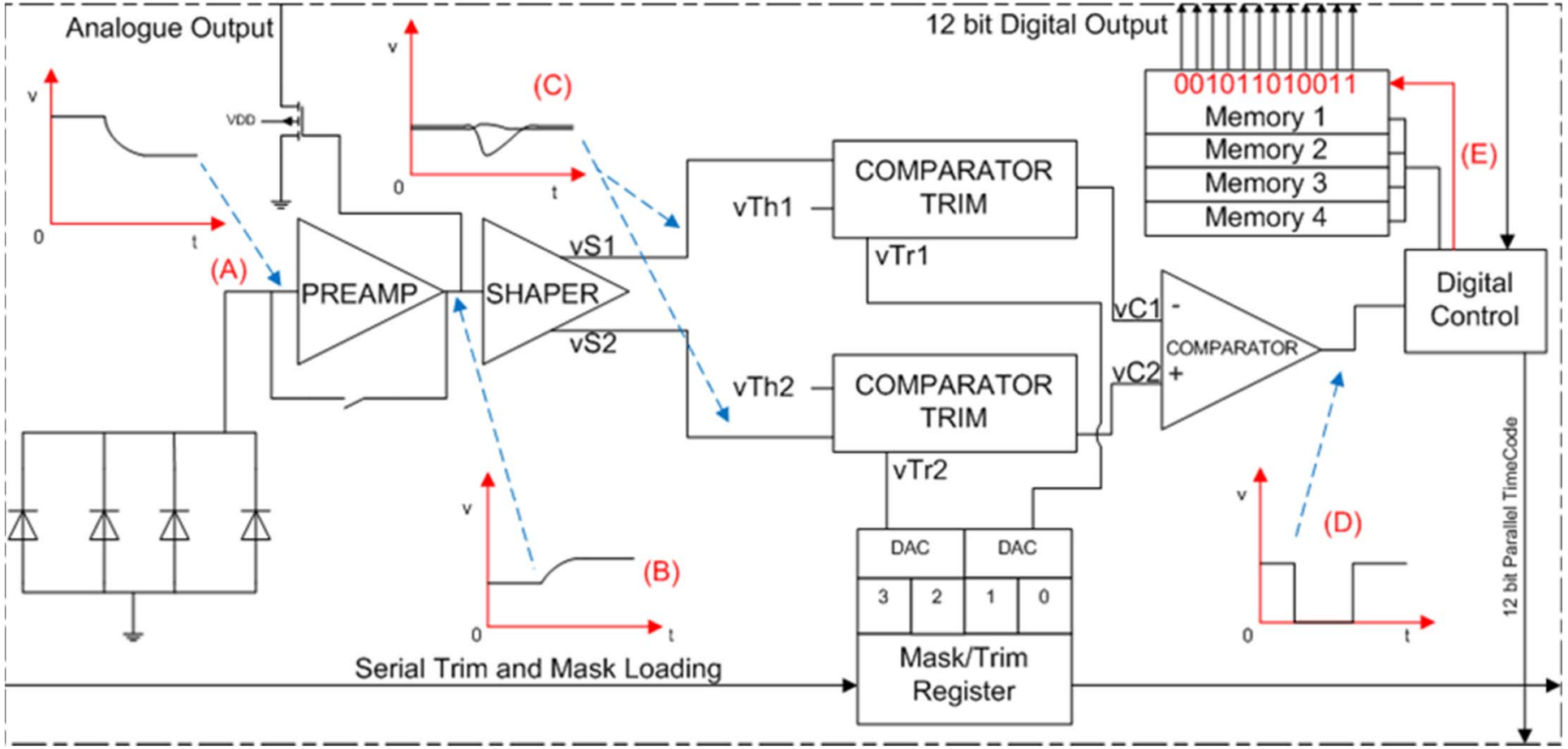
PImMS. A single particle CMOS Image Sensor.

PImMS – Pixel Imaging Mass Spectrometry



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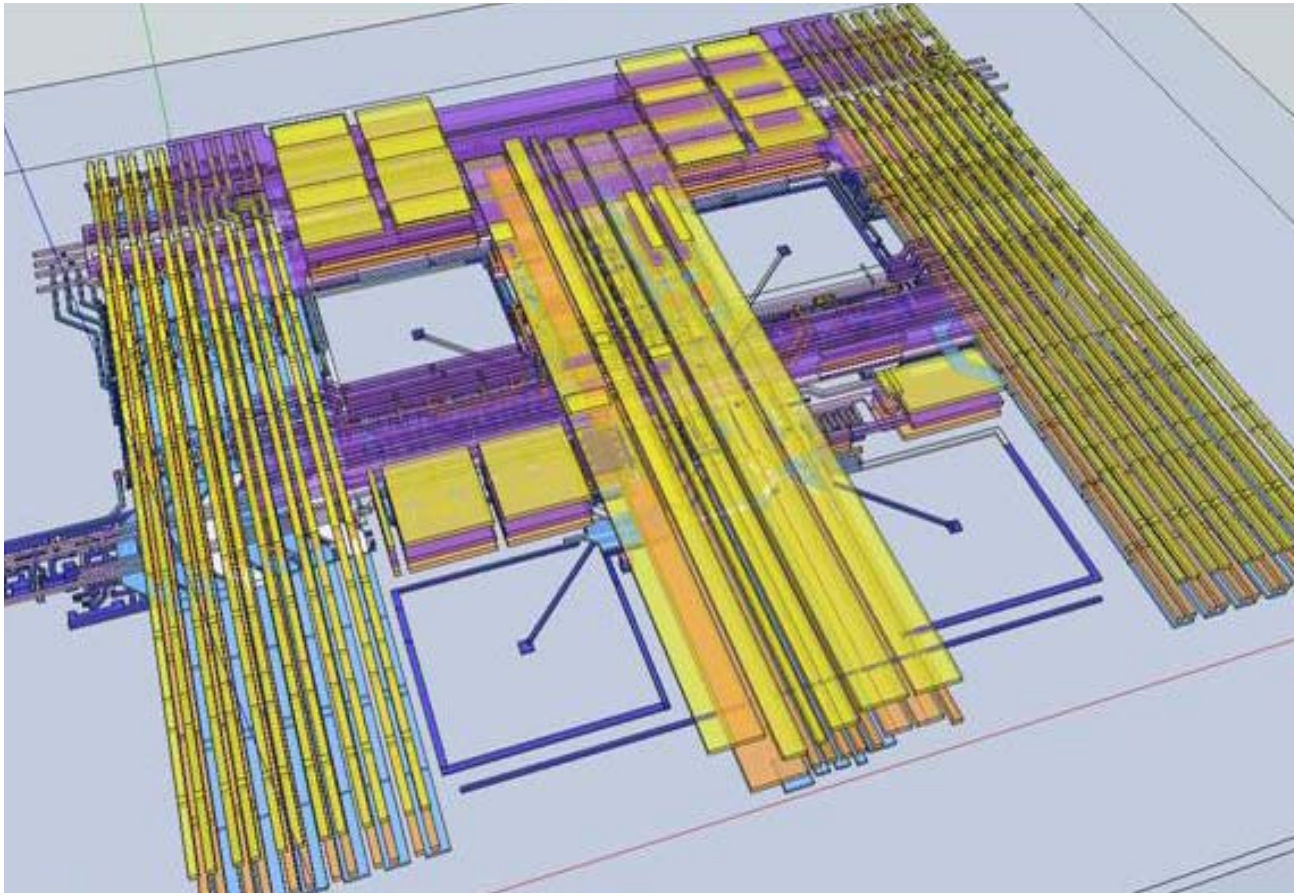
PImMS pixel layout



Over 600 transistors per pixel

Modified process developed with TowerJazz: deep P-implant for 100% fill factor and true CMOS

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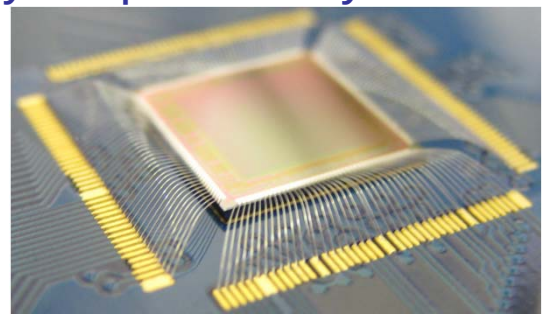
Technology

PImMS family

PImMS1

72 by 72 pixel array



PIMMS USB camera

PImMS2

324 by 324 pixel array
70 µm x 70 µm pixel size

Time-code resolution
= 25 ns (12.5 demonstrated already on PImMS1)

4 event stored in each pixel

12 bit time-code resolution

Analogue readout of intensity information

Equivalent pixel rate for standard full frame camera

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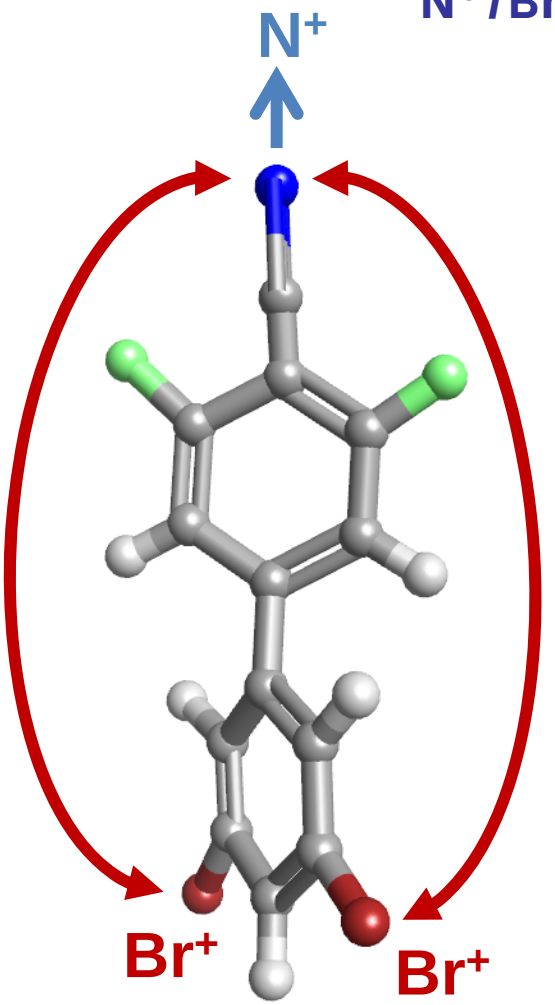
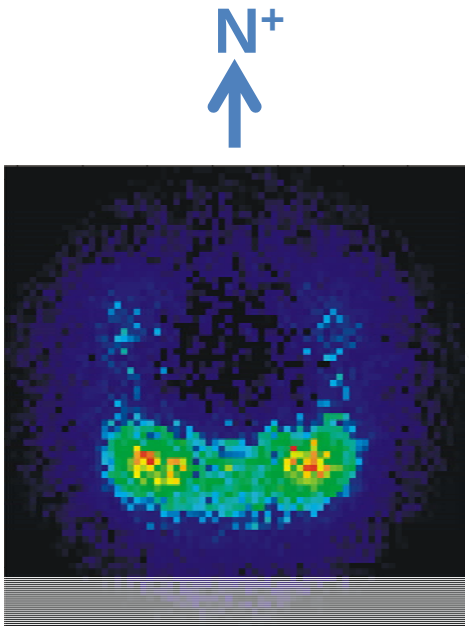
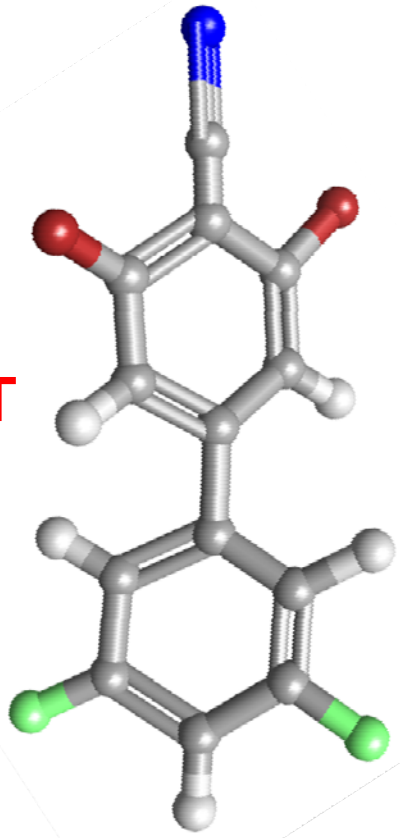
PImMS. First example of scientific results.

N^+/Br^+ covariance – vertical alignment





NOT



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(Ultra)-High speed imaging. Applications

High-speed: 1k to 100kfps
Ultra-high speed: >~ 1M fps

- Combustion Research
- Biological/Microscopy
- Ballistics
- Mechanics
- Cavitation
- Material Research
- Aerospace
- Digital Image Correlation
- PIV

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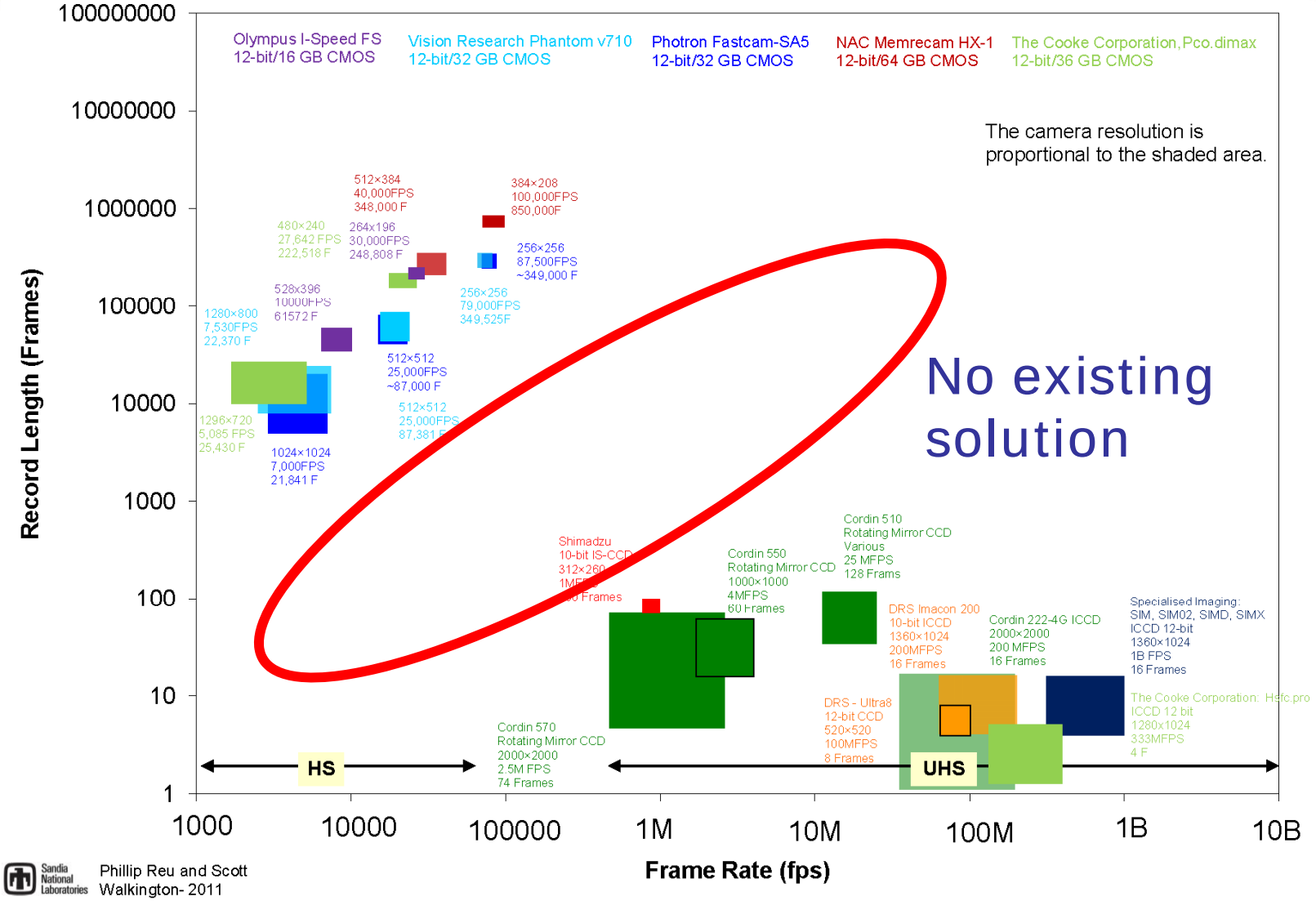
(Ultra)-High speed imaging review



Sandia National Laboratories

Phillip Reu and Scott Walkington- 2011

Science & Technology Facilities Council
Technology

Kirana

- CMOS for ease of use and readout speed
- Start from Tower 180 nm CIS process with dual gate oxide: 3nm + 10nm
- Optimise process for high-speed, high-efficiency charge transfer
- CCD for in-pixel storage

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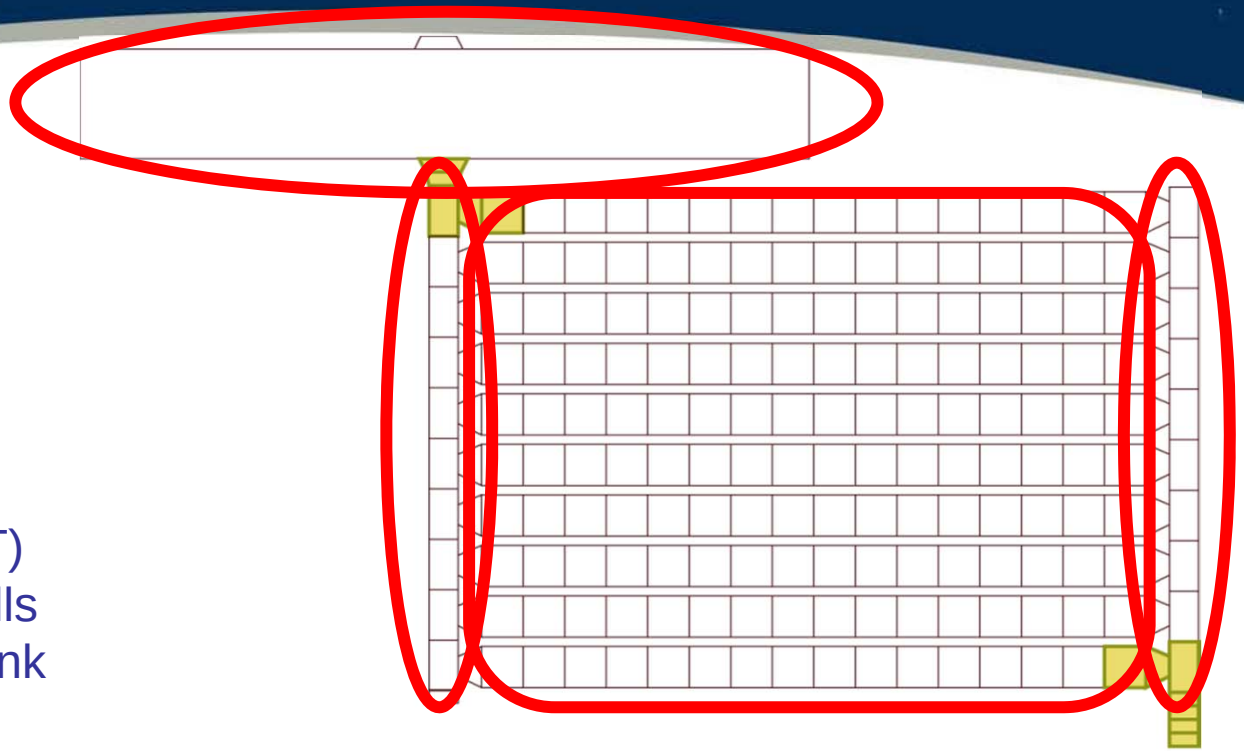
Kirana pixel. 1



Photodiode

Memory bank

- A vertical entry (VEN) bank with 10 cells
- Ten rows of lateral (LAT) banks, each with 16 cells
- A vertical exit (VEX) bank with 10 cells

- Total of 180 memory cells

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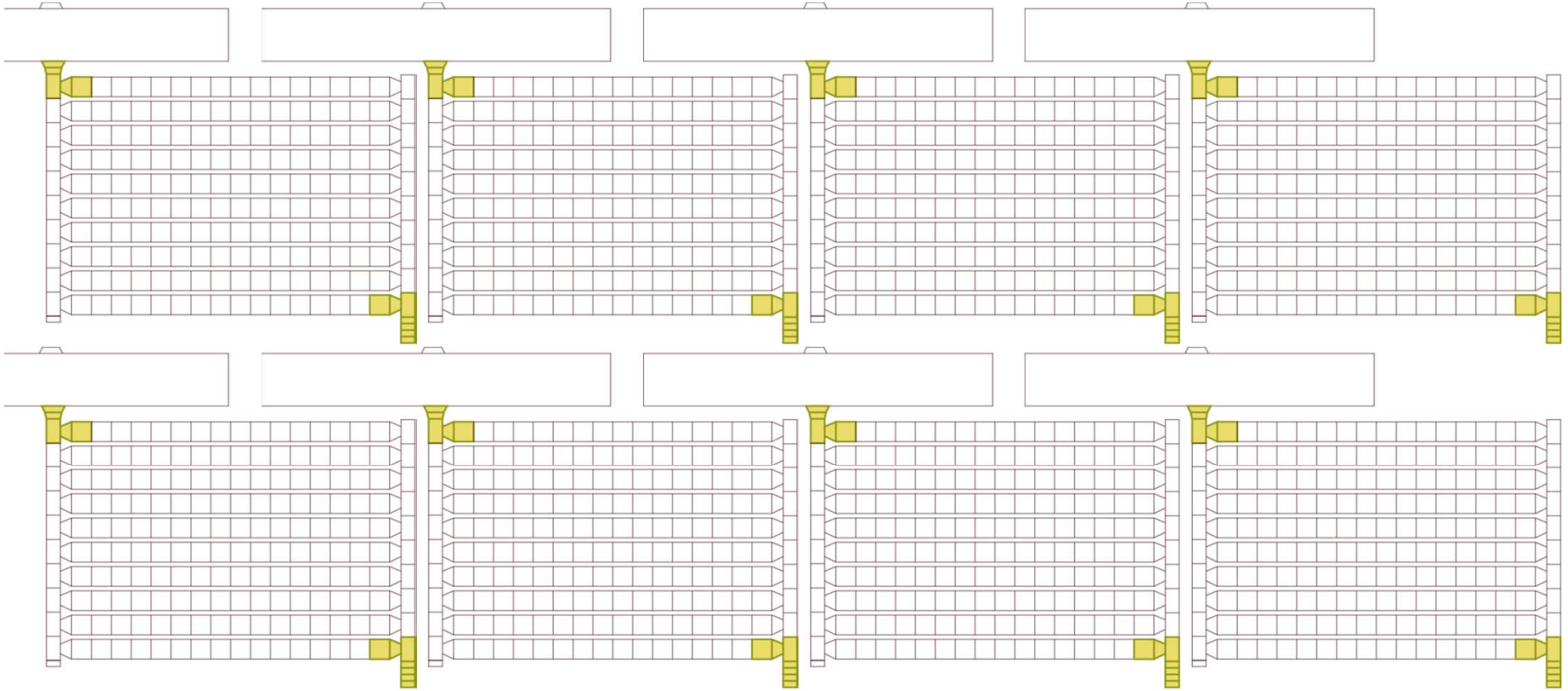
Kirana pixel. 2



Highly scalable architecture:

- **Number of memory cells**
- **Number of pixels**

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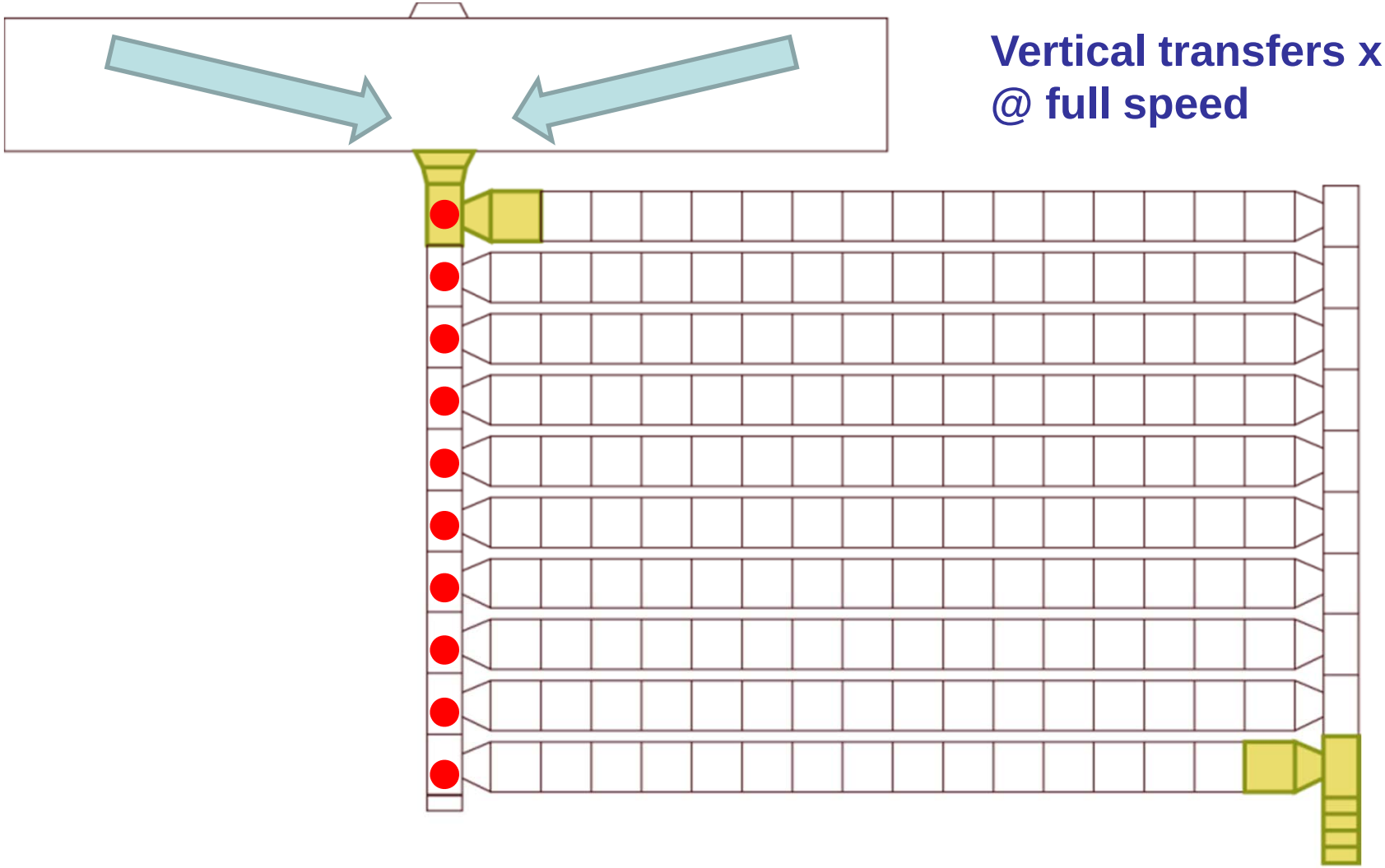
Technology

Burst mode



Vertical transfers x10
@ full speed

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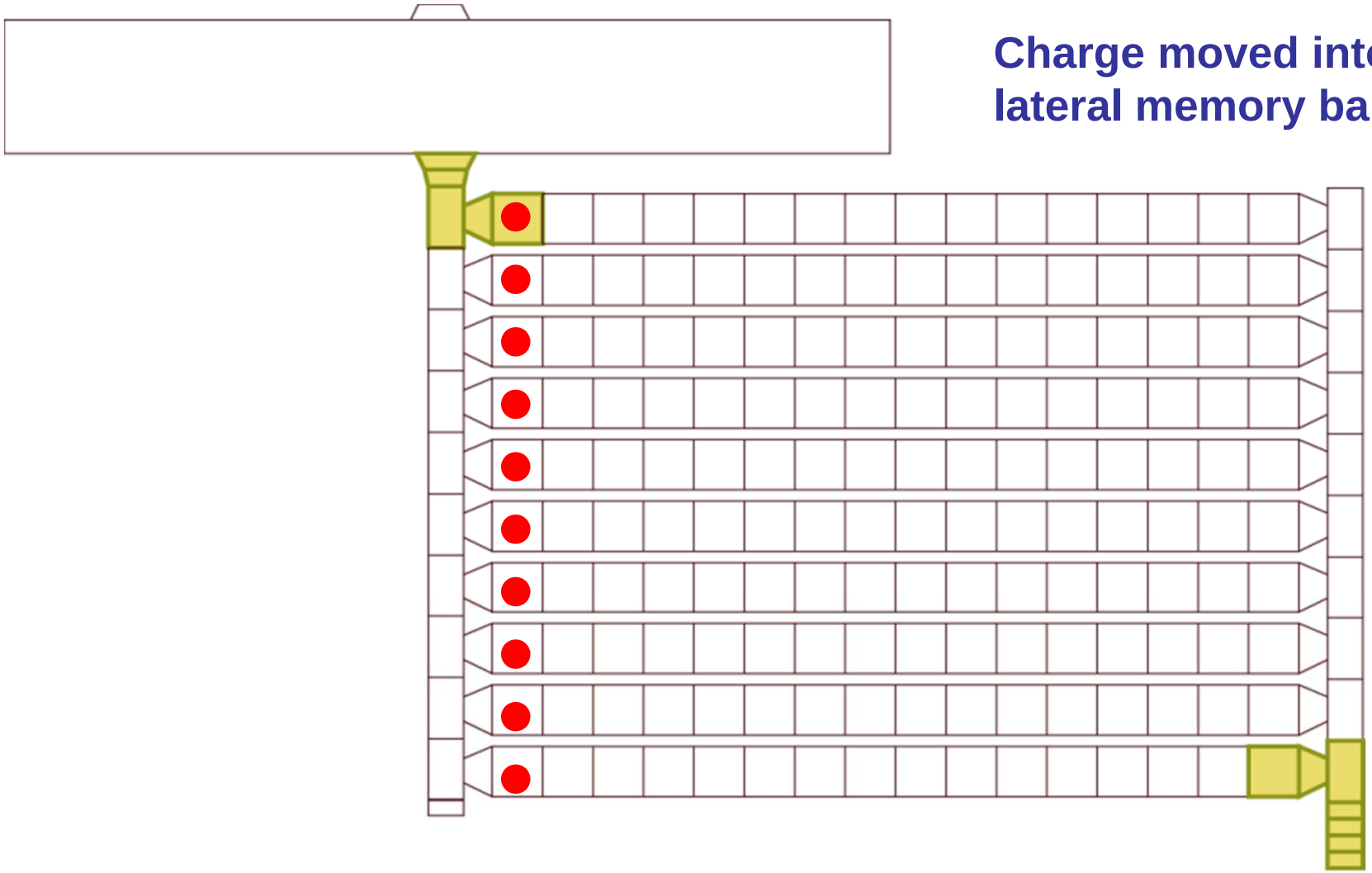
Burst mode



Charge moved into lateral memory bank

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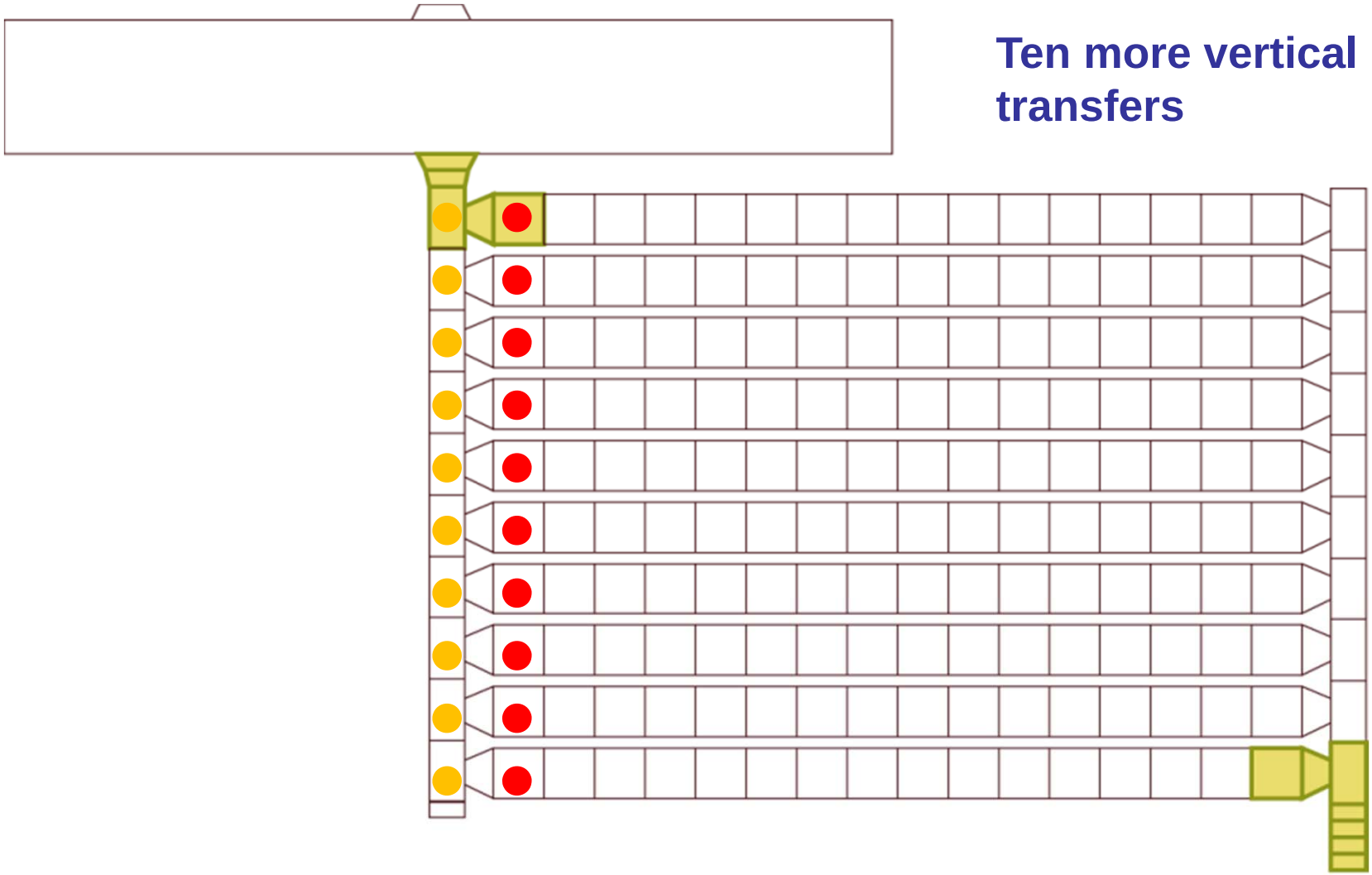
Technology

Burst mode



Ten more vertical transfers

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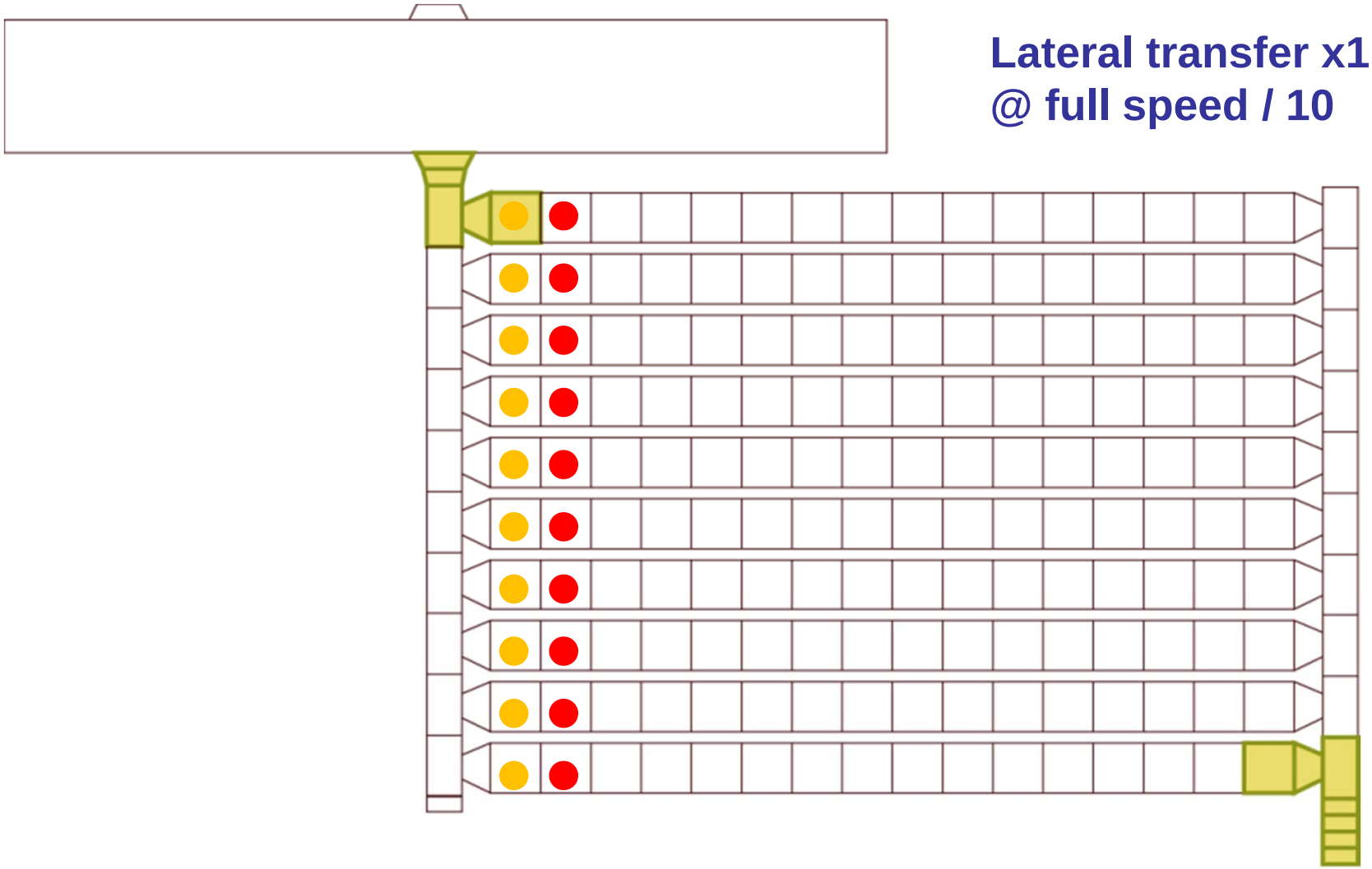
Burst mode



Lateral transfer x1
@ full speed / 10

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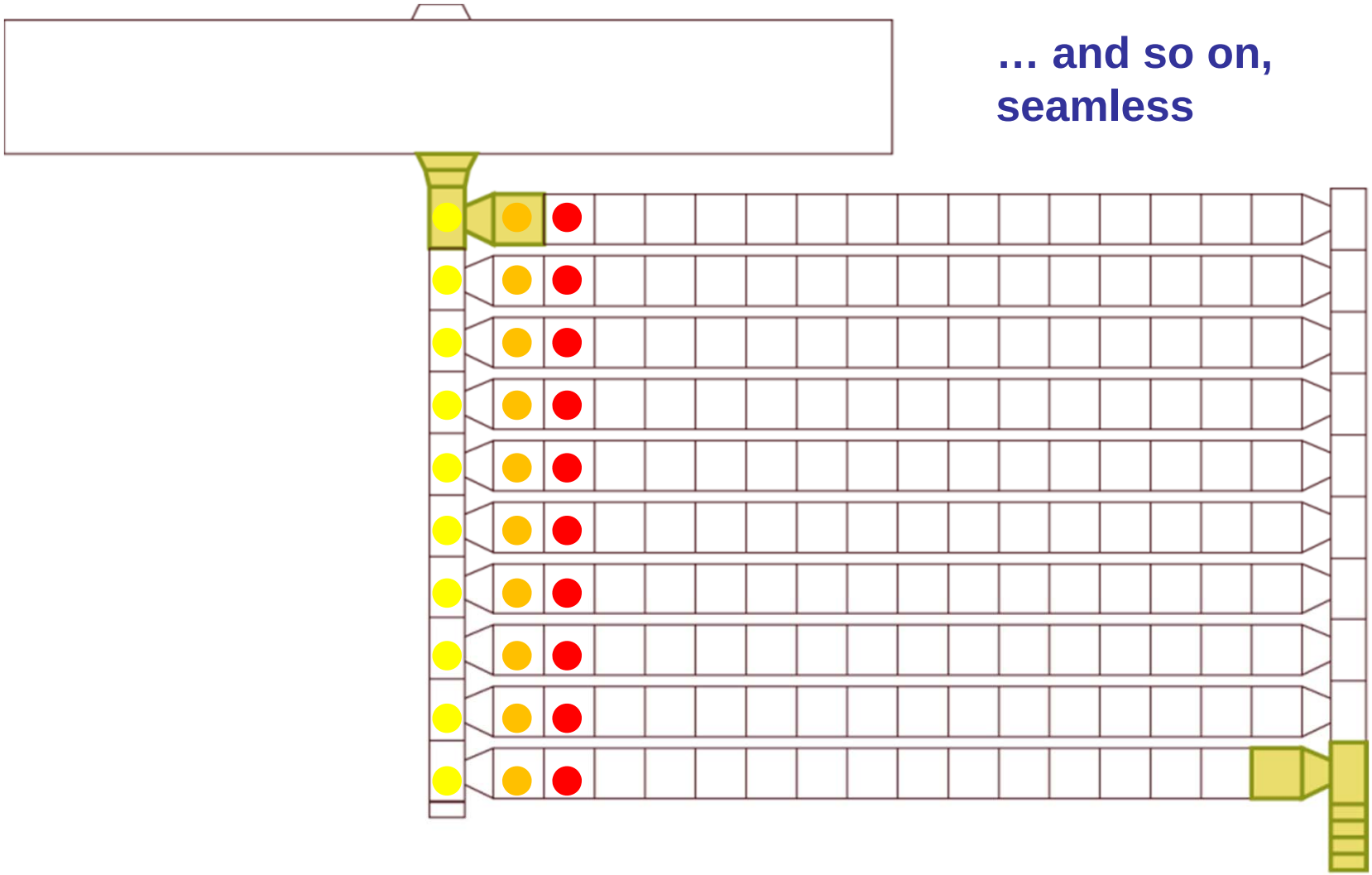
Burst mode



… and so on, seamless

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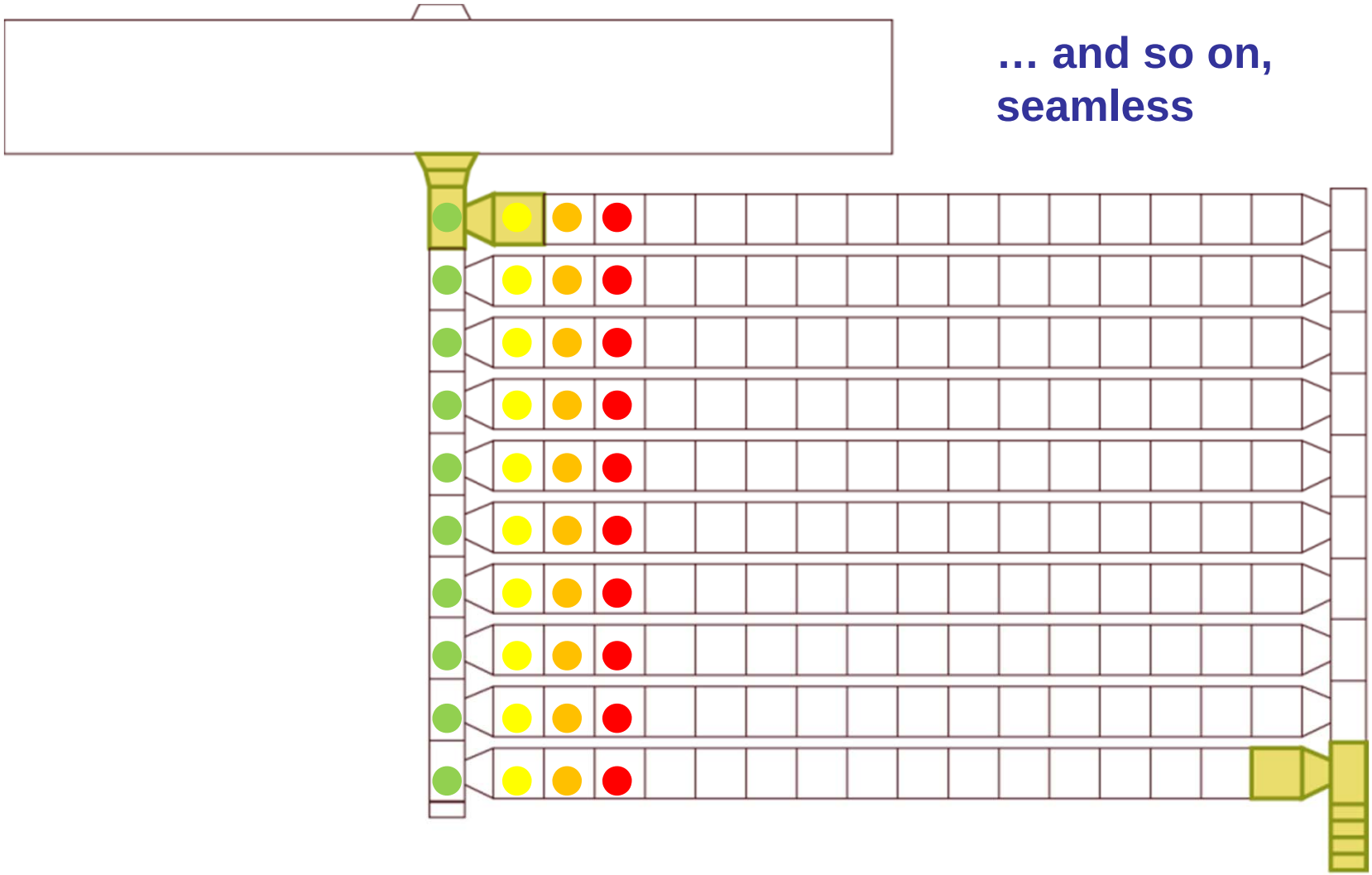
Burst mode



… and so on, seamless

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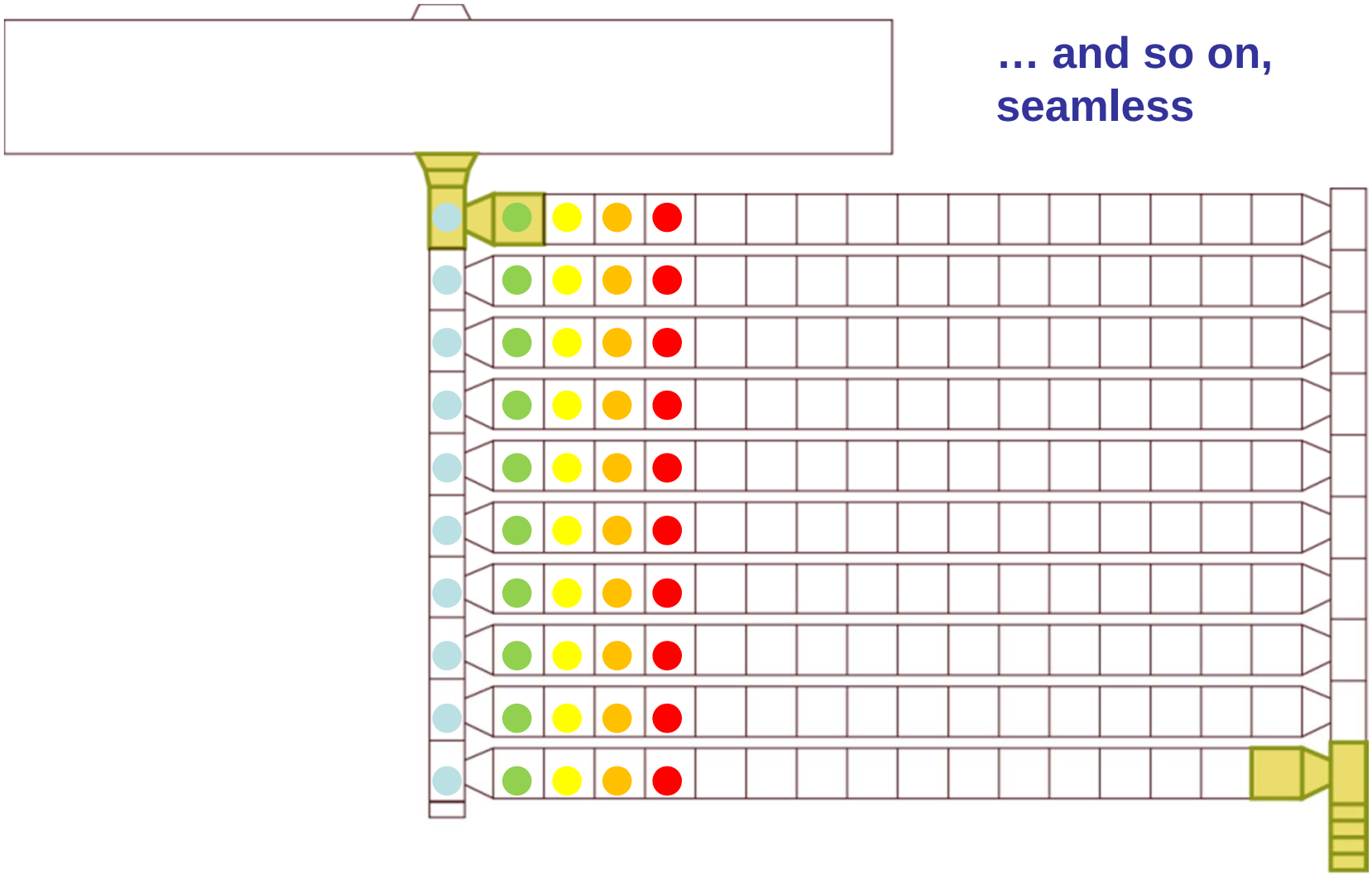
Burst mode



… and so on, seamless

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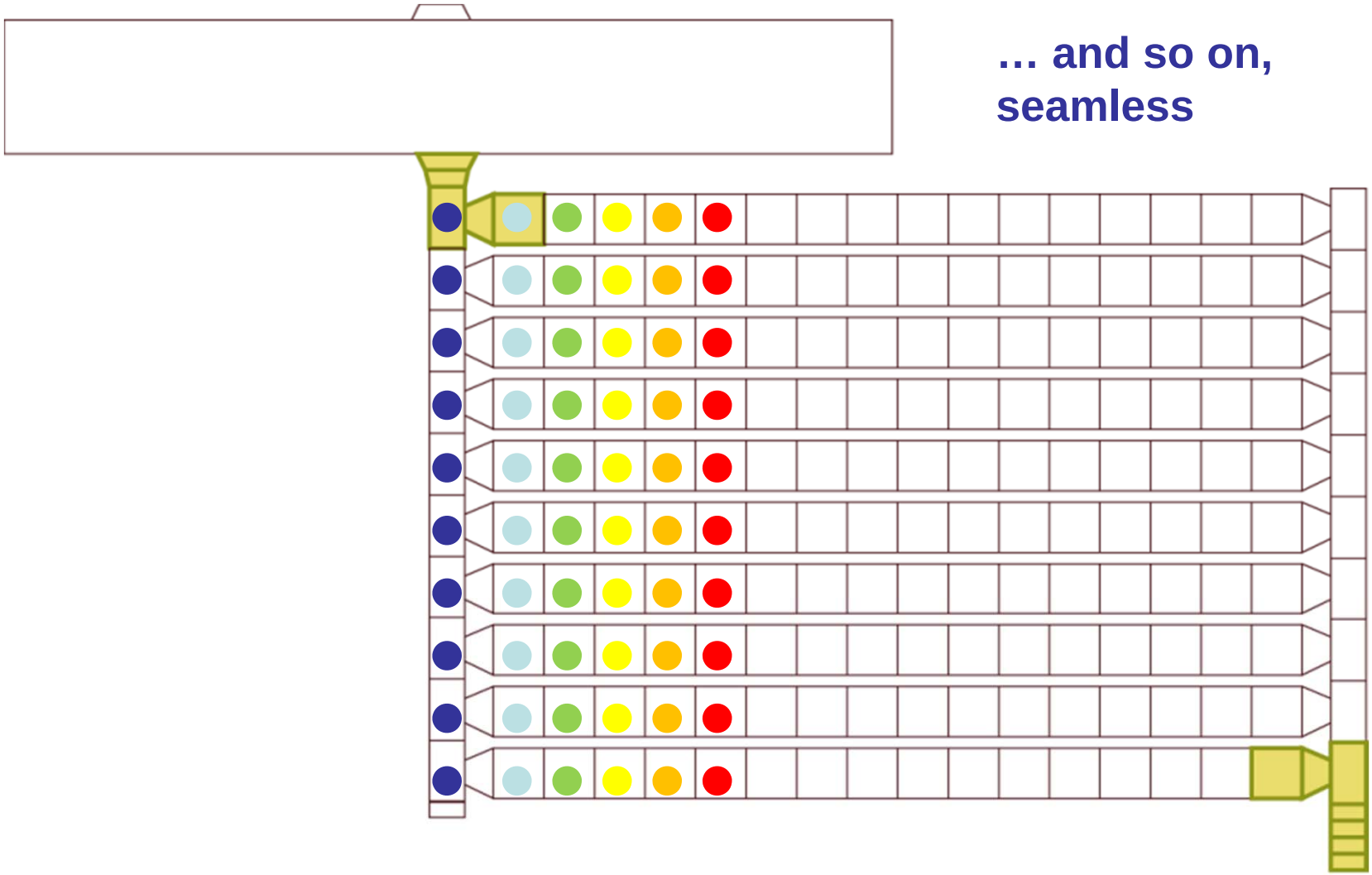
Technology

Burst mode



… and so on, seamless

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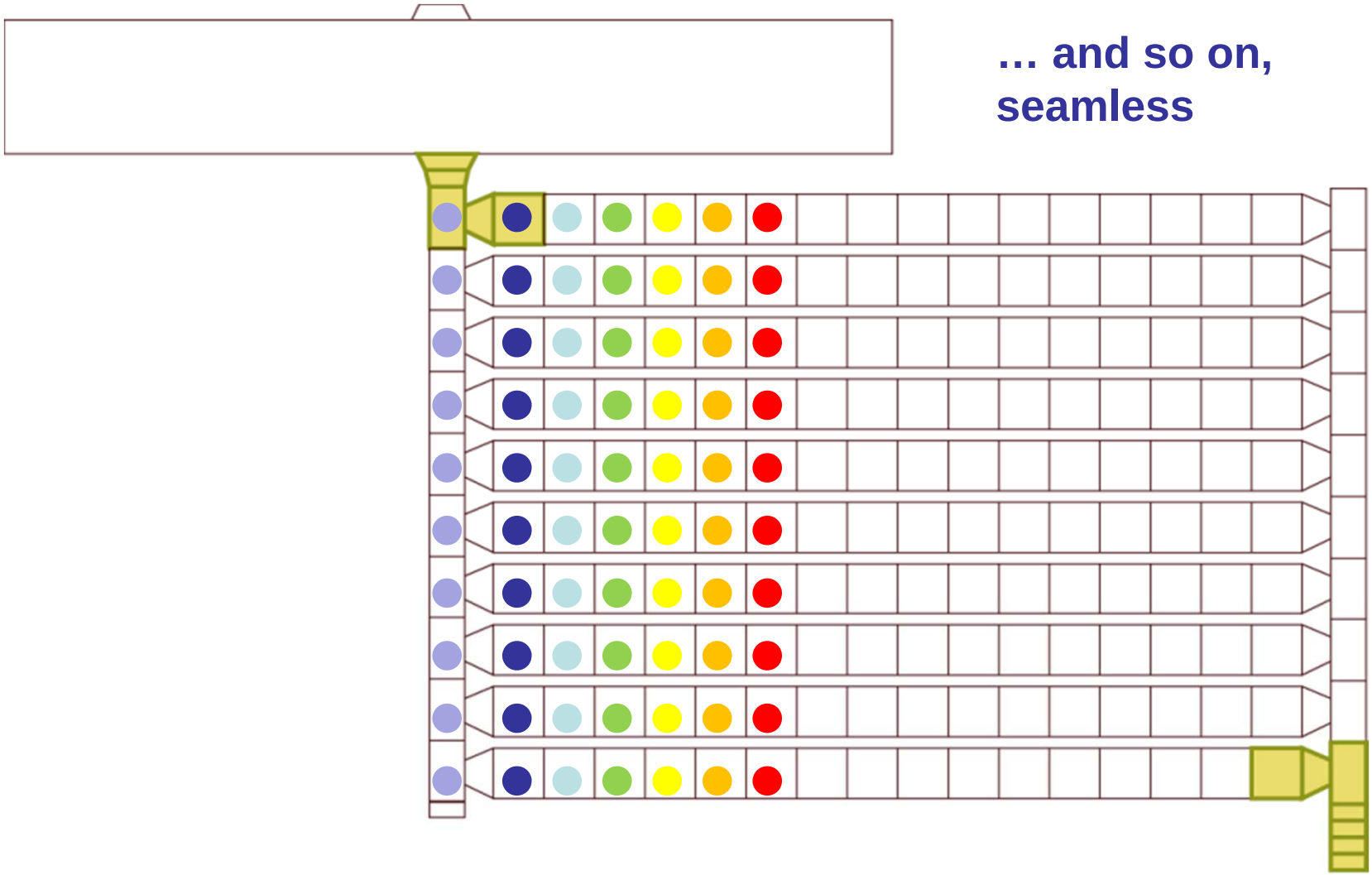
Technology

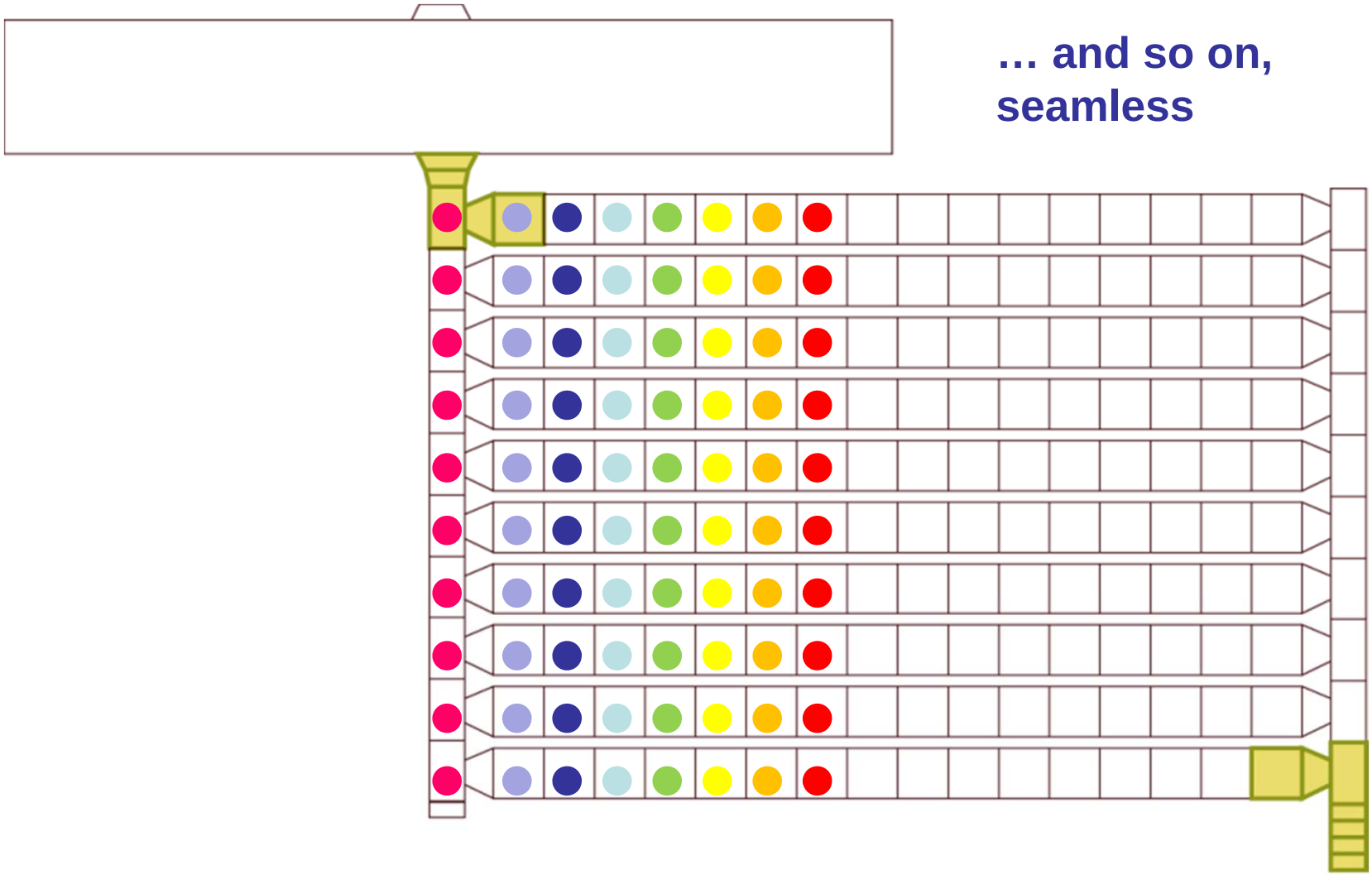
Burst mode



… and so on, seamless

Science & Technology Facilities Council
Technology

Burst mode



… and so on, seamless

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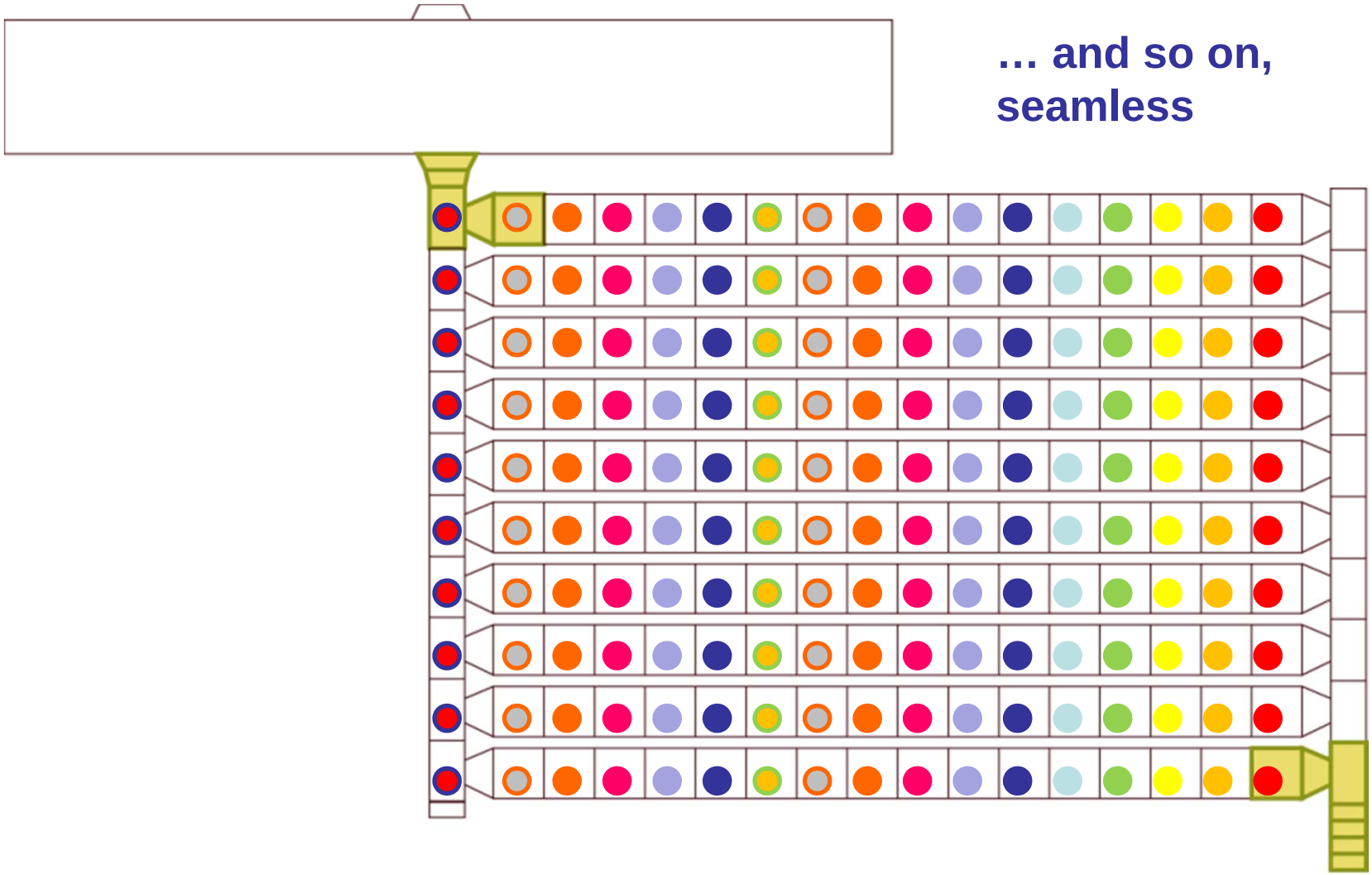
Burst mode



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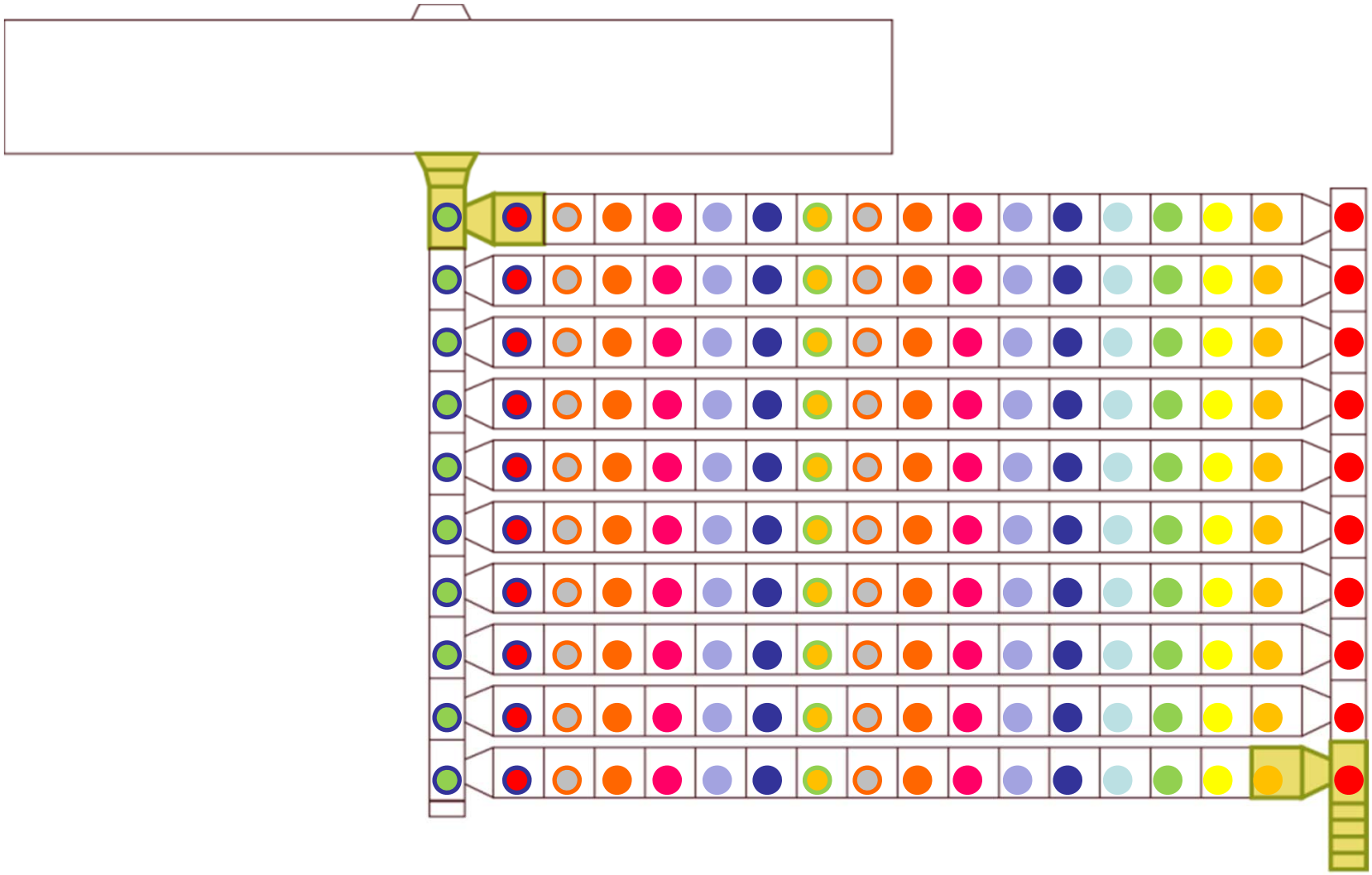
Burst mode



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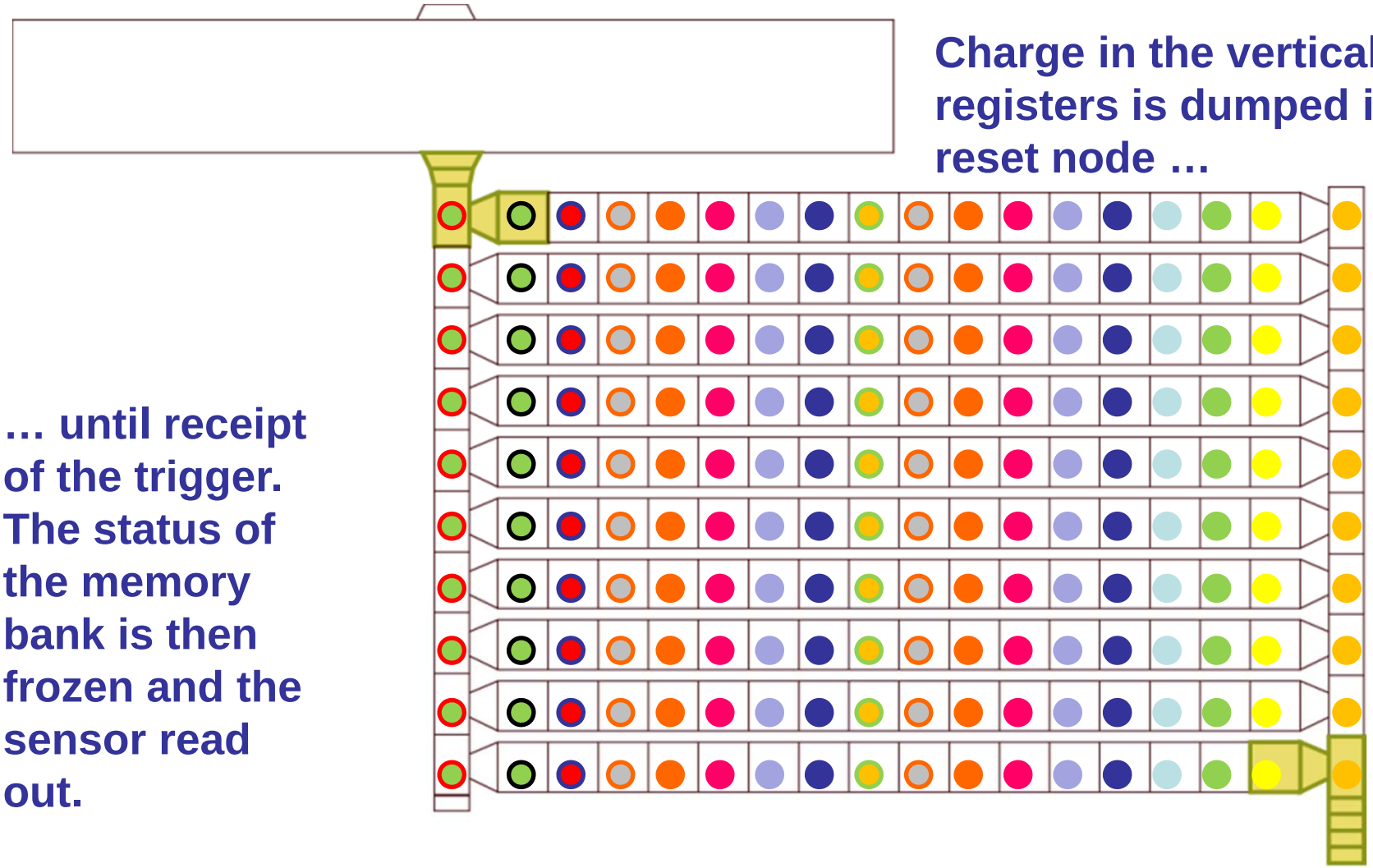
Burst mode



Charge in the vertical exit registers is dumped in the reset node …

… until receipt of the trigger. The status of the memory bank is then frozen and the sensor read out.

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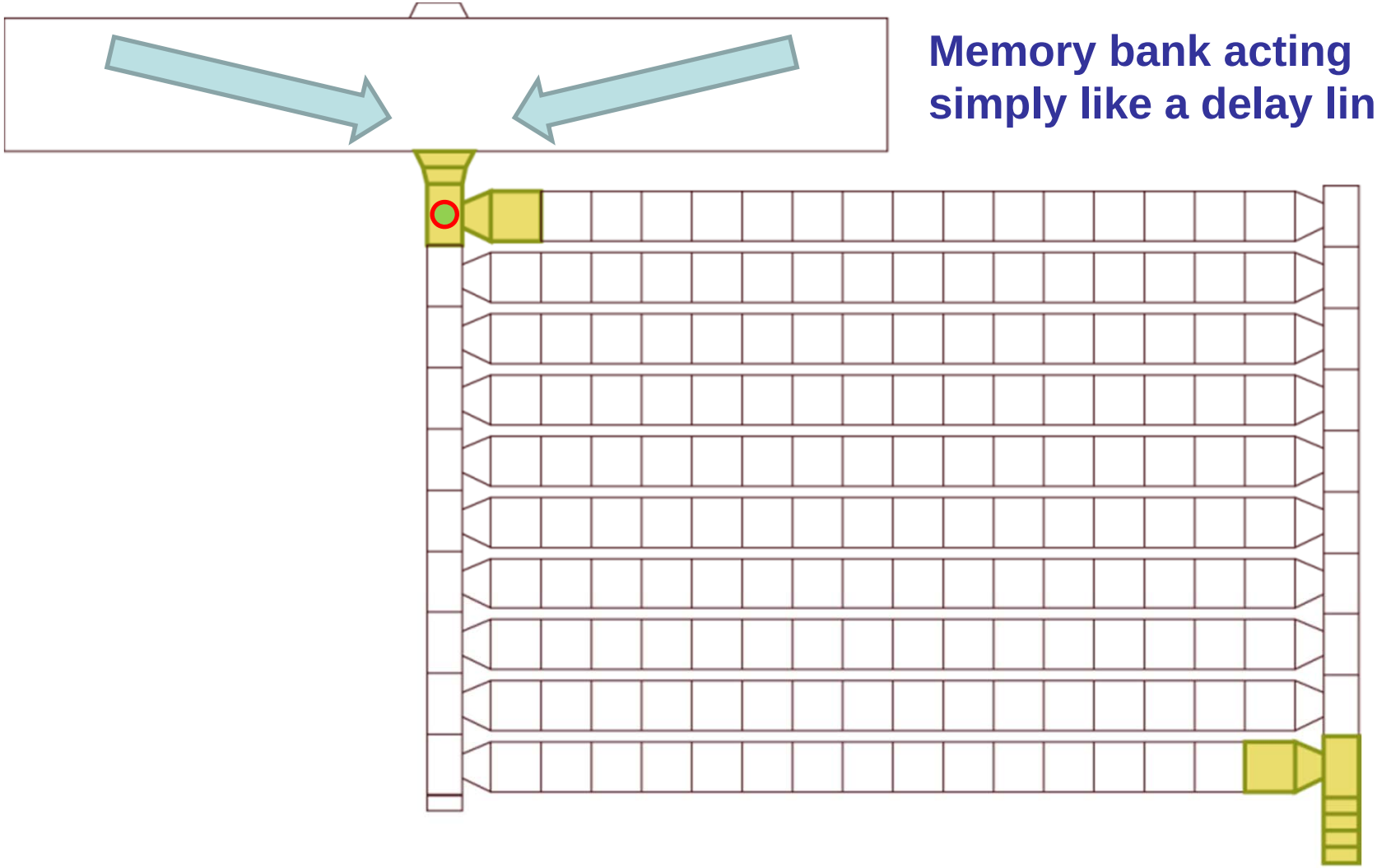
Continuous mode



Memory bank acting simply like a delay line

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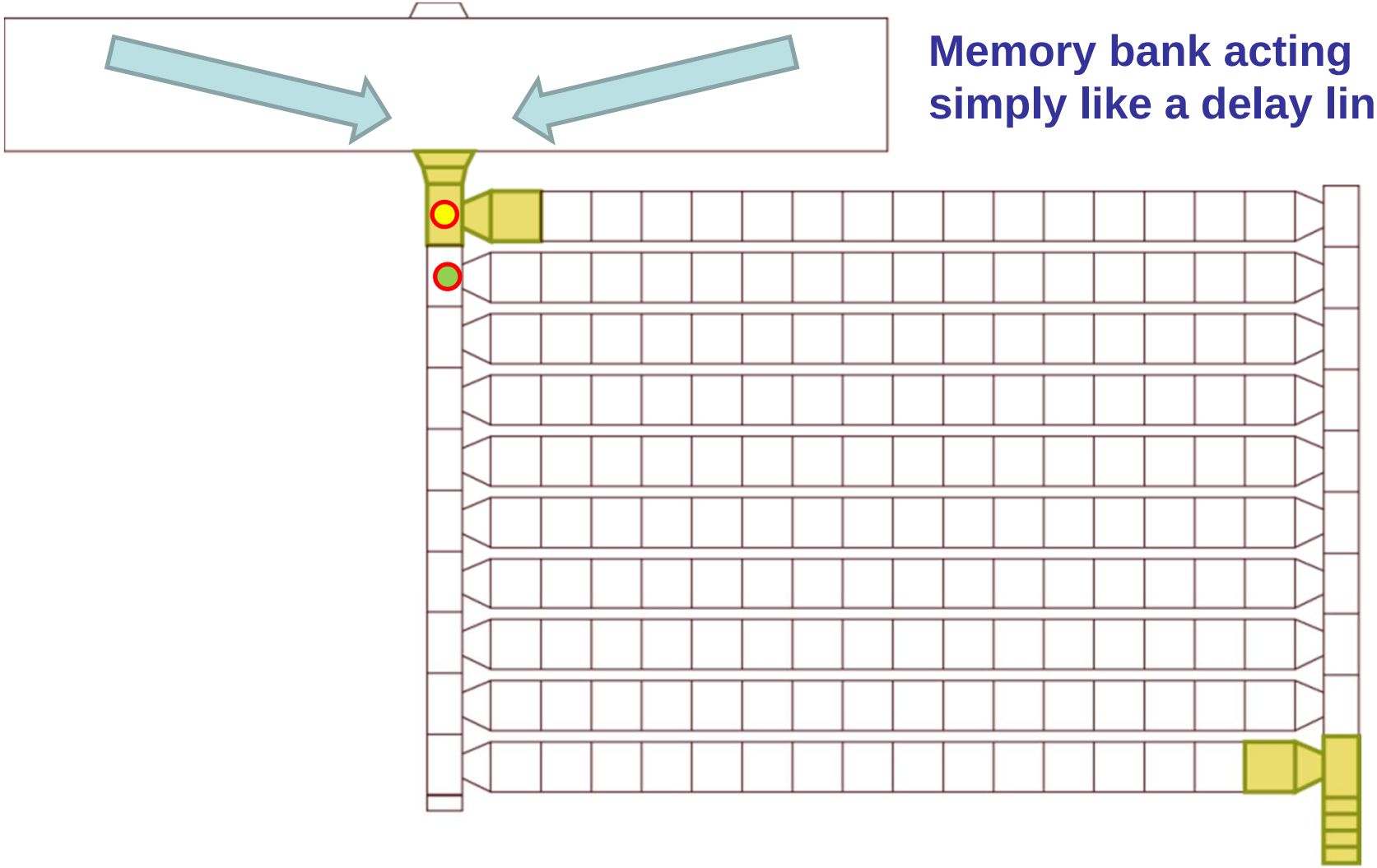
Technology

Continuous mode



Memory bank acting simply like a delay line

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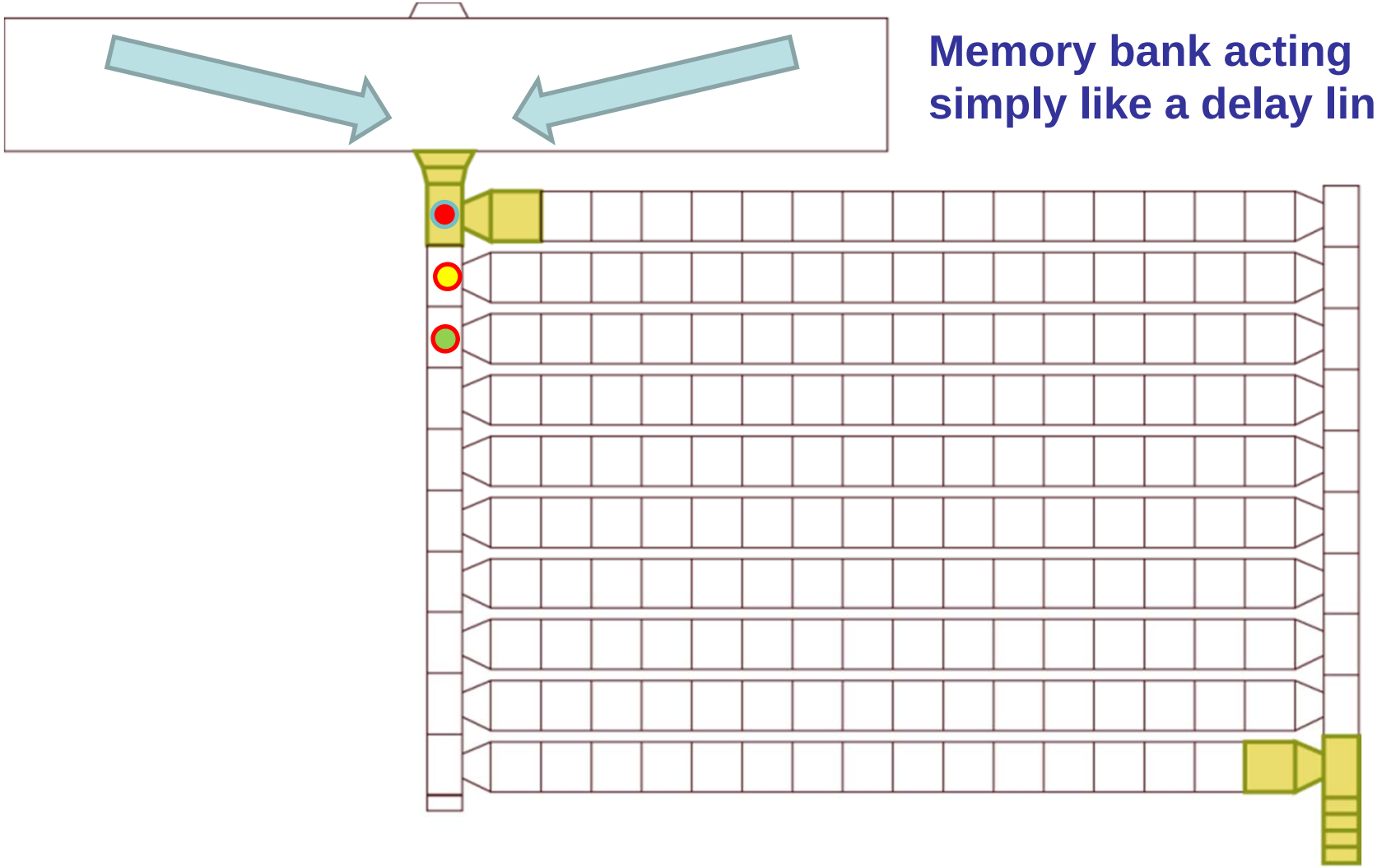
Continuous mode



Memory bank acting simply like a delay line

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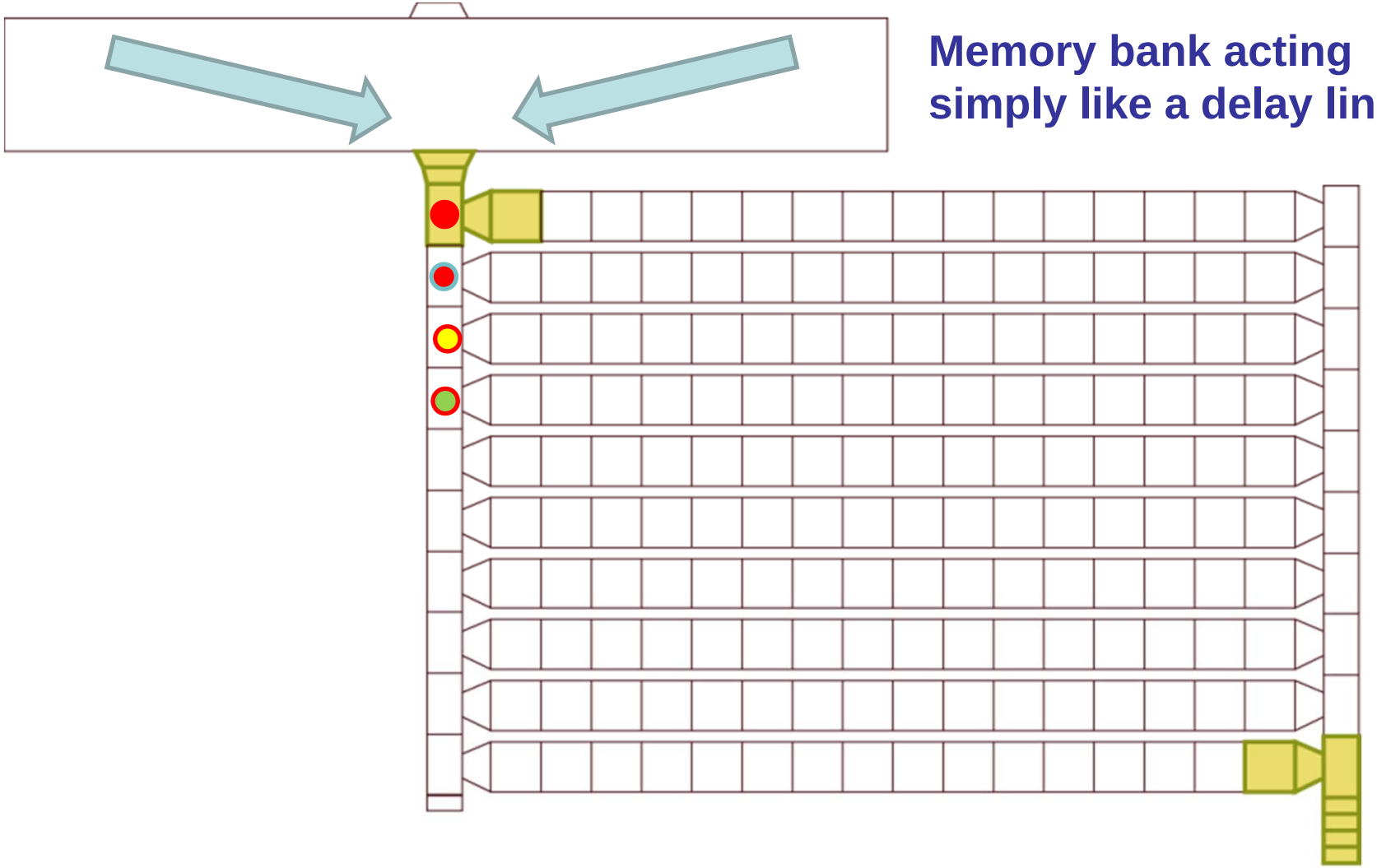
Continuous mode



Memory bank acting simply like a delay line

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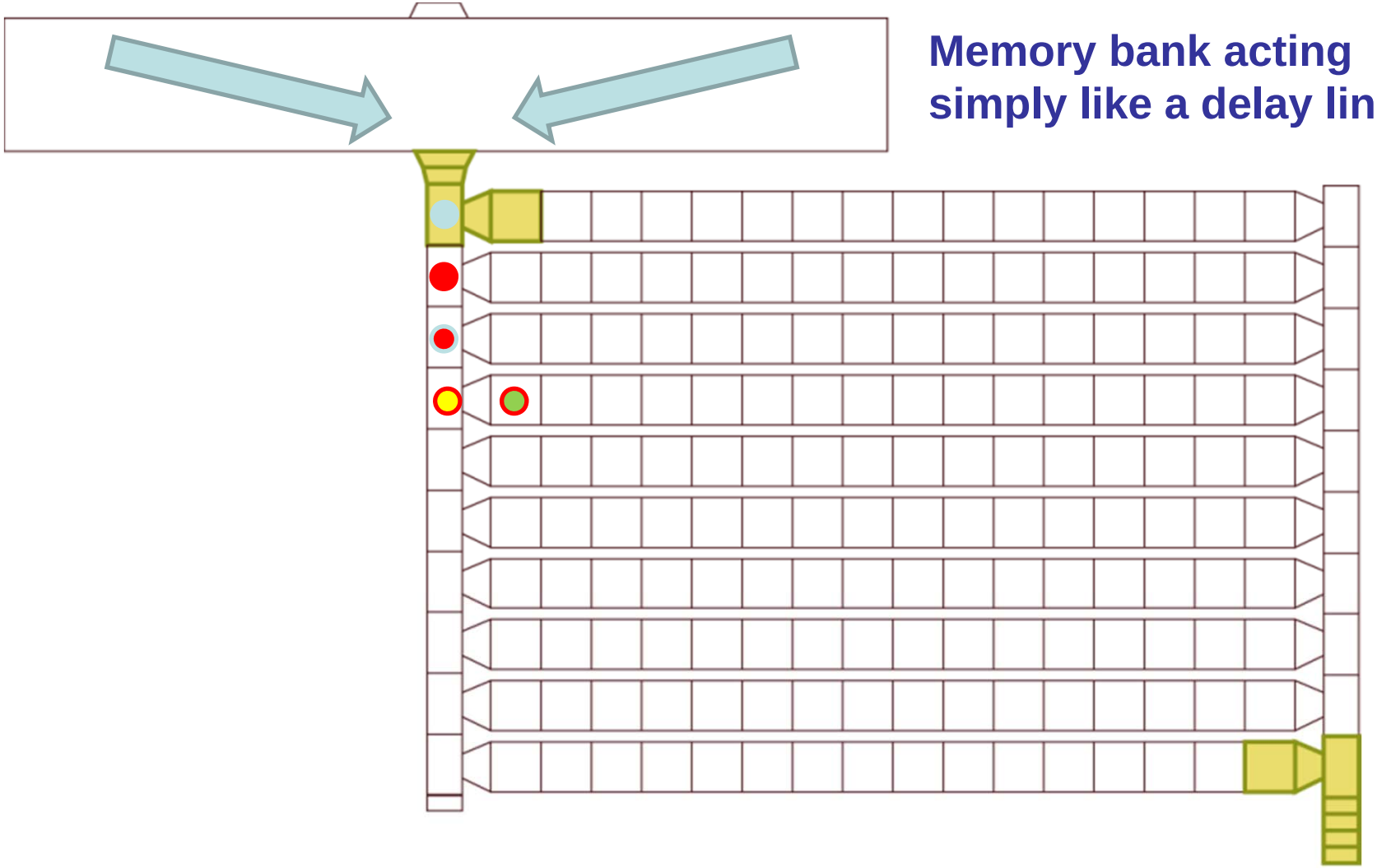
Continuous mode



Memory bank acting simply like a delay line

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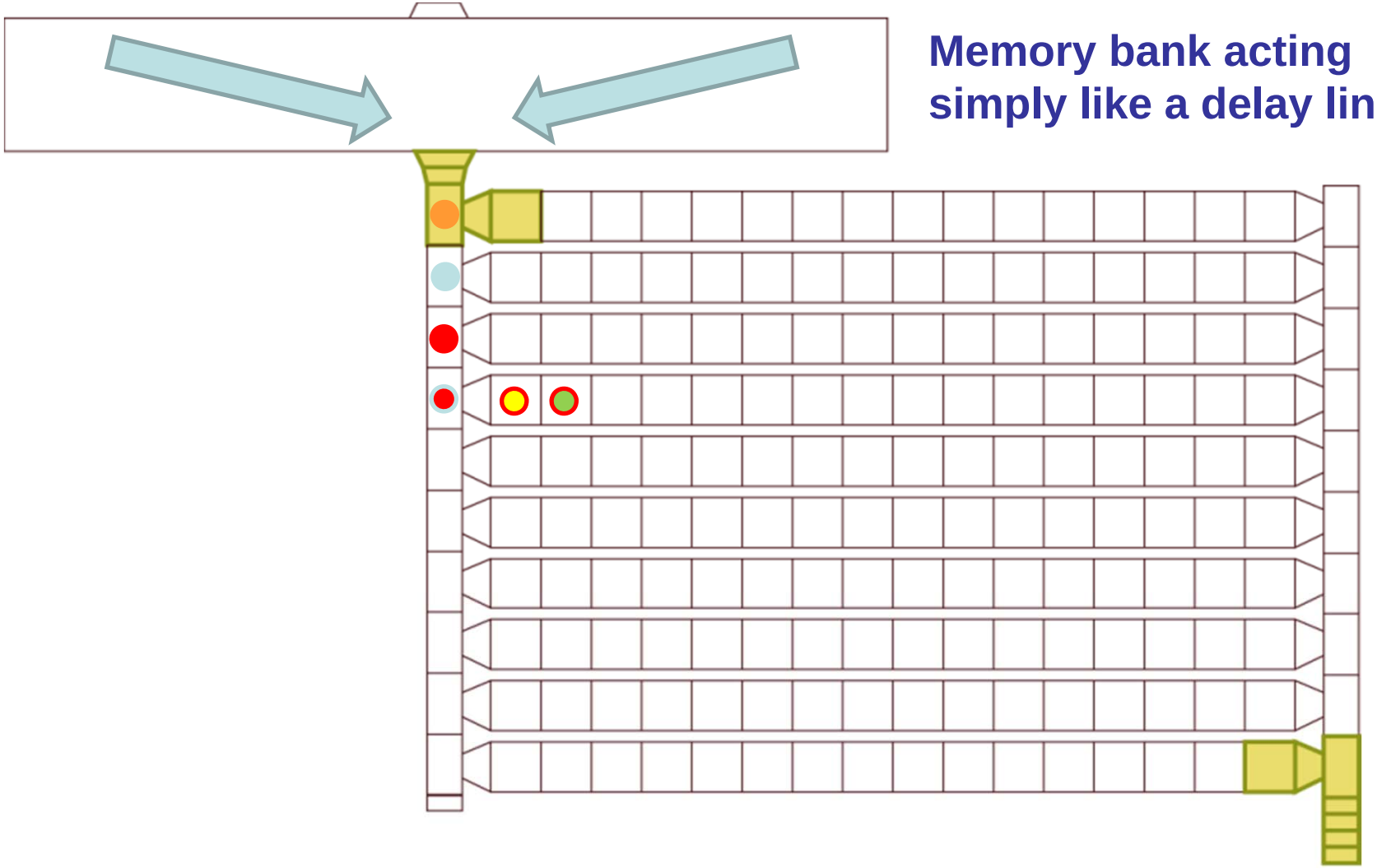
Continuous mode



Memory bank acting simply like a delay line

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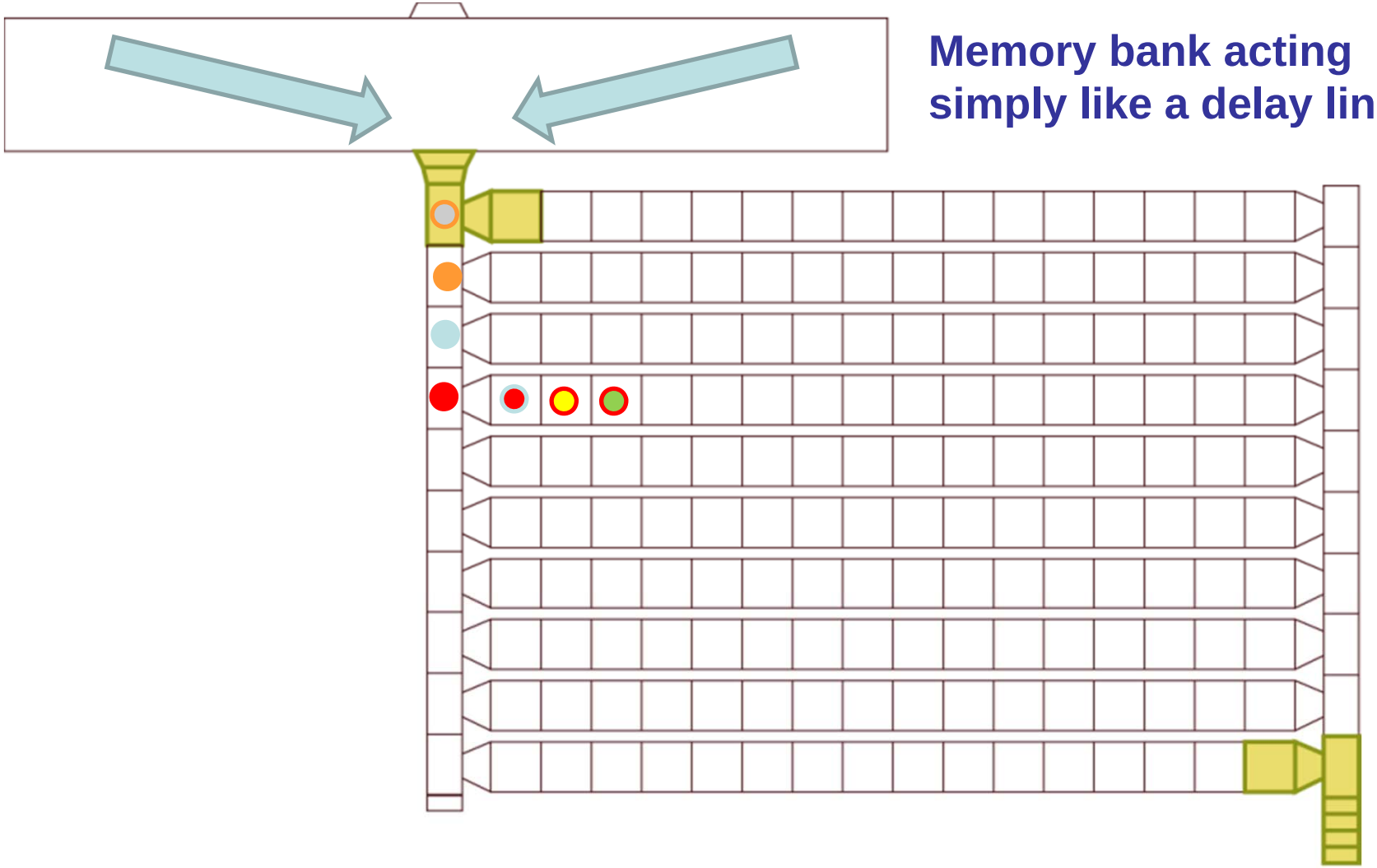
Continuous mode



Memory bank acting simply like a delay line

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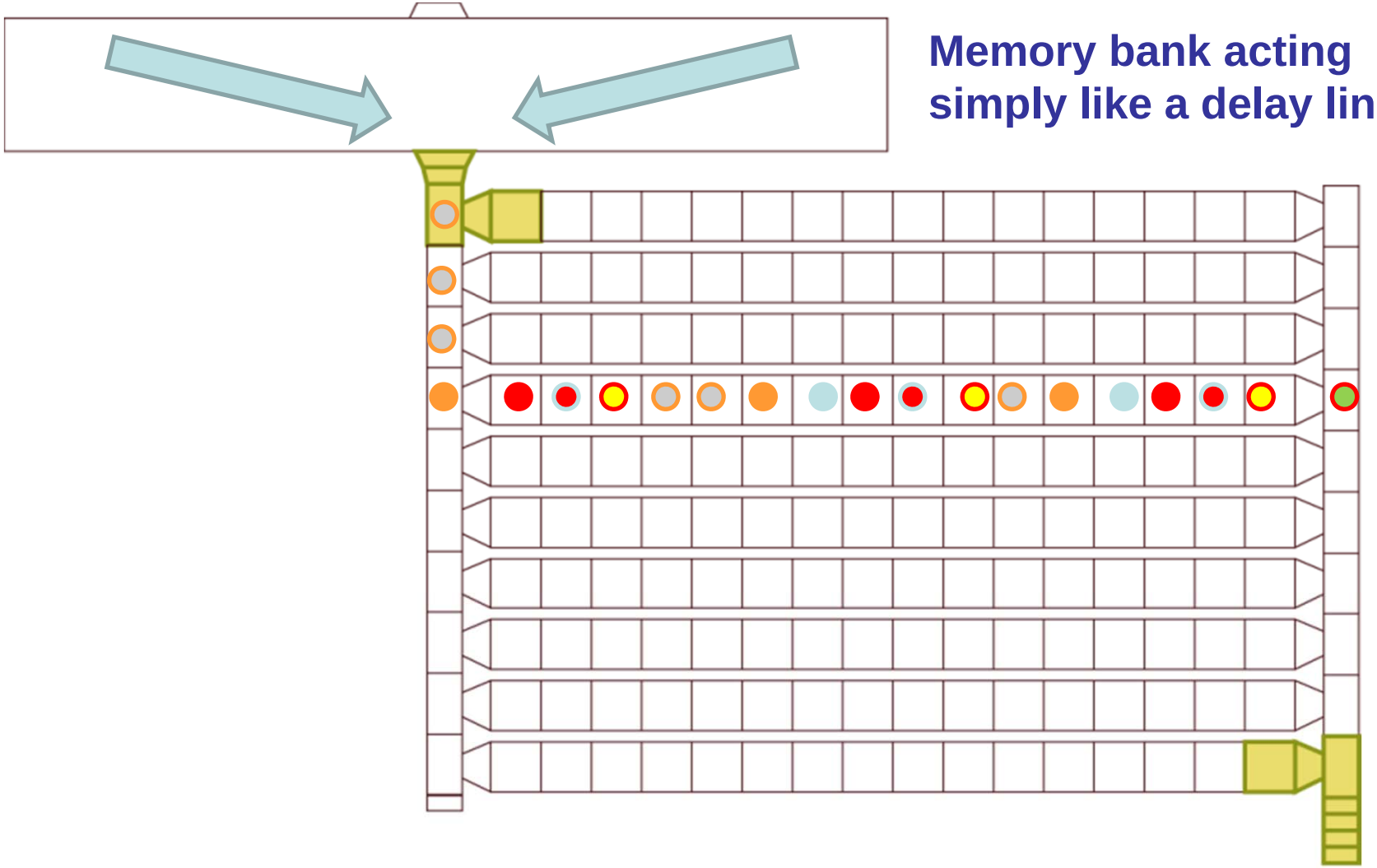
Continuous mode



Memory bank acting simply like a delay line

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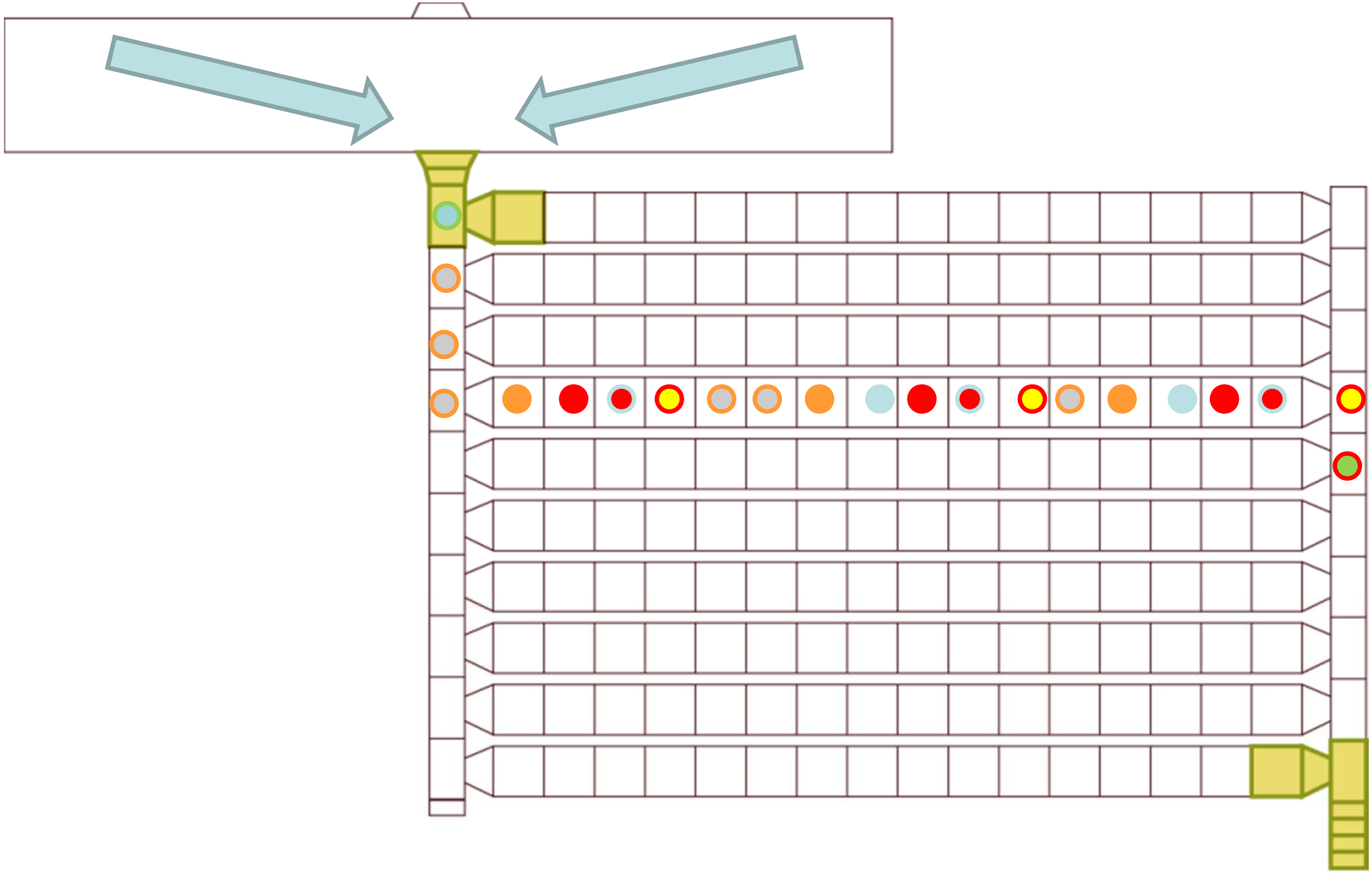
Continuous mode



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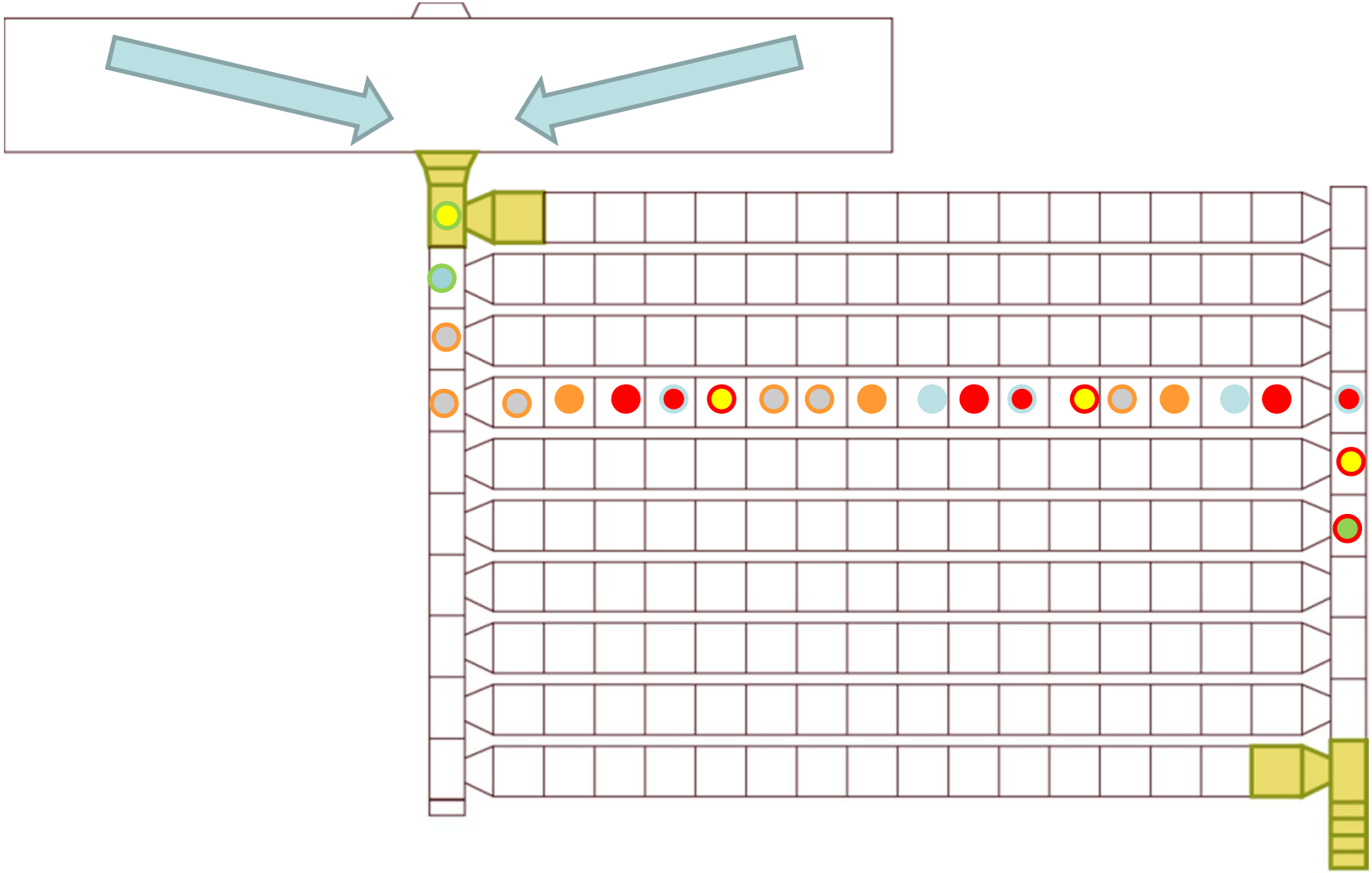
Continuous mode



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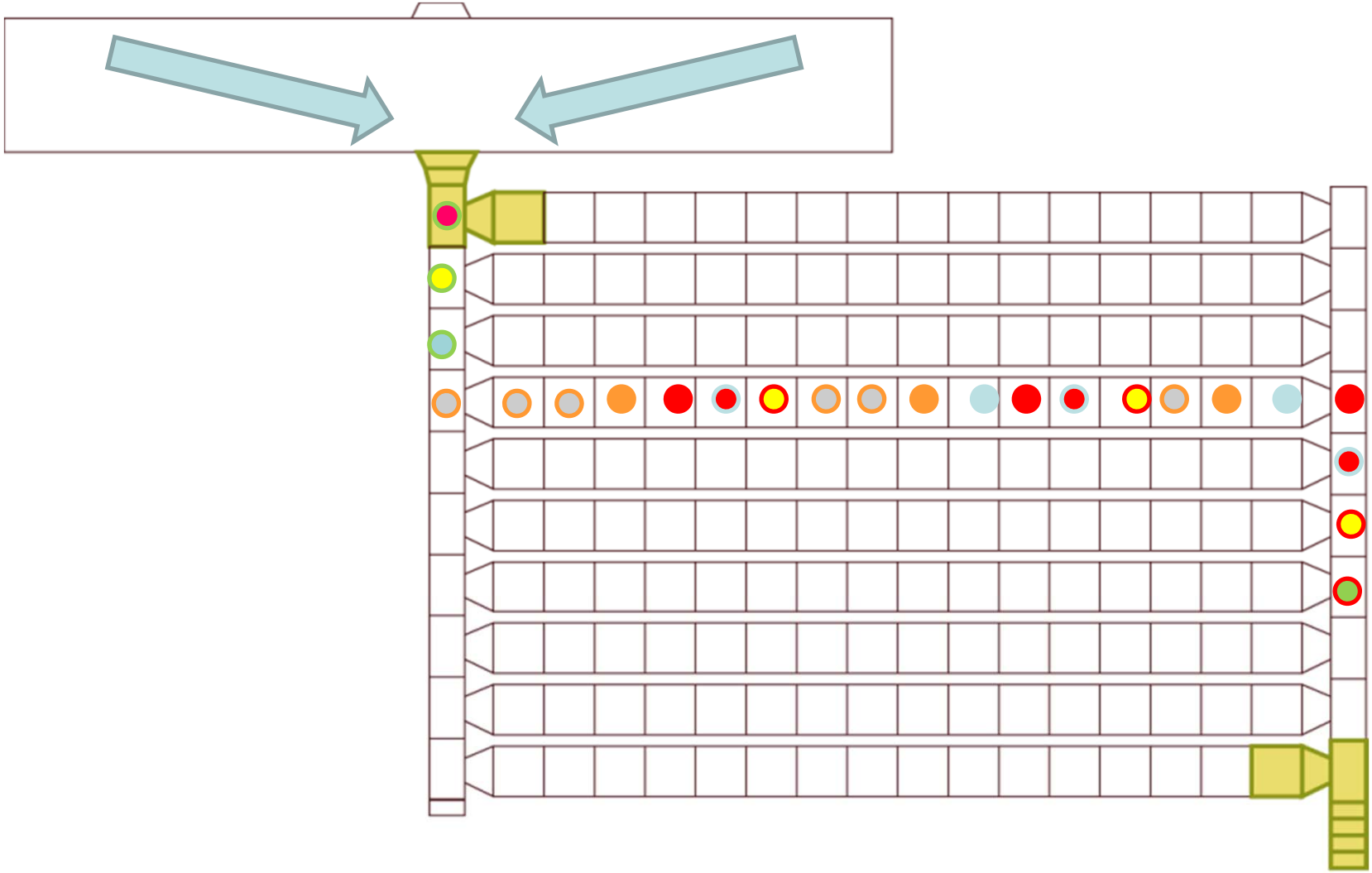
Continuous mode



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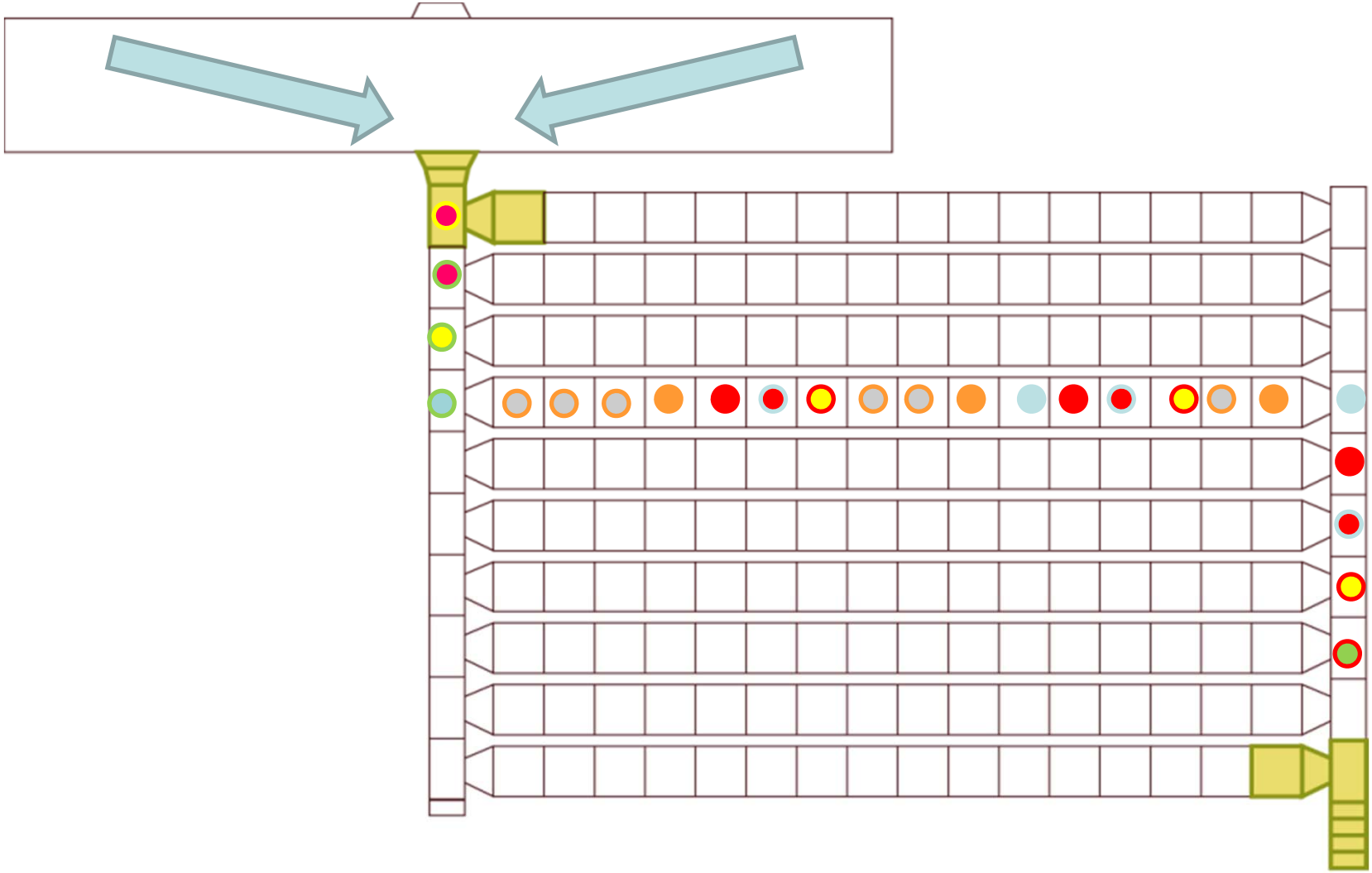
Continuous mode



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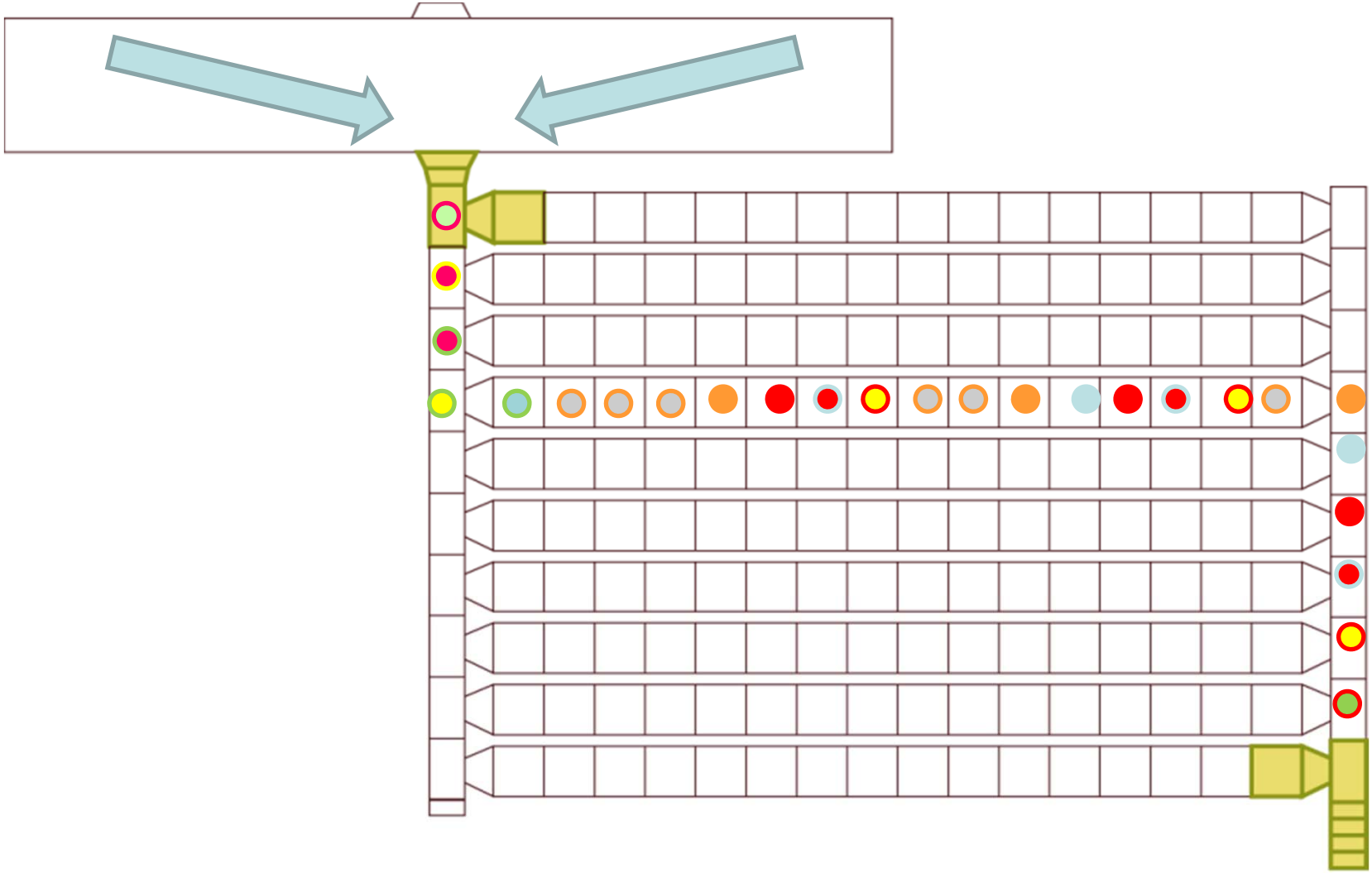
Technology

Continuous mode



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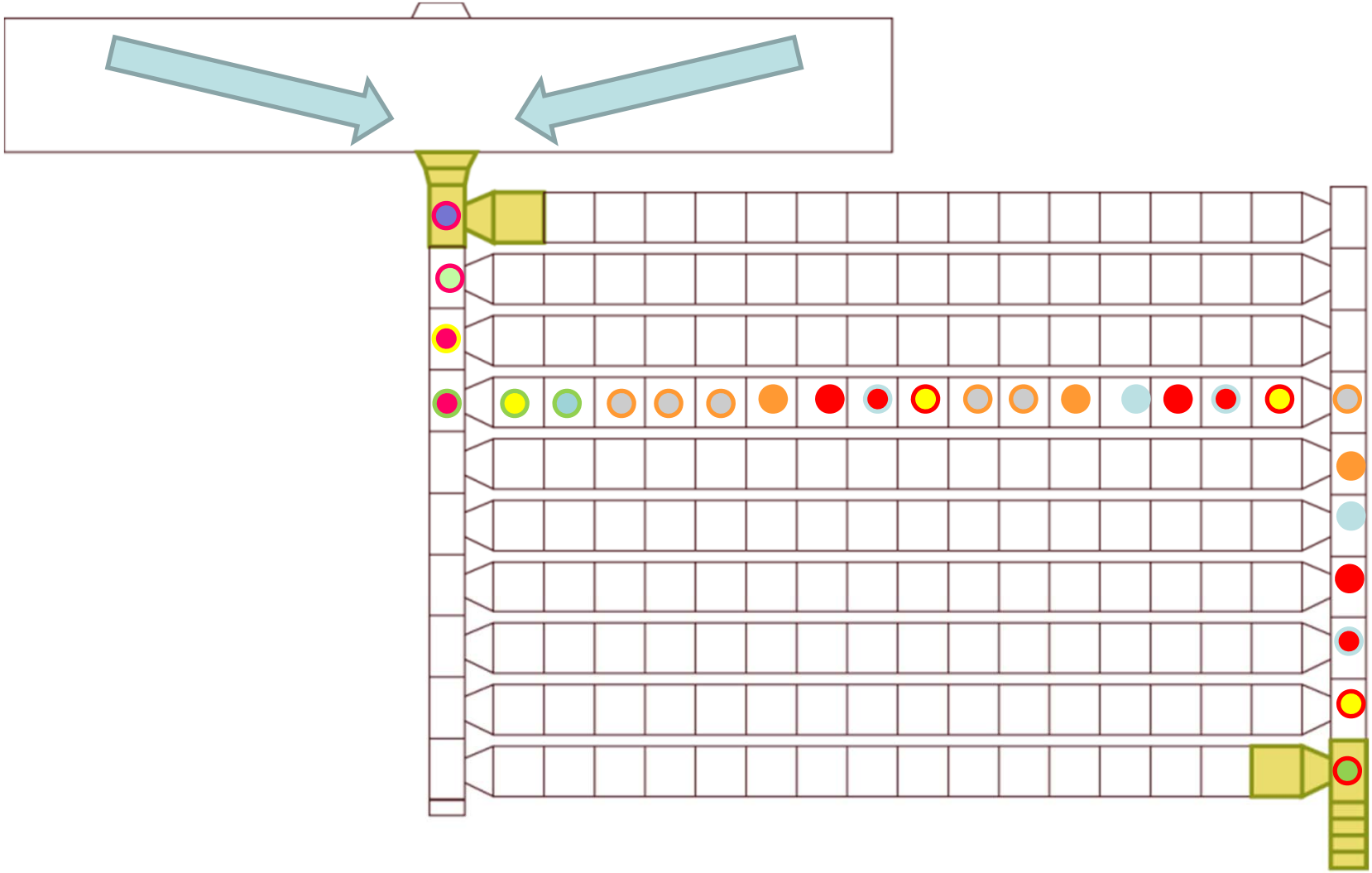
Continuous mode



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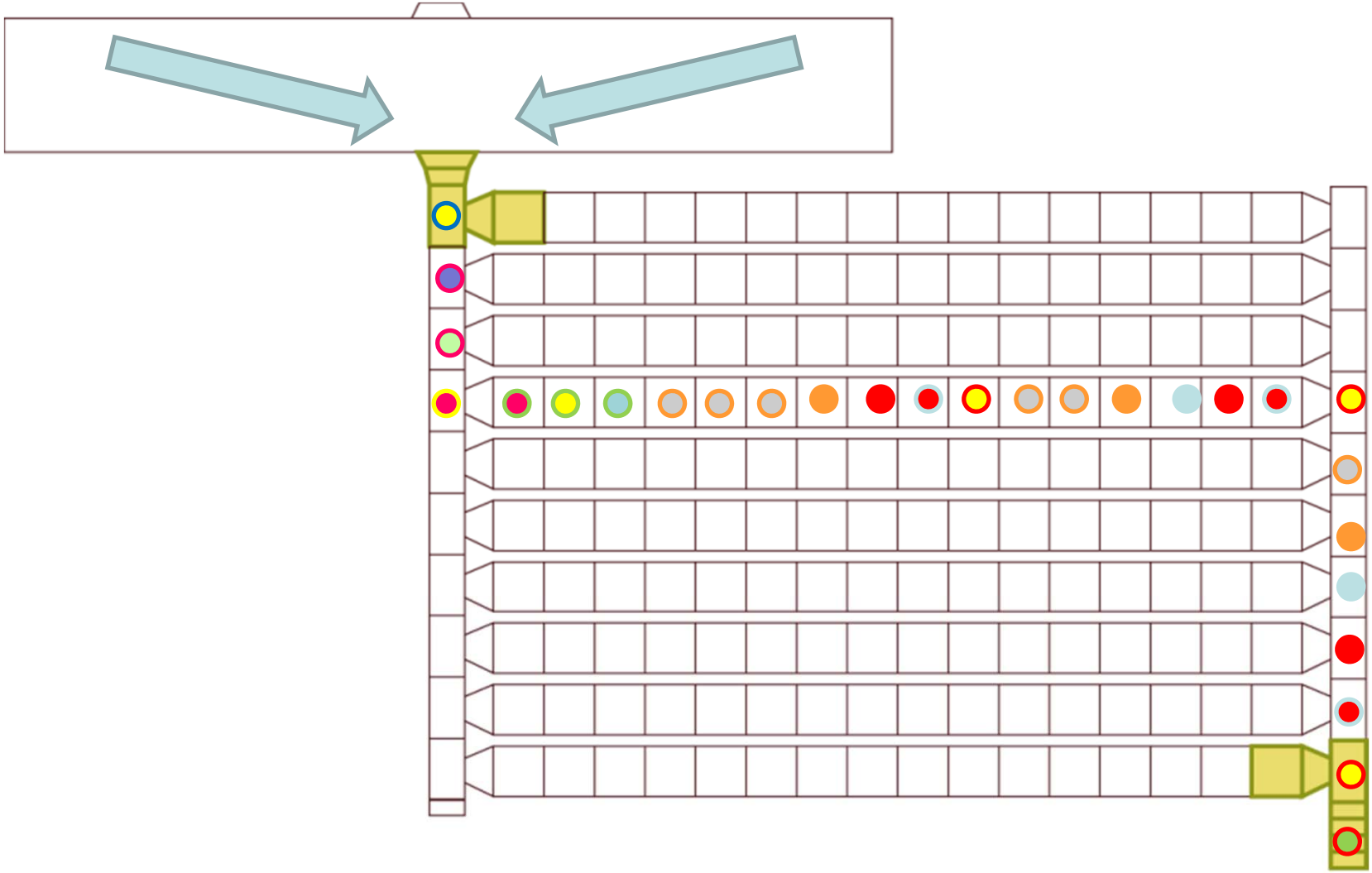
Continuous mode



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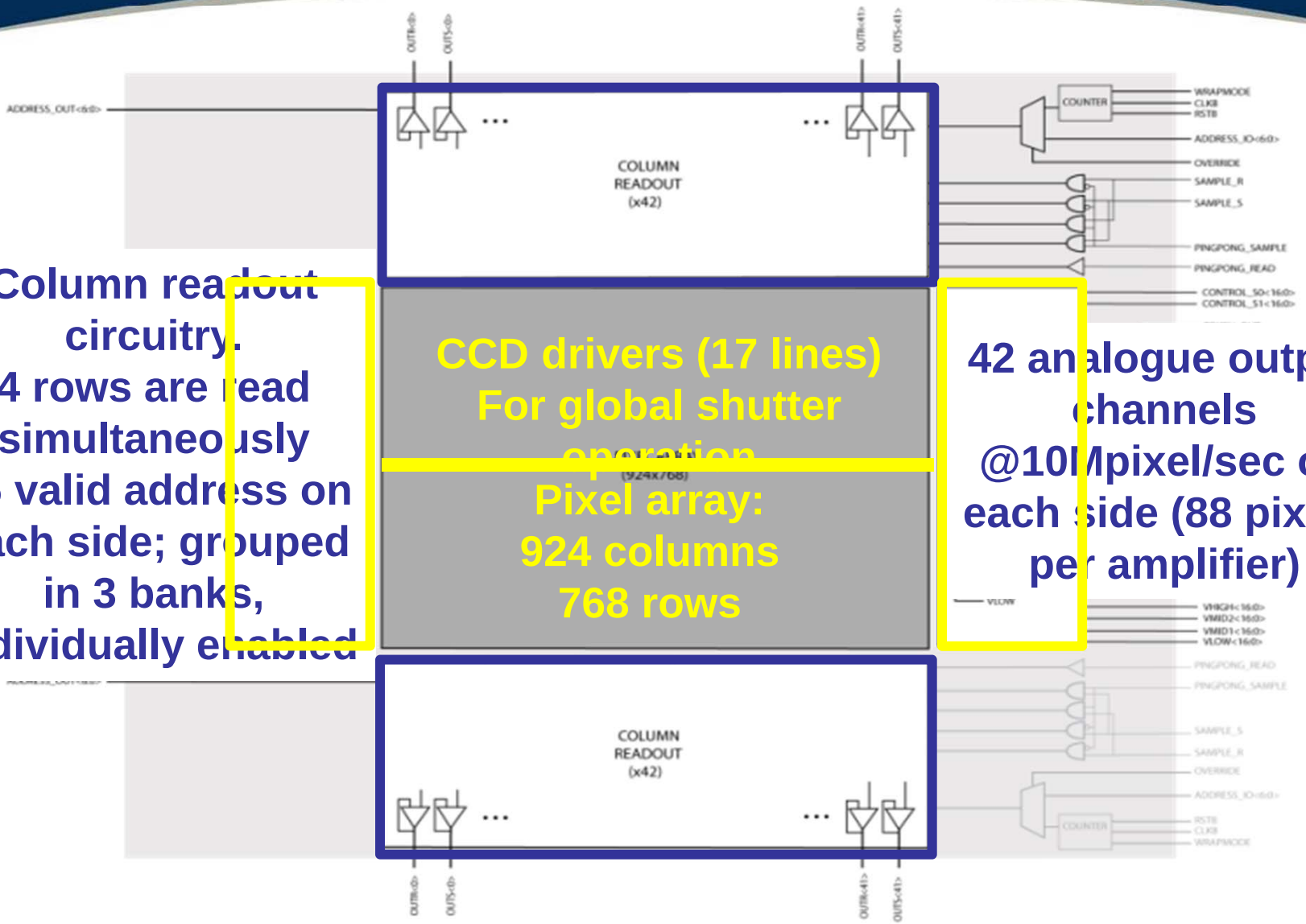
Sensor floorplan



Column readout circuitry.
4 rows are read simultaneously
96 valid address on each side; grouped in 3 banks, individually enabled

42 analogue output channels @10Mpixel/sec on each side (88 pixels per amplifier)

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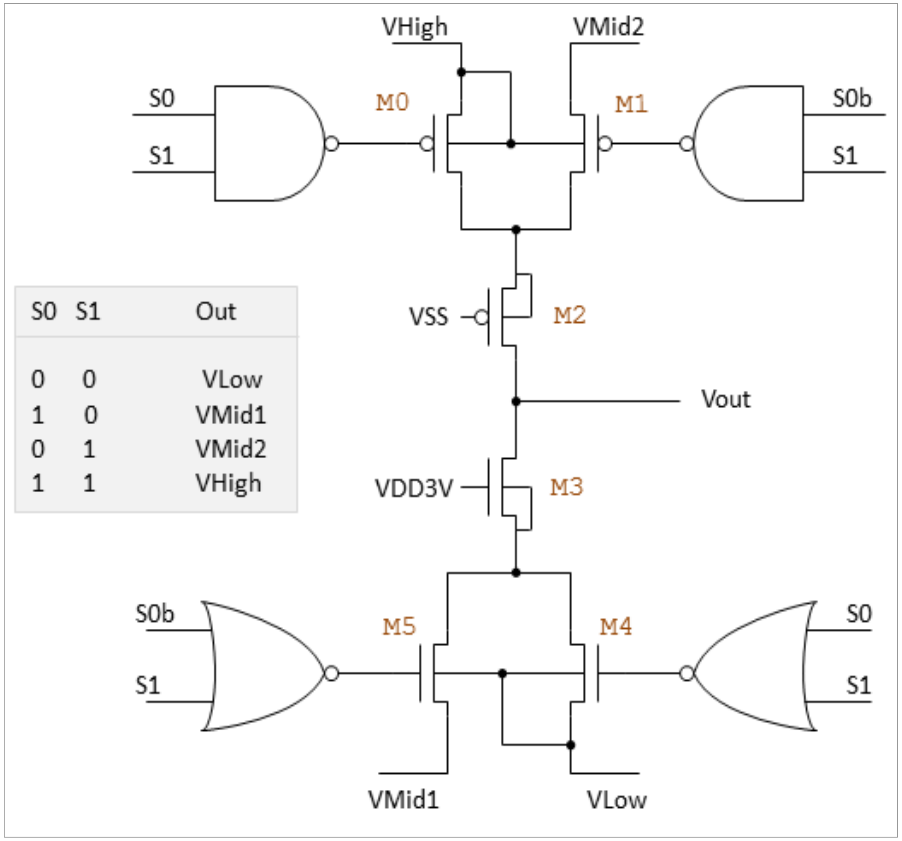
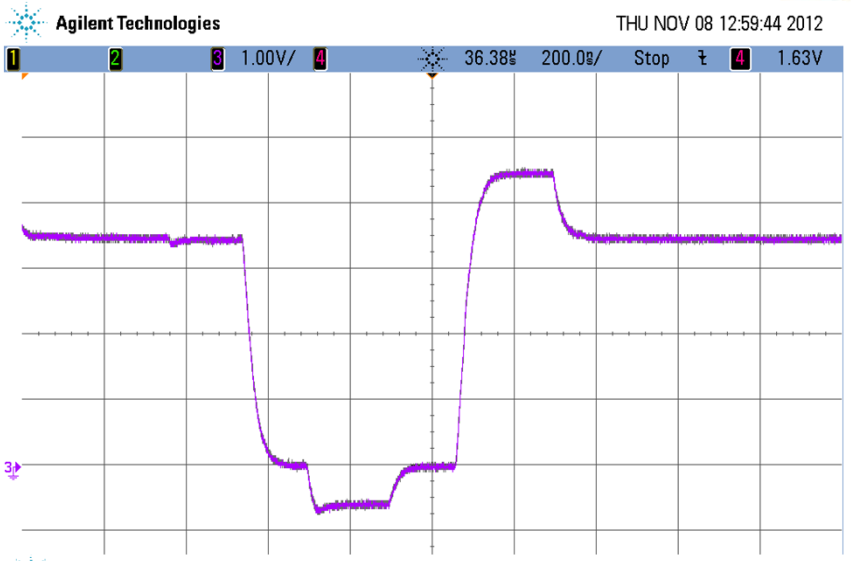
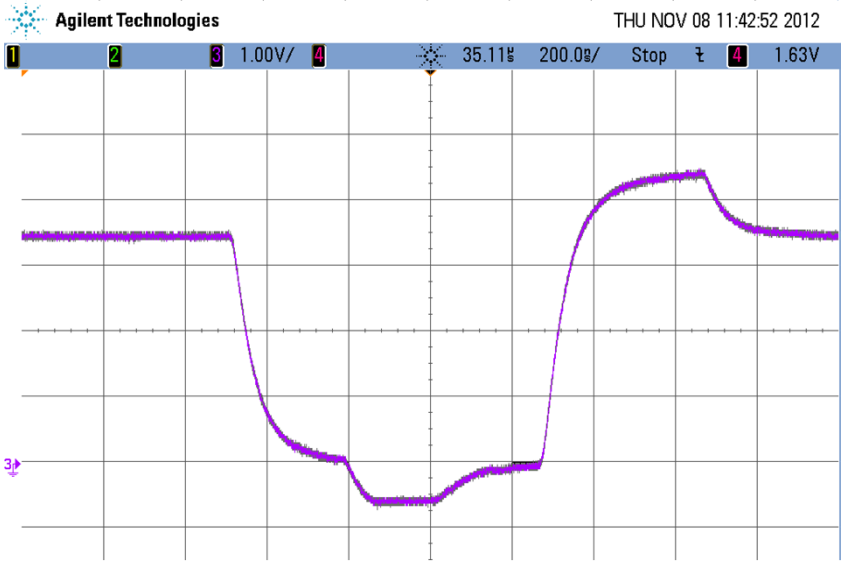
CCD drivers

Allow multiple level drivers.
Signal range: -1V → 6V



S0	S1	Out
0	0	VLow
1	0	VMid1
0	1	VMid2
1	1	VHigh





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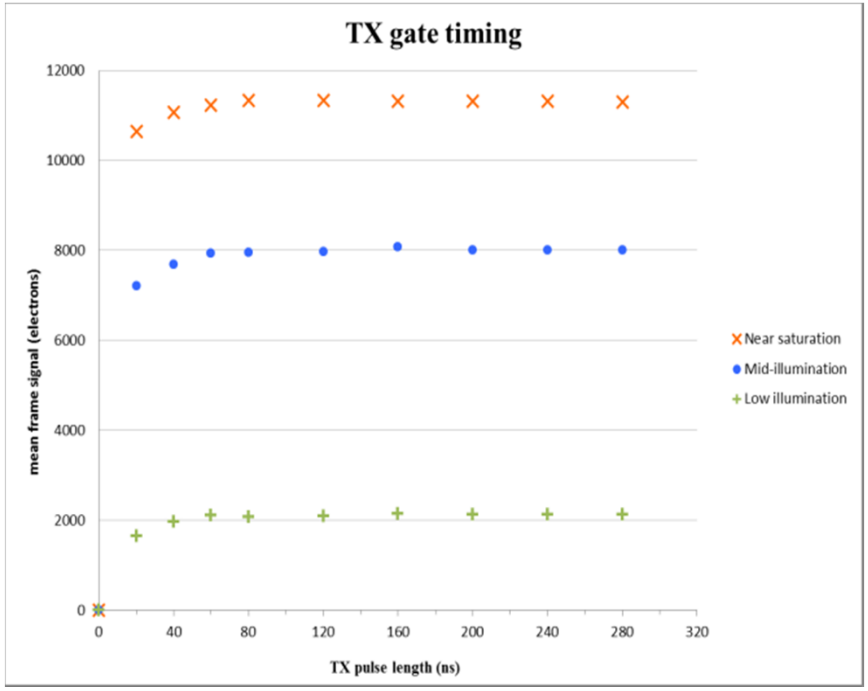
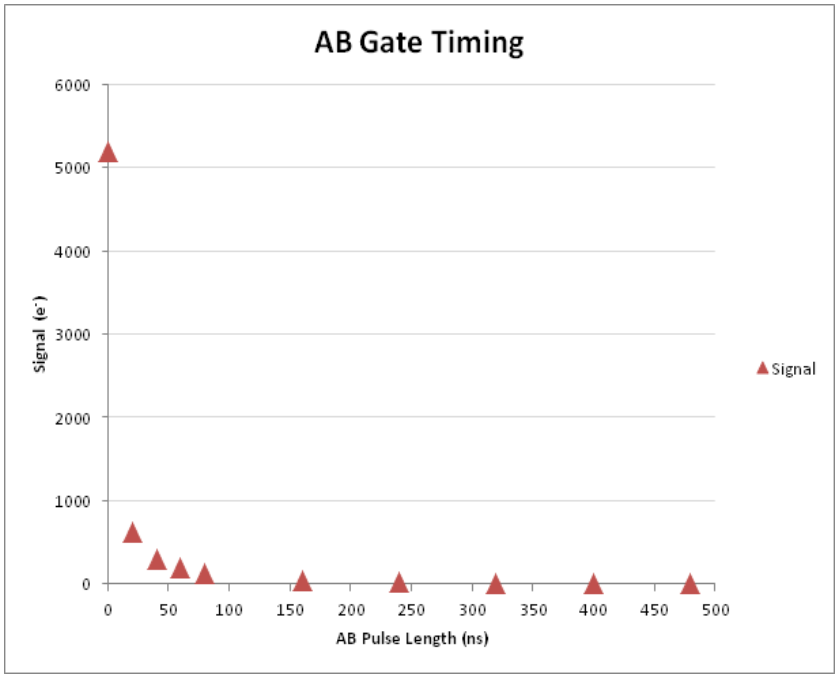
Diode timing





Shutter speed <~ 60 ns

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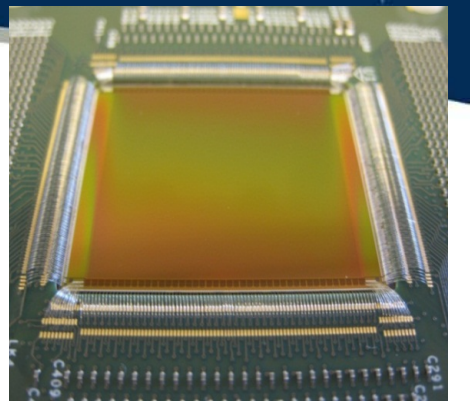
Performance summary

Parameter	Unit	Value
Pixel pitch (X)	um	30
Pixel pitch (Y)	um	30
Pixel format (X)		924
Pixel format (Y)		768
Number of pixels		709,632
Frame rate (burst mode)	fps	5,000,000
Frame rate (continuous mode)	fps	1,180
Pixel rate (burst mode)	Pixel/sec	3.5 T
Pixel rate (continuous mode)	Pixel/sec	0.84 G
Noise	e- rms	<10 e- rms
Full well capacity	e-	11,700
Camera gain	µV/e-	80
Dynamic range		>1,170
	dB	61.4
	bit	10.2
Fill Factor		11%
Quantum efficiency	Without microlens	2.3% (red) 2.2% (blue)



First manufactured on standard epi: 5.5 µm thickness, low resistivity.

New, improved version made on high-res epi and microlenses just received from manufacturing

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Imaging examples

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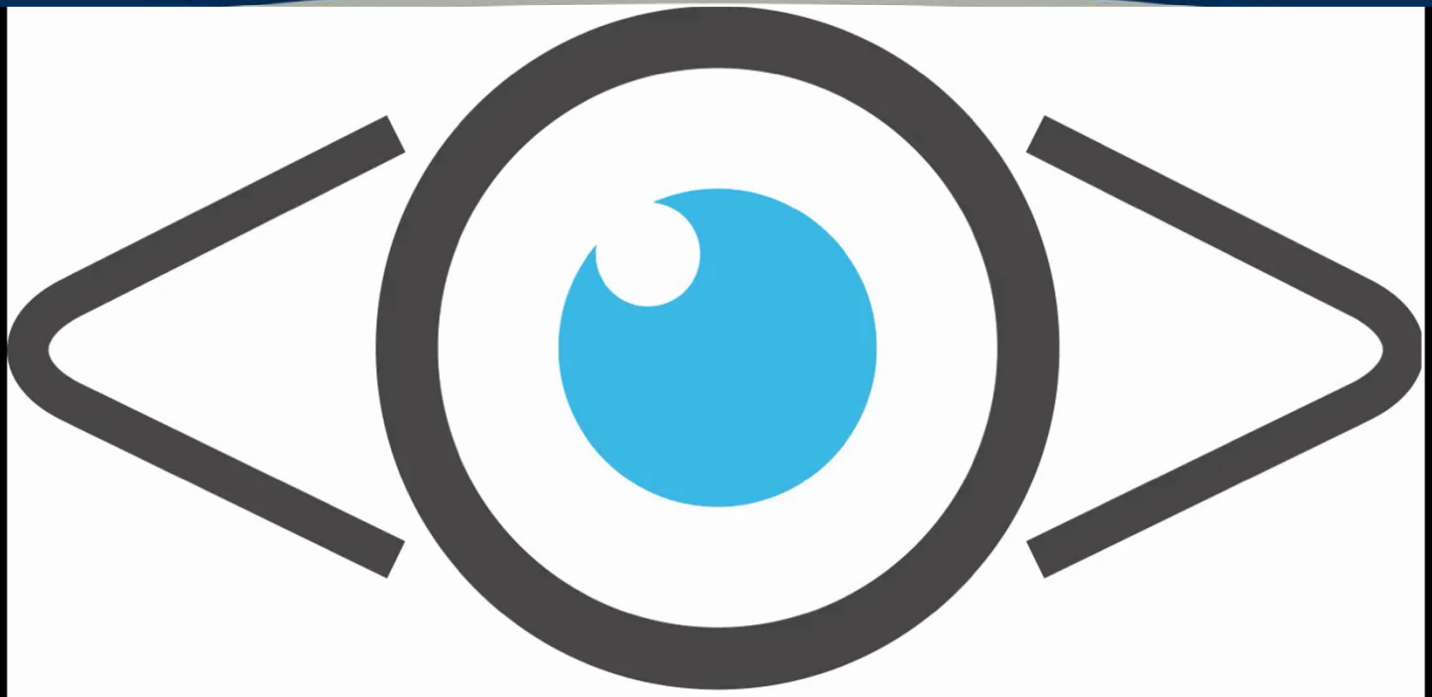
Imaging examples



specialised
imaging

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… and also

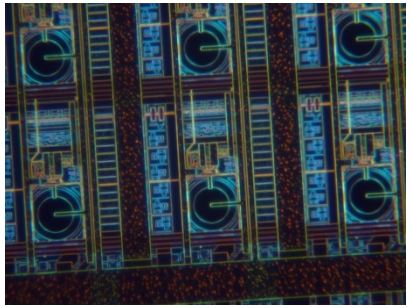
More CMOS image sensors developed (www.dsc.stfc.ac.uk/cmossensors)

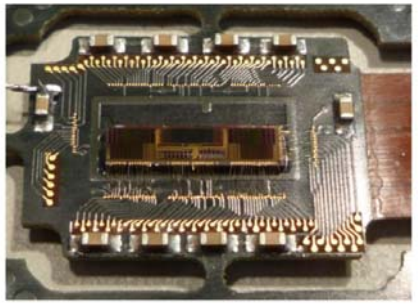
Sensors for Alice at CERN-LHC

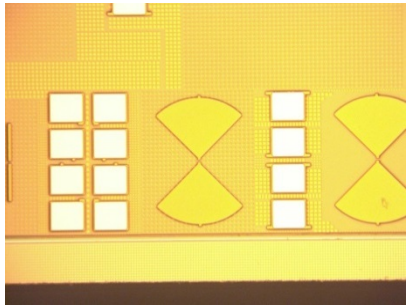
Single Photon Avalanche Detector (SPAD) array

Highly Miniaturised Radiation Monitor (HMRM) for ESA

Terahertz detectors







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Wrap-up

Broad span of technologies developed at STFC-RAL: detectors, ASIC, DAQ, software, mechanics, cooling, …

Hybrid detectors: Hexitec, LPD, …

CMOS image sensors: focus on science applications, with efficient transfer to industry

Large area sensors up to wafer-scale: Achilles for TEM in production, Lassena for medical imaging, Percival for low-energy X-ray detectors.
Ultra-high speed sensors: PIMMS for mass spec, Kirana for imaging
and more!

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Acknowledgements

Colleagues at the Rutherford Appleton Laboratory:

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and at collaborating institutes:

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G. van Hoften (FEI)

M. Brouard, C. Vaillance, R. Nickerson et al. (Oxford University)

W. Chan, K. Taylor (Specialised Imaging)

A. Fenigstein, A. Lahav (TowerJazz Semiconductor)

...

See also **www.dsc.stfc.ac.uk/cmossensors**

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The last slide

Questions?

www.dsc.stfc.ac.uk/cmossensors