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U.S. DEPARTMENT OF ENERGY

# Enhancing Sensor Readout Efficiency: Innovations and Challenges

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PIXEL 2024

**PIXEL 2024**

**18 - 22 NOV 2024**

**STRASBOURG, FRANCE**

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# Problem Definition - 1


➡problem known since ALOHA⬅

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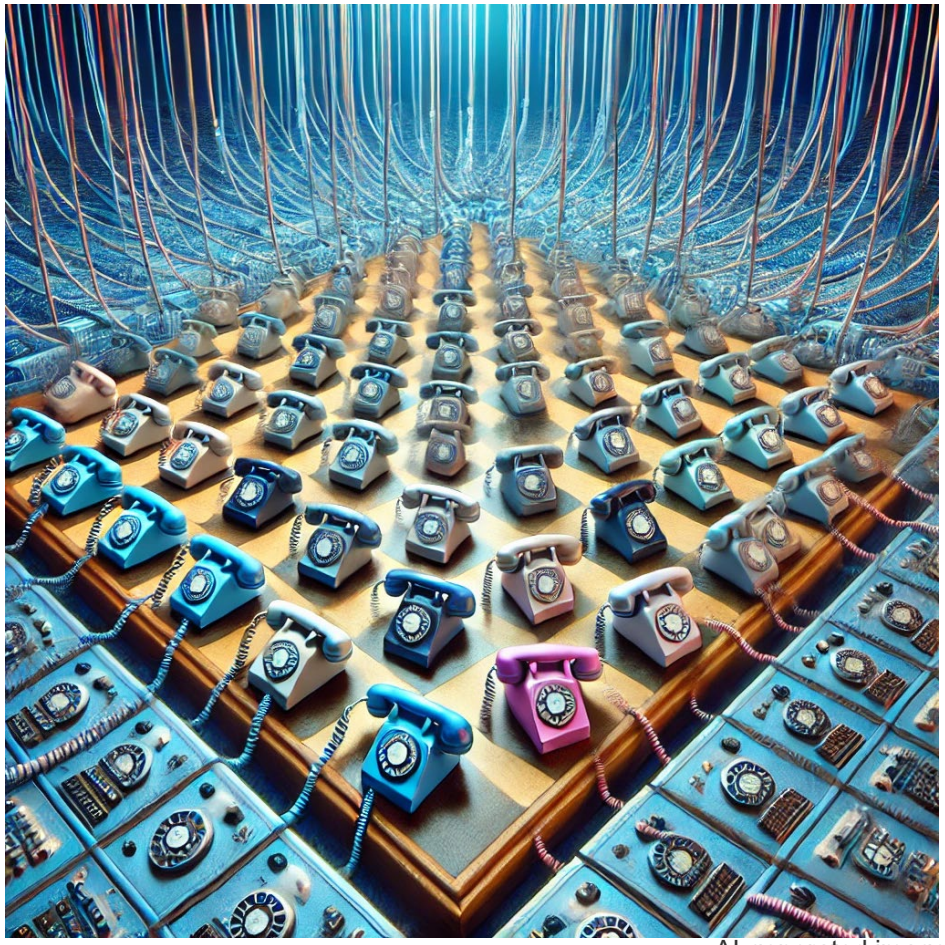
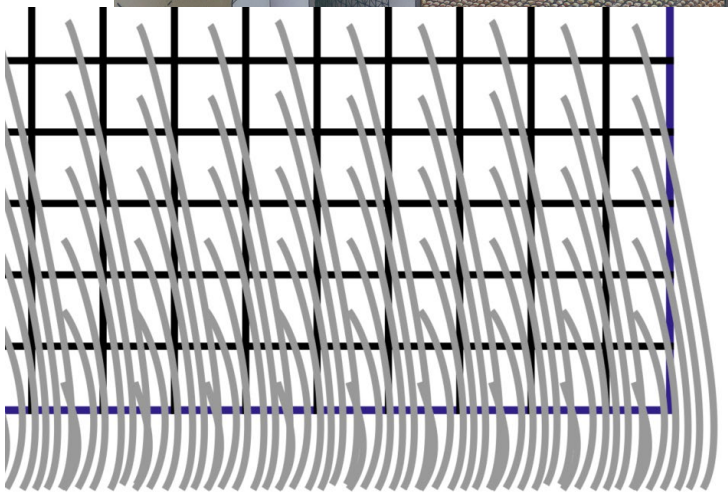
# Problem Definition - 2

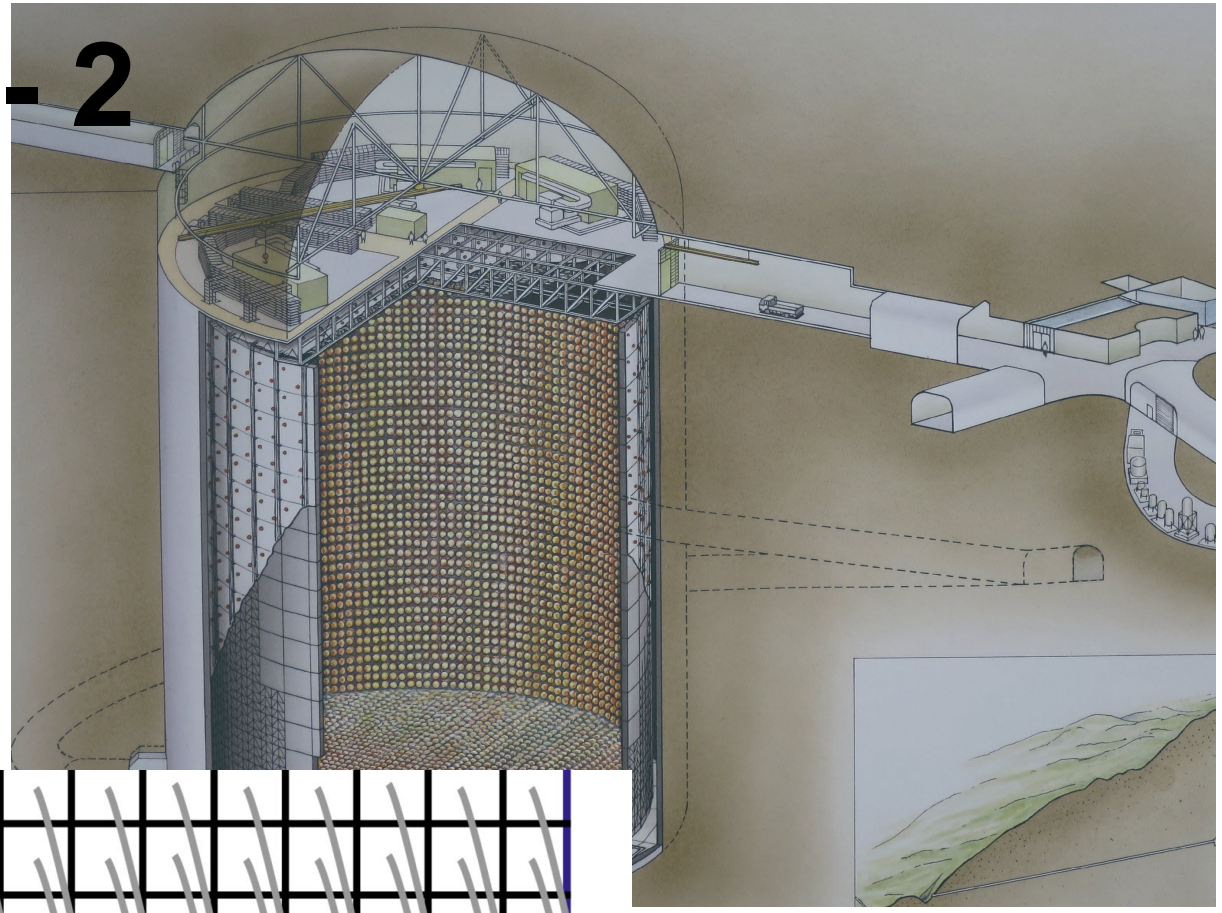


AI-generated image by ChatGPT

**1-to-1 connections ⇨ impossibility of routing**



**interconnects**



- **1-to-1 ⇨ no conflicts on links**
- **an only be applied (almost) in specific case**

https://www-sk.icrr.u-tokyo.ac.jp/en/hk/about/detector

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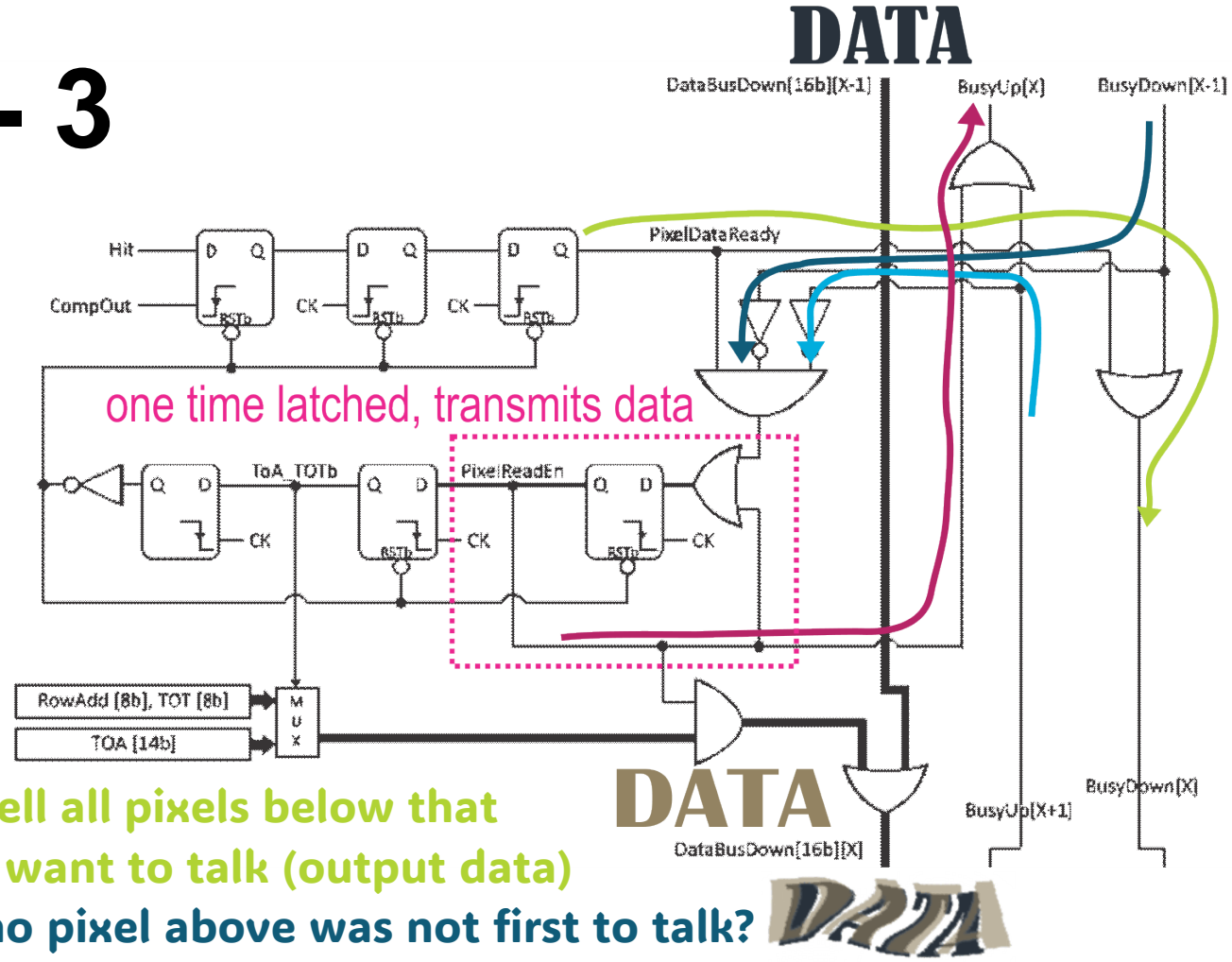
# Problem Definition - 3


AI-generated image
by ChatGPT




- tell all pixels below that I want to talk (output data)
- no pixel above was not first to talk?
- no pixel below is already talking?
- I start talking and tell all pixels above that I'm talking!
- It should prevent talking simultaneously, but information has some latency, and CKs are not the same in all pixels

➡neighbors' states awareness, who is first?⬅

Inspired by: "X-ray Detectors for LCLS-II with real-time information extraction: the SparkPix family", L. Rota, 24th iWoRiD

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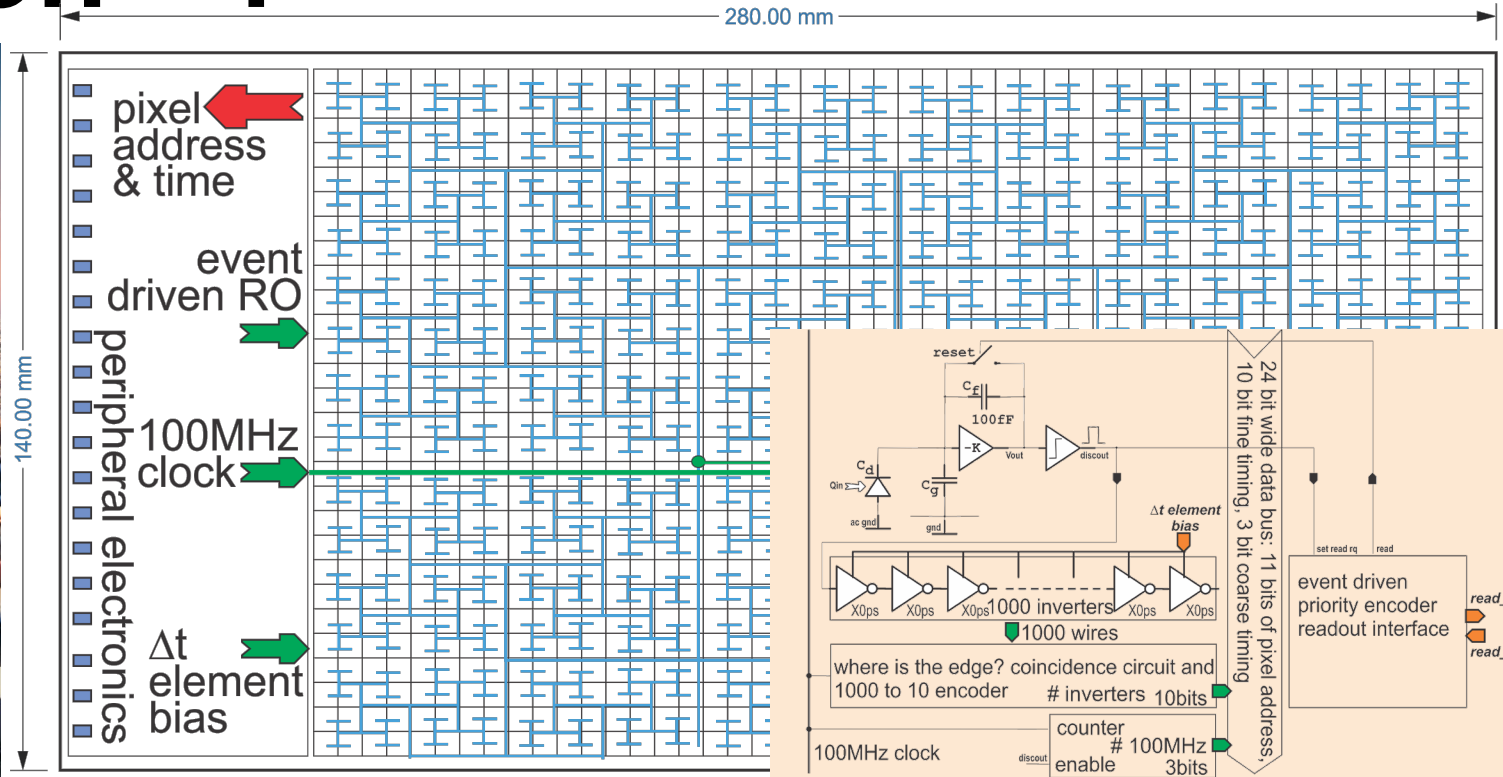
# Problem Definition - 4

AI-generated image by ChatGPT

every pixel has different clock





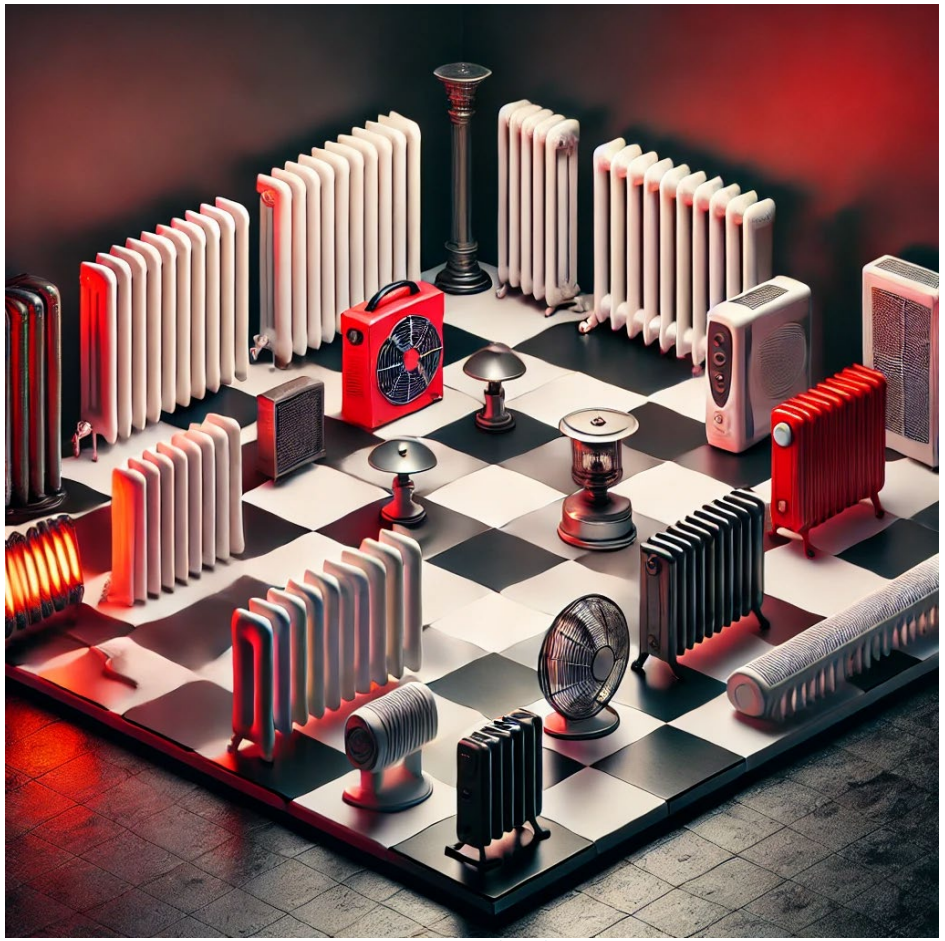


- H-tree cannot assure isochronicity of clocks
- distribution of reference clock for in-pixel TDCs is OK as delays can be calibrated out,
- but wrongly resolved concurrency leads to corrupted data

➡time awareness⬅

Inspired by: “Associate Particle Imaging Readout Concept”, G.W. Deptuch

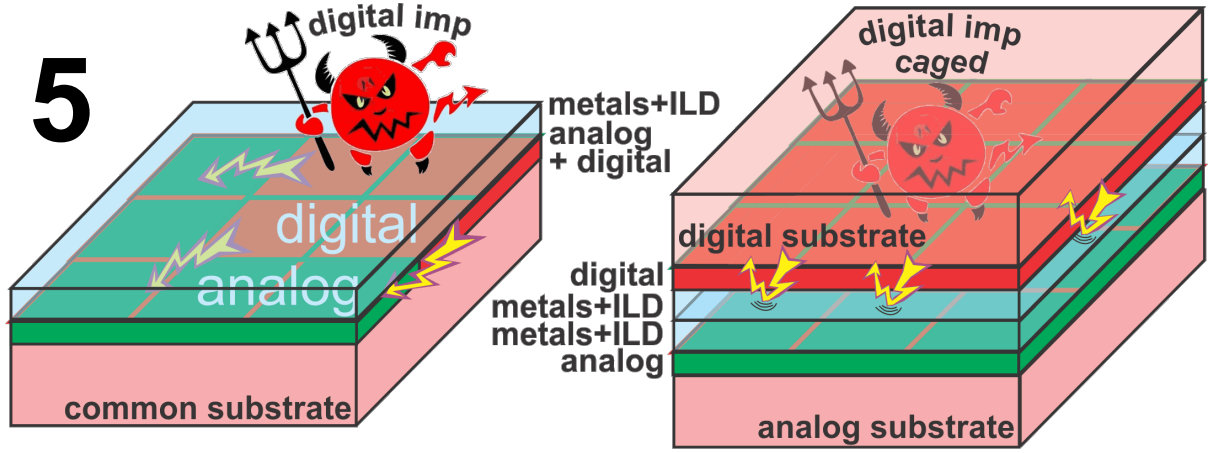
# Problem Definition - 5



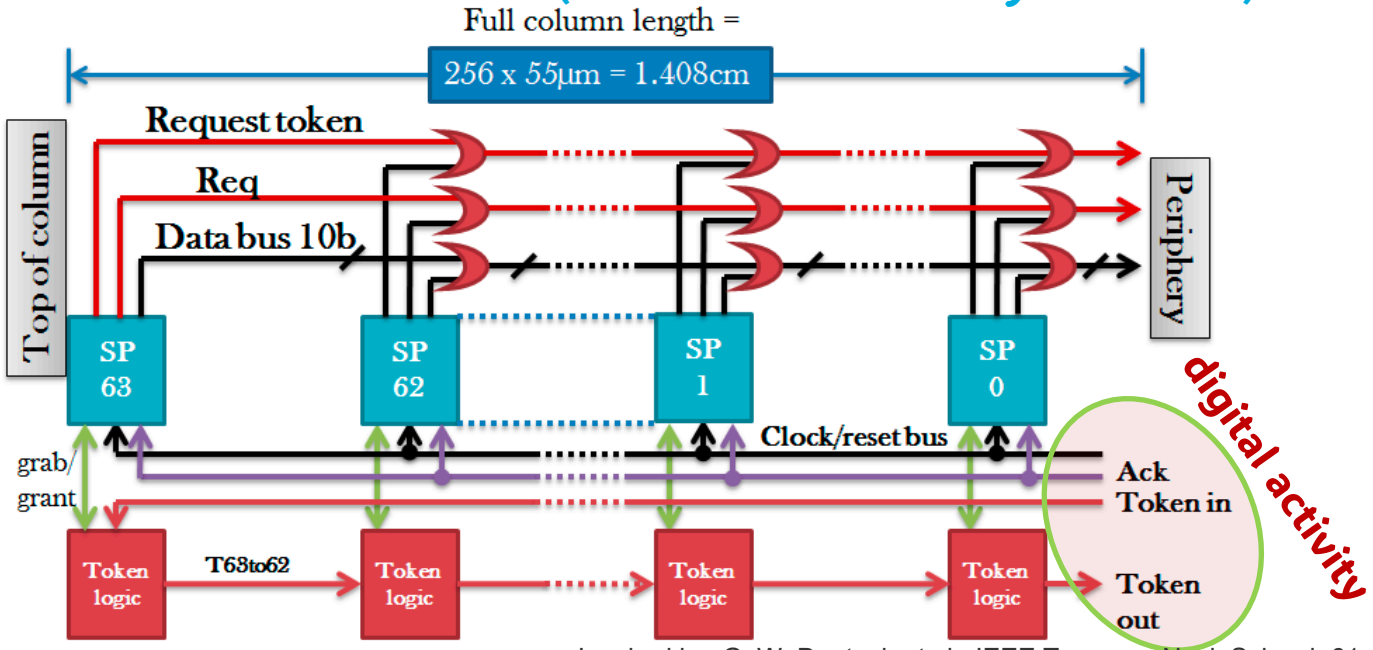
AI-generated image by ChatGPT

more activity

⇨more dissipated heat and more interferences




- clocks, tokens, strobes etc., reaching all pixels:
  - need charging discharging of capacitances;
  - causes interferences (and 3D-IC is not always available)




➡power and interferences⬅

Inspired by: G. W. Deptuch et al., IEEE Trans. on Nucl. Sci. vol. 61, no. 1, pp. 663-674, Feb. 2014, doi: 10.1109/TNS.2013.2294673 and T. Poikela "Readout Architecture for Hybrid Pixel Readout Chips", PhD thesis 2015

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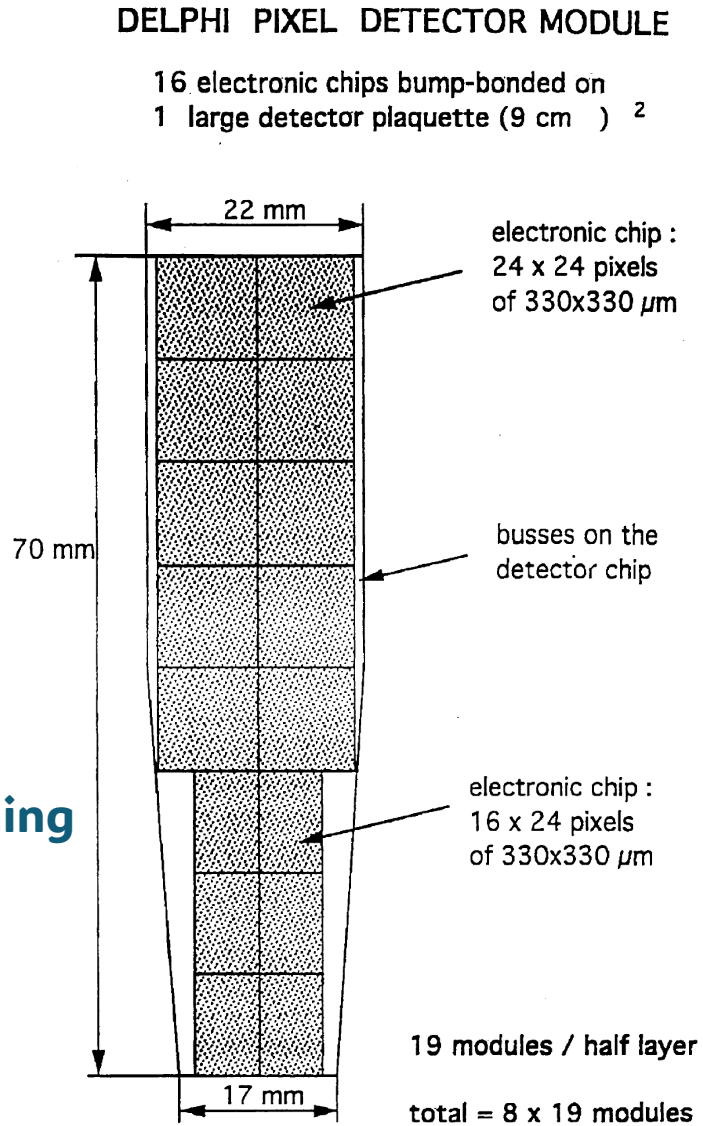
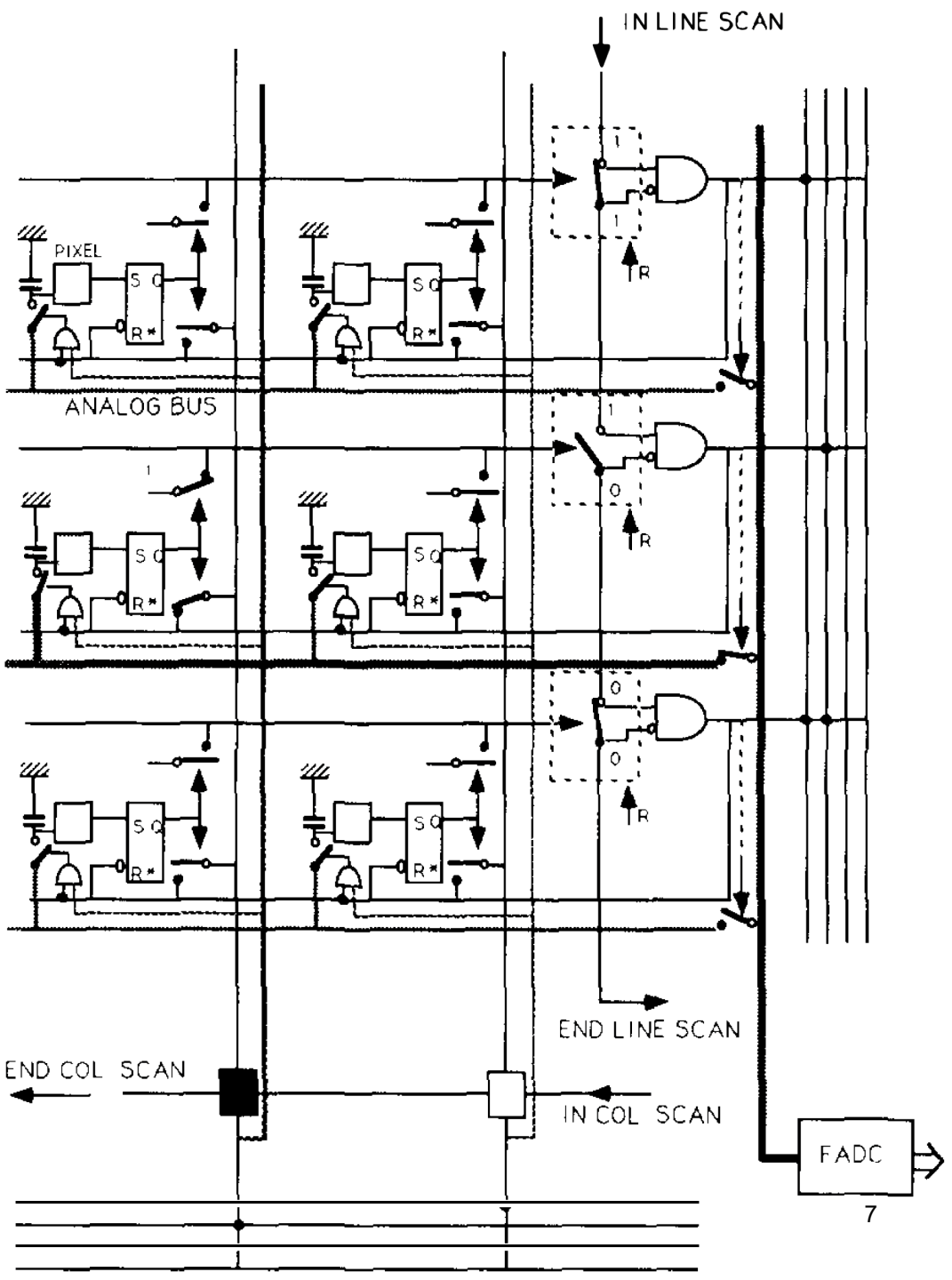
# From the Past - 1

AI-generated image
by ChatGPT

**pixel detector readout,**
**with two-dimensional**
**X-Y signaling and scanning**
**sparse data scan**
**(with added feature of**
**analog readout)**
**2D ambiguity**





P. Delpierre and J.J. Jaeger, Nuclear Instruments and Methods in Physics Research A305 (1991) 627
Erik H.M. Heijne, spk., CERN DRDC/93-54 RD19 Status Report 1 January 1994

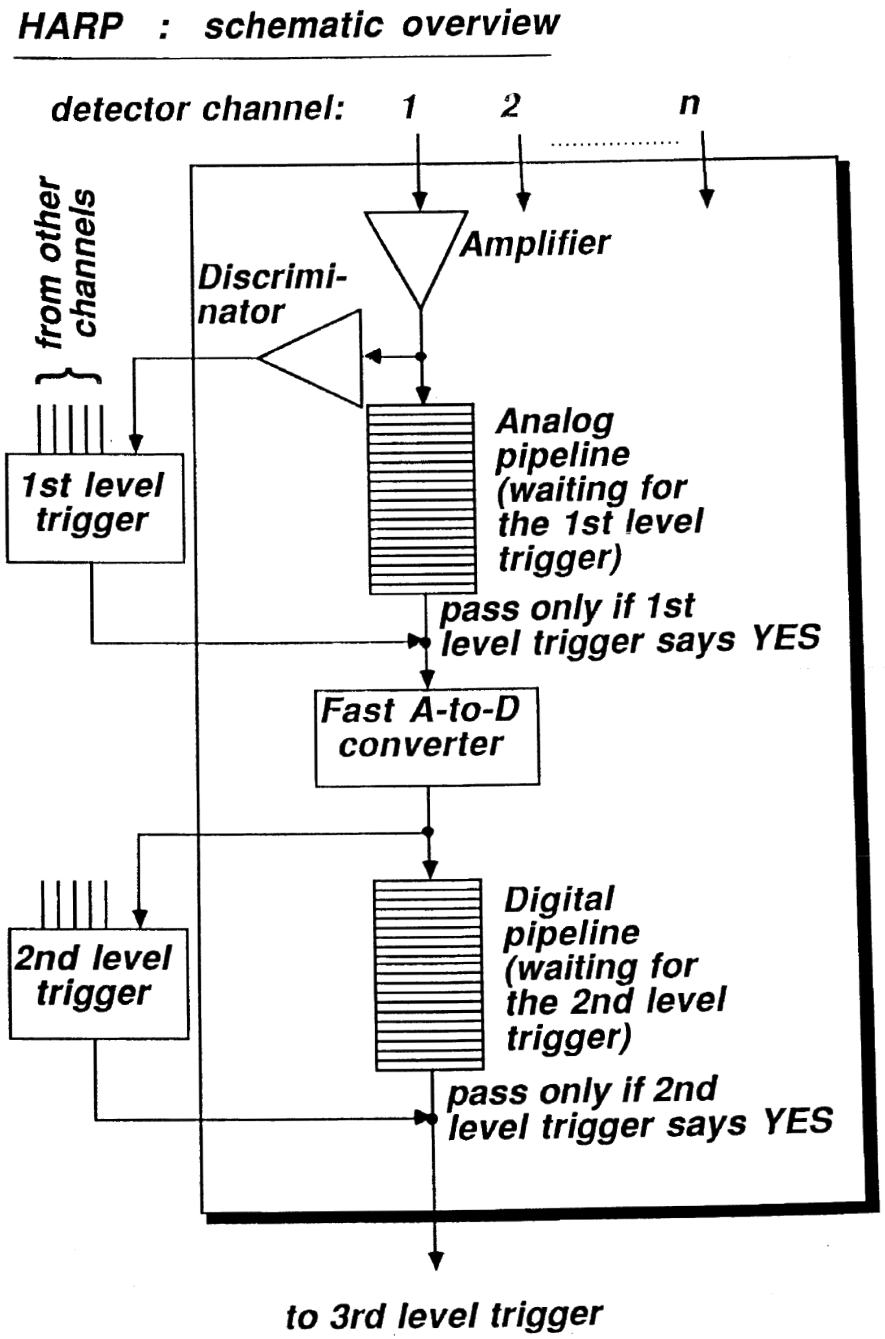
# 2 Steps in Data Flow

AI-generated image
by ChatGPT

**two steps:**

- **get data from pixels to periphery (buffers)**
- **organize output awating trigger arrival**

**focus on extracting data from within pixel matrix to peripherals**




F. Anghinolfi, et al., CERN/EF 89-14 CERN/LAA/SD 89-11 13 September 1989

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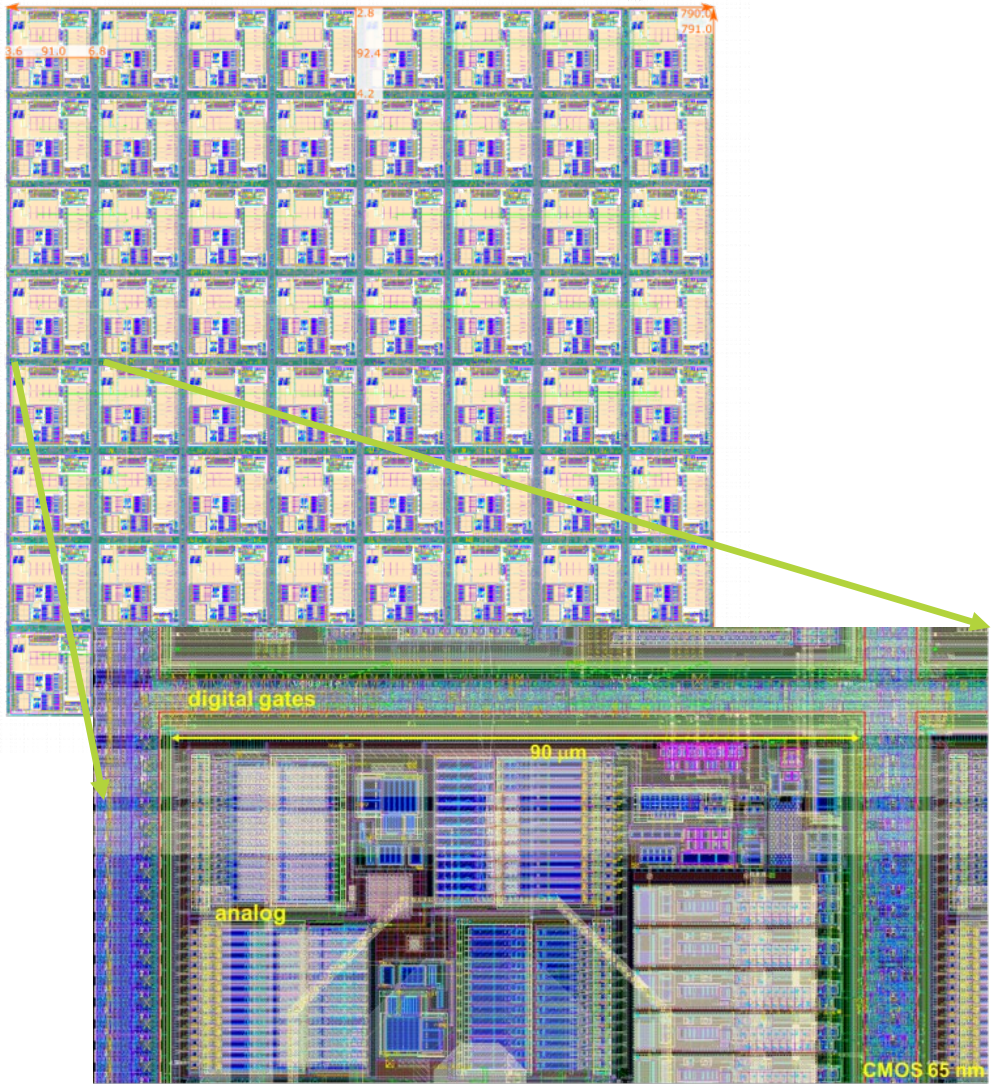
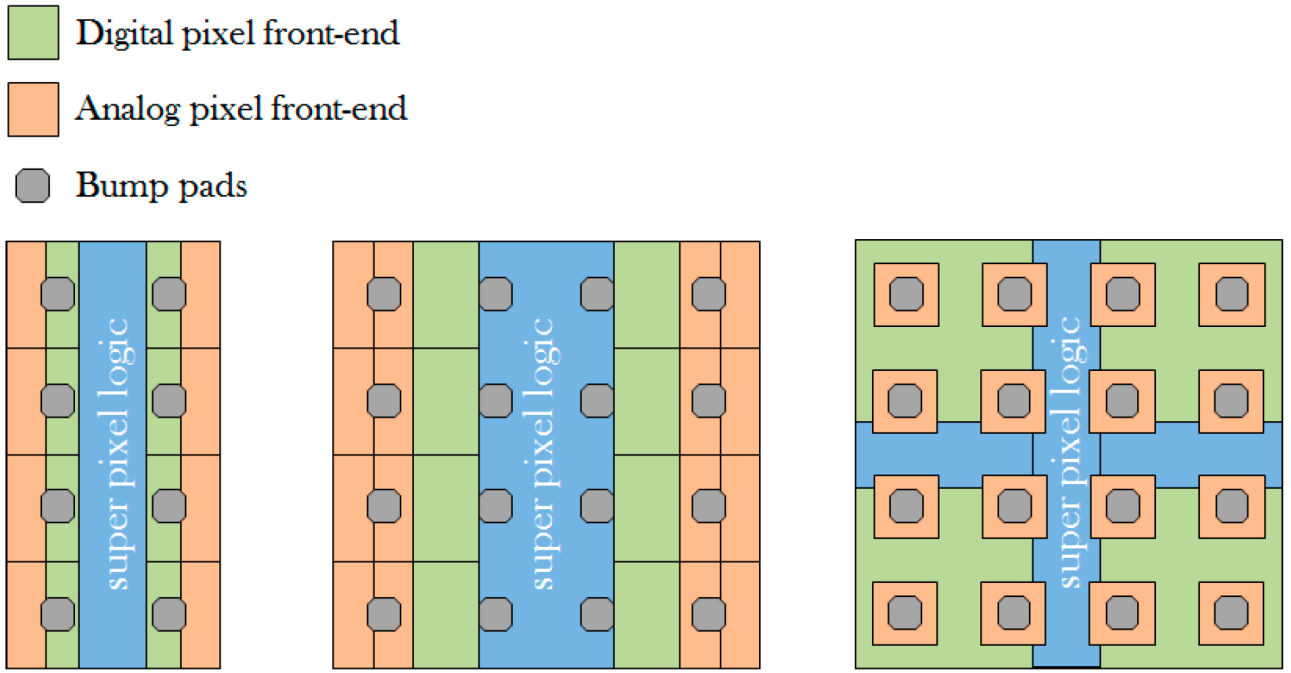
# Design with Selected Readout Platform




common approach of building
- super pixel 2×4, 4×4 and 4×4
- analog islands encircled by logic.




➡logic (arbitration tree) placed in space between channel cores (e.g. AFE)⬅

and T. Poikela “Readout Architecture for Hybrid Pixel Readout Chips”, PhD thesis 2015

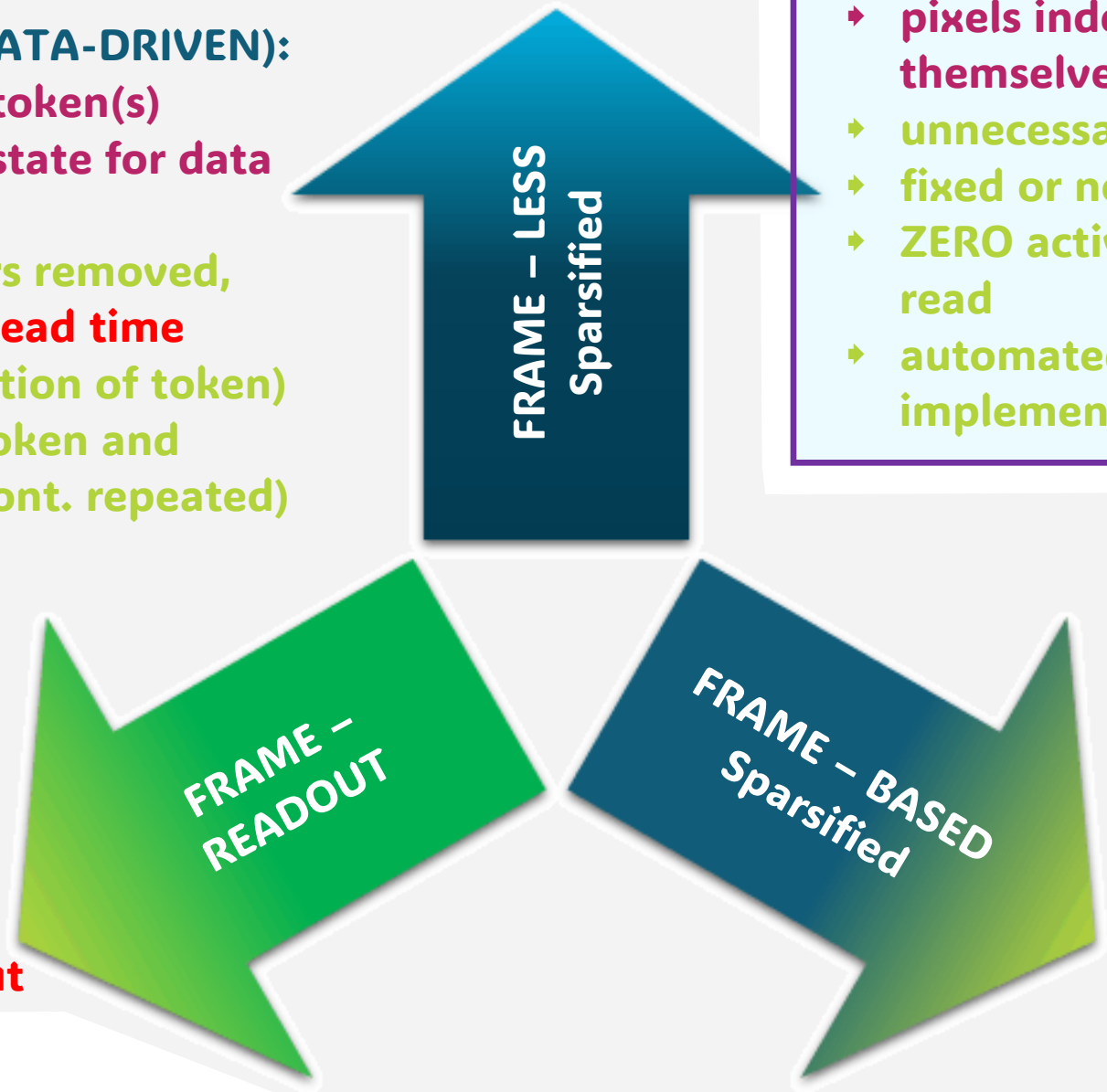
# Summary of Solutions - 1

**Frame-less POLLING (DATA-DRIVEN):**

- typically circulating token(s) queries each pixel's state for data to transmit
- unnecessary transfers removed,
- varrying latency or dead time introduced (propagation of token)
- continuos activity (token and strobes need to be cont. repeated)

**Frame-readout:**

- all pixels are read out sequentially
- predefined order of data retrieval
- large amounts of dubious information
- no timing from readout



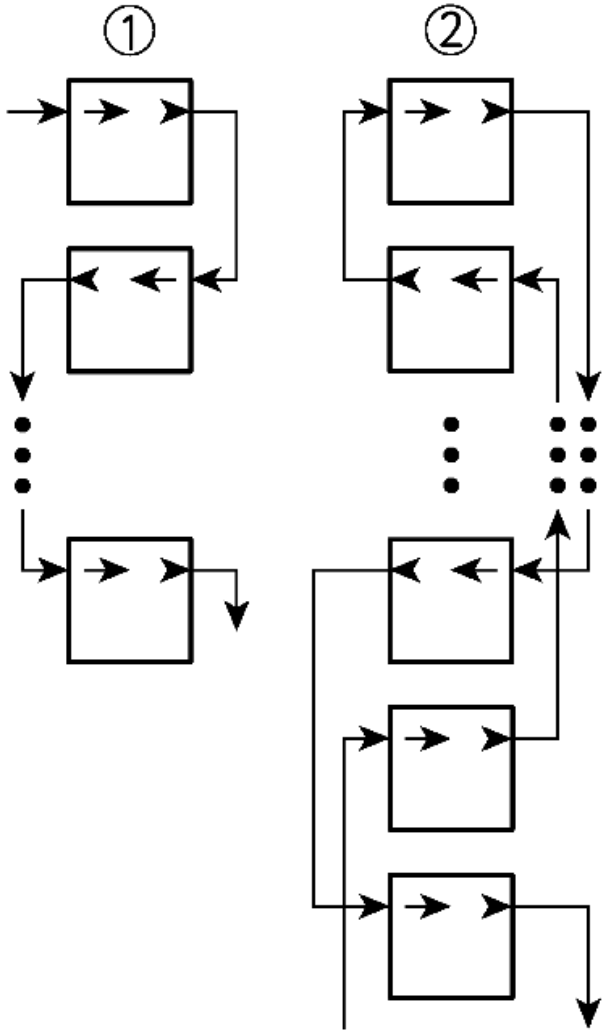

**Frame-less EVENT-DRIVEN:**

- pixels independently signal themselves for readout
- unnecessary transfers removed,
- fixed or no latency or dead time
- ZERO activity until anything to read
- automated CAD/EDA circuital implementation possible

**Frame-based sparsified:**

- snapshot taken first
- static arbitration – predefined order
- pixels fished out with:
  - priority encoder
  - token passing
- zero-supressed
- no timing from readout

# Summary of Solution - 2




## Frame readout

**typically snaky style – shift registers:**

- **data out** (typically count values in SPC mode)
- **data in** (configuration)

- data accumulated during exposure window moves a long shift registers
- often shift registers are reconfigured counters for real estate efficiency
- many detectors developed for Photon Science operating in SPC mode

- very simple ⇨ will not spend time on this type

➡ threshold for using is occupancy⬅

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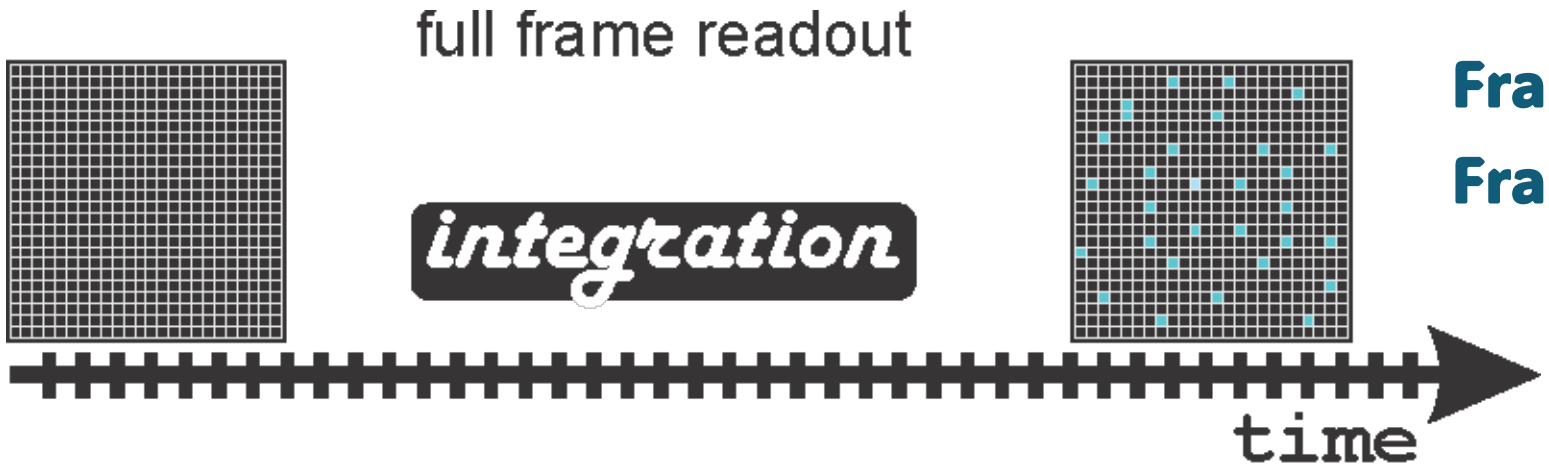
# Summary of Solution - 3

## Comparison



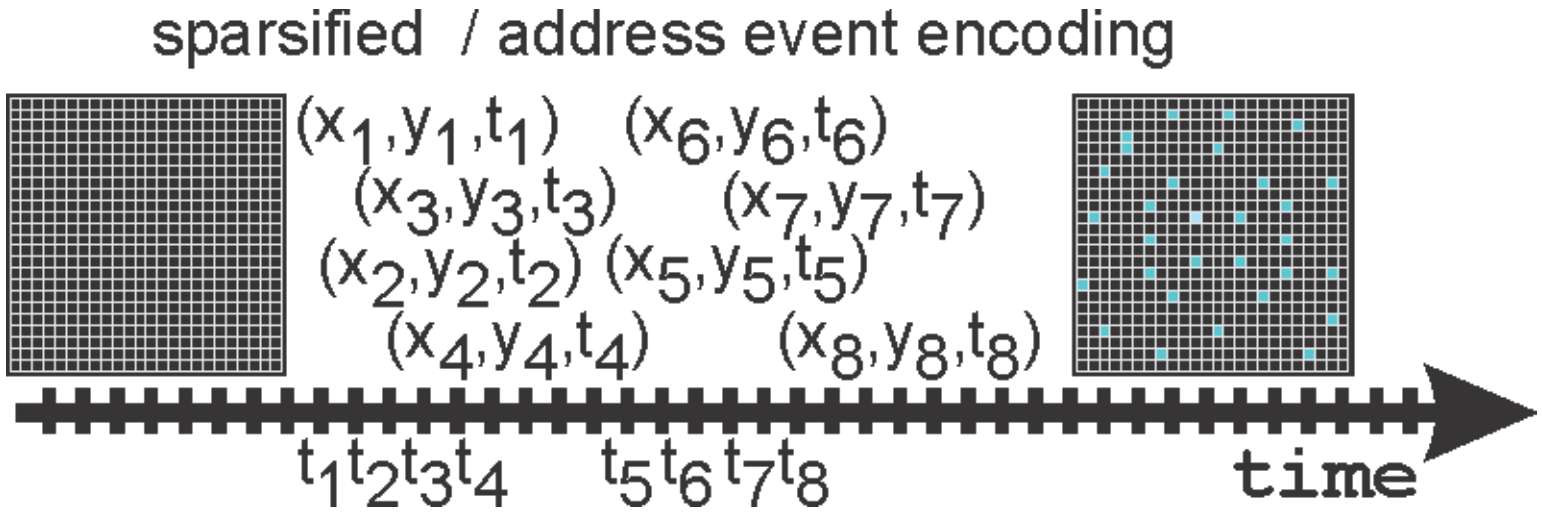

**Frame- Based**

**Frame Based Sparsified**

**Frame- Less**

**Polling**

**Event-Driven**

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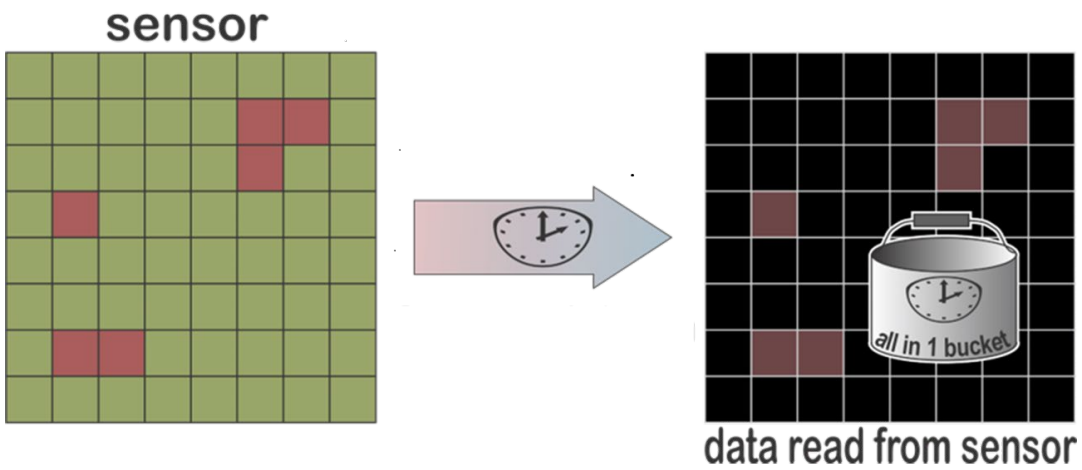
# Arbitration methods

## Static Arbitration:

**with combinational logic**
**(priority encoder / token passing)**

- state of matrix snapshot before readout to prevent corruption if requests with higher priority arrive
- data sent in packages (with period of snapshotting clock)

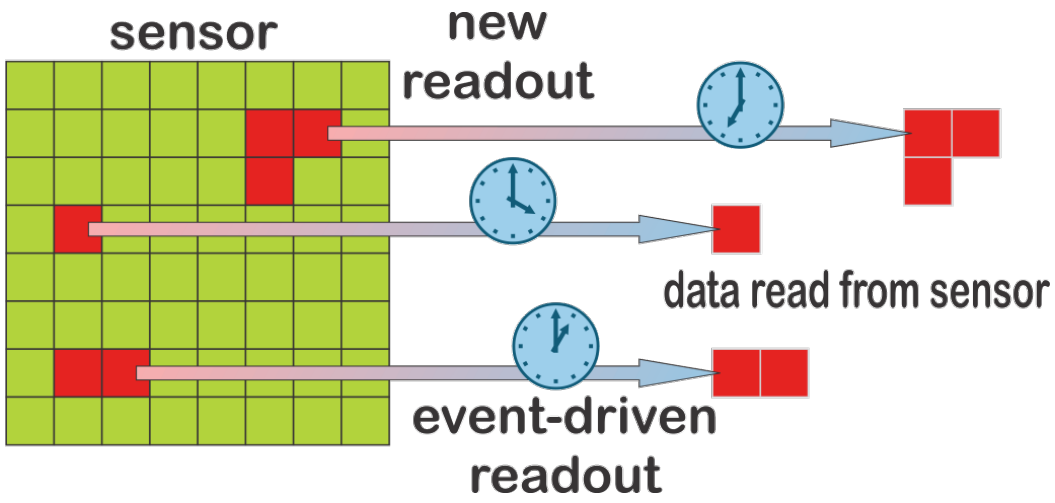



➡limited capacity and resolution⬅

## Dynamic Arbitration:

**true event-driven with sequential logic**
**(queuing with memory elements)**

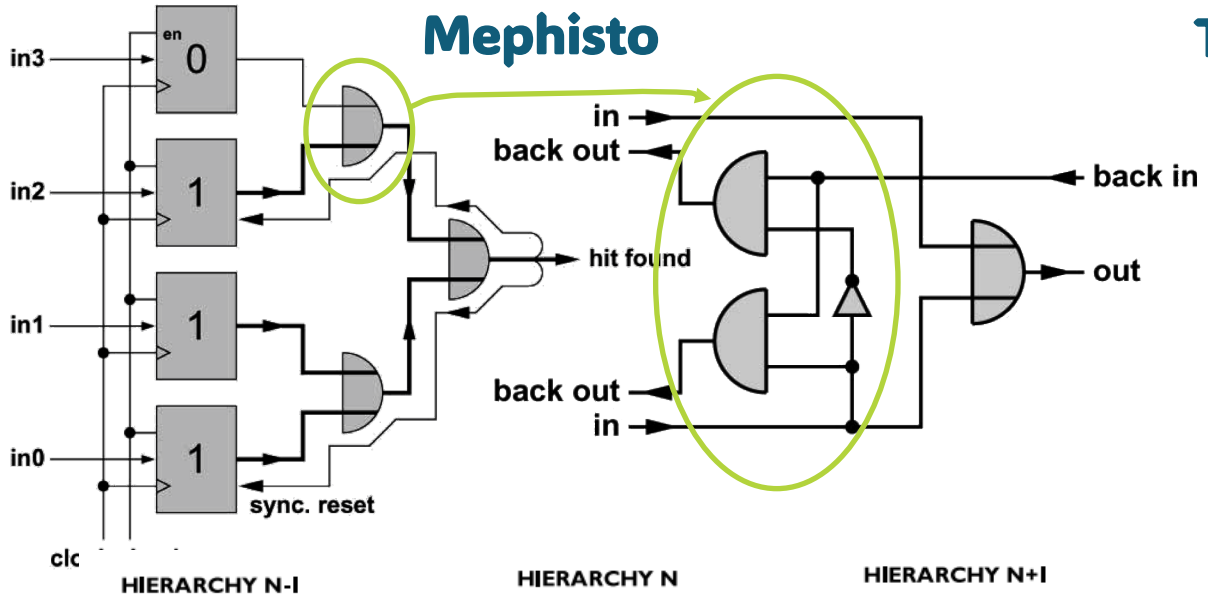
- arbiter cell stops and queues requests clearing them one by one
- data points sent one by one (time resolution depends event rate)



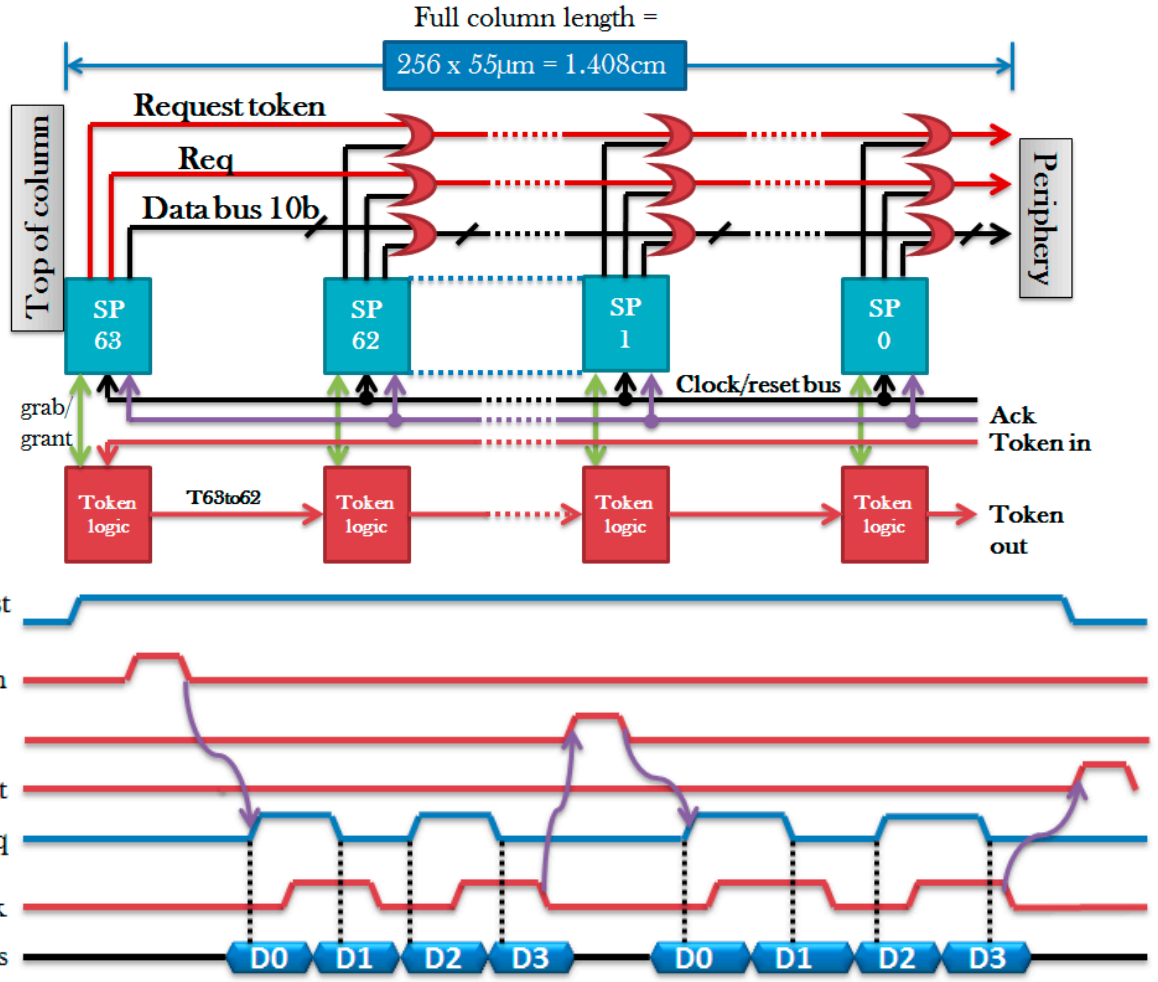

➡maximum capacity and resolution⬅

# Arbitration methods - examples

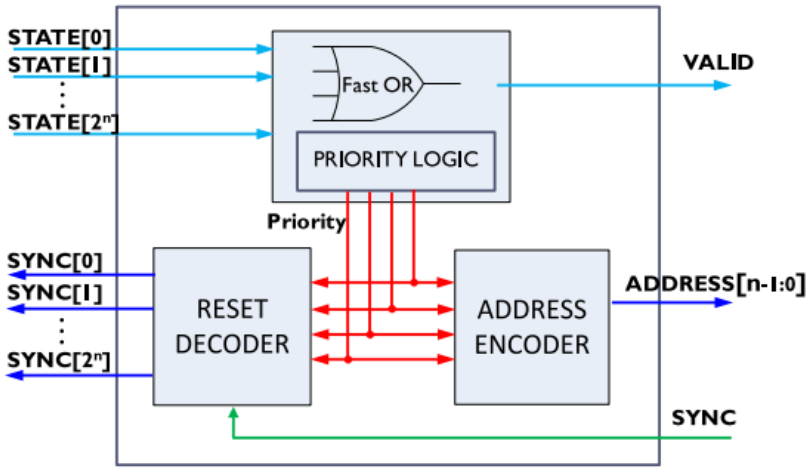
## Mephisto




## Token Passing - Timepix



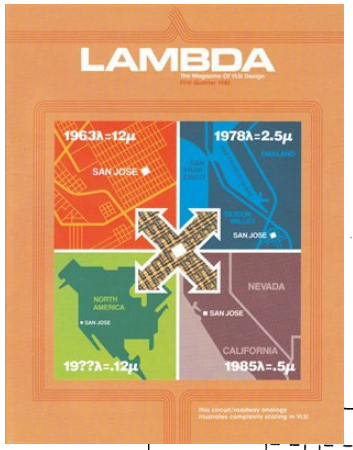

## ALICE ITS





P. Fischer, Nuclear Instruments and Methods in Physics Research A 461 (2001) 499–504
P. Yang et al., Nuclear Instruments and Methods in Physics Research A 785, pp. 61–69, 2015
G.W.Deptuch, https://lss.fnal.gov/archive/test-tm/2000/fermilab-tm-2709-ppd.pdf
T Poikela et al 2014 JINST 9 C01007

# Dynamic Arbitration: GALS ➲ LAGS - 1




IDEAS ABOUT ARBITERS

Charles L. Seitz

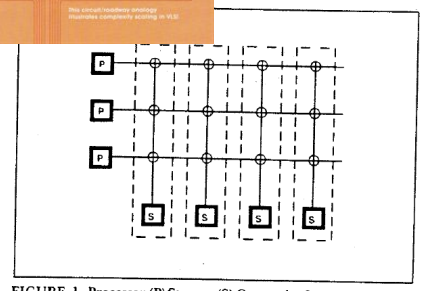


FIGURE 1 Processor (P)/Storage (S) Crosspoint Structure.

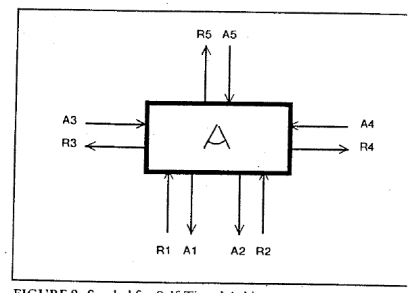



FIGURE 2 Symbol for Self-Timed Arbiter.

An arbiter is a mechanism that governs the sharing of a resource among a number of processes. An everyday example is a stoplight at an intersection. It is intended to allow the street crossing to be shared safely between two traffic flows. The traffic-actuated type of stoplight is considered to be superior to the clock-cycled type, because it does a better job of keeping the resource (the street crossing) active and the traffic flowing. Using a mechanism that allocates the resource dynamically in response to the demand achieves a better use of the resource.

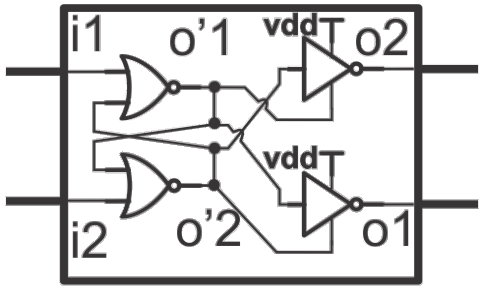
One of the most common examples of arbitration in digital systems is the sharing of the main (random-access) storage of a computer system amongst a number of processors—instruction processors, peripheral processors, data channels, and so forth. Figure 1 shows a crosspoint structure that allows multiple processors to make concurrent accesses to main storage distributed across several independent boxes. The systems within the dashed lines are multiport stores, each of which covers a different range of addresses and can operat independently of the other storage boxes.

One might think of processors as placing an addres and a request for a storage cycle on the (horizontal paths that thread through the storage boxes. Eacl storage box can detect the request and whether th address is one of its own. If more than one reques appears on a storage box's ports, how does the stor determine which request to service next?

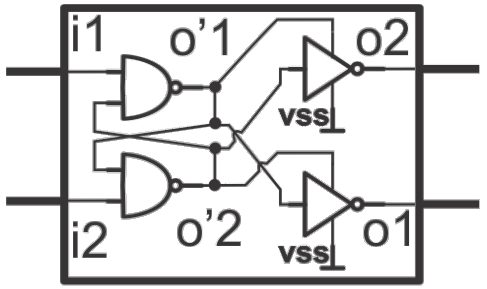
The required arbitration is sometimes accomplishec by a fixed allocation of the store to different processor on different periodically repeated time slots. This ap proach is not unlike the clock-cycled stoplight, and i guaranteed to leave a lot of bus and storage cycles unused unless the load is perfectly balanced. Dynamic allocation of time slots that are fixed within a synchron ous communication discipline is workable scheme whose implementation is straightforward. The only disadvan tages of this scheme are the usual problems inherent to synchronous systems in (1) clock distribution and (2)

10 LAMBDA *First Quarter 1980*

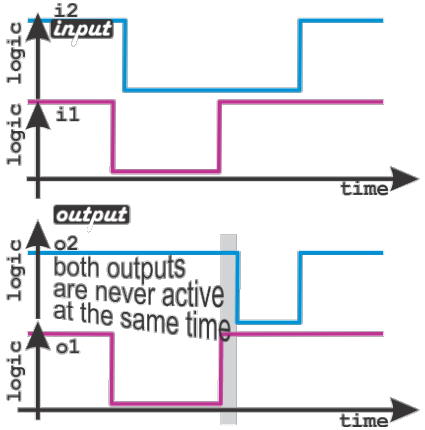
C.L. Seitz, "Ideas About Arbiters", Lambda 1st Quarter 1980: Vol. 1 Iss. 1, pp. 10-14

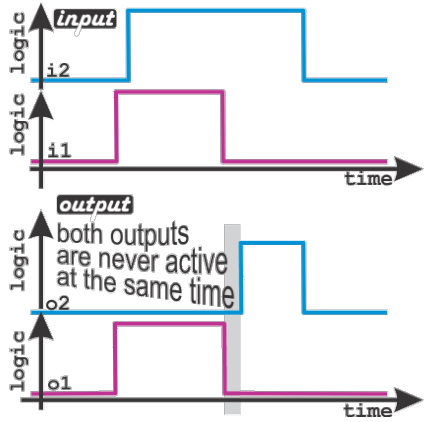



Seitz's arbiter (N)




Seitz's arbiter (P)



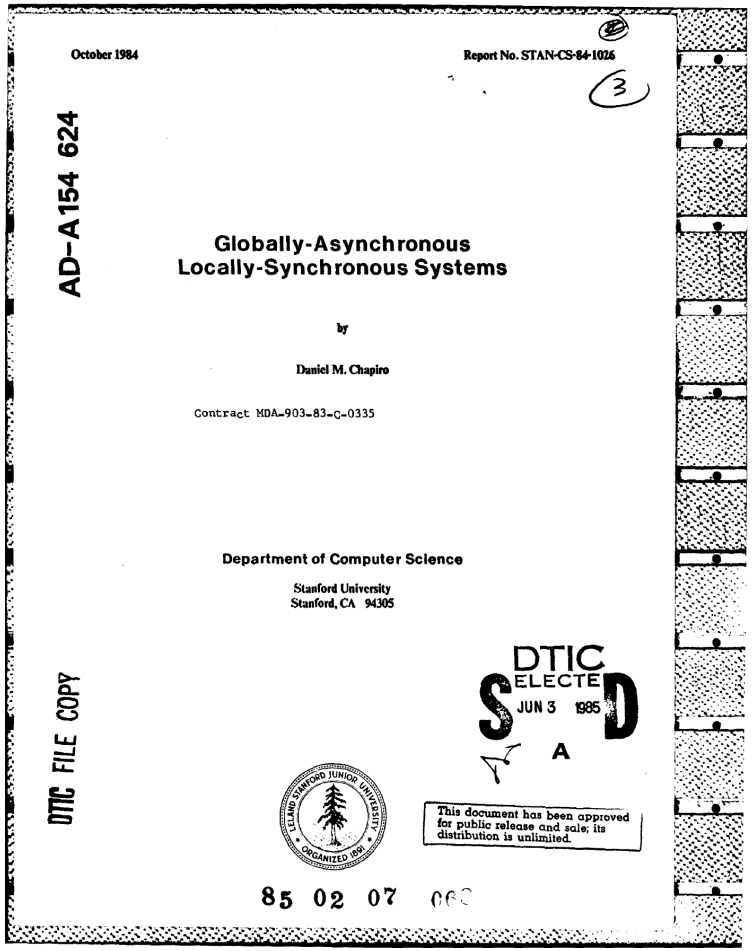

**functionally, Seitz's arbiters are metastability filters**

| i1 | i2 | o'1 | o'2 | o1 | o2 |
|---|---|---|---|---|---|
| 0 | 0 | 1 | 1 | 0 | 0 |
| 0 | 1 | 1 | 0 | 0 | 1 |
| 1 | 0 | 0 | 1 | 1 | 0 |
| 1 | 1 | previous | | previous | |

"ghost paper" everyone cites it, but nobody can see it

📖 if someone is interested: I can send a copy of this paper!

# Dynamic Arbitration: GALS ➲ LAGS - 2



October 1984

Report No. STAN-CS-84-1026

AD-A154 624

Globally-Asynchronous
Locally-Synchronous Systems

by

Daniel M. Chapiro

Contract MDA-903-83-C-0335

Department of Computer Science

Stanford University
Stanford, CA 94305

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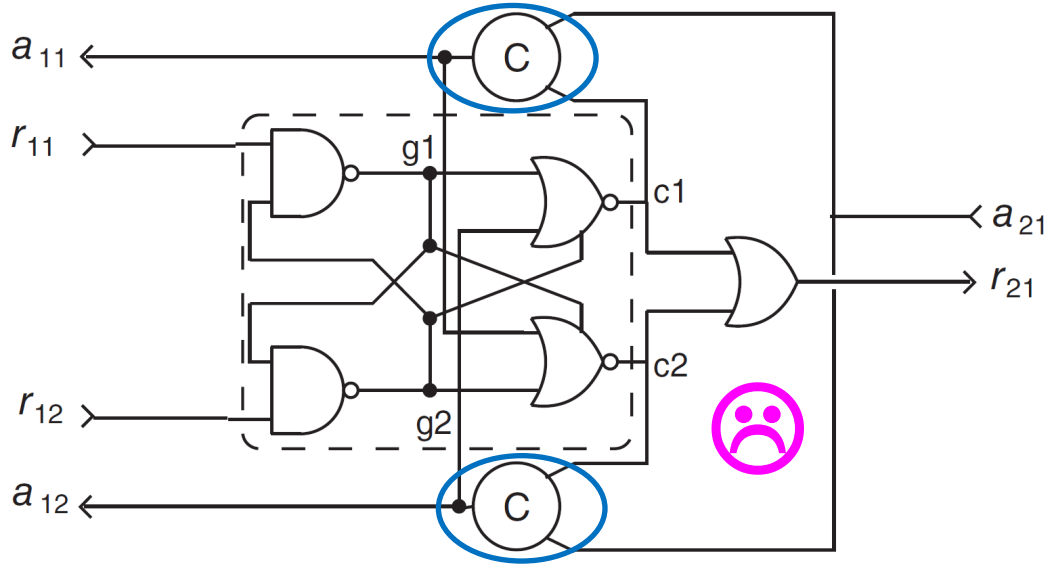
D.M. Chapiro, PhD thesis,
https://apps.dtic.mil/sti/pdfs/ADA154624.pdf

- in inter-processor networks (CALTECH), sources are synchronous and acquisition is asynchronous (Global Asynchronous – Local Synchronous)
- arbiters with Mueller-C gates, where:
  - access granted can only be canceled by source, and
  - communication with source is impossible after Mueller-C gate is set
- each source has to 🕑 its access to medium

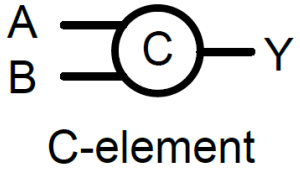



- but pixel systems are LAGS!!

➡memory is needed to avoid switching⬅

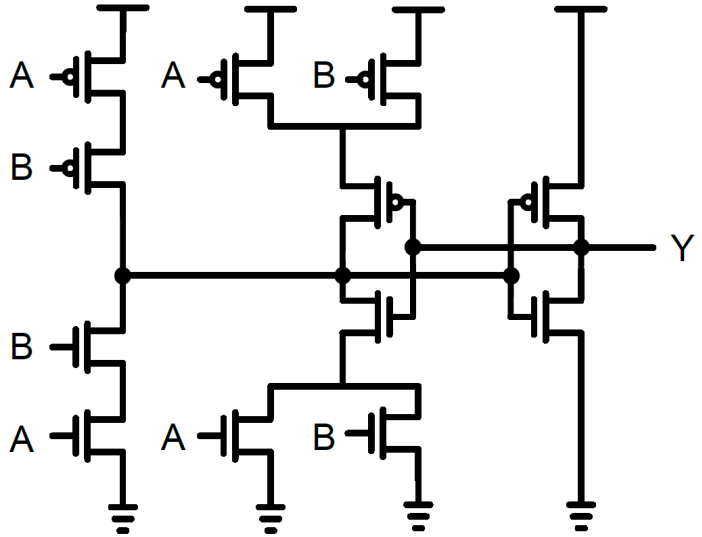
Park, Jongkil, PhD thesis,
https://escholarship.org/uc/item/0sc4s9v7
Shih-Chii Liu, et al, "Event-Based Neuromorphic Systems", Wiley 2015

# Dynamic Arbitration: GALS ➲ LAGS - 3

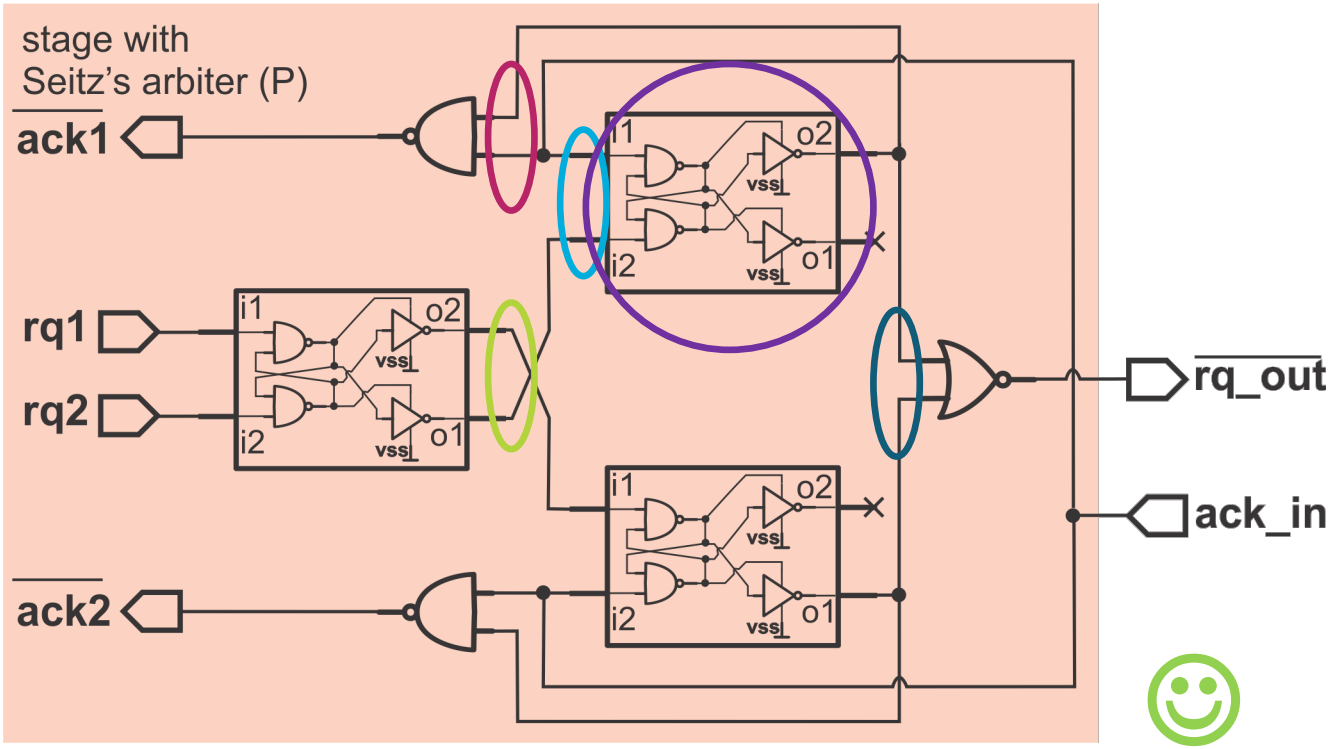



C-element

| A | B | Y |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 1 | NO CHANGE |
| 1 | 0 | NO CHANGE |
| 1 | 1 | 1 |




➡once the C-gate is set, both inputs must deactivate, but interaction with other side is blocked⬅




- who was first? (glitch-less)
- Who is first, req or ack? (req blocked if ack high first)
- req goes up if any req passed through (@ ack low)
- if req passed though any ack change will pass down!
- this arbiter disallows any rq1 - rq2 grappling (gone + appear again, faster than deactivation of ack, etc )

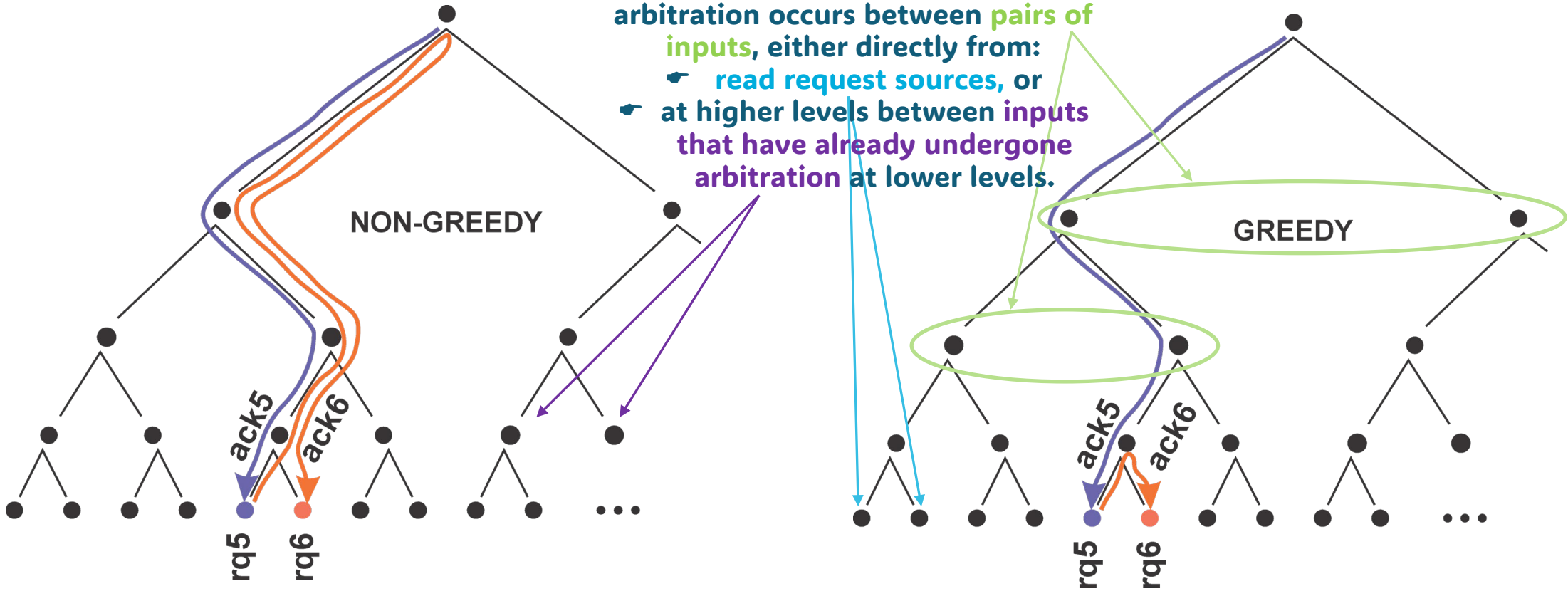
➡interaction with other side is unblocked⬅

Park, Jongkil, PhD thesis, https://escholarship.org/uc/item/0sc4s9v7

D.S. Gorni, G.W. Deptuch, S. Miryala, **WO 2022/221068 A1 - EVENT-DRIVEN READOUT SYSTEM WITH NON-PRIORITY ARBITRATION FOR MULTICHANNEL DATA SOURCES**

# Non-Greedy and Greedy Arbitration

arbitration occurs between pairs of inputs, either directly from:
- read request sources, or
- at higher levels between inputs that have already undergone arbitration at lower levels.



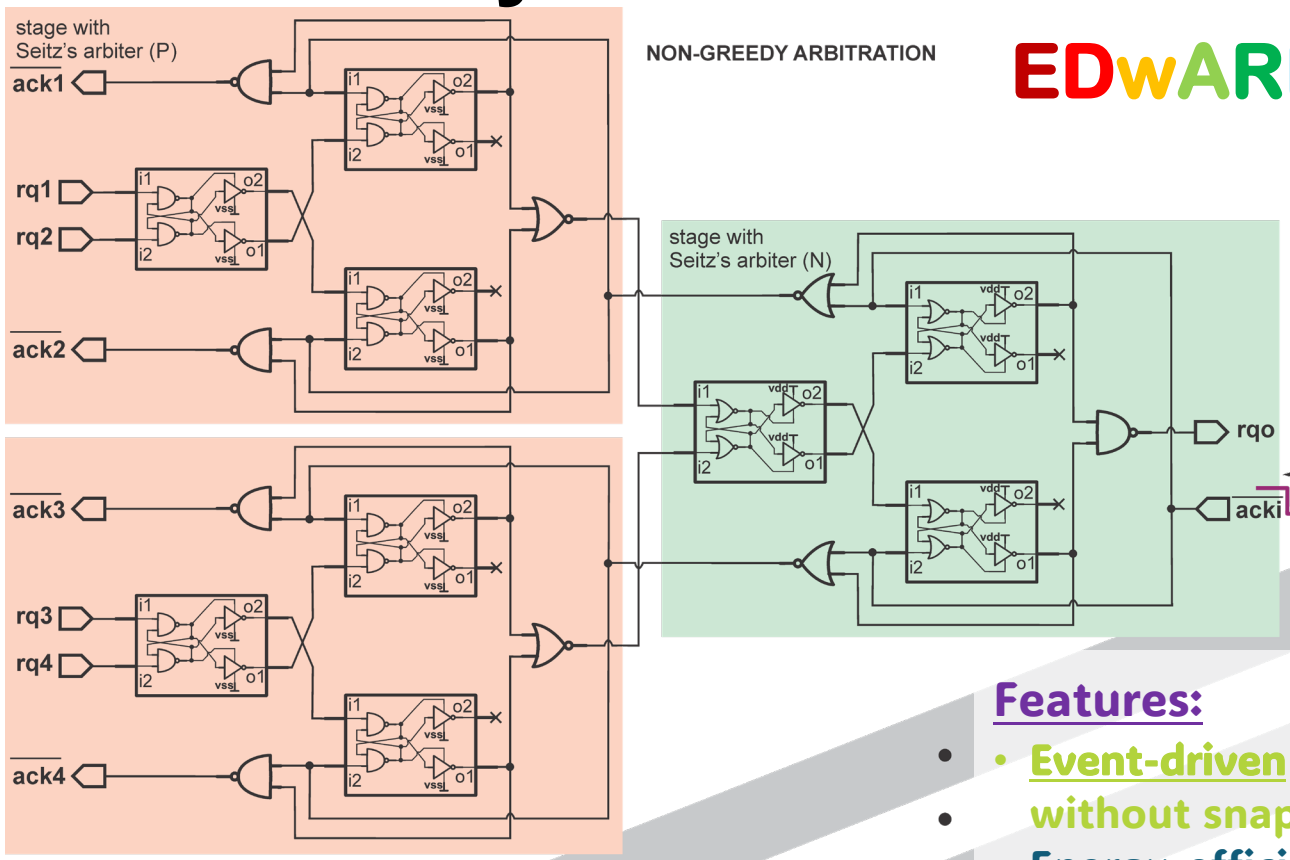

search for a new data source always resets
randomizes/democratizes data retrieval but disrupts geometrical associations

search favors the same or neighboring source
may show preference for certain part of detector where rates of requests are higher due to e.g. noise

➡preference? not clear⬅

N. Bingham and R. Manohar, in IEEE Trans. on Circuits and Systems I: Regular Papers, vol. 67, no. 12, pp. 4960-4969, Dec. 2020, doi: 10.1109/TCSI.2020.3011552.

# Non-Greedy EDWARD




handling of requests and responding with acknowledges

ack5
rq5
rq6
ack6
ackn-1
rqn-1
rqn
ackn

fastest, selective, dead-timeless readout

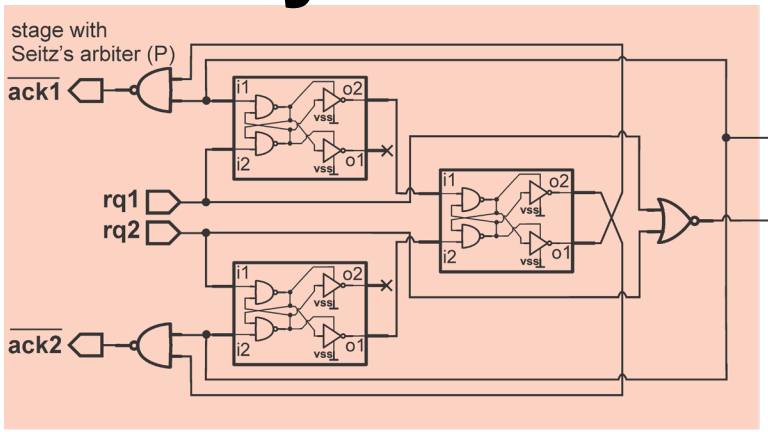
**EDwARD** = Event Driven with Access and Reset Decoder

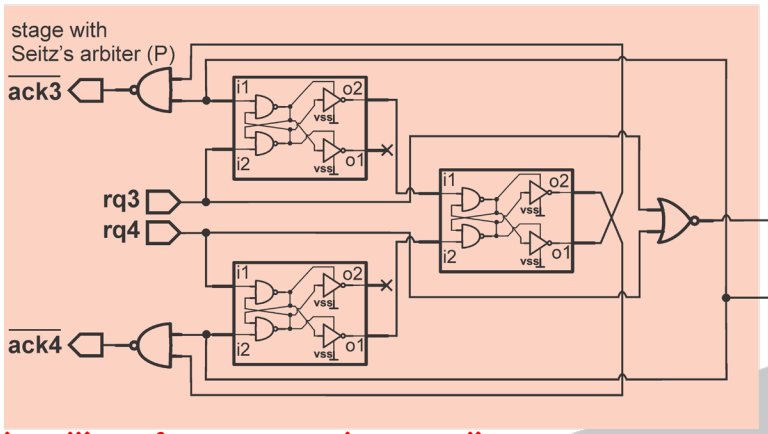
This "clock" does not propagate unless there is read request and It is routed only to pixel with read request

## Features:

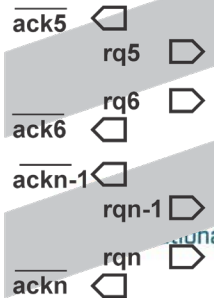
- Event-driven ➡ hits extracted from matrix of pixels on the fly, without snapshotting in readout frames;
- Energy-efficient ⬅ no clock, no strobes distributed to other but being read out pixel;
- No:
  - built-in geo-priority;
  - timing circuitry in pixels (not like GALS);
- Possible multi-access to single pixel per single read request ➡ data extracted in phases
- Automatic synchronization with data acquisition (LAGS)

# Greedy EDWARD



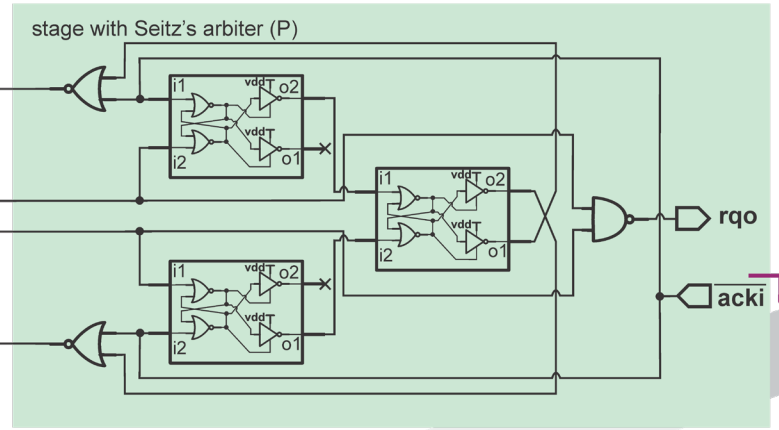




handling of requests and responding with acknowledges




fastest, selective, dead-timeless readout

GREEDY ARBITRATION (I)

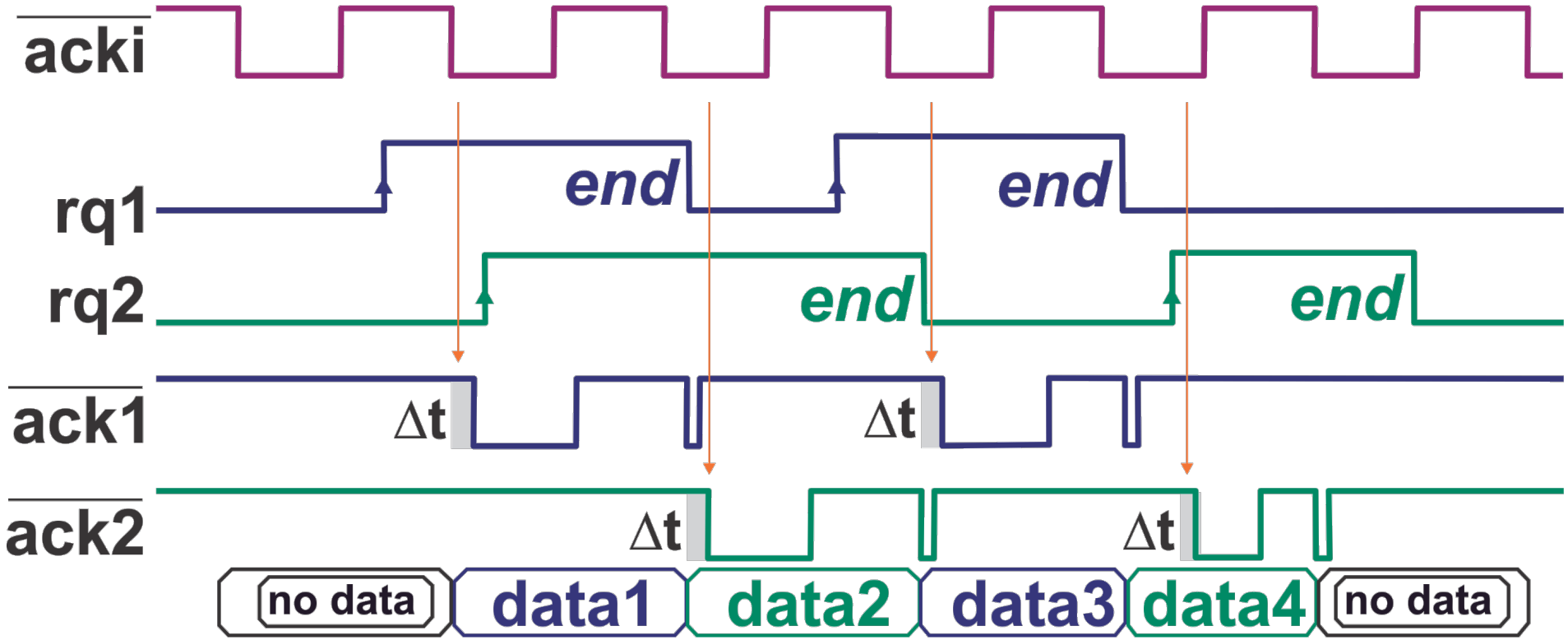



**EDwARD** = Event Driven with Access and Reset Decoder

## Features:

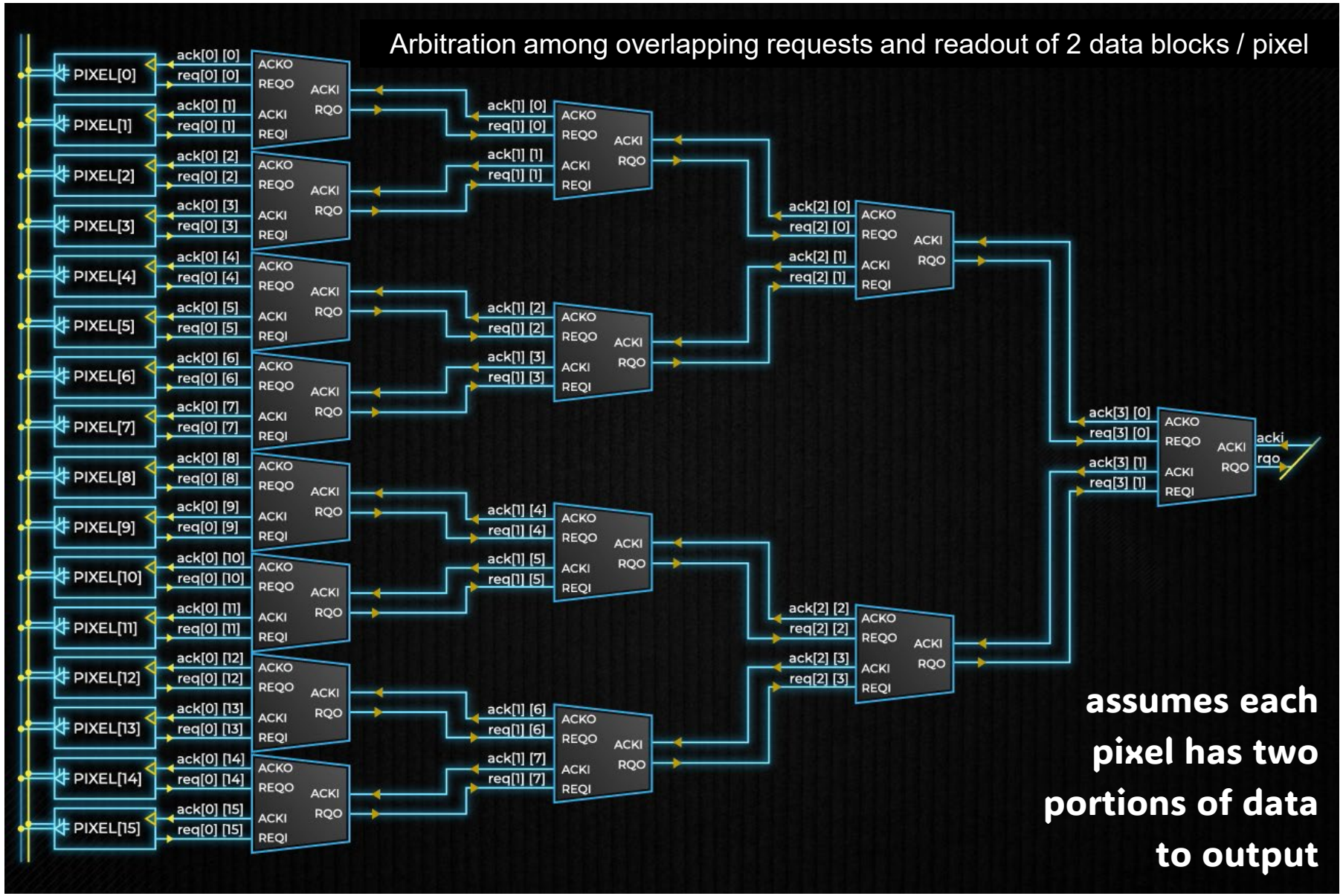
- Event-driven ➡ hits extracted from matrix of pixels on the fly, without snapshotting in readout frames;
- Energy-efficient ⬅ no clock, no strobes distributed to other but being read out pixel;
- No:
  - built-in geo-priority;
  - timing circuitry in pixels (not like GALS);
- Possible multi-access to single pixel per single read request ➡ data extracted in phases
- Automatic synchronization with data acquisition (LAGS)

# Data Flow in Non-Greedy EDWARD



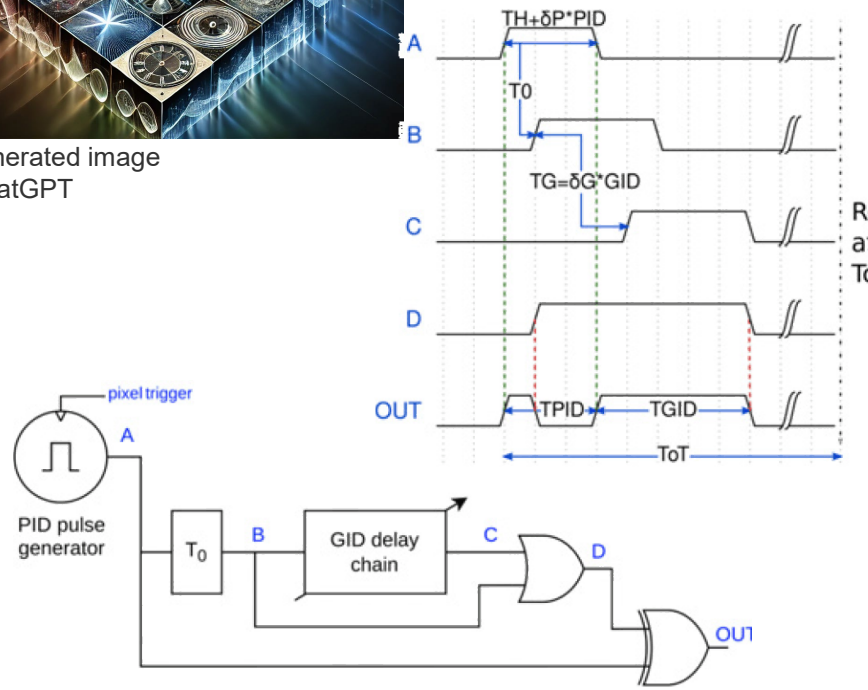

➡data can flow without any dead time⬅

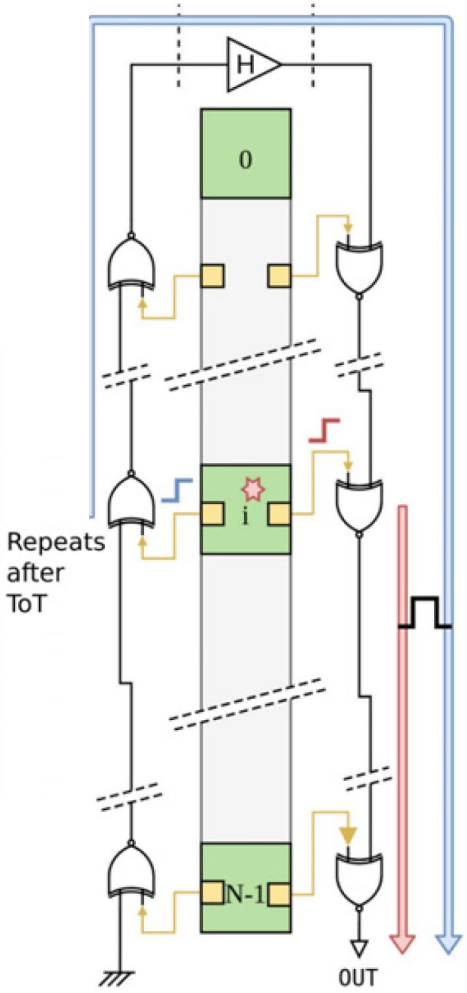
# Readout in Non-Greedy EDWARD

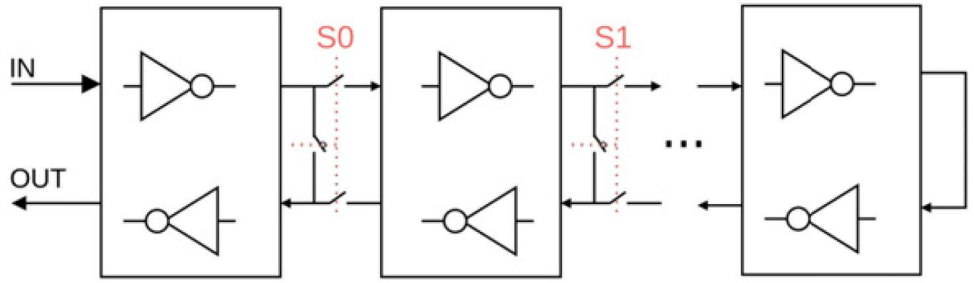


# Time Instead Voltage/Current -1

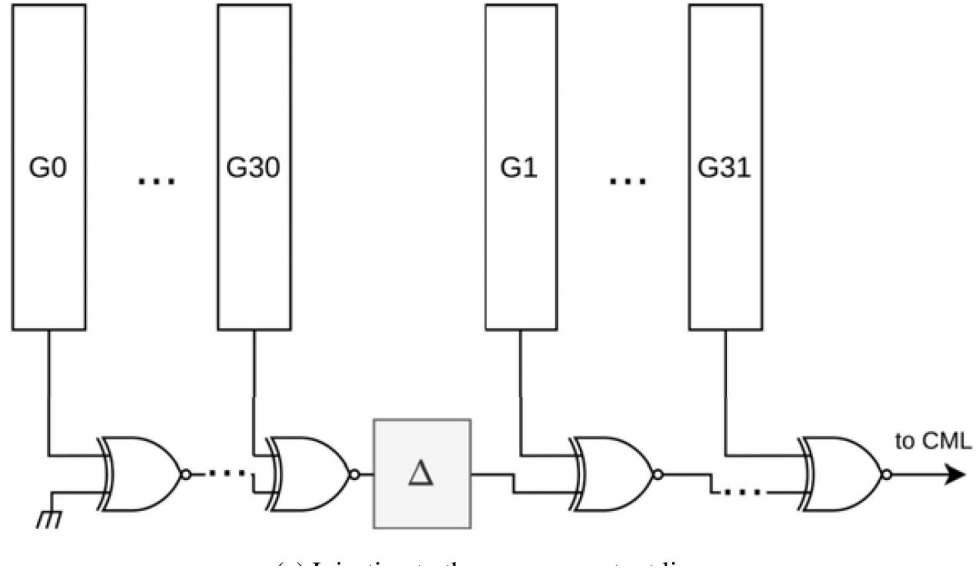
AI-generated image
by ChatGPT




(b) GID delay chain




**reading using a single line, relying on the time interval between pulses and the position of the pixel being read**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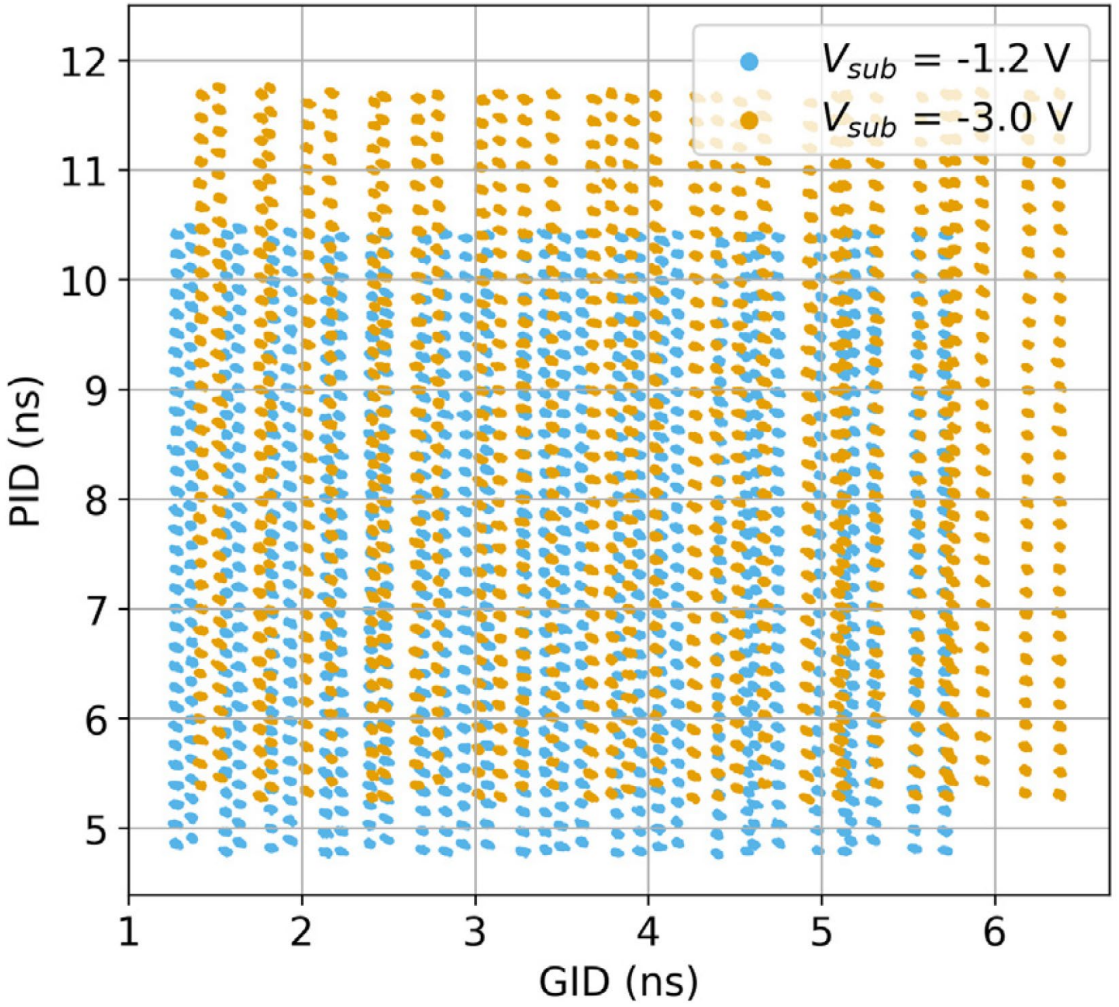
# Time Instead Voltage/Current -2

**challenge of method:**

- dependence of propagation speeds of pulses on power supplies and biases
- dependence on production process variations and measurement conditions
- dependence on temperature

- how to provide continuous calibration?
- time measurement needed to decode positions
- CAD/EDA tools do not provide equivalence of STA (time enclosure) for time-domain circuit design

**perspective and inspirational!**

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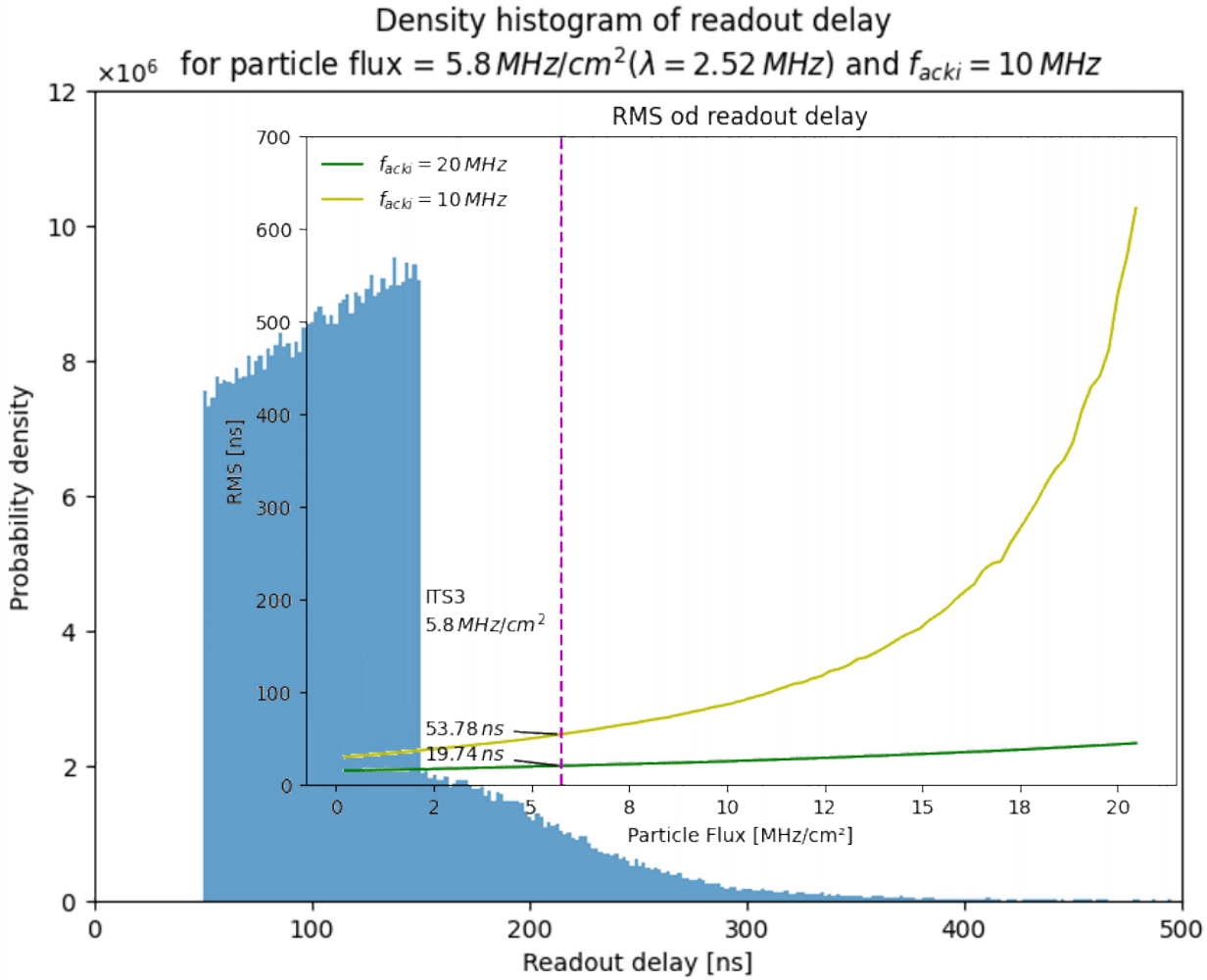
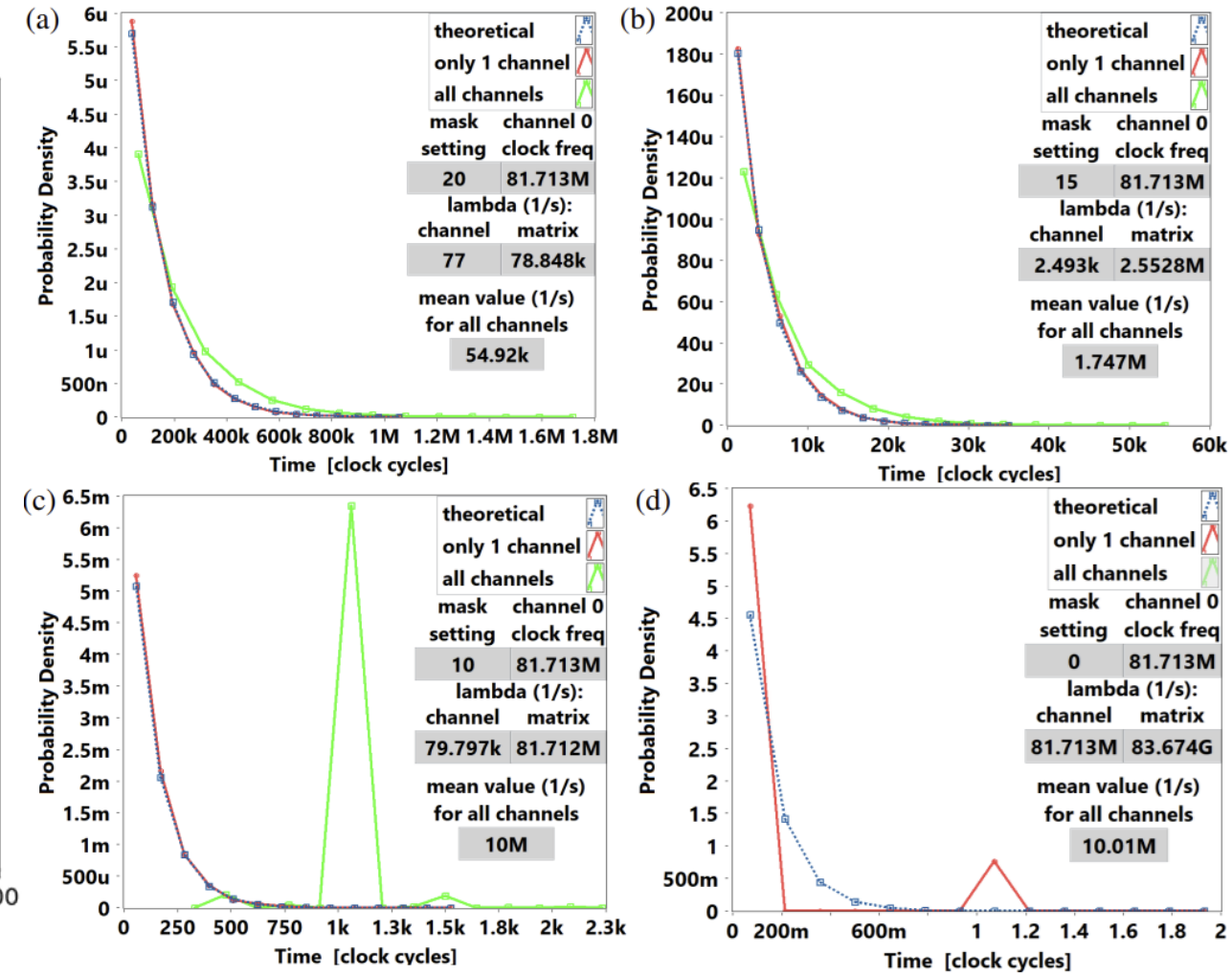
# Intrinsic Timing Resolution

EDwARD




➡simulation of queueing⬅

➡measurements of matrixed Poissonian generators read event-driven⬅

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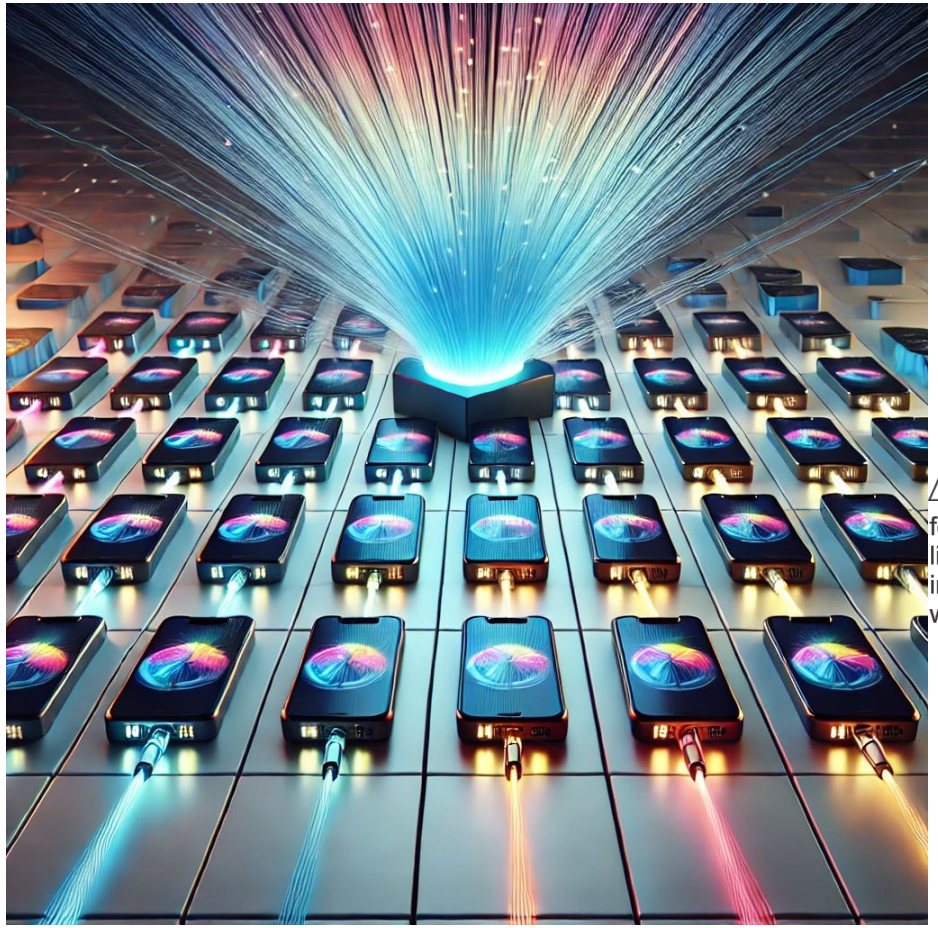
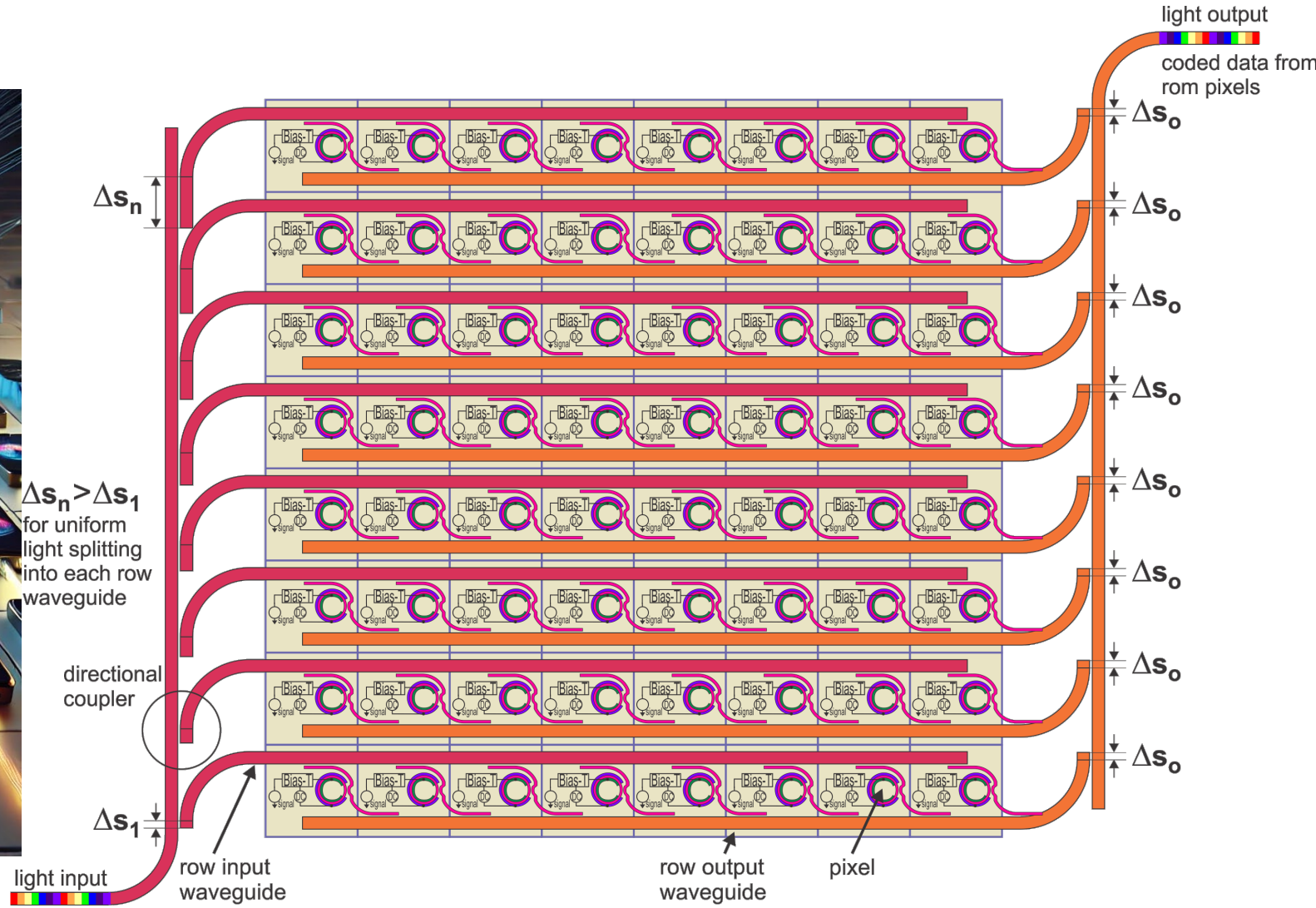
D.Gorni et. al, 2024 JINST 19 C04035

# Future?



AI-generated image
by ChatGPT

**… and there was light…**
**Genesis 1:3**




**optical MAPS**

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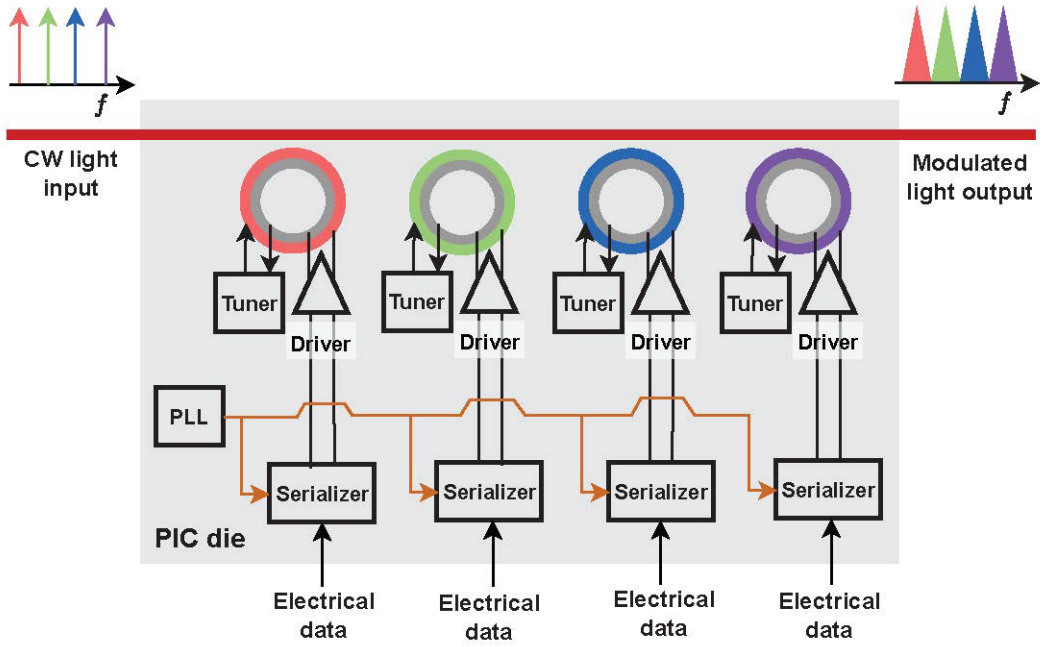
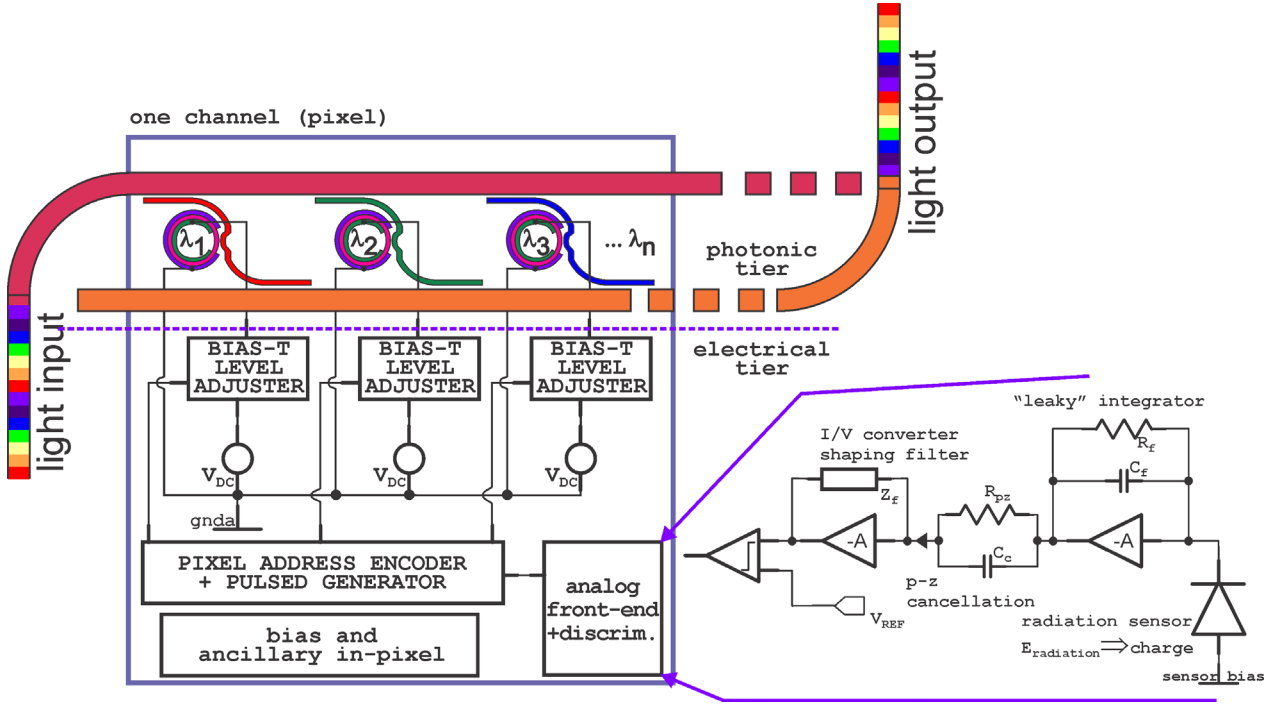
**➡ you ☞, work with us!⬅**

# Future?




micro-ring resonant modulators are used for data transmission, allowing modulation of CW in data transmission




through 3D integration of MAPS with Si-photonics, electrical data transfer can be eliminated

# Summary

- Optimizing Readout of segmented radiation detectors:
  - Goal: data integrity at minimal resource overhead
  - Challenges: balancing speed and power consumption
  - Focus: efficient data acquisition for radiation detectors
- Evolutionary path for zero-suppressed readouts

  from:
  - X-Y coordinate signaling
  - covering large areas token passing
  - static arbitration
  - data polling

  to event-driven no clock/strobe distributed/broadcasted and total silence before request
    - voltage domain (EDWARD)
      - ➧ RTL code for implementation parameterized and scalable including individual pixel configuration available upon request to accelerate design
    - time domain (DPTS)
      - ➧ very compact implementation
      - ➧ challenging calibration

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