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Q-Pix:

pixel-based charge readout for kton scale LArTPC

Shion Kubota
The University of Manchester

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Liquid Argon Time Projection Chamber (LArTPC)

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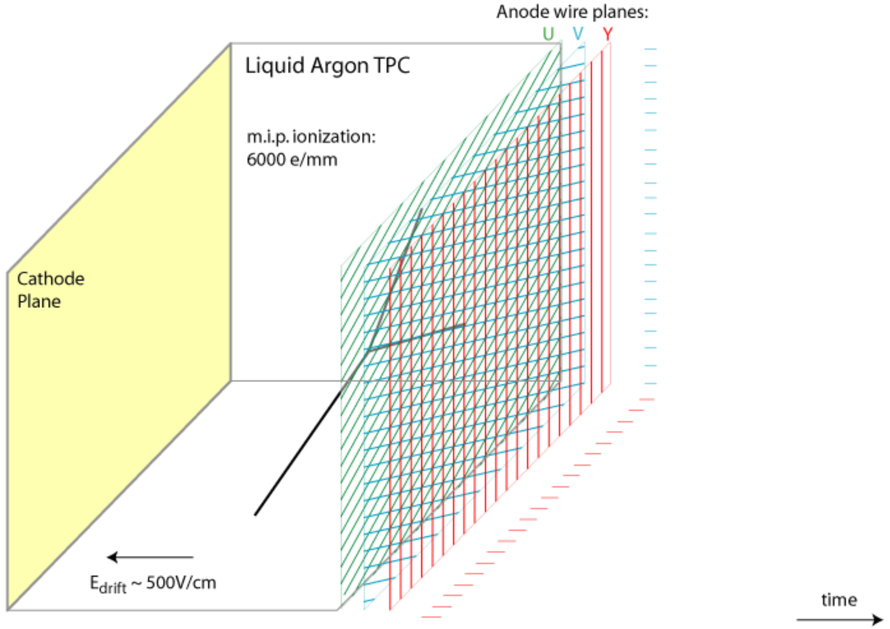
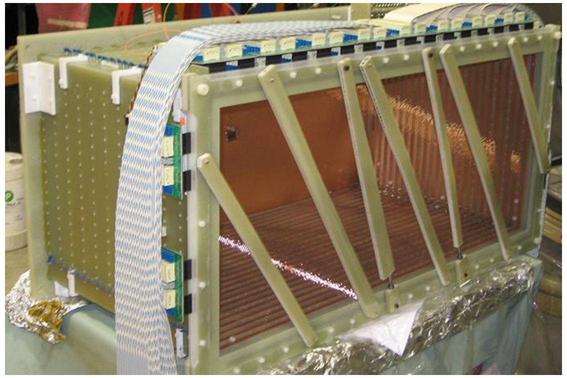
Traditional wire-based LArTPC has been used in many different periments



MicroBooNE

DUNE



ArgoNeut

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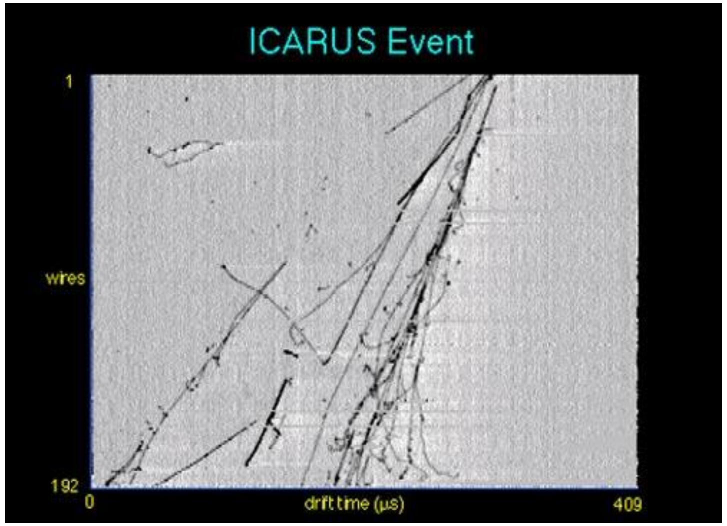
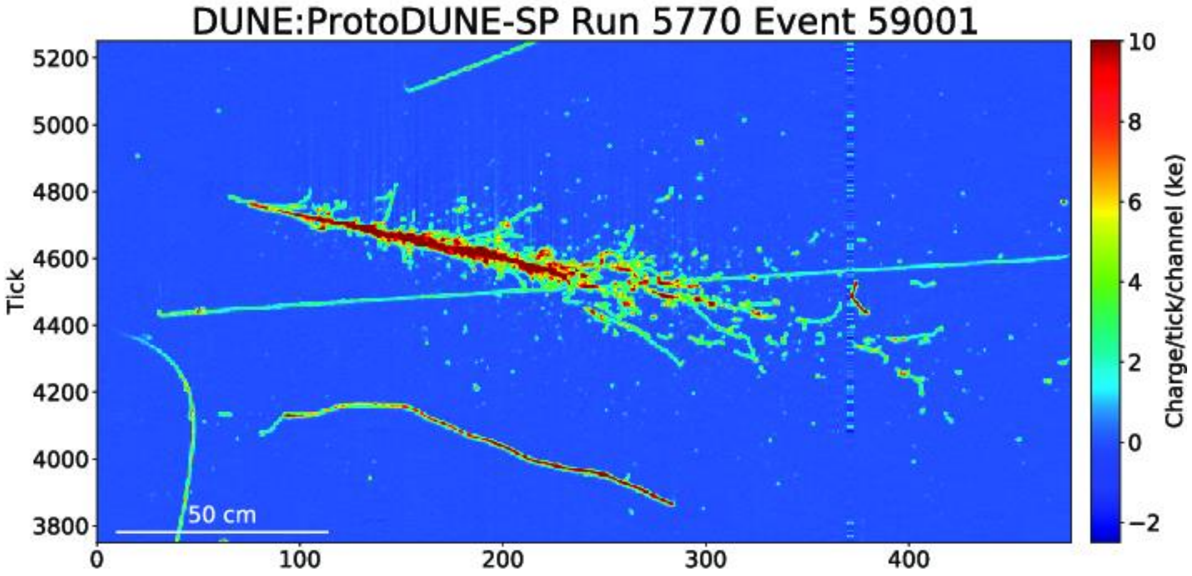
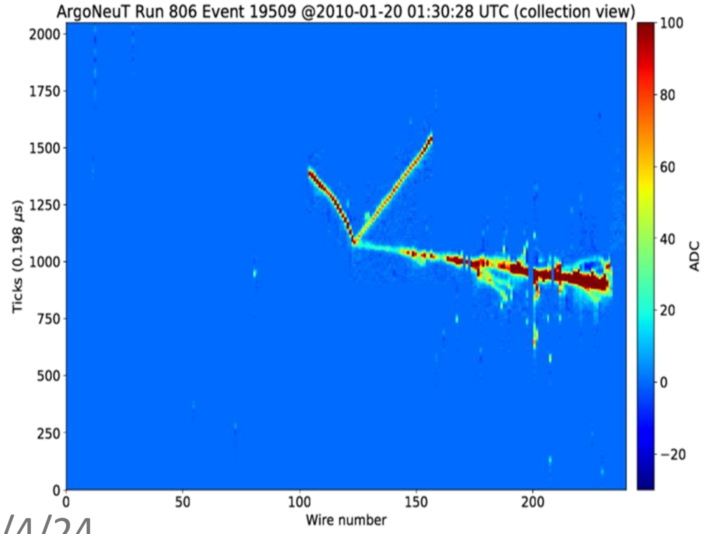
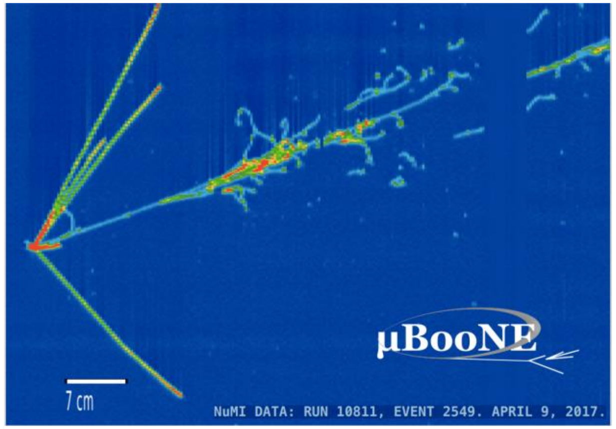
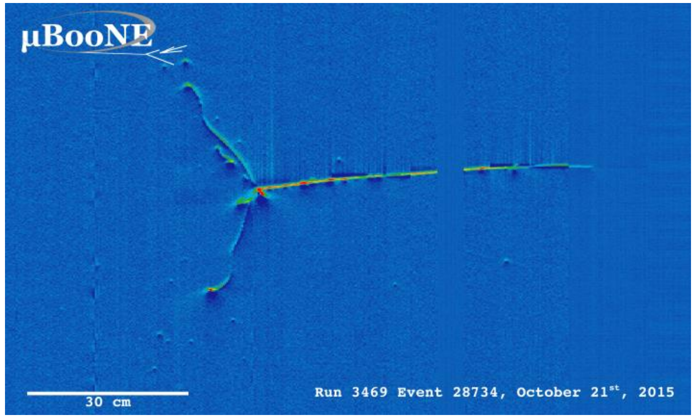
Liquid Argon Time Projection Chamber (LArTPC)











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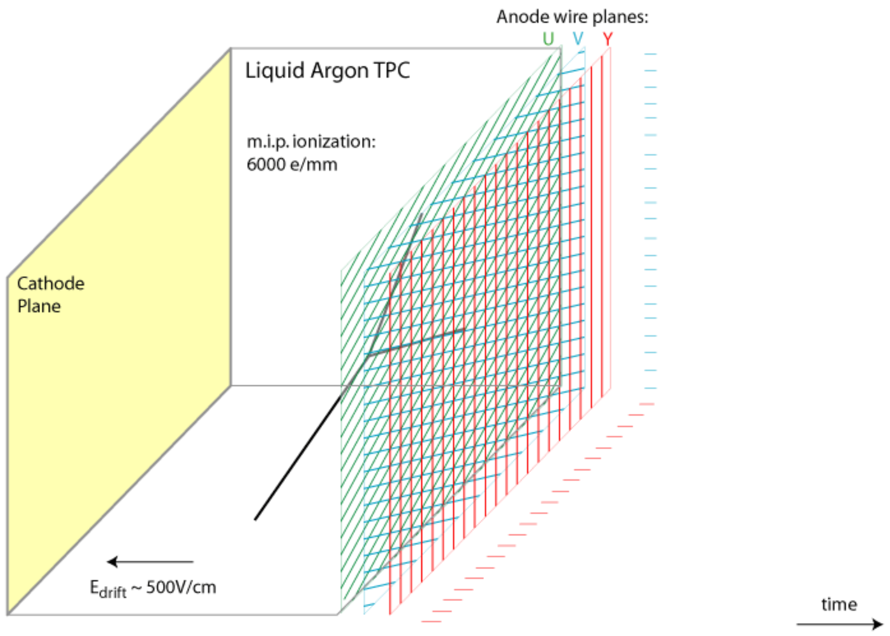
Challenges of LArTPC



- Depending on the topology, degeneracies in the solution when reconstructing 3D tracks of particles from the 2d projections of the wire readout
- ”wrapped wire” geometry can introduce more complexity and ambiguities in reconstruction

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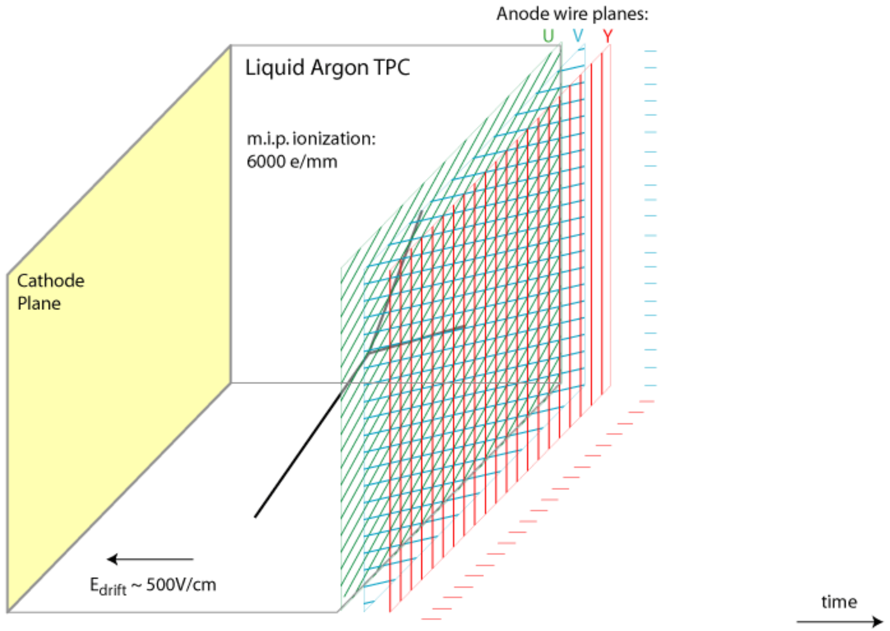
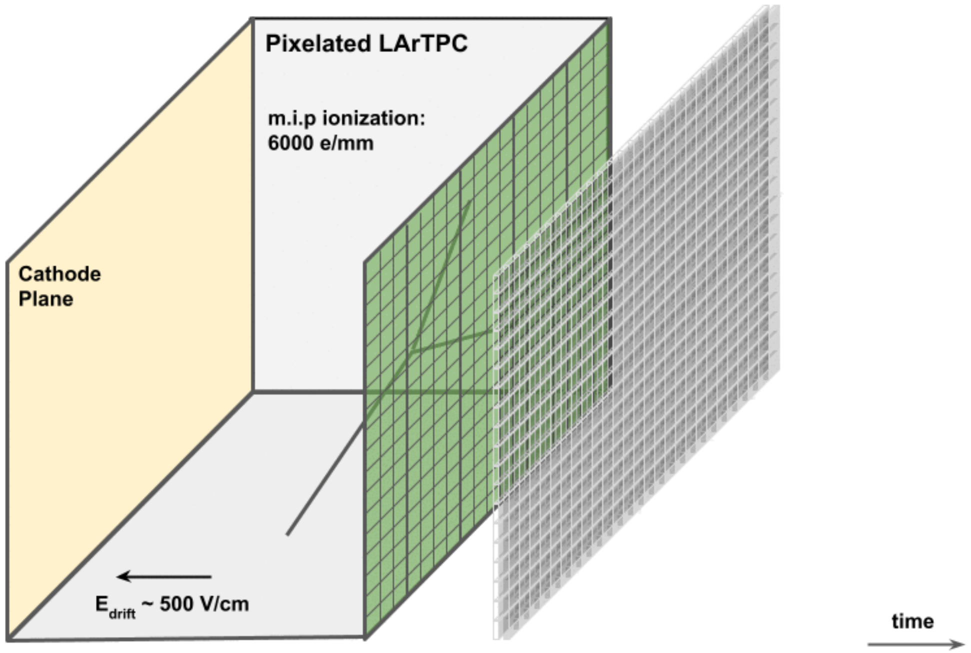
Solution : Pixelization





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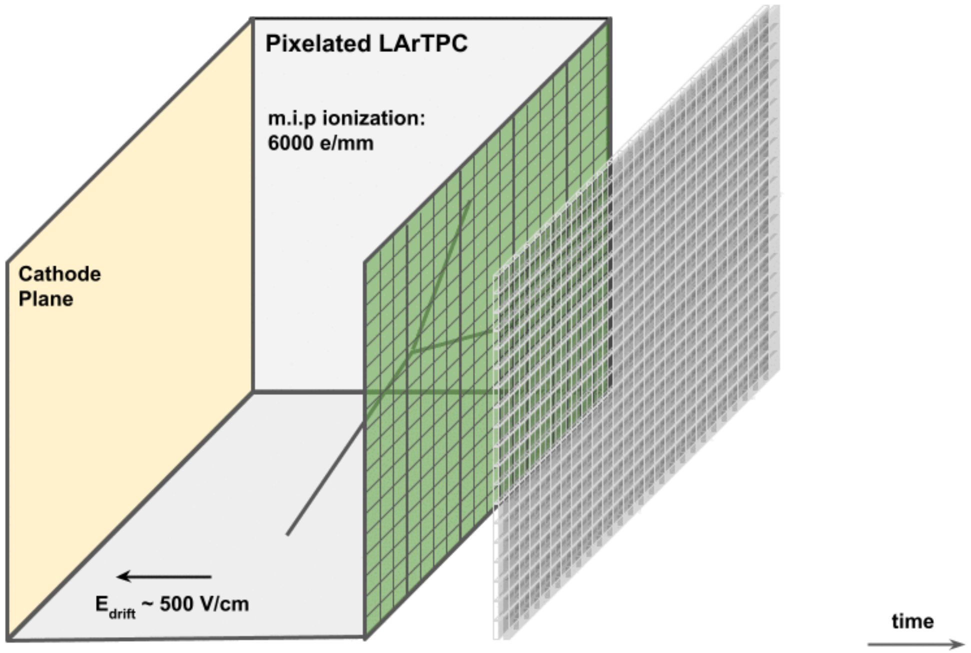
Solution : Pixelization

Challenge:
Great increase in
1) the number of channels
2) the amount of data

Solutions:
1) Electronic principle of least action
2) New way to quantize information



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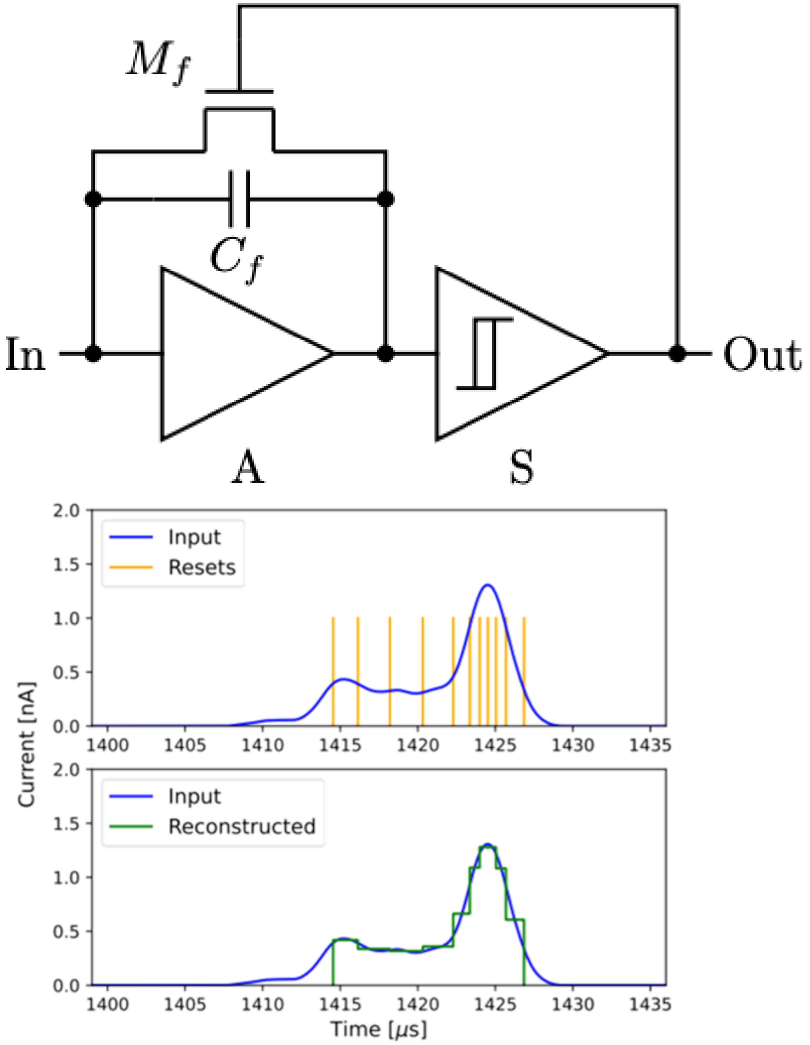

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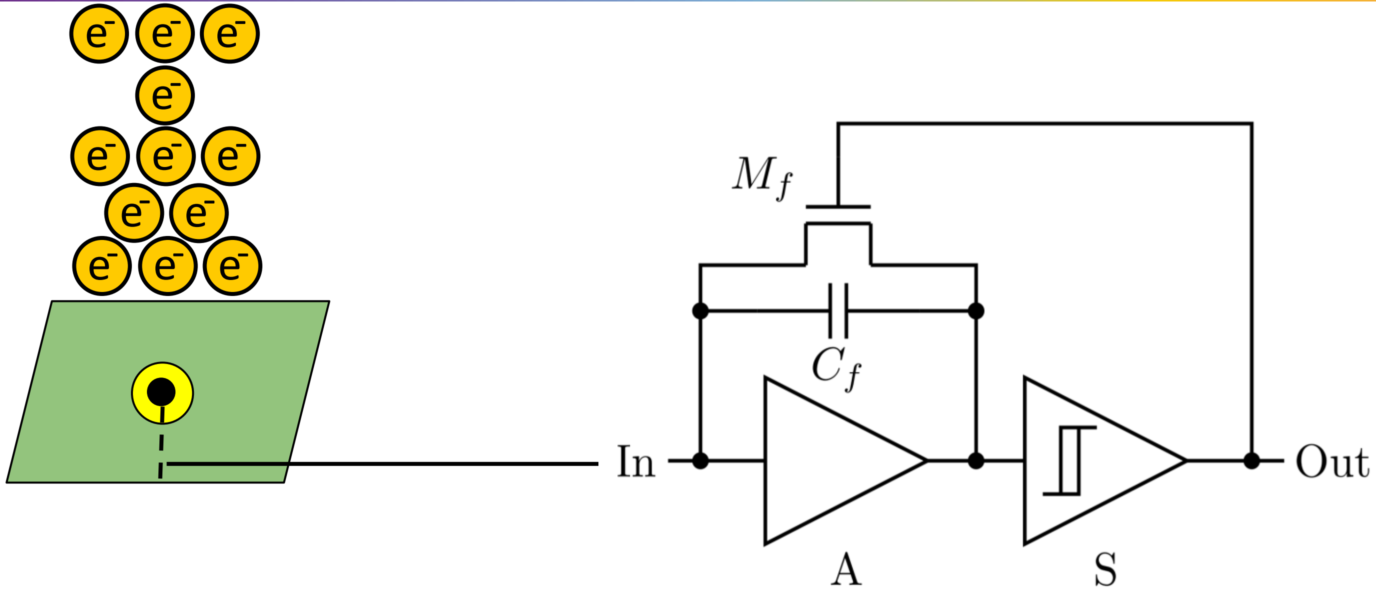
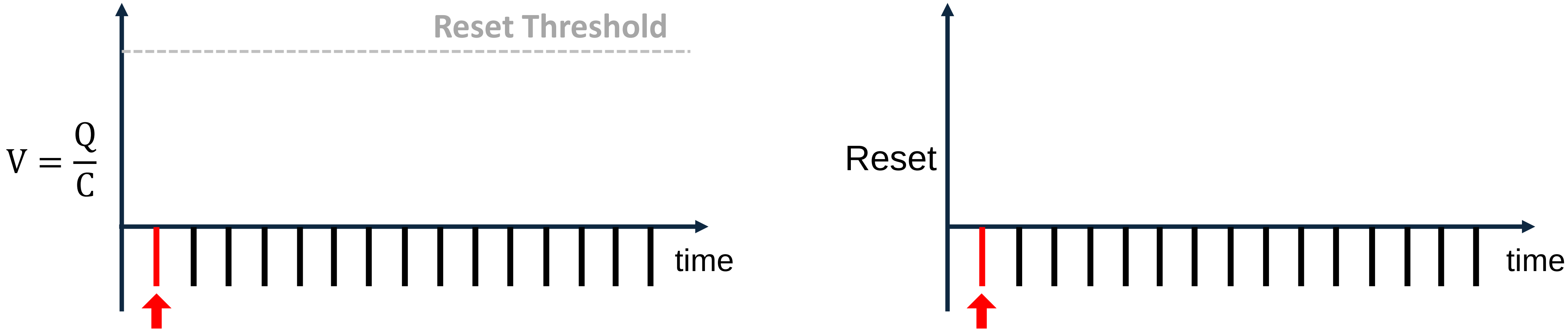
Toy Example

※ the reset happens for 5 electrons





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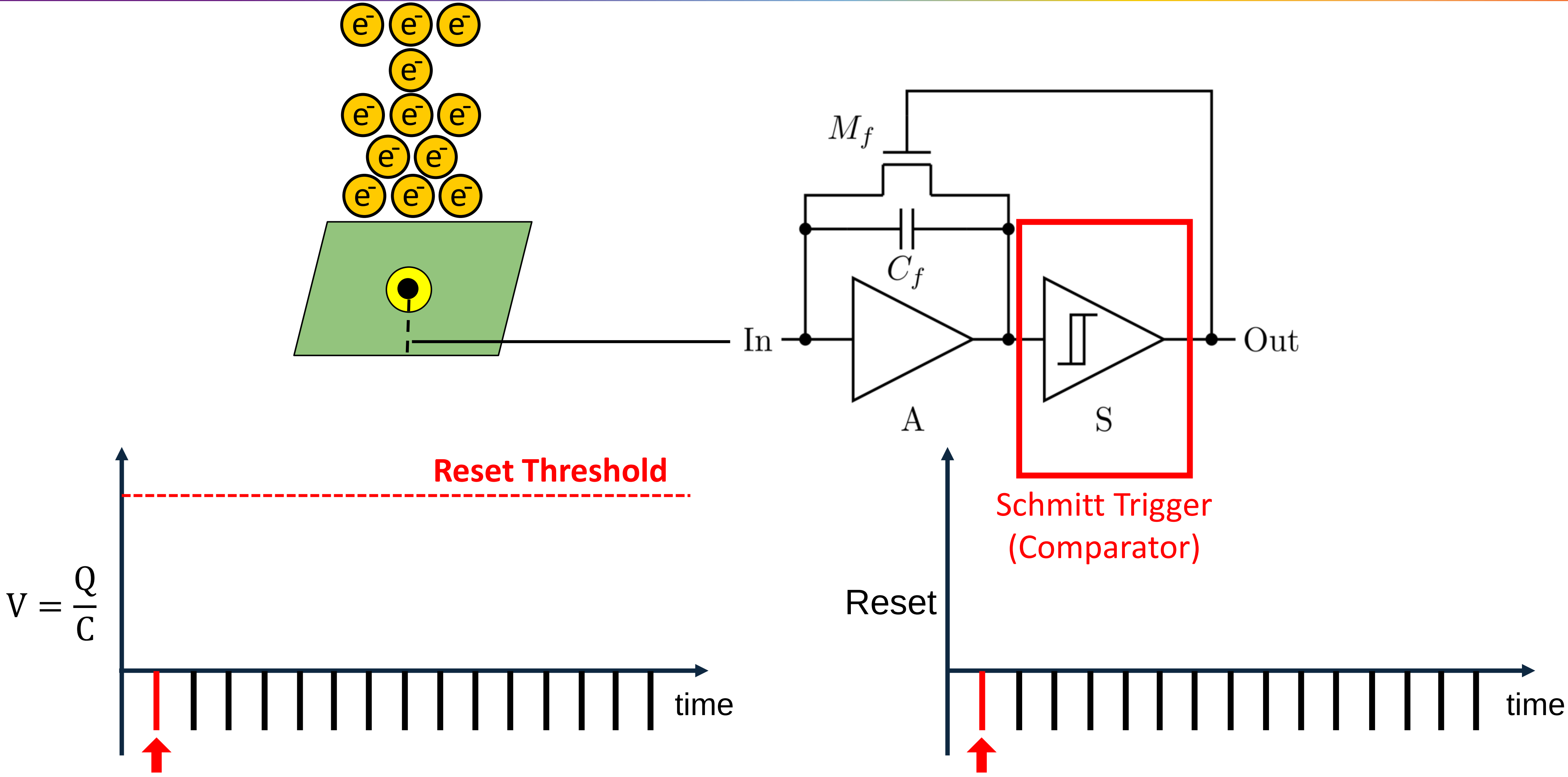

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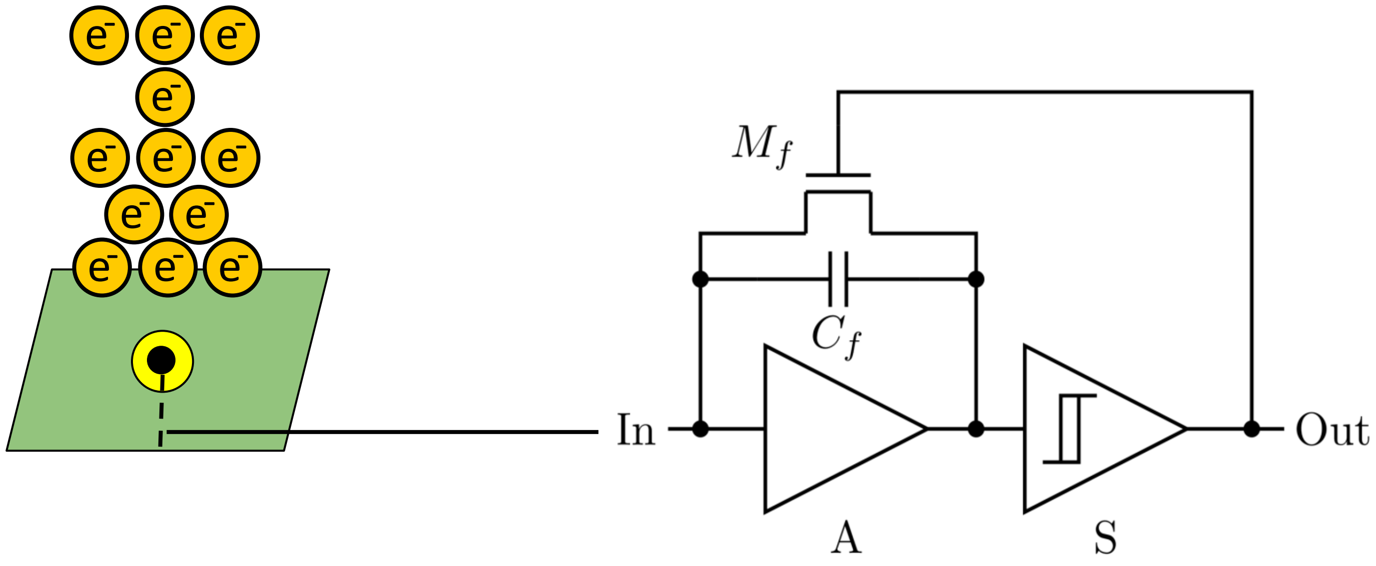

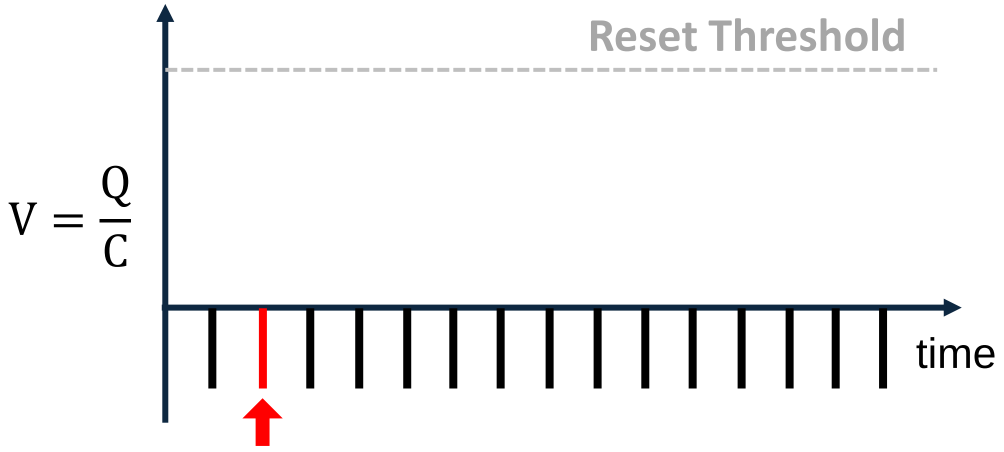

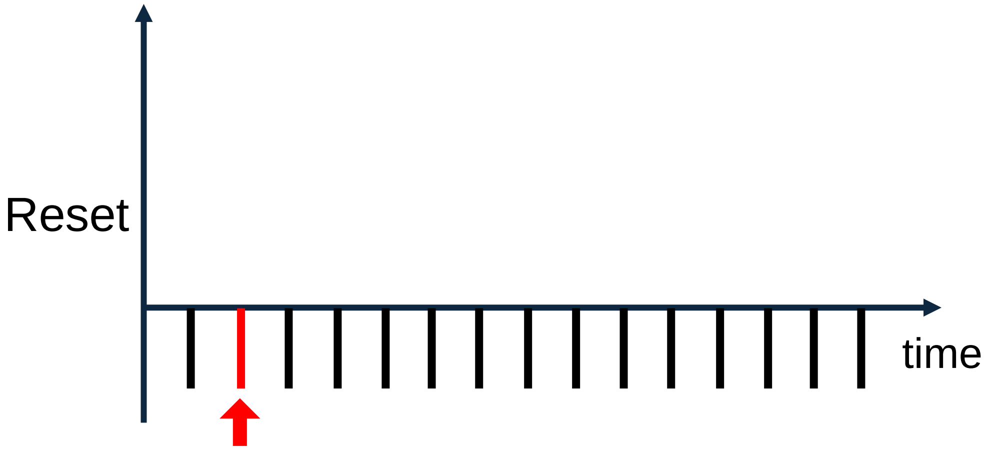

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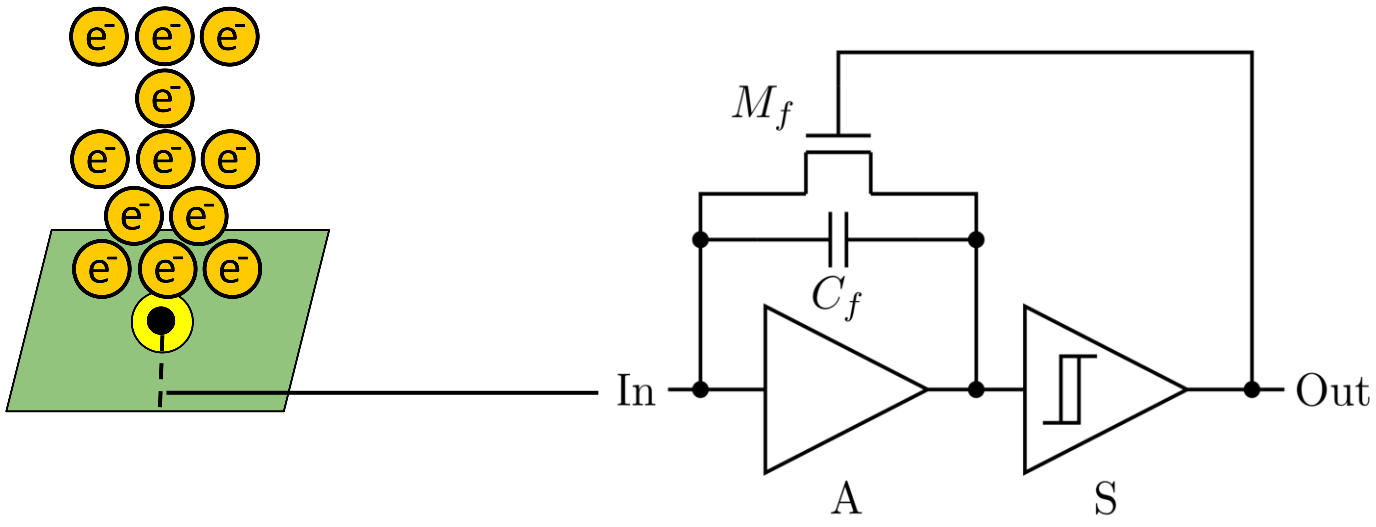

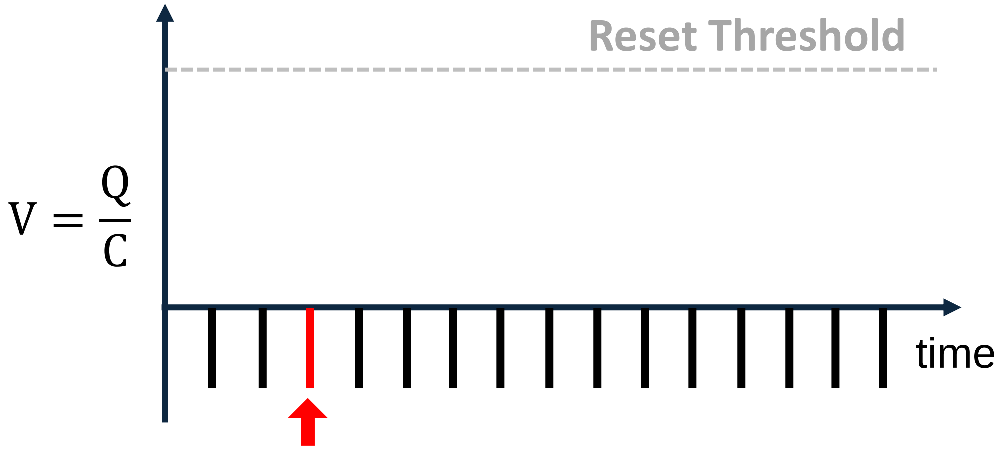

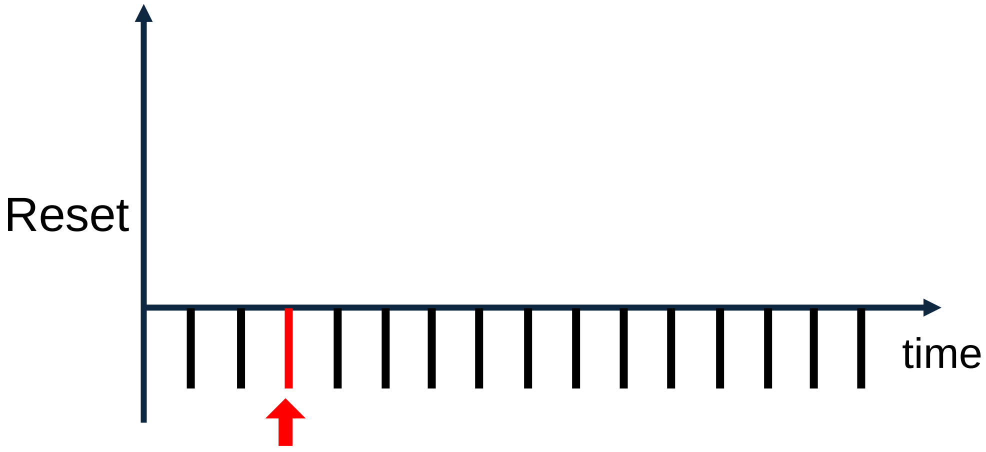

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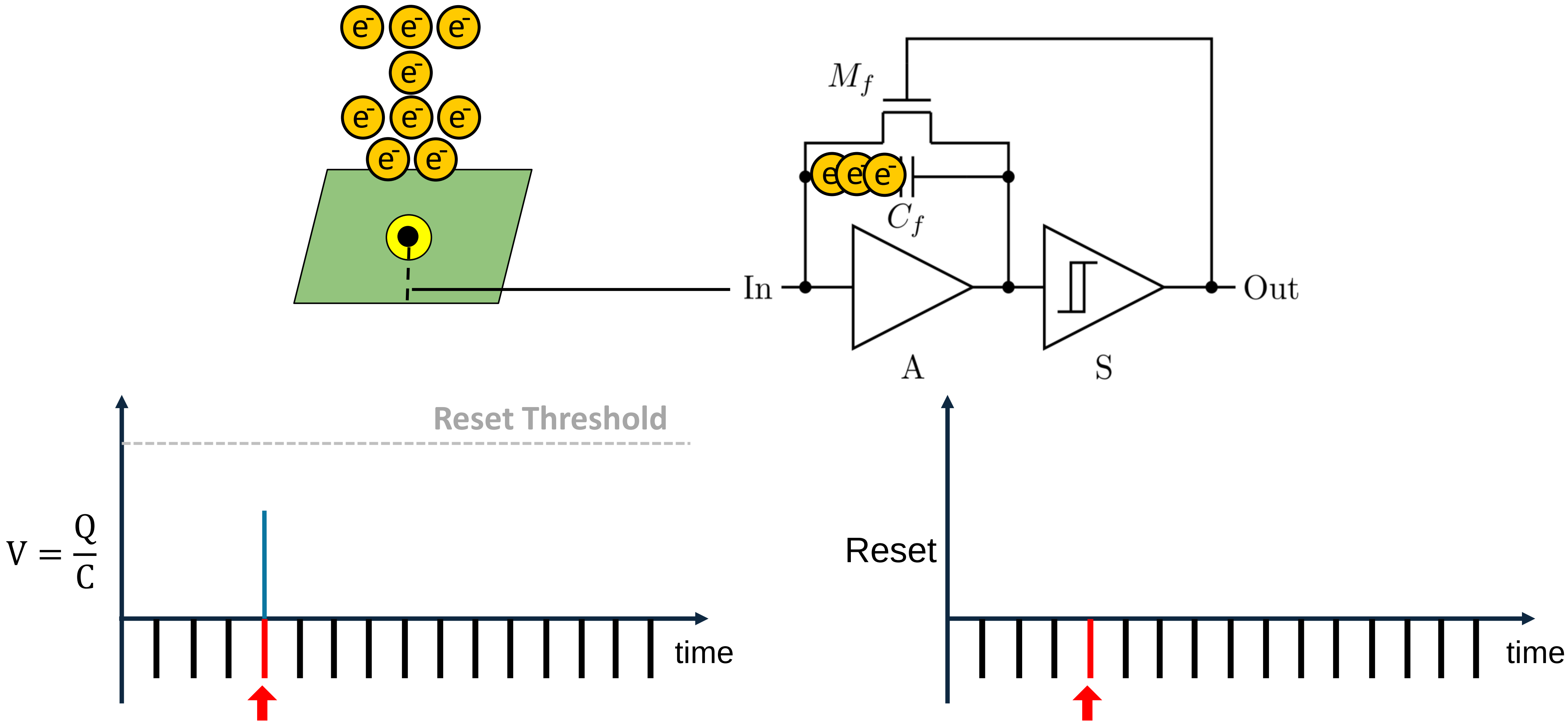

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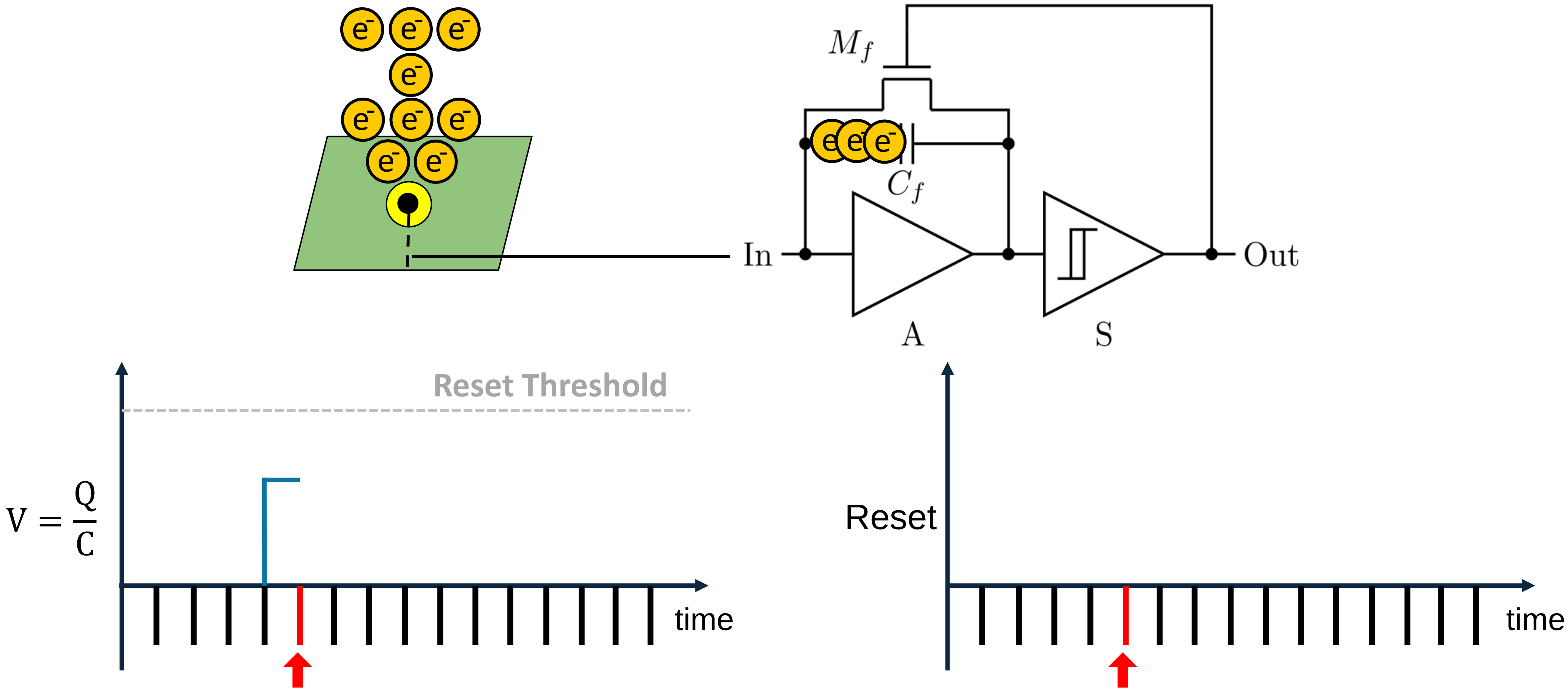

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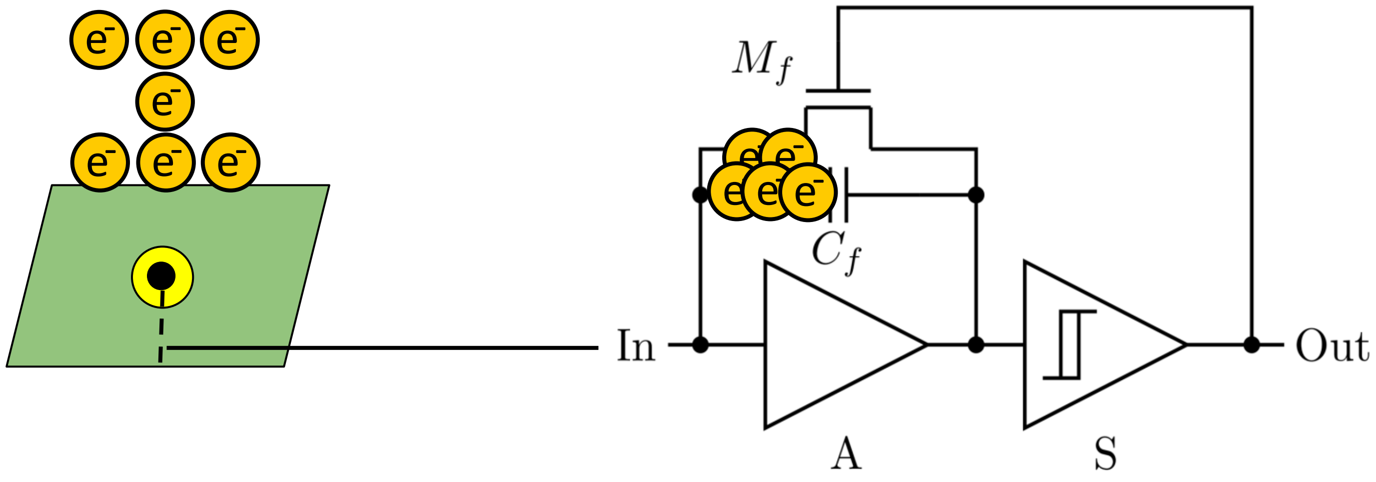

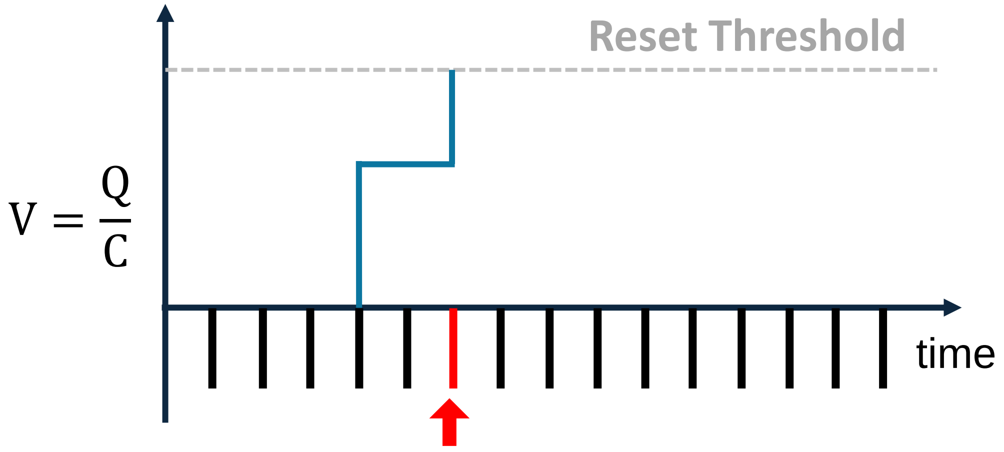

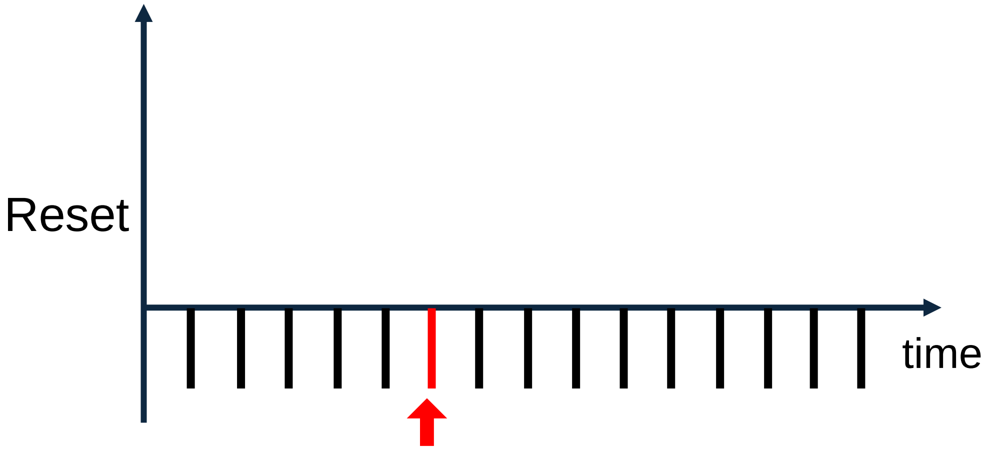

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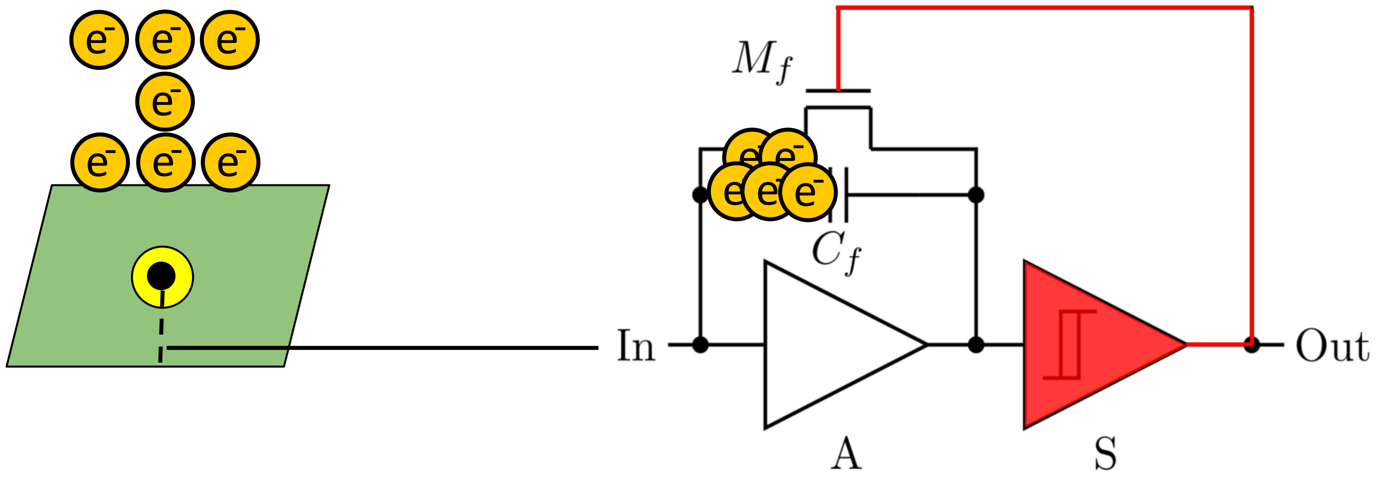

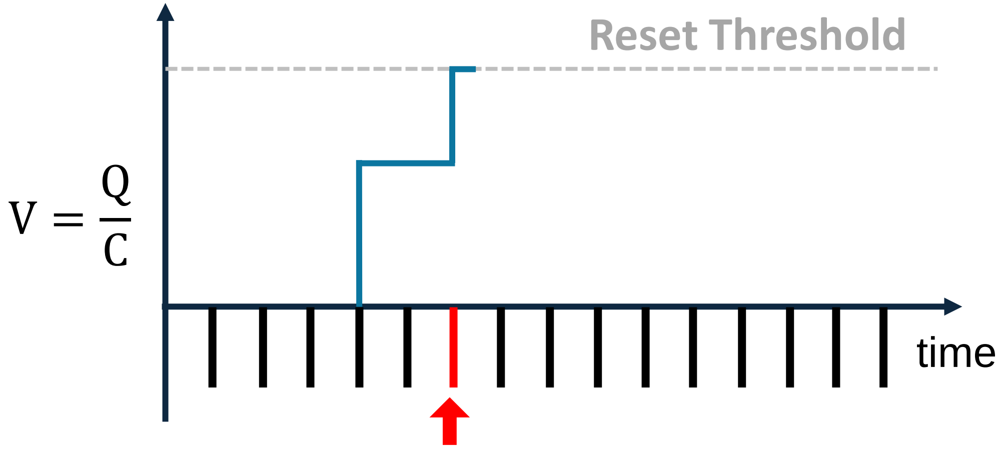

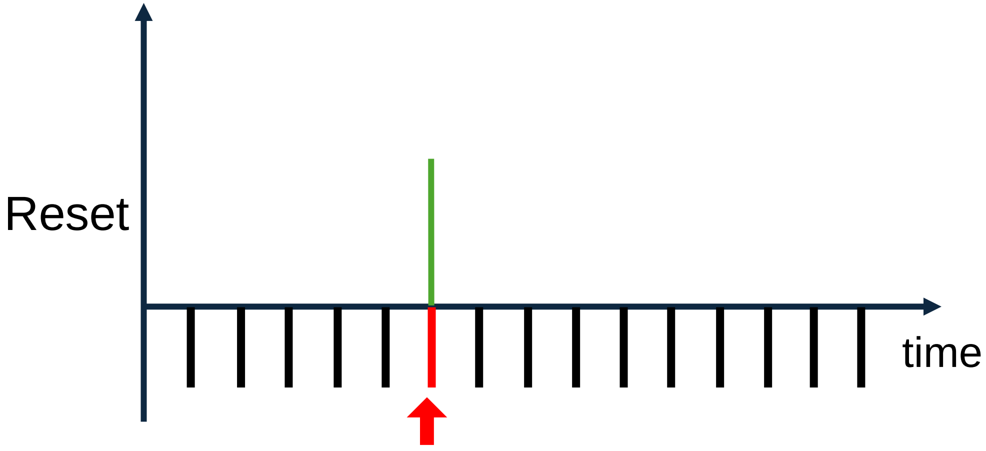

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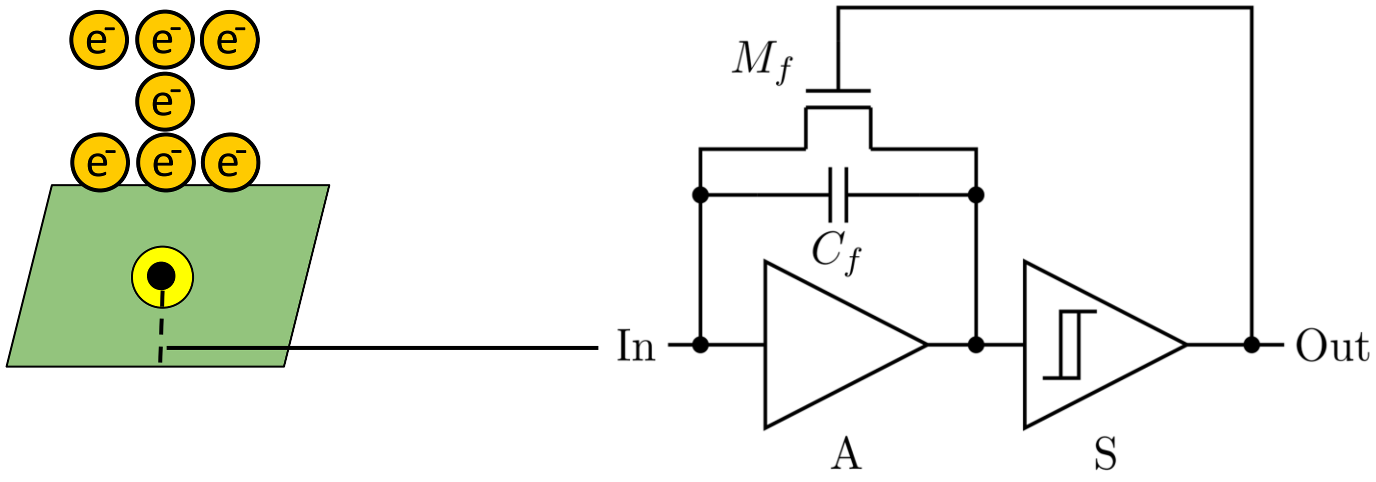

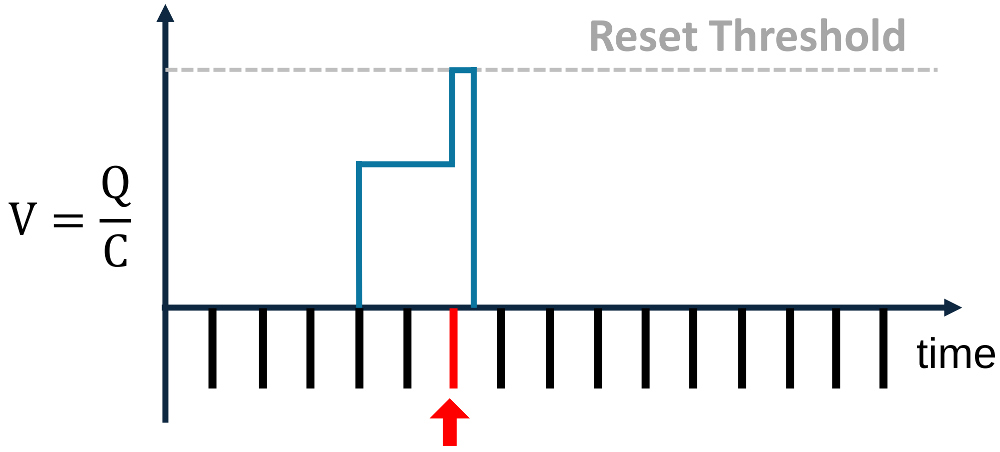

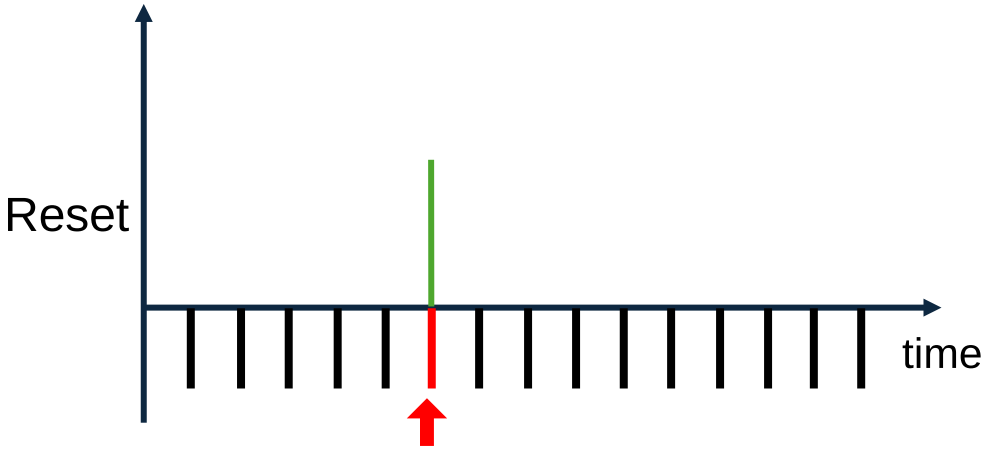

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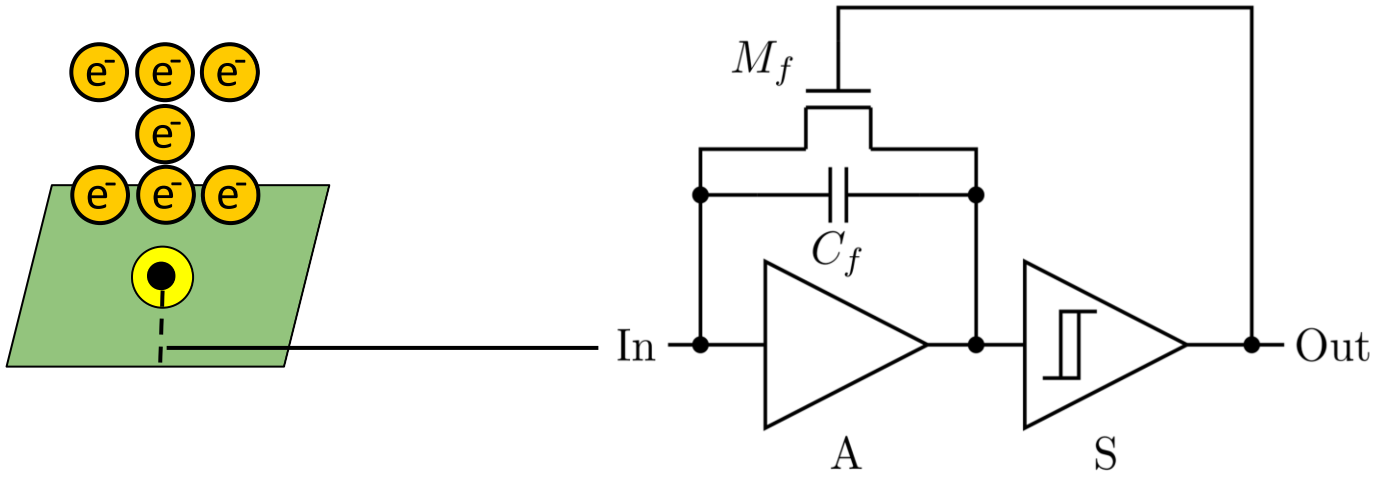

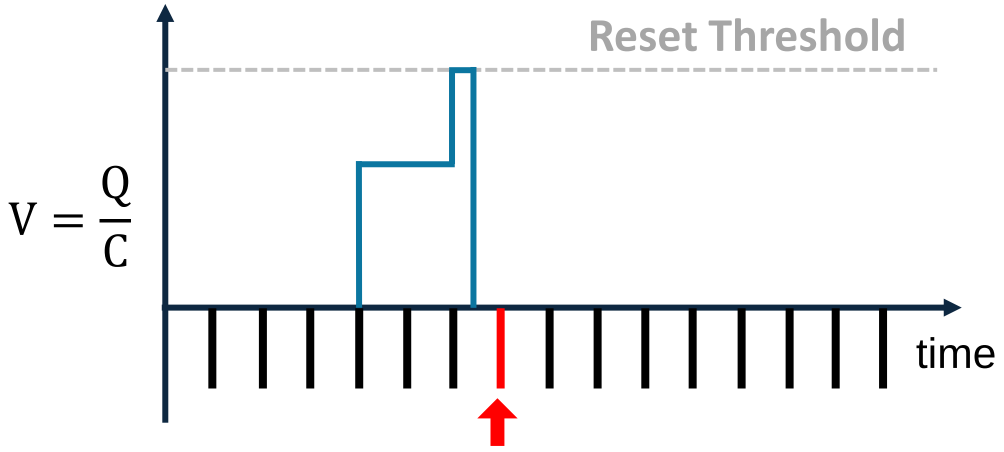

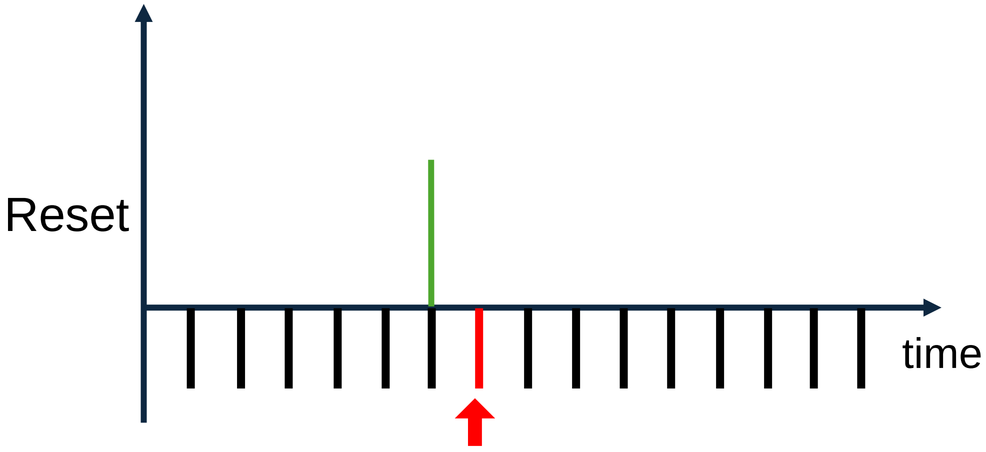

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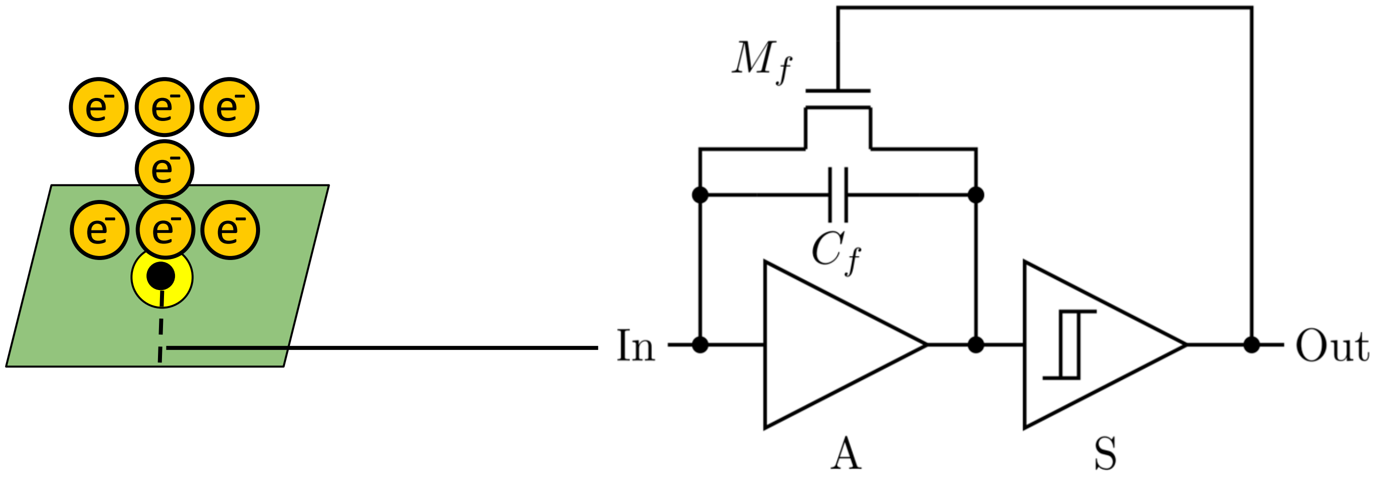

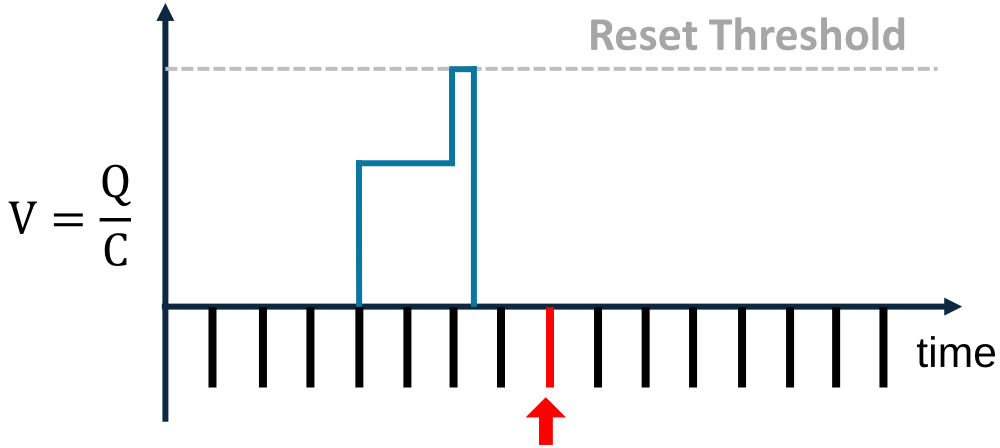

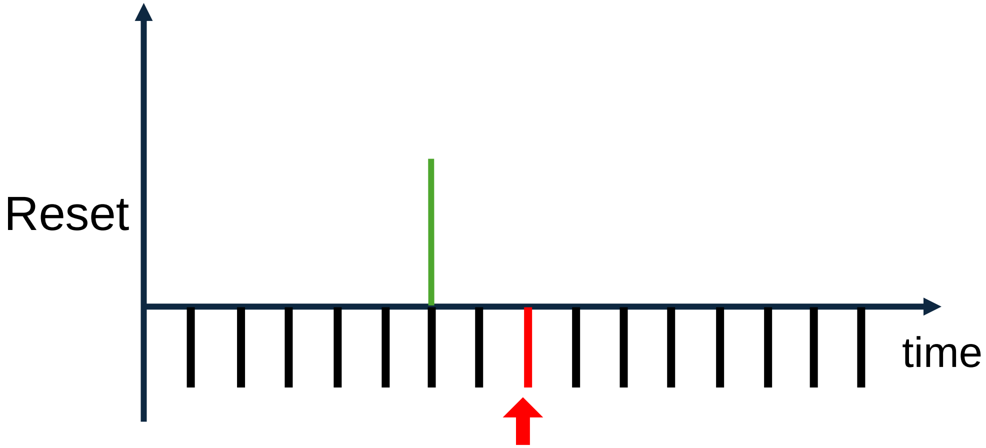

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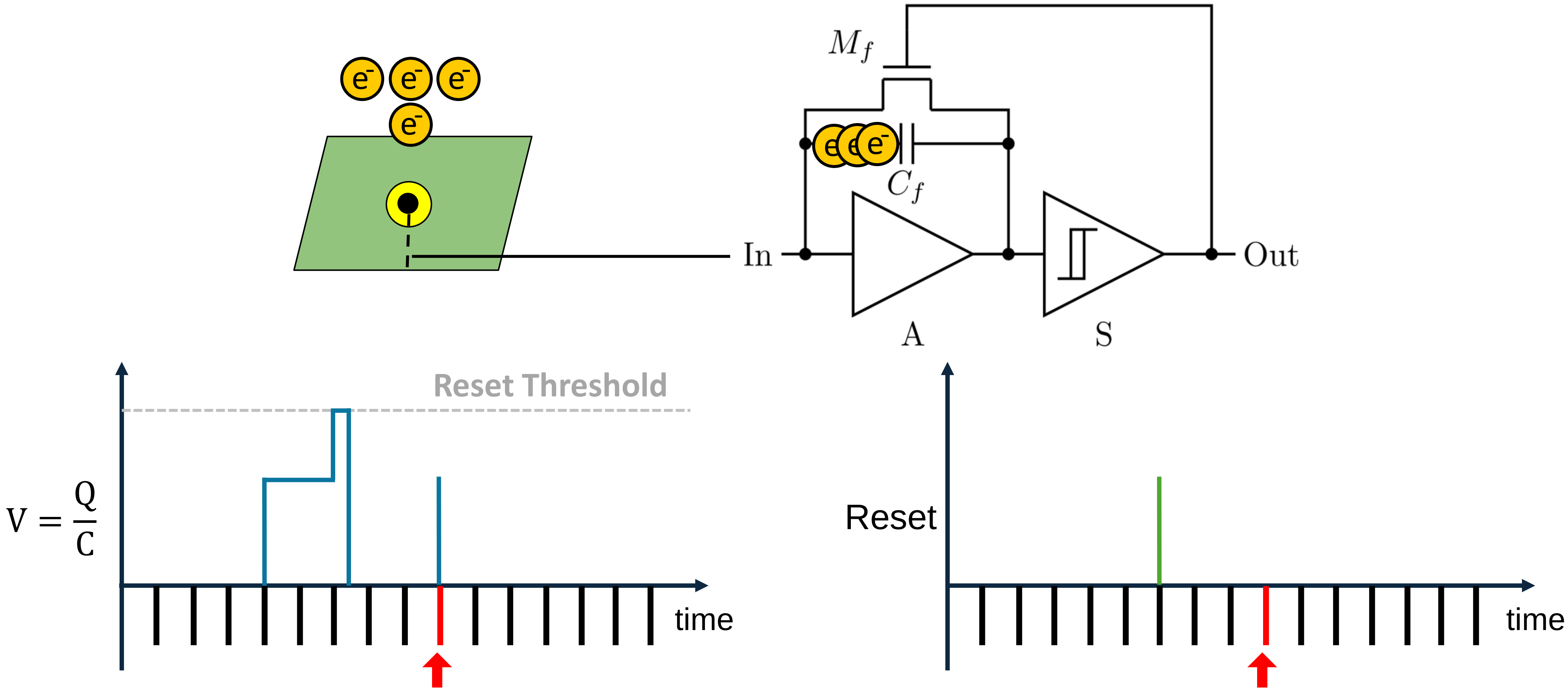

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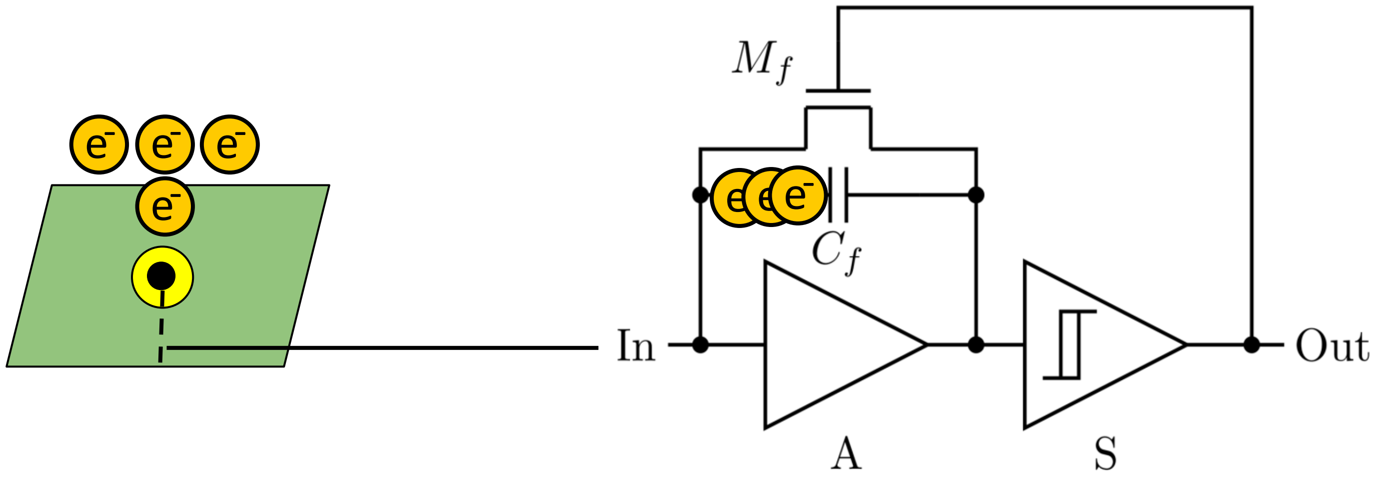

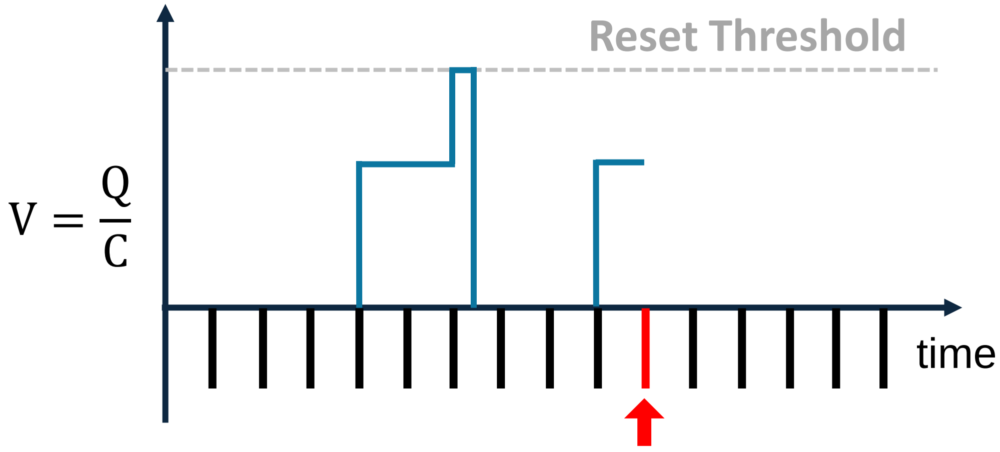

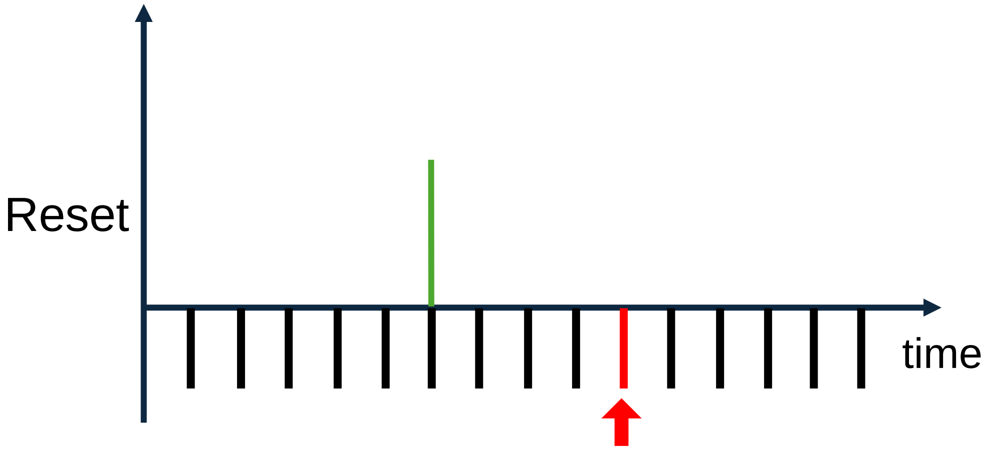

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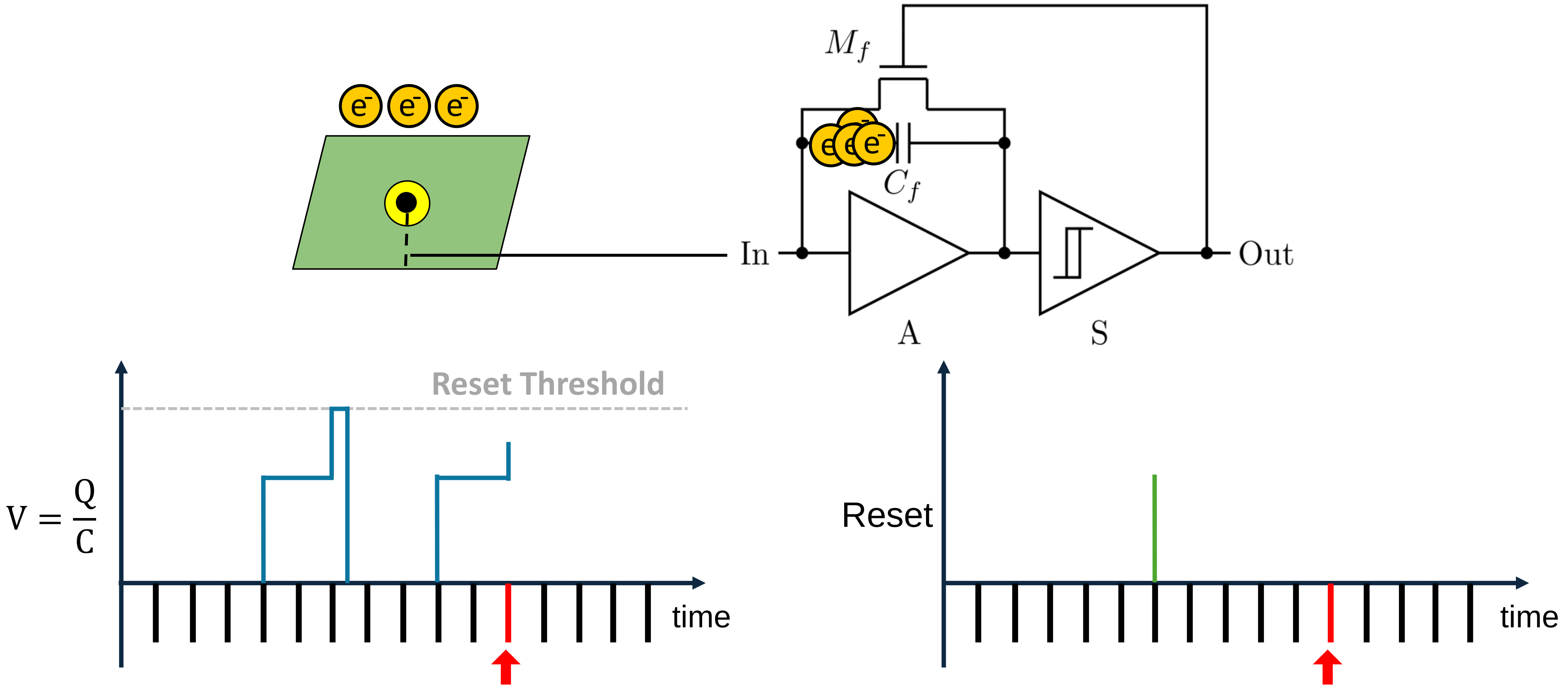

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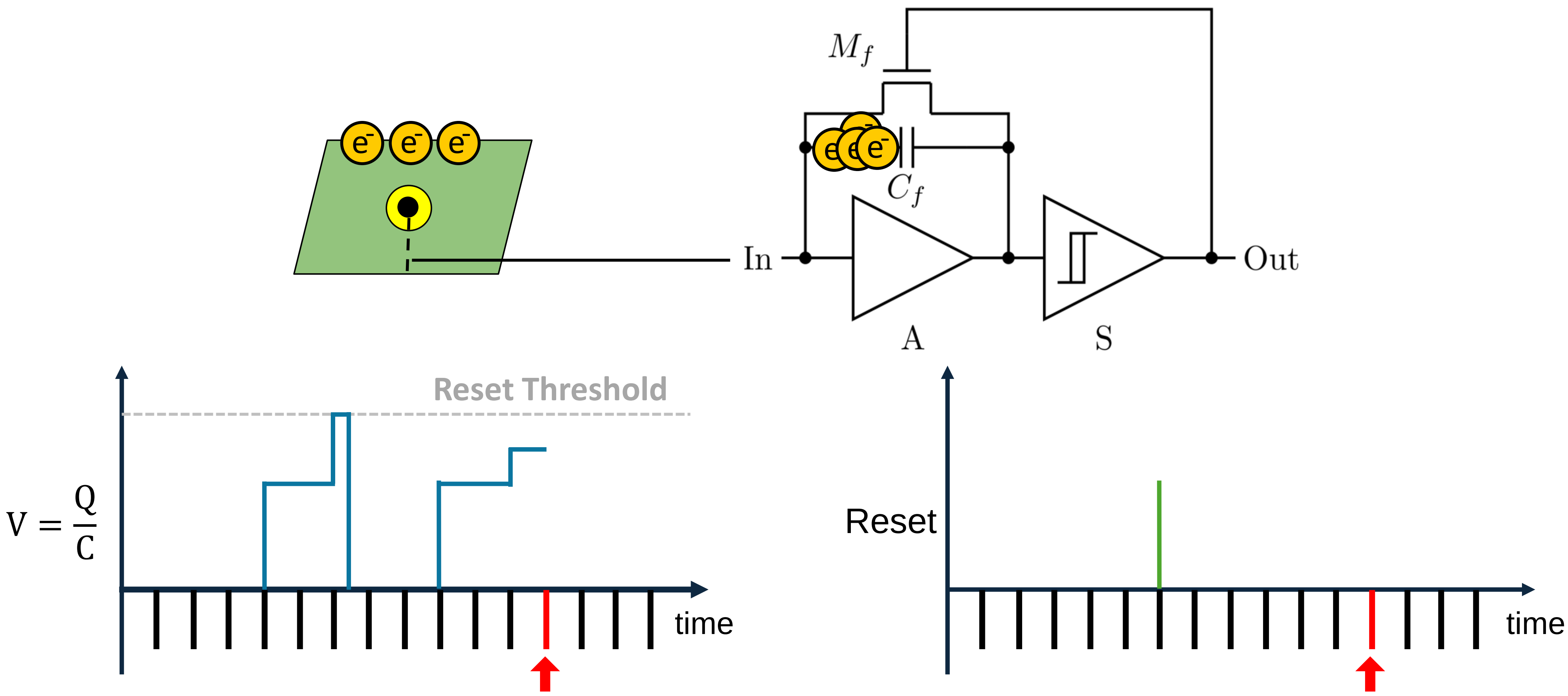

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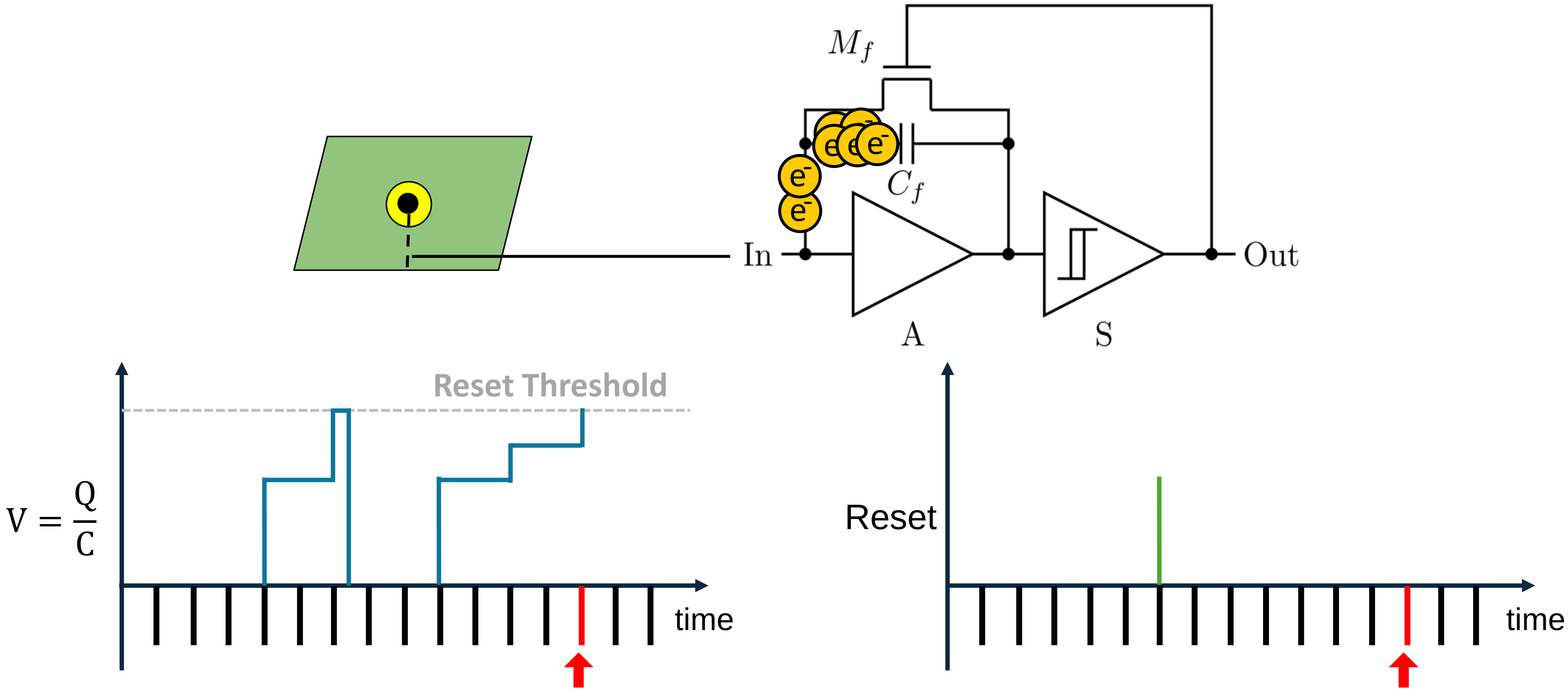

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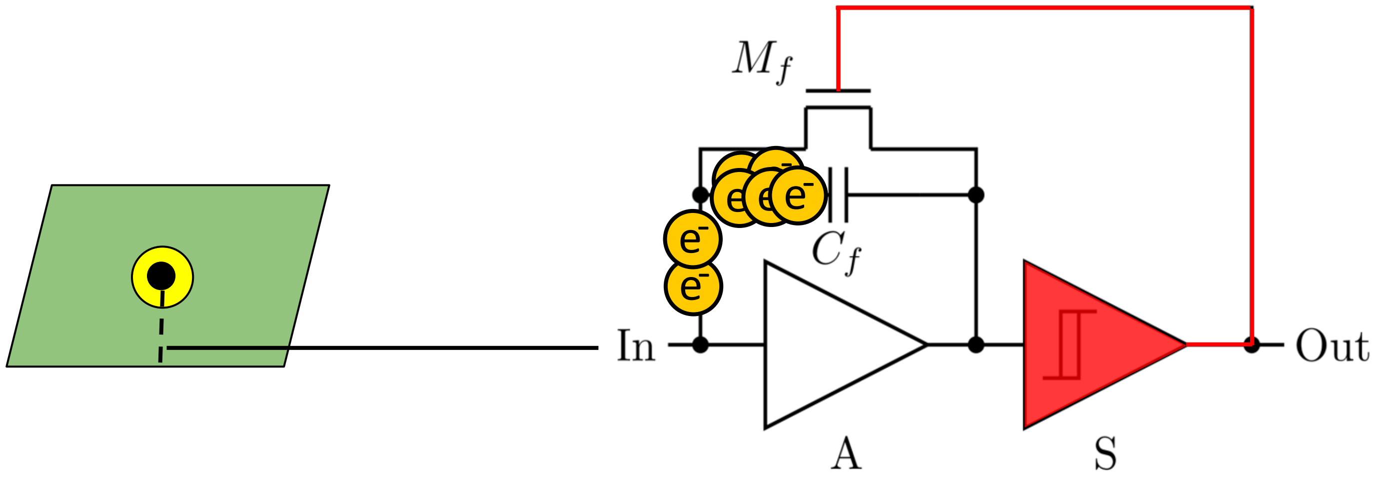

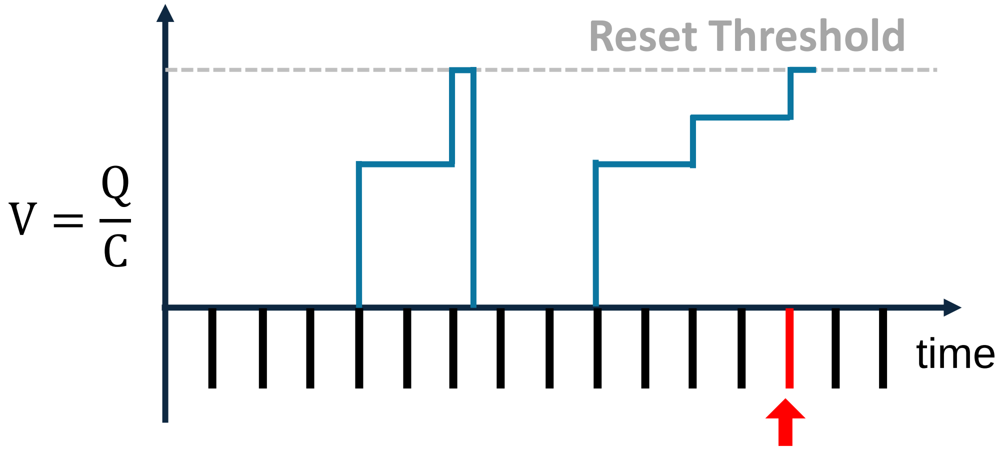

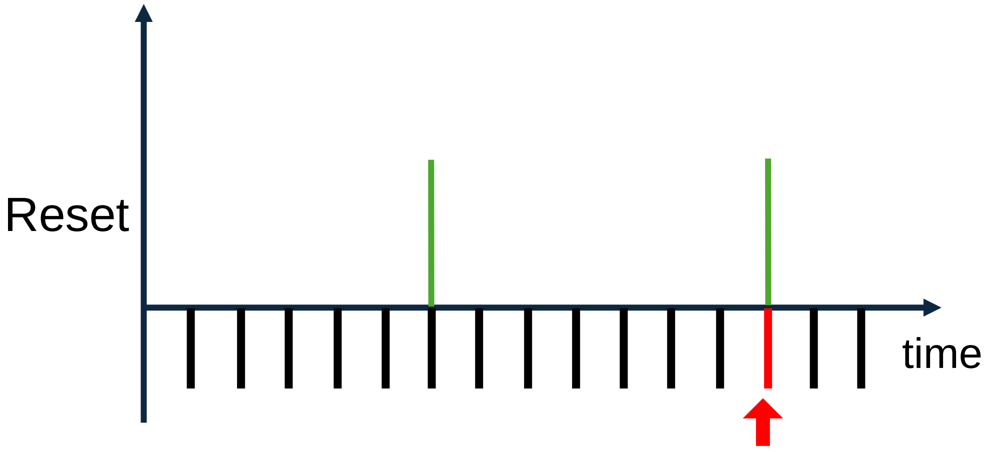

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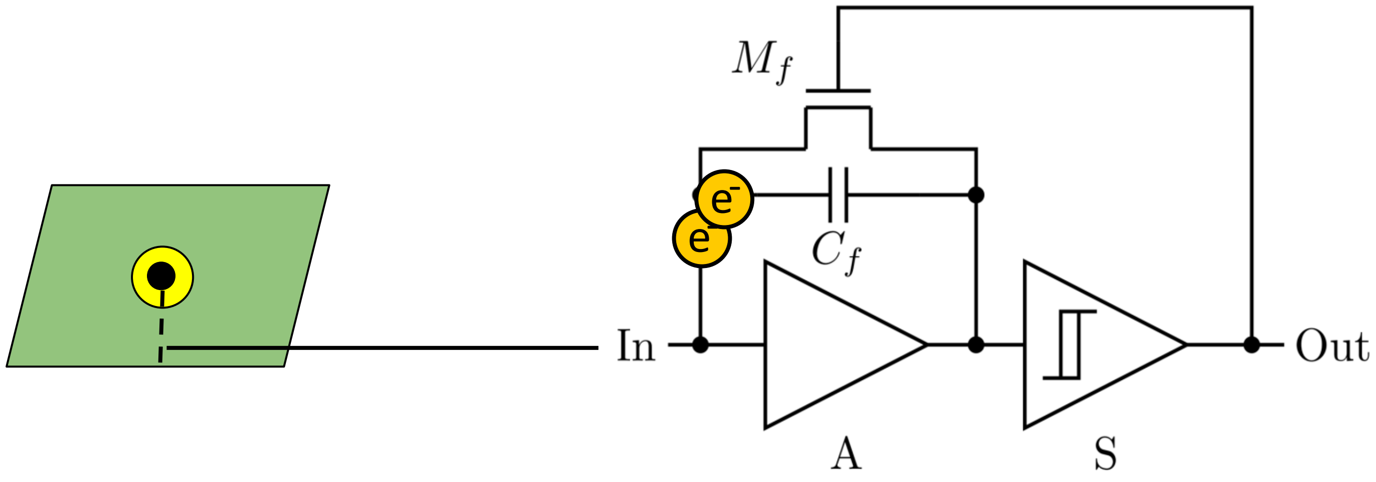

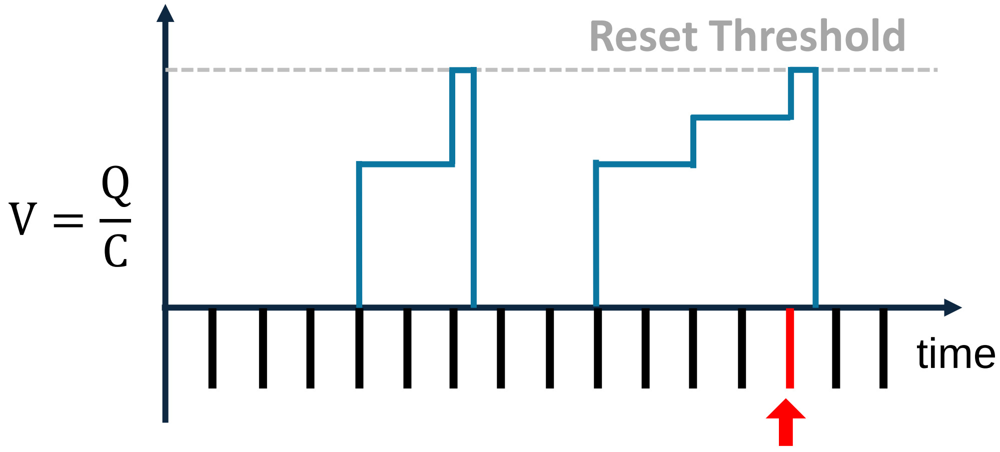

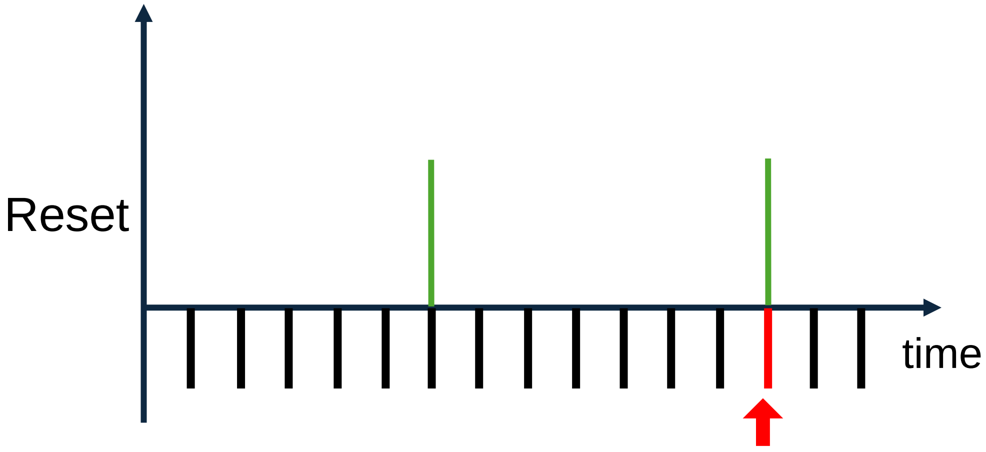

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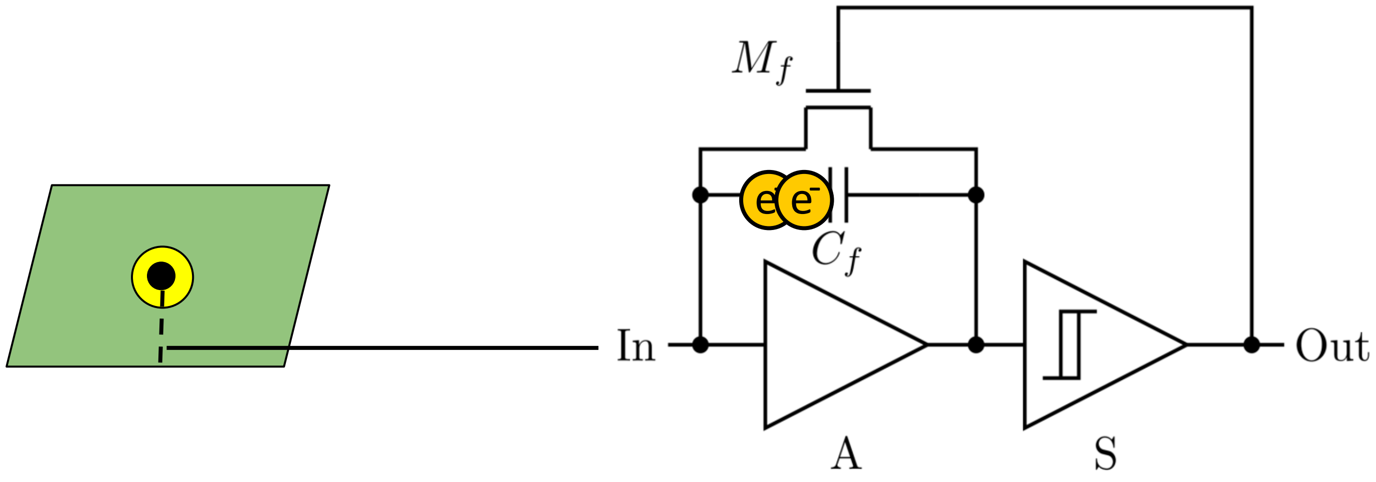

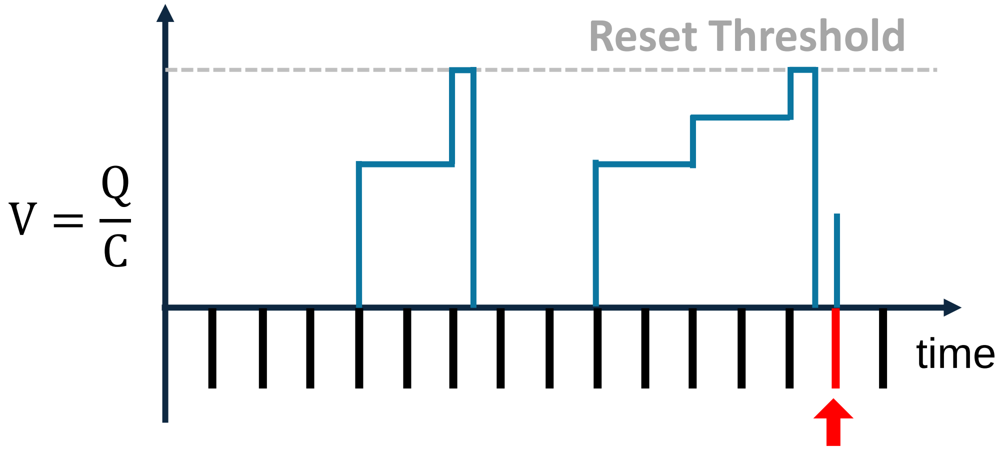

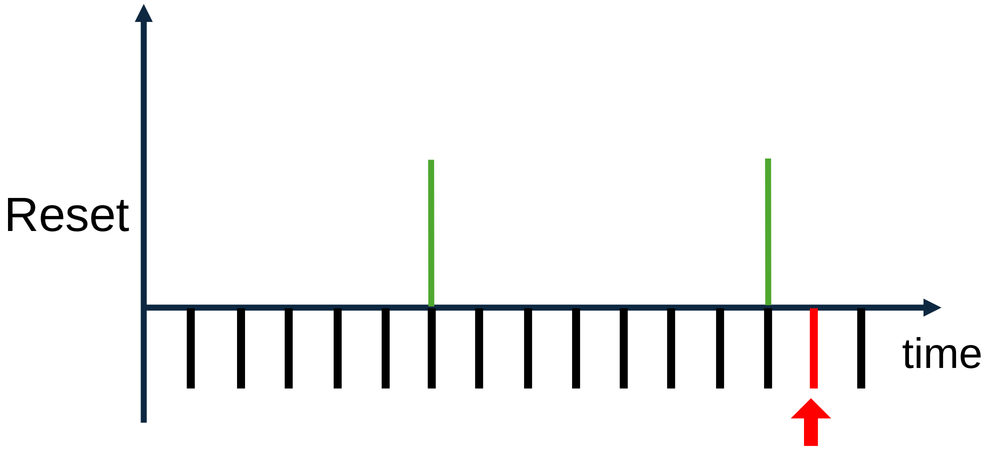

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Toy Example

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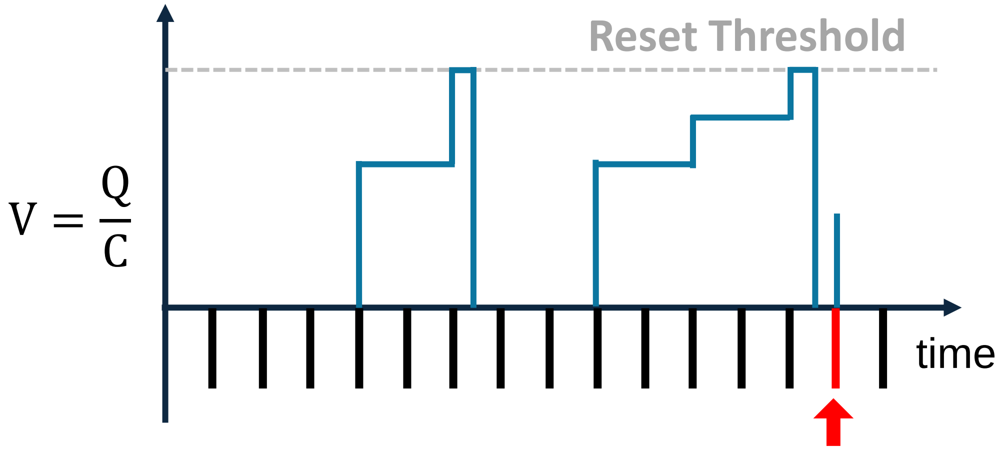
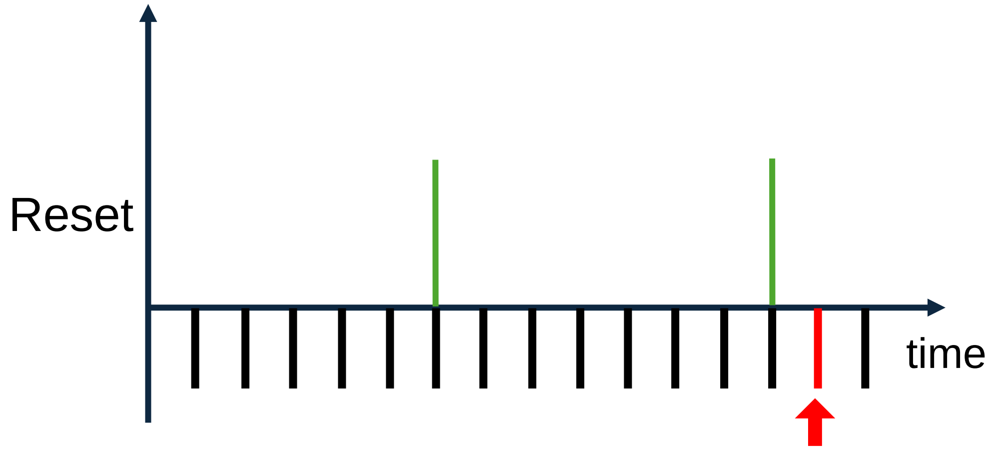
We are measuring
how long it took (Δt) to accumulate fixed amount of Q

Just with time stamps of reset signal,
we can reconstruct the current detected by the pixel





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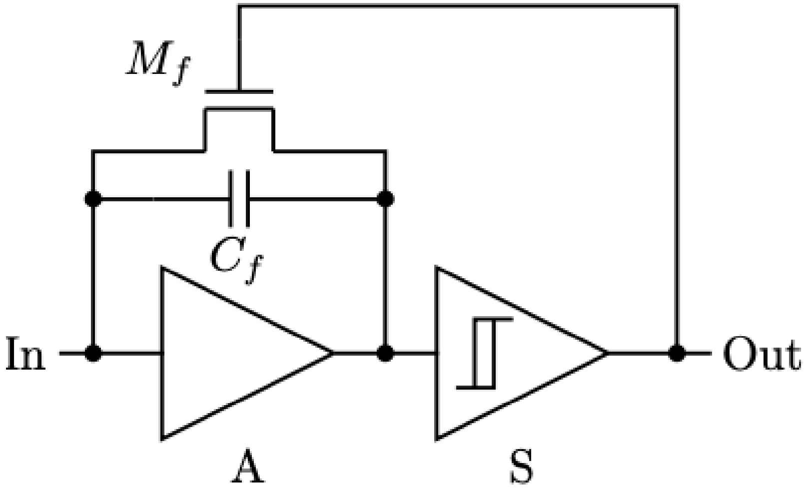

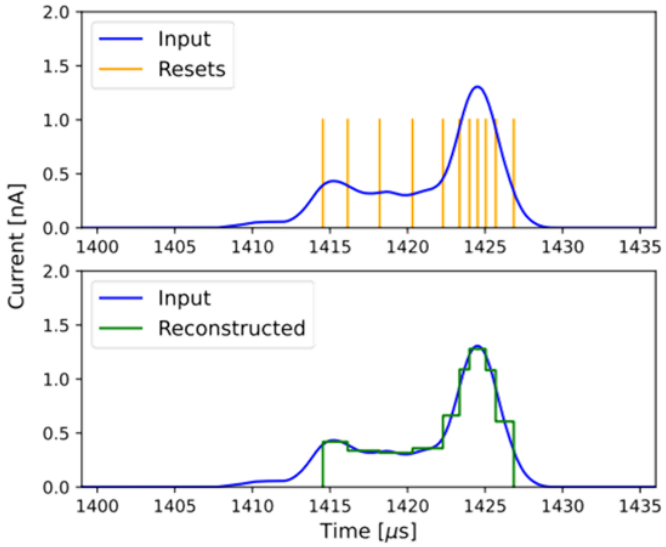

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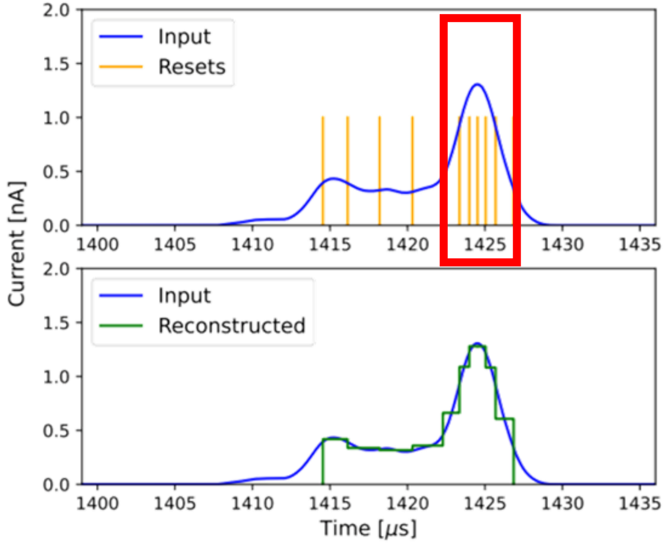
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

Solution : Pixelization

Challenge:
Great increase in
1) the number of channels
2) the amount of data

Solutions:
1) Electronic principle of least action
2) the quantization of charge

Denser area
⇩
took pixel **less** time to get unit amount of charge
⇩
More current



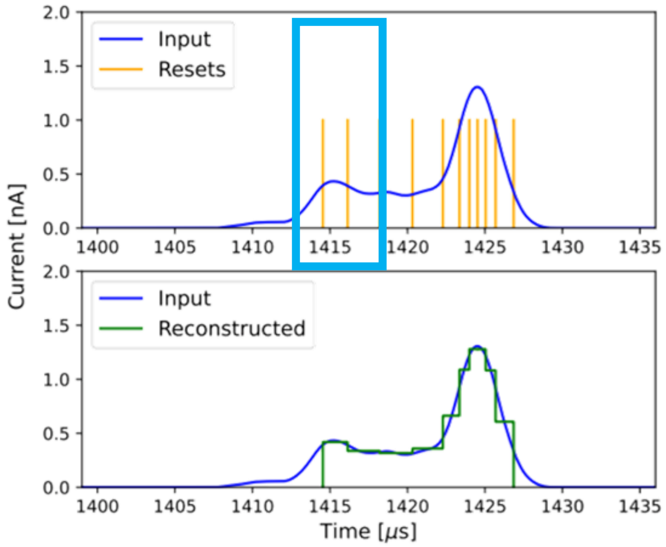
1.
a)
b)
c)
2.
a)
b)
3.
a)
b)
c)

Solution : Pixelization

Challenge:
Great increase in
1) the number of channels
2) the amount of data

Solutions:
1) Electronic principle of least action
2) the quantization of charge

Sparse area
⇩
took pixel **more** time to get unit amount of charge
⇩
Less current



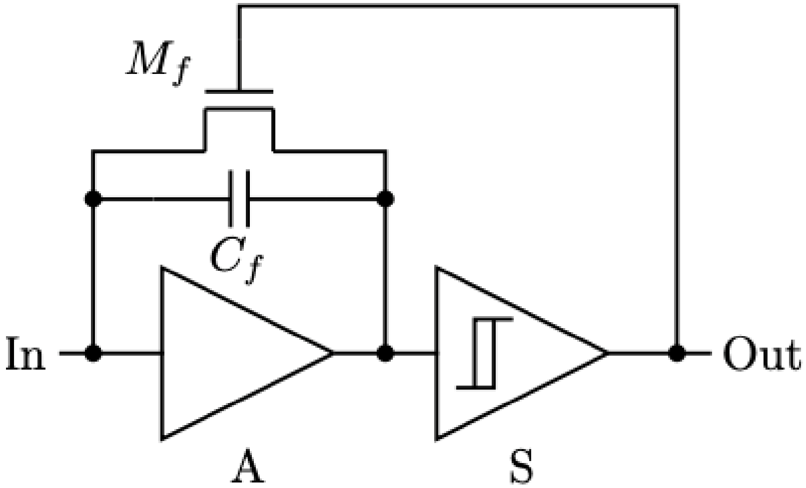
1.
a)
b)
c)
2.
a)
b)
3.
a)
b)
c)

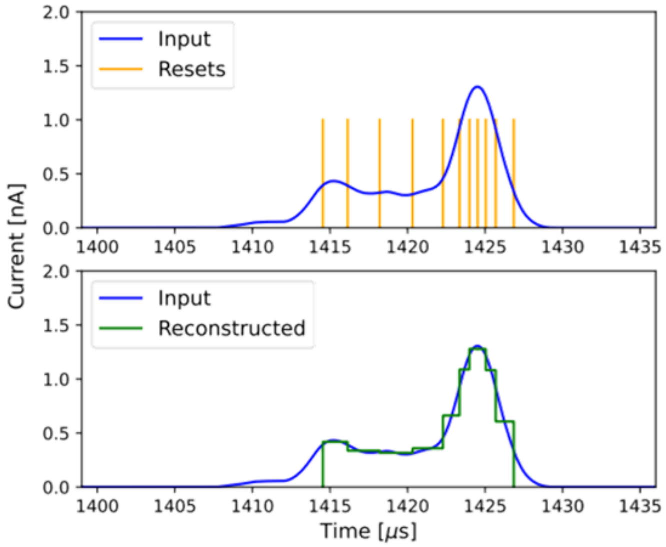
Solution : Pixelization

Challenge:
Great increase in
1) the number of channels
2) the amount of data

Solutions:
1) Electronic principle of least action
2) the quantization of charge

→ The data rate is 10^6 times less than the traditional wire readout
(5.7 MB/s for 10kTon at 147 keV deposited energy threshold)





1.
a)
b)
c)
2.
a)
b)
3.
a)
b)
c)

Physics with Q-Pix

'maximize the discovery potential of a kiloton scale LArTPC'

1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

Physics with Q-Pix

‘maximize the discovery potential of a kiloton scale LArTPC’

Paper published from JINST in 2020

Enhancing beam event studies

Paper published from PRD in 2022

Enhancing supernovae studies

Paper In preparation

Enabling solar studies

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1.
a)
b)
c)
2.
a)
b)
3.
a)
b)
c)

Beam physics with Q-Pix

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Paper published from JINST in 2020

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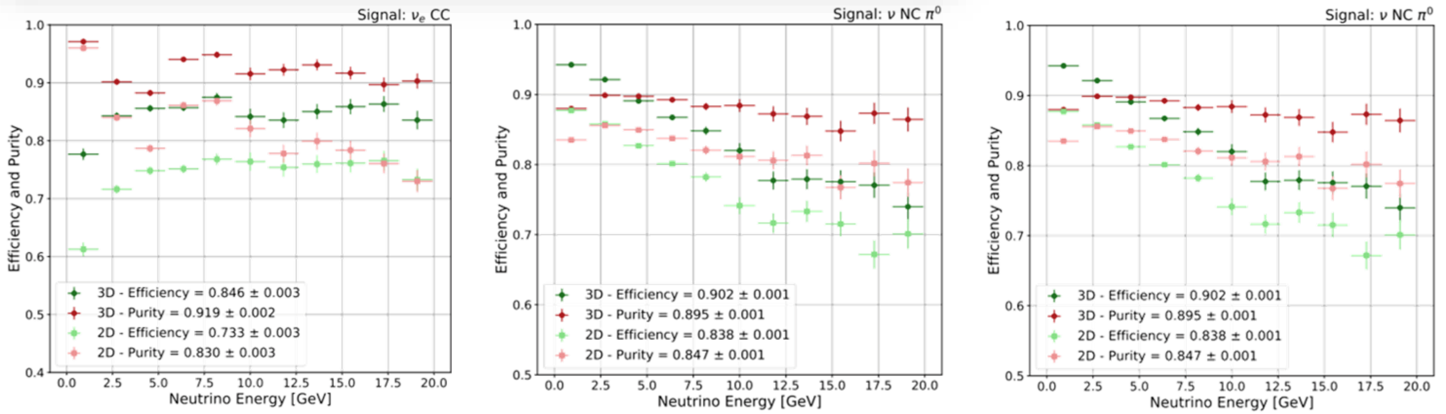
Enhancing neutrino event reconstruction with pixel-based 3D readout for liquid argon time projection chambers

C. Adams,[a,1] M. Del Tutto,[b,c] J. Asaadi,[d] M. Bernstein,[c] E. Church,[e] R. Guenette,[c] J.M. Rojas,[c,2] H. Sullivan[d] and A. Tripathi[d]

[a] *Argonne National Laboratory, Lemont, IL, U.S.A.*
[b] *Fermi National Accelerator Laboratory, Batavia, IL, U.S.A.*
[c] *Harvard University, Cambridge, MA, U.S.A.*
[d] *University of Texas-Arlington, Arlington, TX, U.S.A.*
[e] *Pacific Northwest National Laboratory, Richland, WA, U.S.A.*

Category	Accuracy [%] 3D	2D
Neutrino Interaction	**94**	91
Proton Multiplicity	**91**	87
Charge Pion Presence	**94**	91
Neutral Pion Presence	**95**	94



1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

Beam physics with Q-Pix

Good tracking

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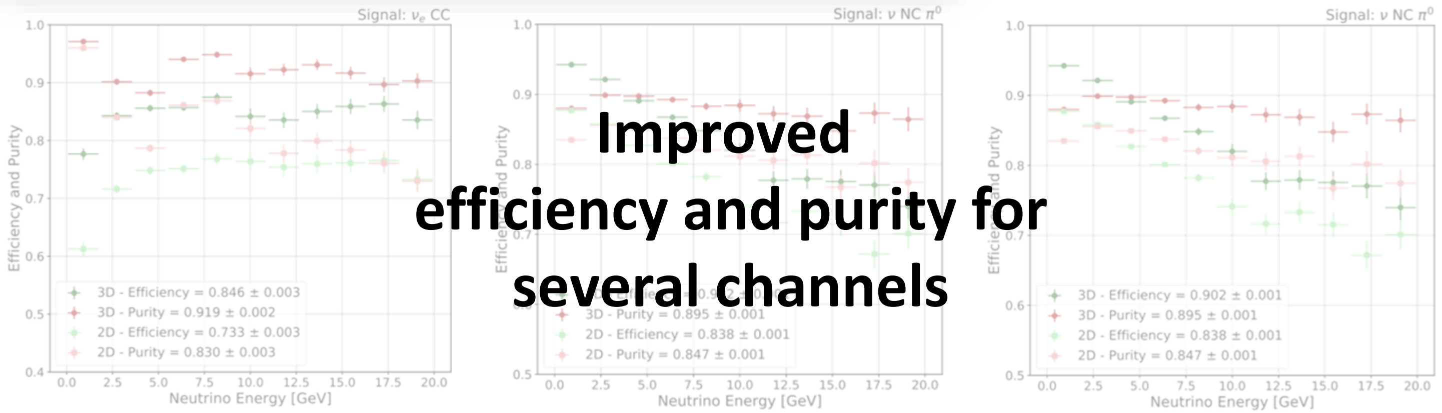
Category	Accuracy [%] 3D	2D
Neutrino Interaction	94	91
Proton Multiplicity	91	87
Charge Pion Presence	[illegible]	91
Neutral Pion Presence	95	94

Enhanced event reconstruction accuracy



Improved efficiency and purity for several channels

1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

Good tracking

Supernova physics with Q-Pix

Paper published from JINST in 2020

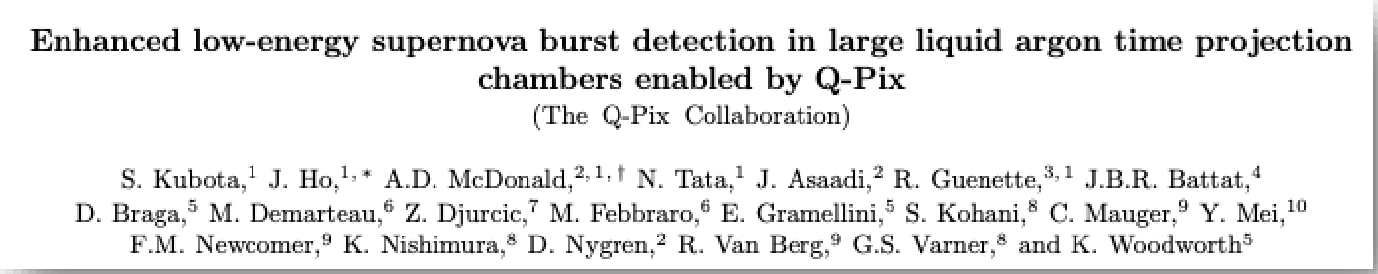
Enhancing beam event studies

[Paper published from PRD in 2022]

Enhancing supernovae studies

Paper In preparation

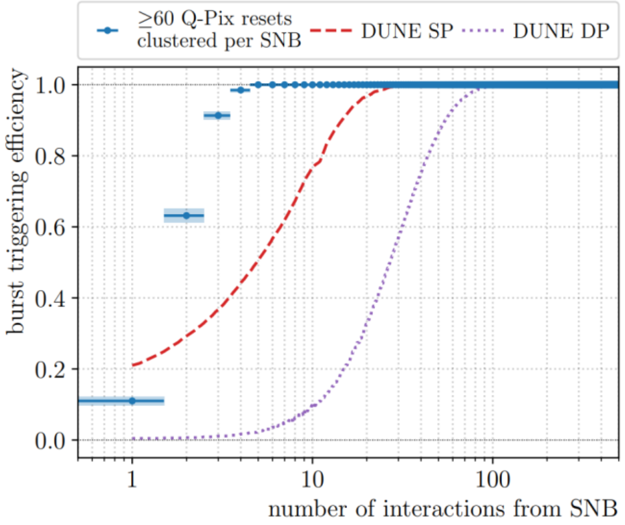
Enabling solar studies

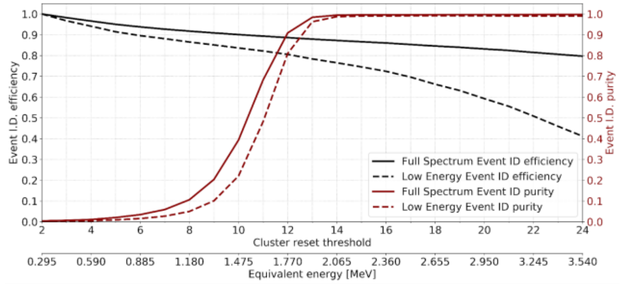


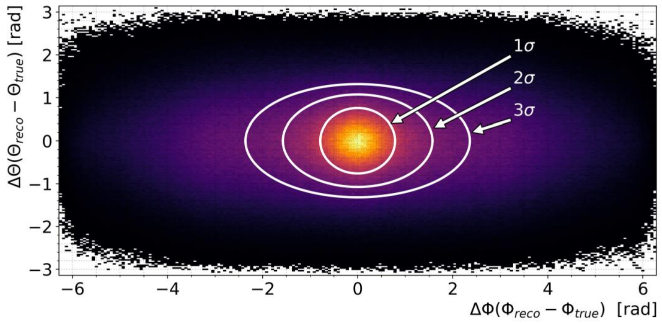
Enhanced low-energy supernova burst detection in large liquid argon time projection chambers enabled by Q-Pix

(The Q-Pix Collaboration)

S. Kubota,[1] J. Ho,[1,*] A.D. McDonald,[2,1,†] N. Tata,[1] J. Asaadi,[2] R. Guenette,[3,1] J.B.R. Battat,[4] D. Braga,[5] M. Demarteau,[6] Z. Djurcic,[7] M. Febbraro,[6] E. Gramellini,[5] S. Kohani,[8] C. Mauger,[9] Y. Mei,[10] F.M. Newcomer,[9] K. Nishimura,[8] D. Nygren,[2] R. Van Berg,[9] G.S. Varner,[8] and K. Woodworth[5]







1.
a)
b)
c)
2.
a)
b)
3.
a)
b)
c)

Supernova physics with Q-Pix

Good tracking
Low energy threshold
Better energy resolution

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Paper published from JINST in 2020

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Paper In preparation

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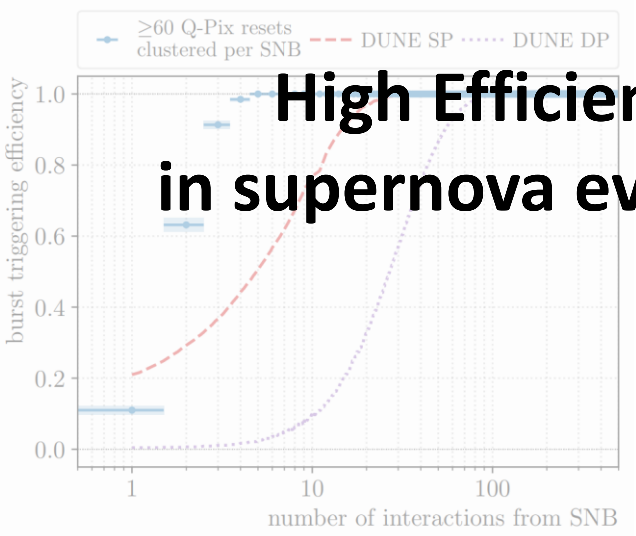
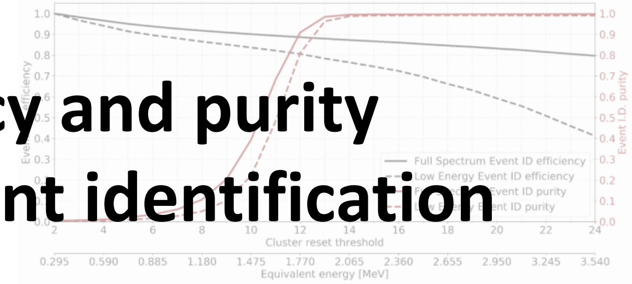
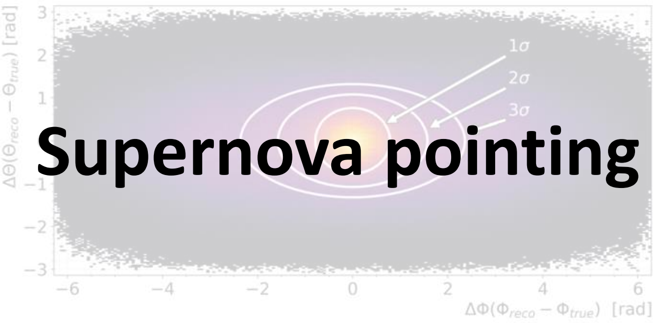




High Efficiency and purity in supernova event identification



Supernova pointing

1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

Solar physics with Q-Pix

Good tracking
Low energy threshold
Better energy resolution

Paper published from JINST in 2020

Enhancing beam event studies

Paper published from PRD in 2022

Enhancing supernovae studies

Paper In preparation

Enabling solar studies

Solar neutrinos offer many opportunities

- Enhancement in oscillation parameters measurement
- Understanding solar models
- Potential discovery of hep neutrinos

→ Requires :

better tracking

lower energy threshold

better energy resolution

1.
 a)
 b)
 c)
2.
 a)
 b)
3.
 a)
 b)
 c) ←

Solar physics with Q-Pix

Good tracking
Low energy threshold
Better energy resolution

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Paper published from
JINST in 2020

**Enhancing
beam event studies**

Paper published from
PRD in 2022

**Enhancing
supernovae studies**

Paper
In preparation

**Enabling
solar studies**

Solar neutrinos offer many opportunities

- Enhancement in oscillation parameters measurement
- Understanding solar models
- Potential discovery of hep neutrinos

→ Requires :

better tracking

lower energy threshold

better energy resolution

Exactly the improvements Q-Pix can offer!

1.
a)
b)
c)
2.
a)
b)
3.
a)
b)
c)

Conclusion

- Wire based LArTPC has been proven to be successful in many neutrino experiments but have some challenges.

- Q-Pix is a new technology whose default state is 'do-nothing' – which is suited for large scale detector

Good tracking

Low energy threshold

Better energy resolution

- Q-Pix offers enabling solar neutrino studies.

1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

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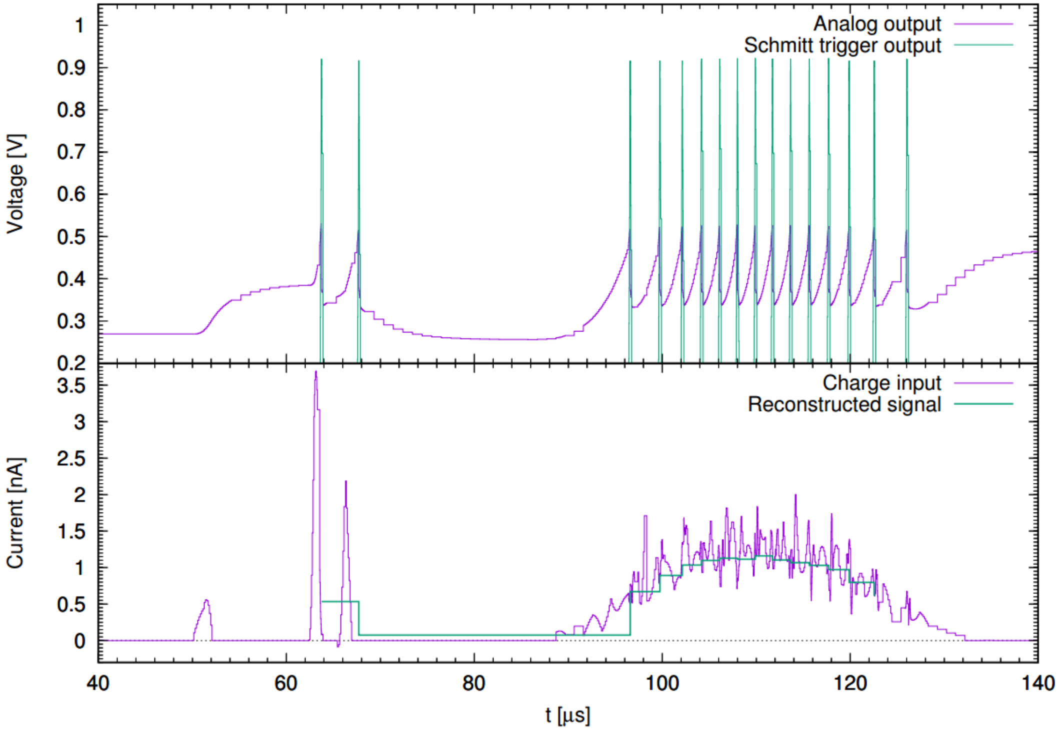
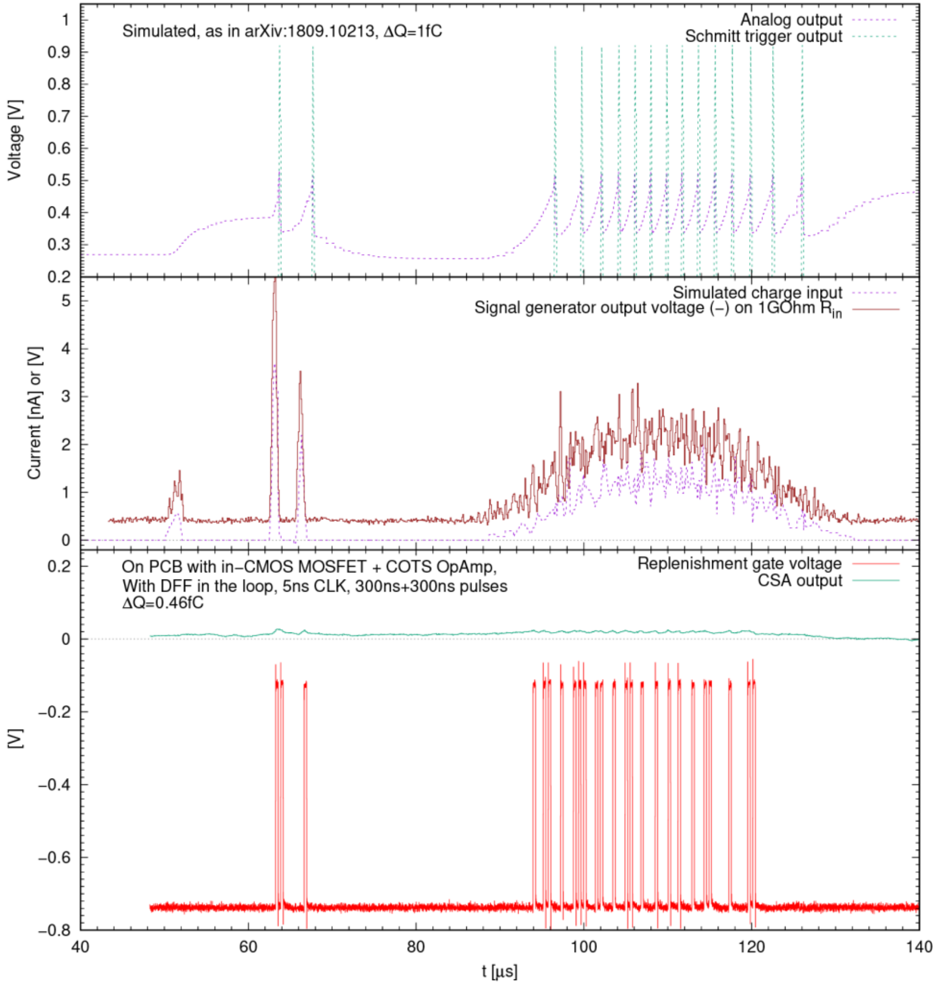
Backup

Q-Pix tests

$\Delta Q = 1$ fC (simulated)



$\Delta Q = 0.46$ fC



1.
 a)
 b)
 c)
2.
 a)
 b)
3.
 a)
 b)
 c)

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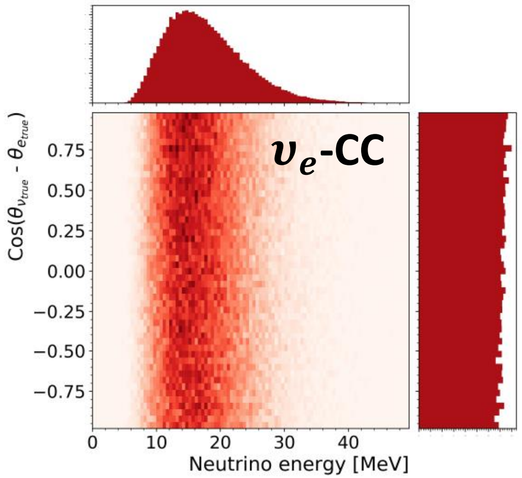
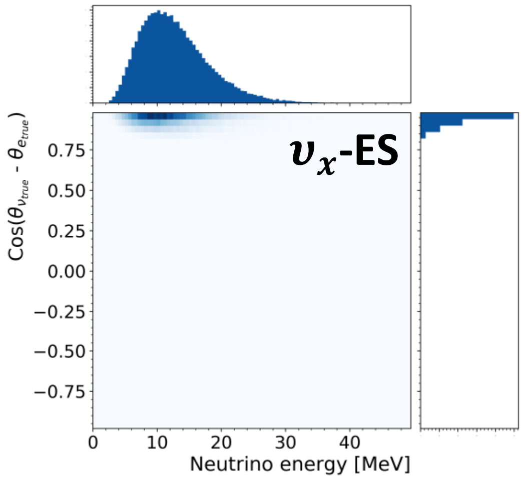
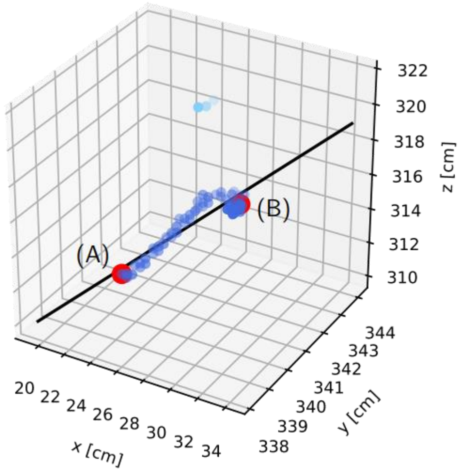
Supernova Pointing

- The intrinsic 3D nature of the pixel data collected by Q-Pix allows us to get directional information from the identified supernova events.
- ~10% of all the events collected are neutrino-electron elastic scattering events (υ_x ES) and the rest are neutrino-charged current (υ_e-CC).
- υ_x-ES events preserve information about the direction of the neutrino
  - The direction of the neutrino tells us where in the sky the supernova burst occurs
  - This is a critical aspect of the identification of a SNB event for astronomers and particle physicists!



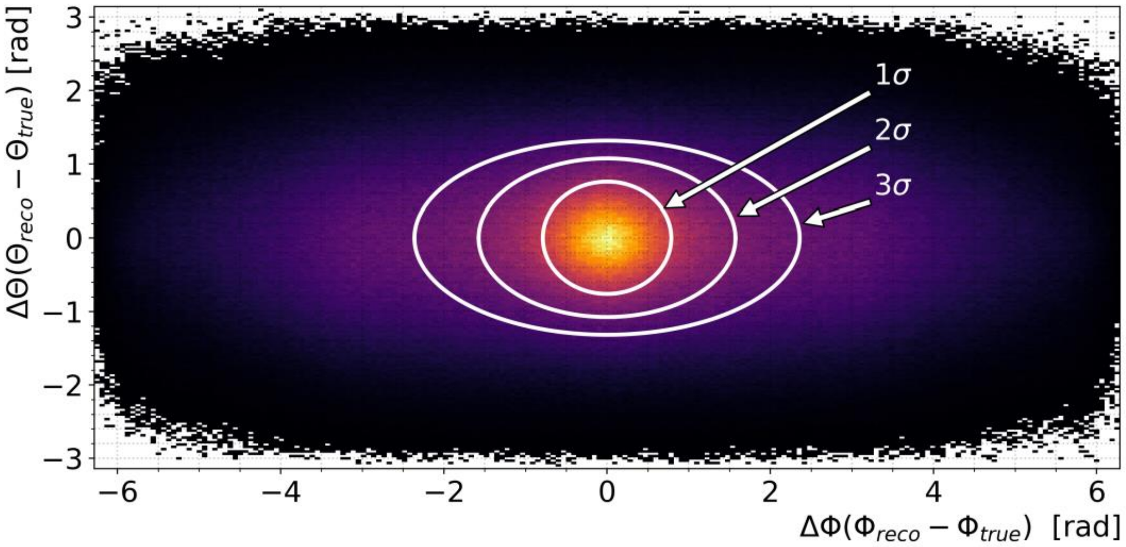




1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

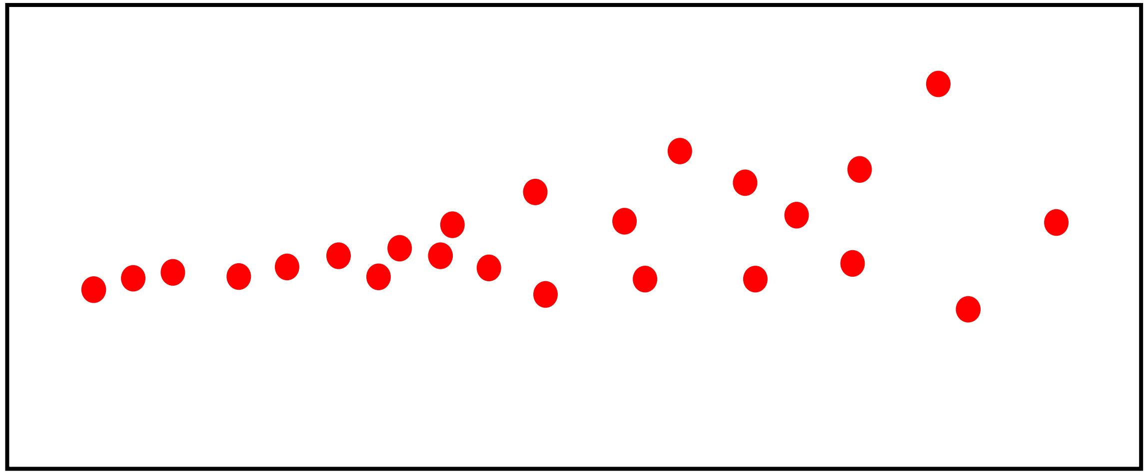
Supernova Pointing

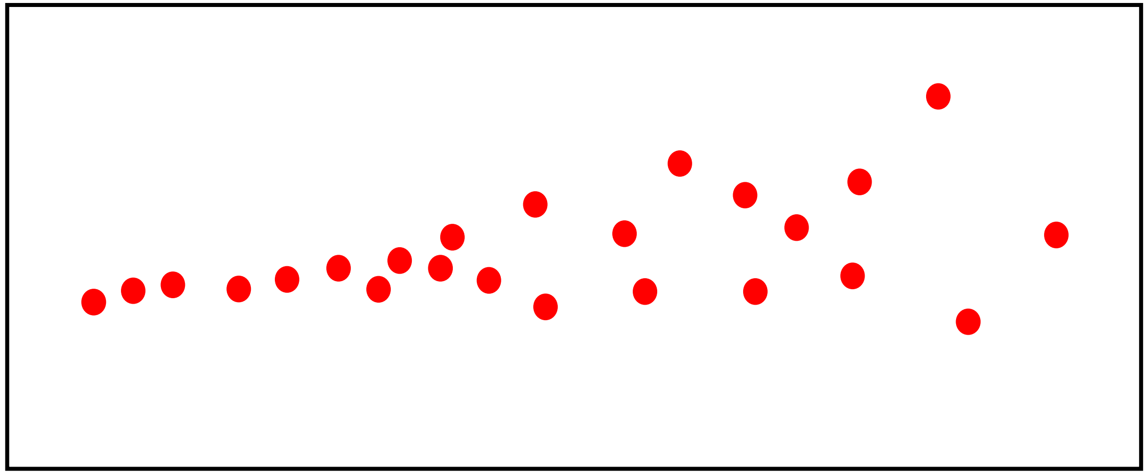
- By reconstructing a direction vector for each neutrino interaction, we can come up with a hypothesis of where the SBN event occurred in the sky
  - We correctly identify the SBN direction within 20 degrees 80% of the time
  - The other 20% we have the direction wrong by 180 degrees
- Repeating this over 10,000 unique SBN events, we computed how confident we are with the direction with a 10 kTon Q-Pix module
  - 10 kpc supernova would be reconstructed within θ = 33◦ and φ = 45◦ at 1σ, and θ = 99◦ and φ = 135◦ at 3σ.



1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

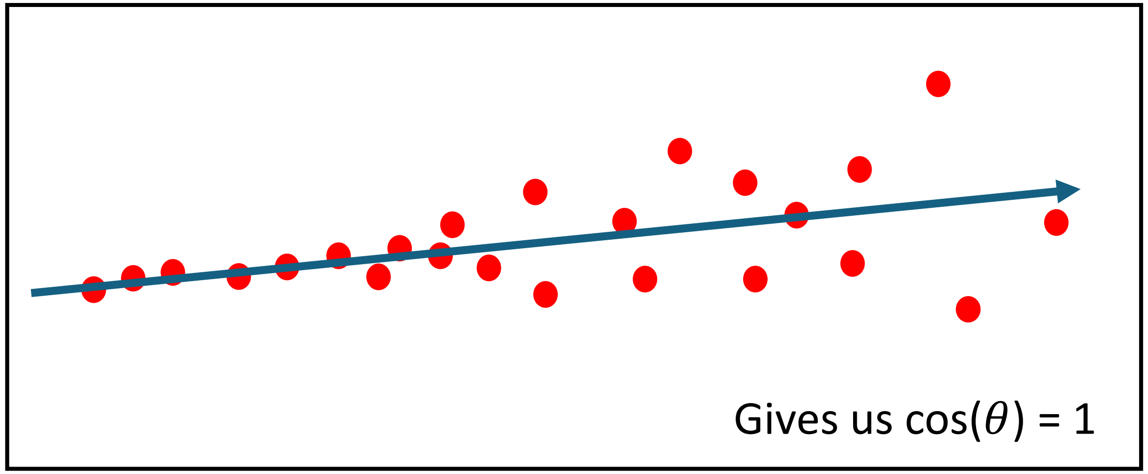
Directionality Flipping

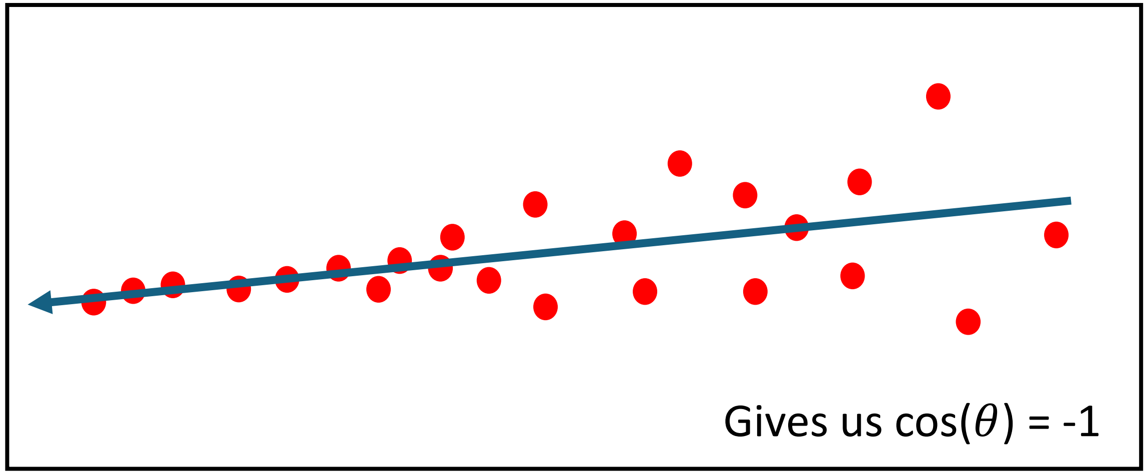




1.
    a)
    b)
    c)
2.
    a)
    b)
3.
    a)
    b)
    c)

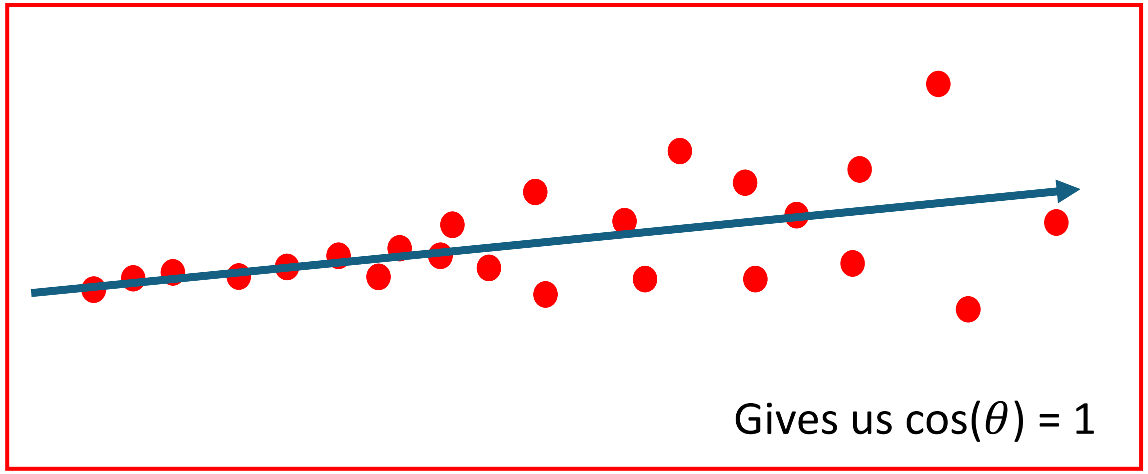
Directionality Flipping

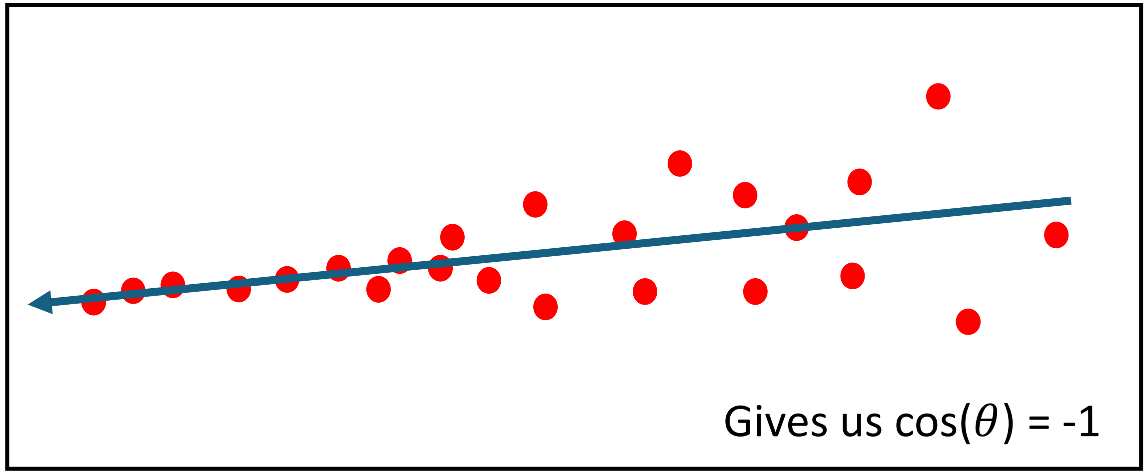




1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

Directionality Flipping



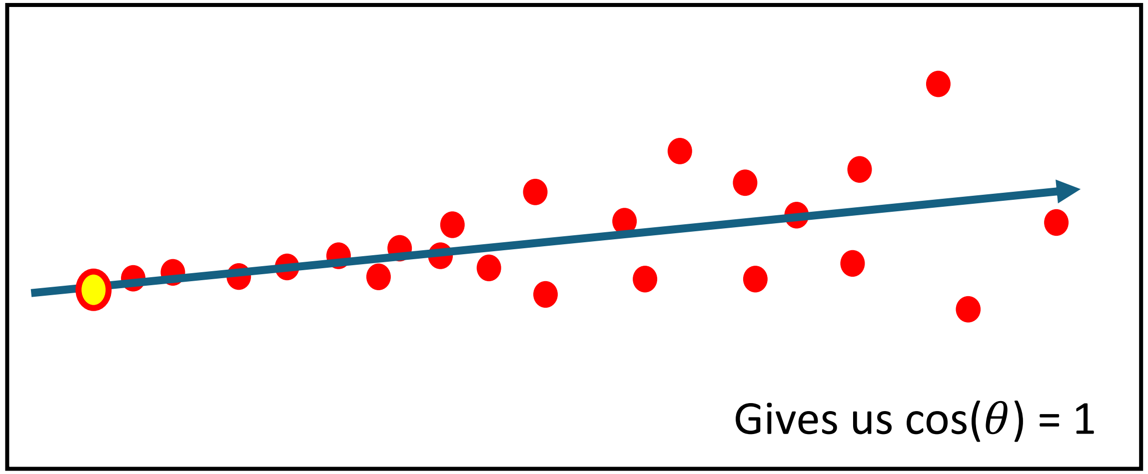


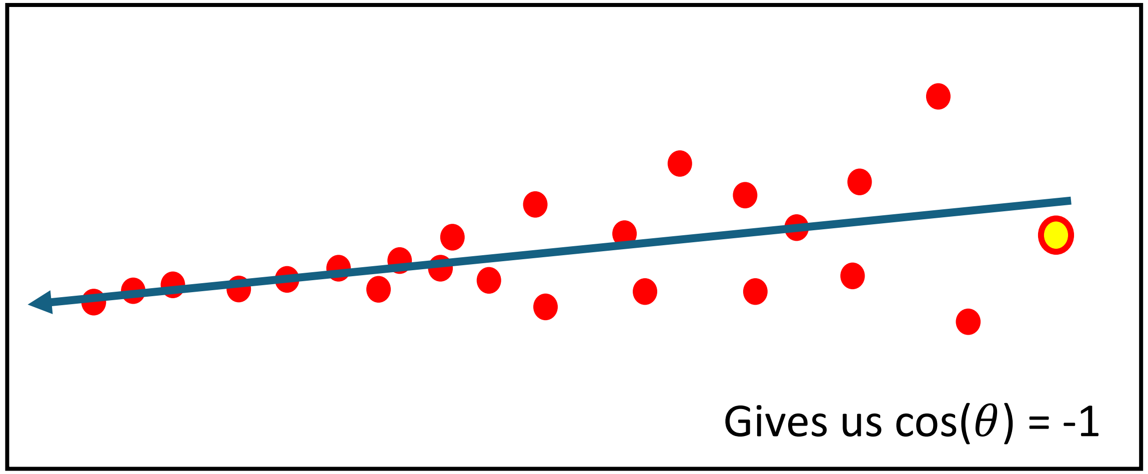
Electron scatters more often as it loses energy.

More scattered = less energy = end of the track
Less scattered = more energy = beginning of the track

1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

Directionality Flipping

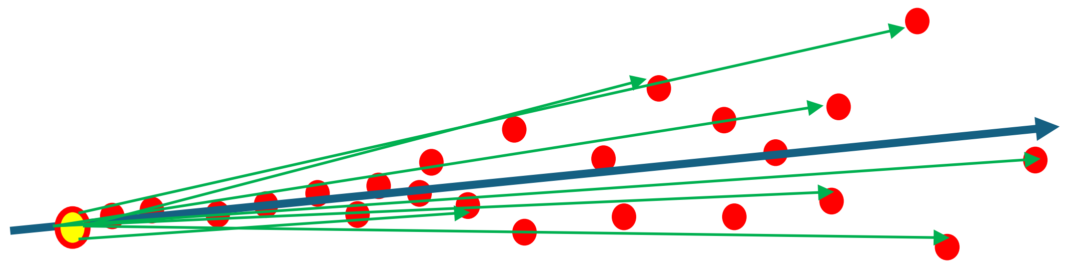




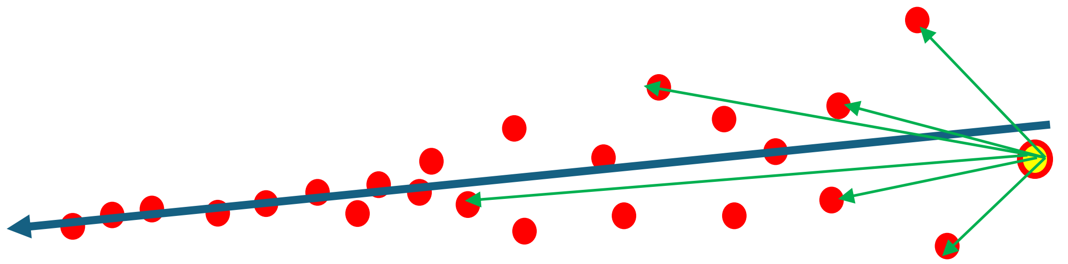
Pick data points at both ends

1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

Directionality Flipping



Gives us cos(θ) = 1



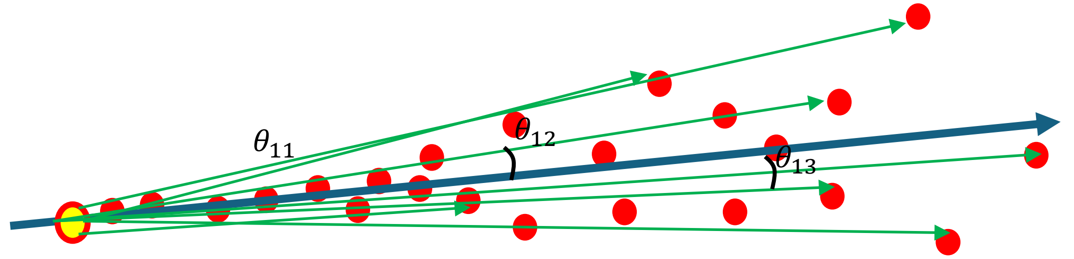
Gives us cos(θ) = -1

Pick data points at both ends

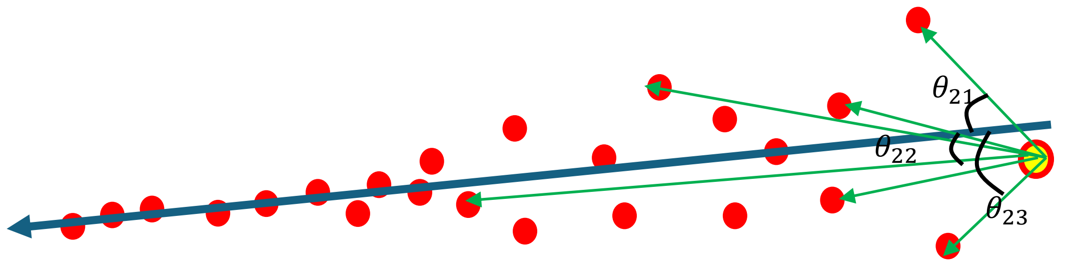
Draw line from two ends to every single data point

1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

Directionality Flipping



Gives us cos(θ) = 1



Gives us cos(θ) = -1

Pick data points at both ends

Draw line from two ends to every single data point

Calculate the cosine of angle between the lines and computed axis, and sum them

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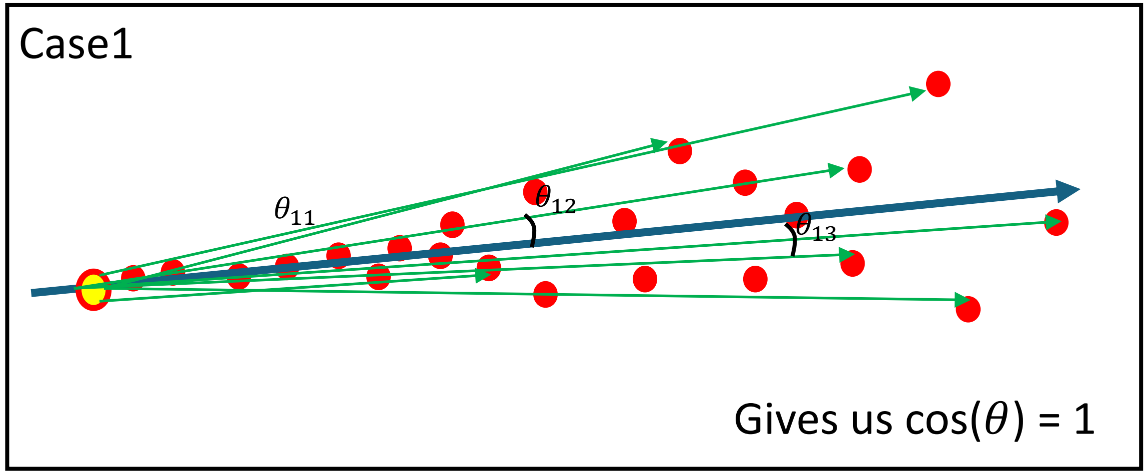
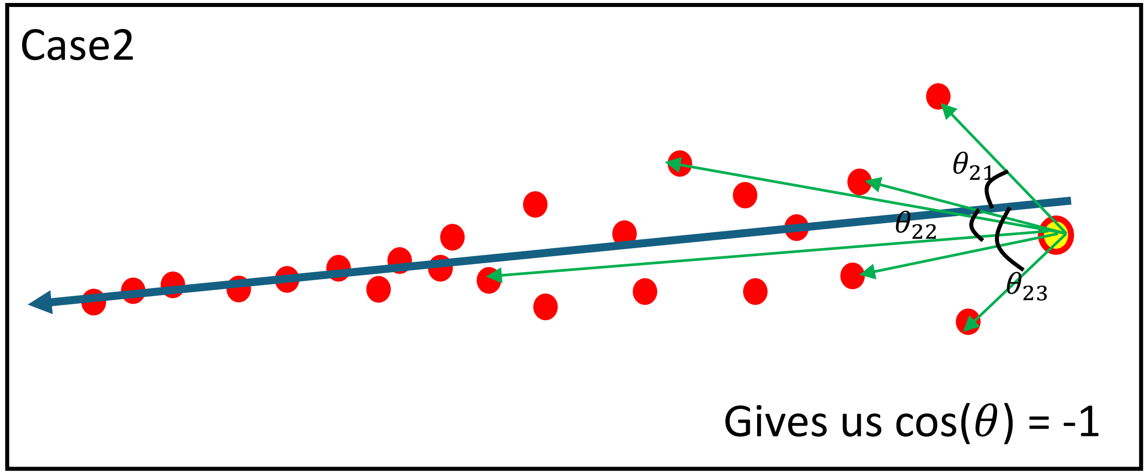
1.
   a)
   b)
   c)
2.
   a)
   b)
3.
   a)
   b)
   c)

Directionality Flipping





Pick data points at both ends

Draw line from two ends to every single data point

Calculate the cosine of angle between the lines and computed axis, and sum them

θ values are smaller $\rightarrow$ cos(θ) values are bigger

sum_cos_case1 = $\cos(\theta_{11}) + \cos(\theta_{12}) + \cos(\theta_{13}) \cdot\cdot\cdot$

θ values are bigger $\rightarrow$ cos(θ) values are smaller

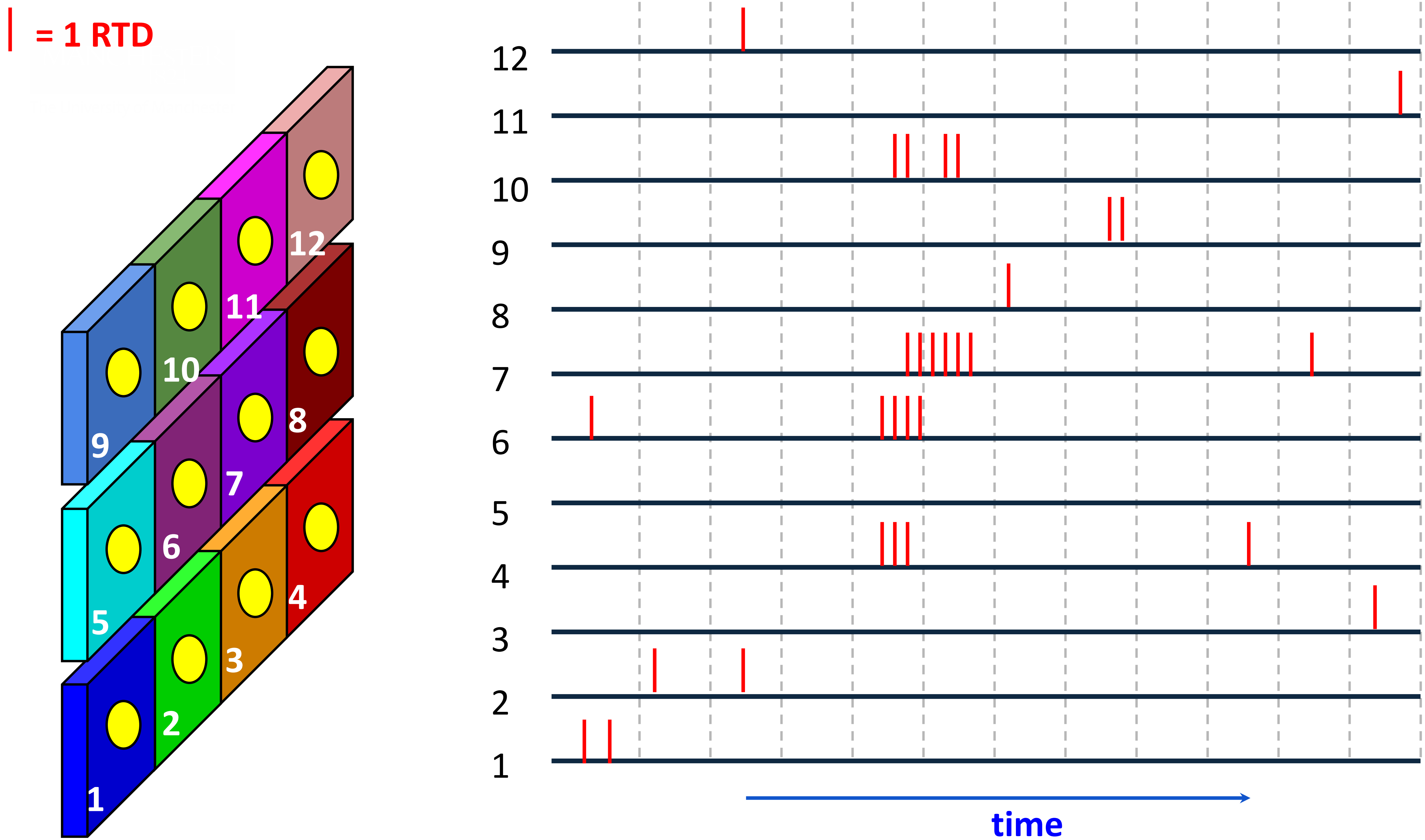
sum_cos_case2 = $\cos(\theta_{21}) + \cos(\theta_{22}) + \cos(\theta_{23}) \cdot\cdot\cdot$

sum_cos_case1 > sum_cos_case2

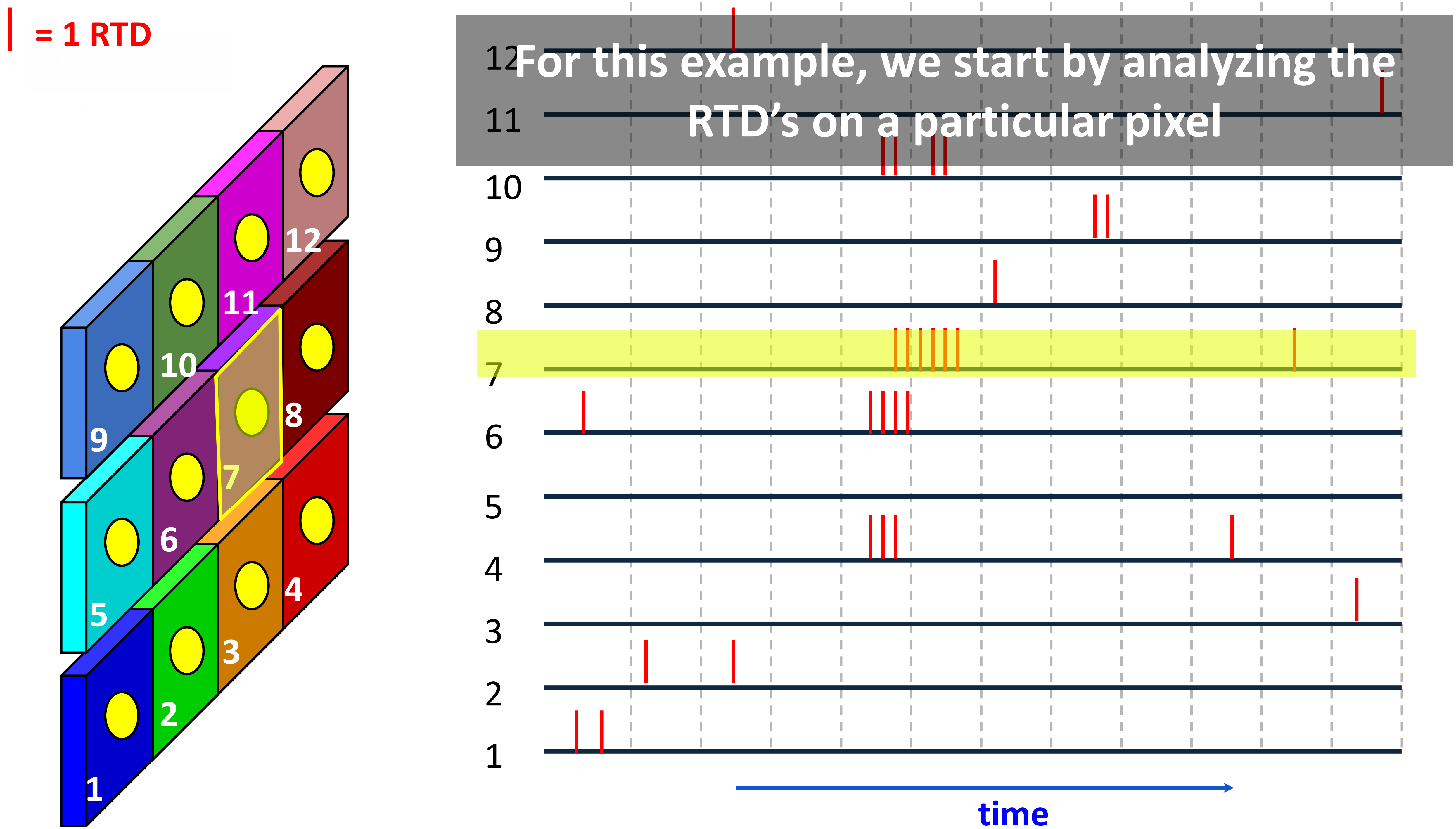
1.
 a)
 b)
 c)
2.
 a)
 b)
3.
 a)
 b)
 c)

Clustering

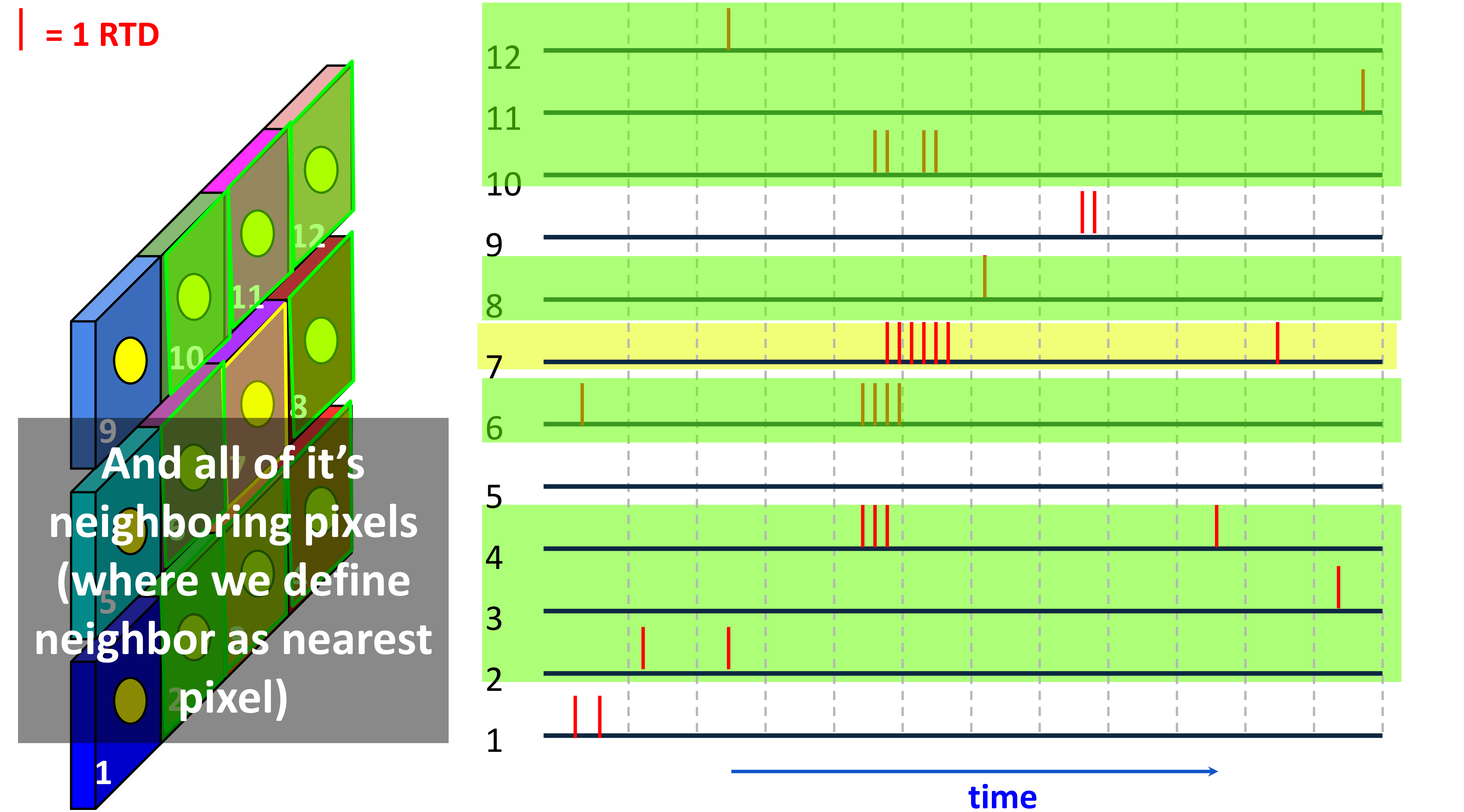
1.
    a)
    b)
    c)
2.
    a)
    b)
3.
    a)
    b)
    c)



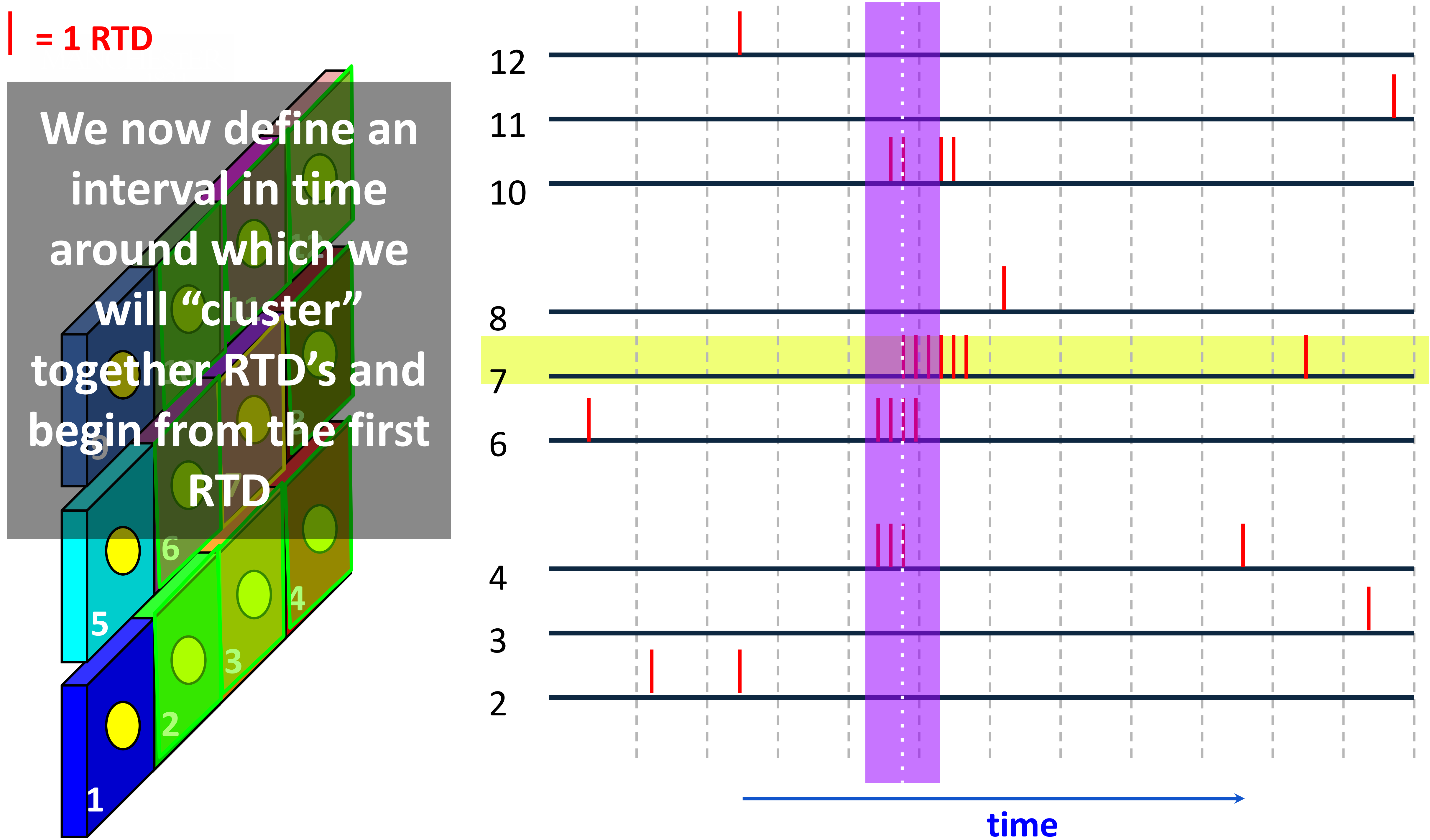
= 1 RTD
12
11
10
9
8
7
6
5
4
3
2
1
time



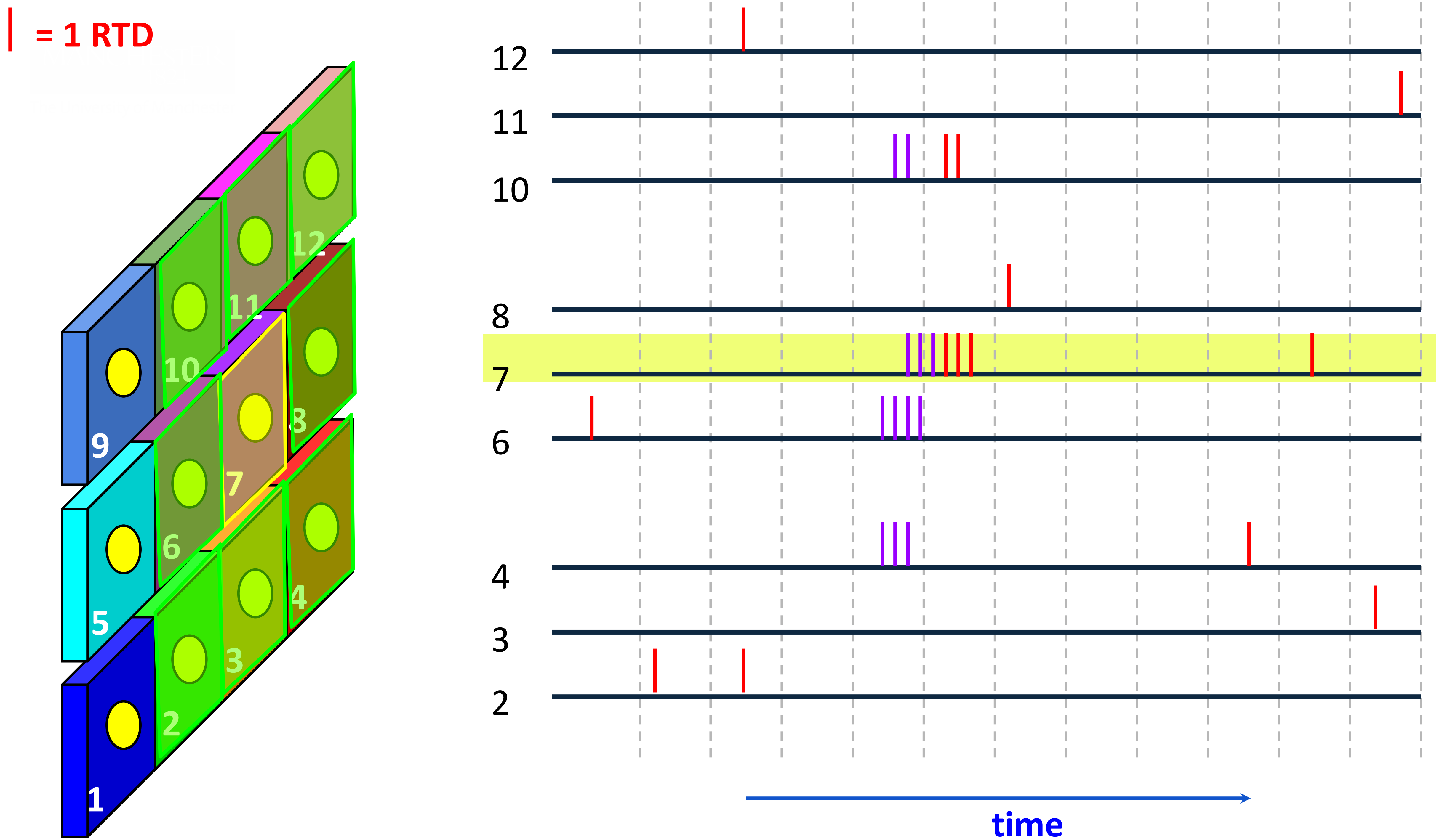
= 1 RTD
For this example, we start by analyzing the RTD's on a particular pixel
12
11
10
9
8
7
6
5
4
3
2
1
time

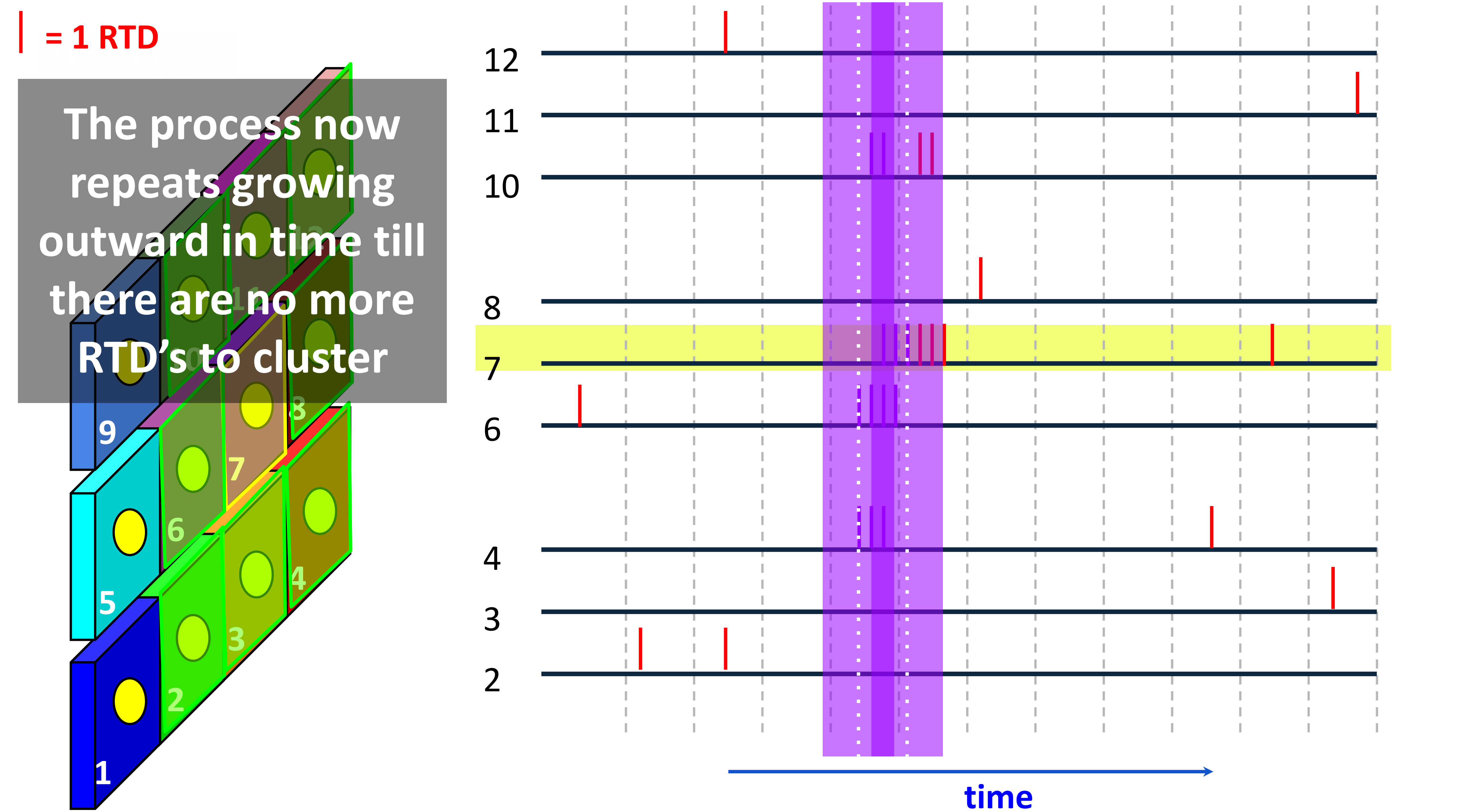


= 1 RTD
And all of it's neighboring pixels (where we define neighbor as nearest pixel)
12
11
10
9
8
7
6
5
4
3
2
1
time



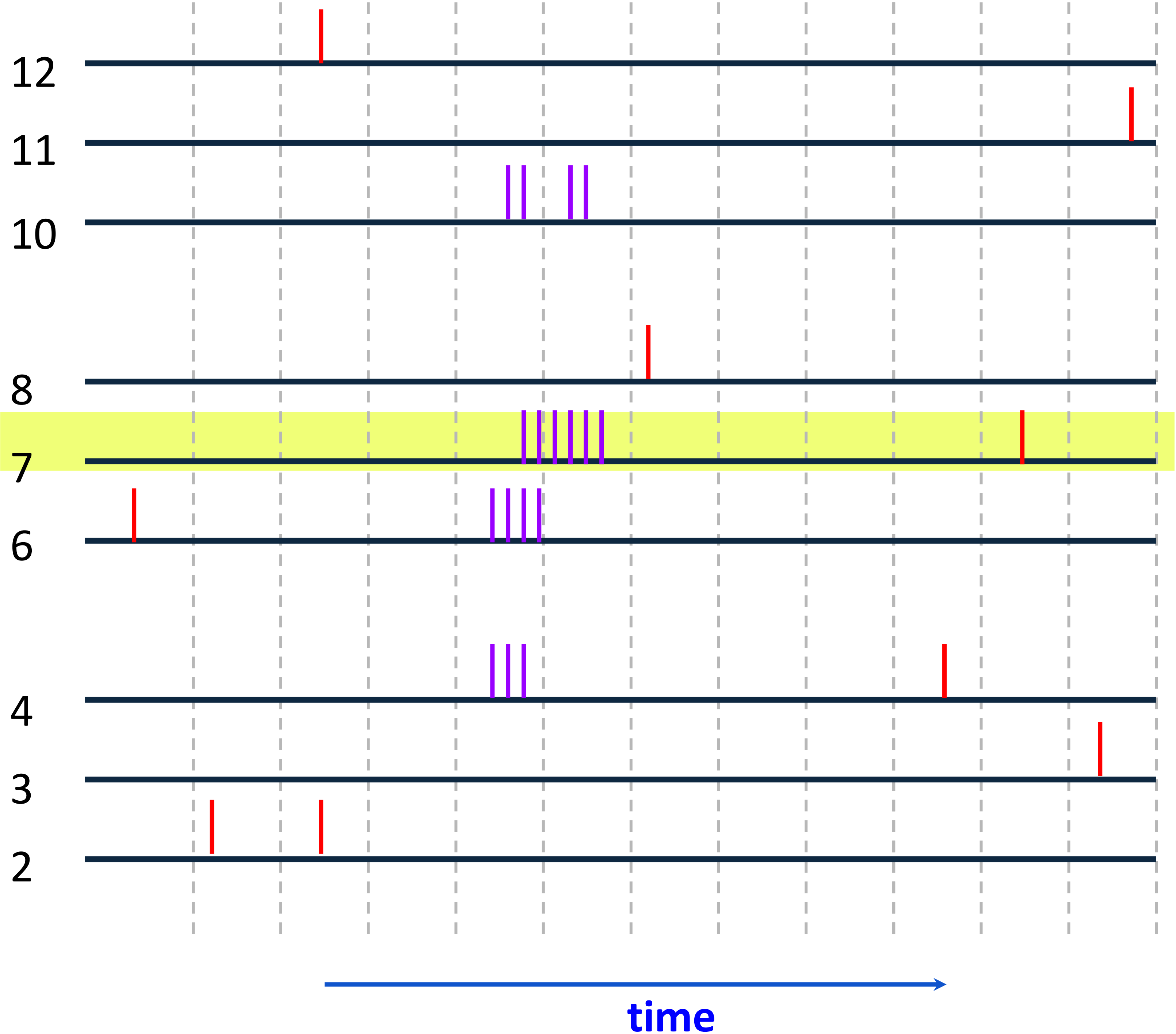
= 1 RTD
We now define an interval in time around which we will "cluster" together RTD's and begin from the first RTD
1
2
3
4
5
6
12
11
10
8
7
6
4
3
2
time

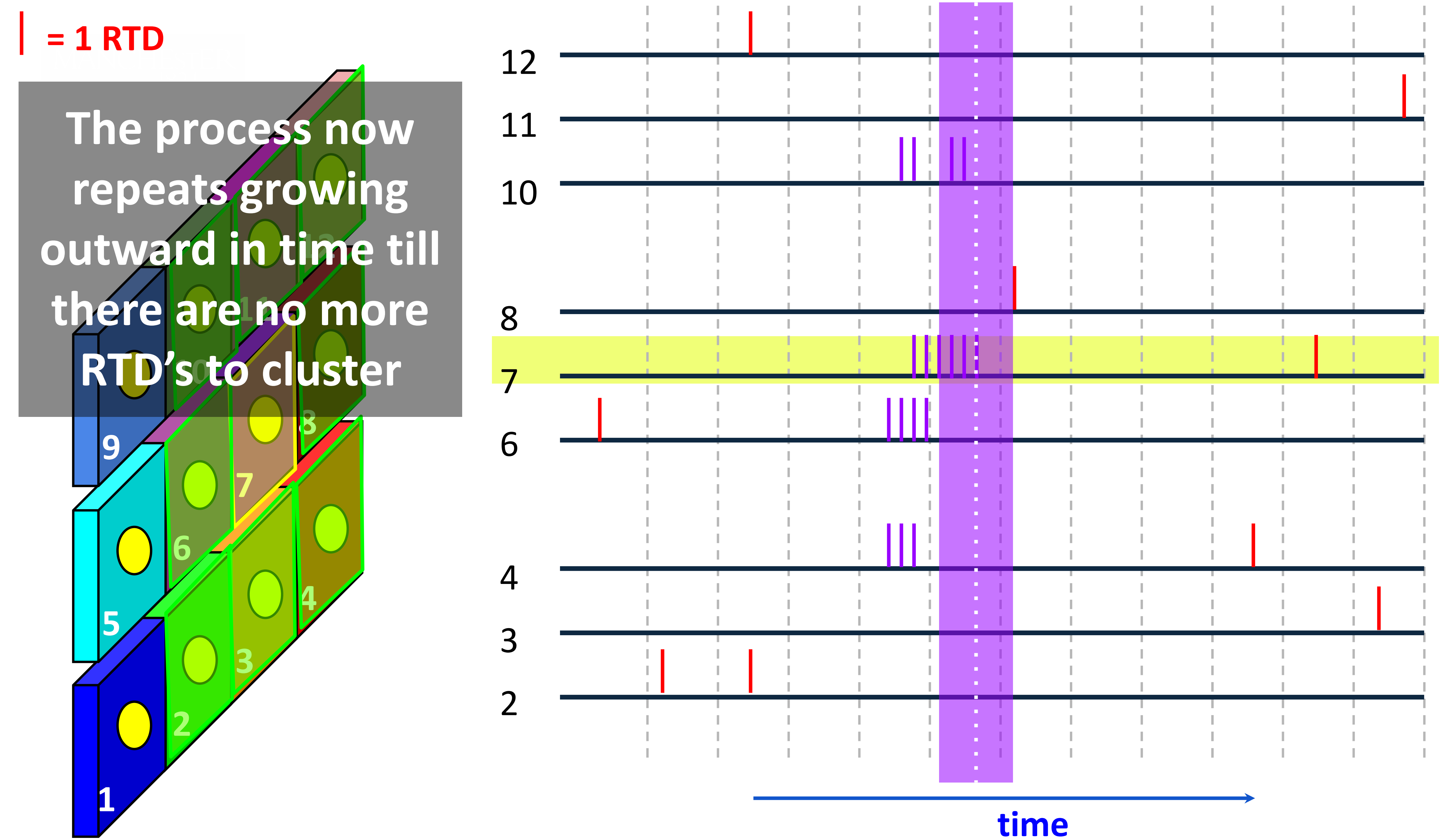

= 1 RTD
9
10
11
12
5
6
7
8
1
2
3
4
12
11
10
8
7
6
4
3
2
time


= 1 RTD
The process now repeats growing outward in time till there are no more RTD's to cluster
12
11
10
8
7
6
4
3
2
9
5
1
time

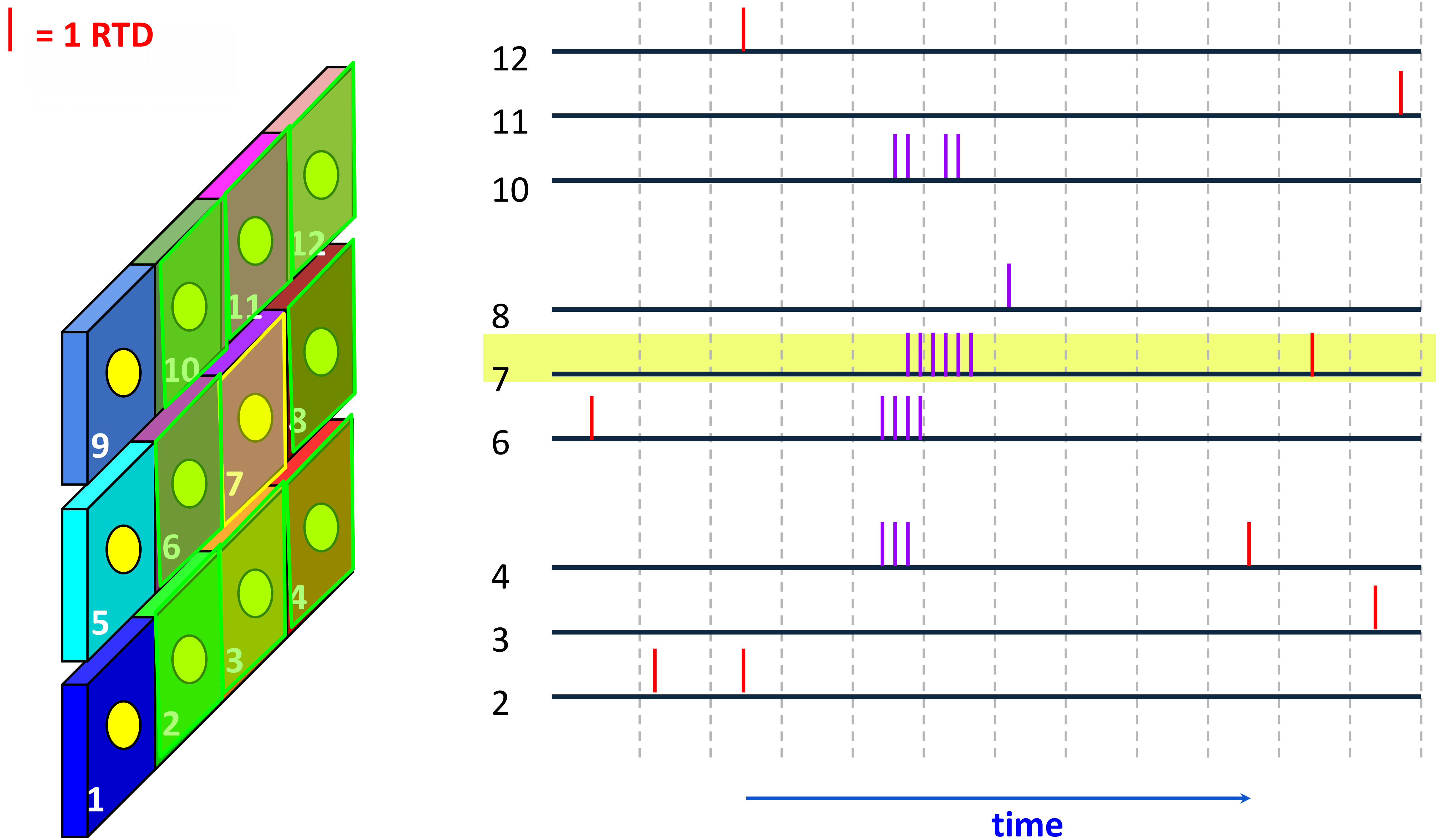
| = 1 RTD

The process now repeats growing outward in time till there are no more RTD's to cluster

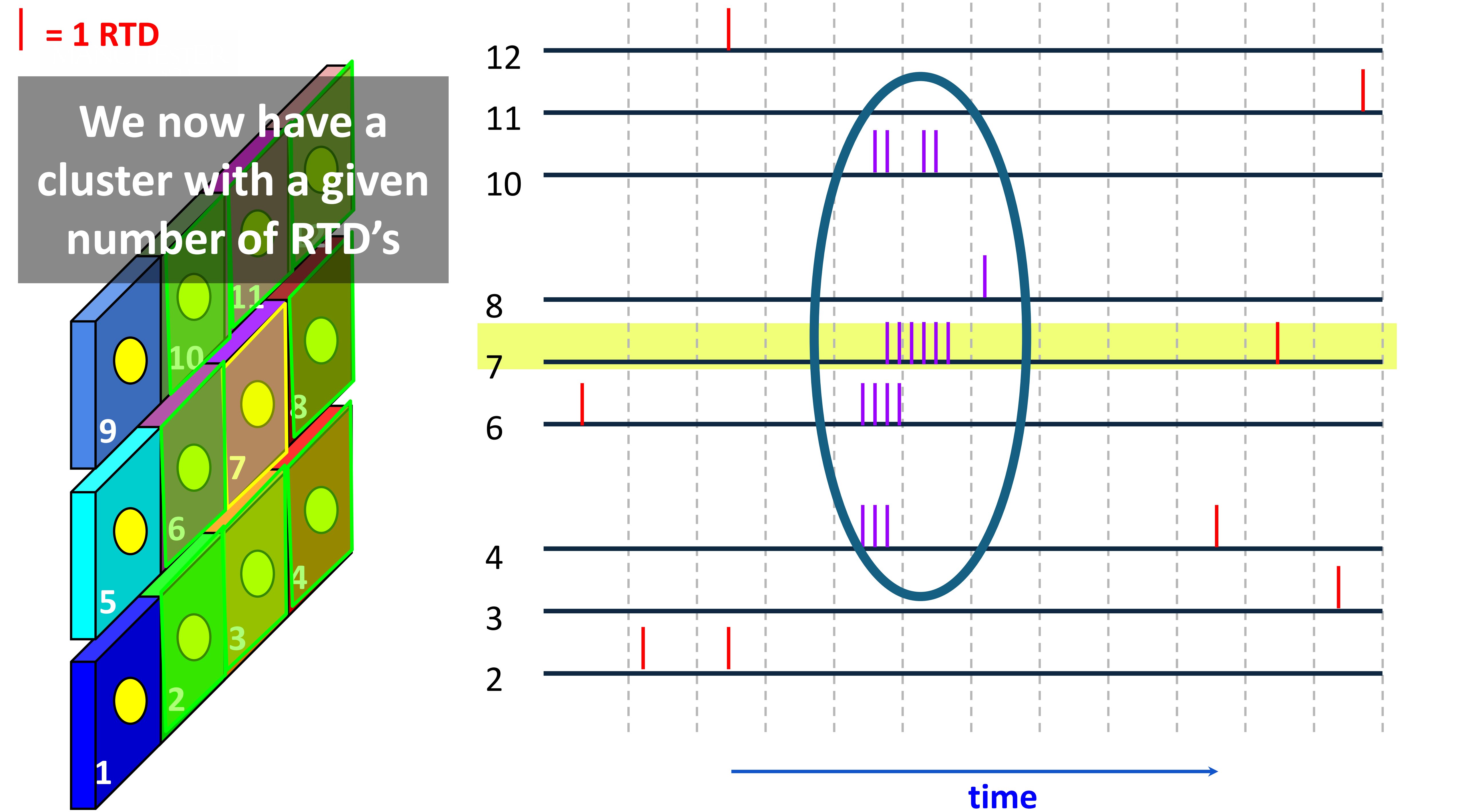


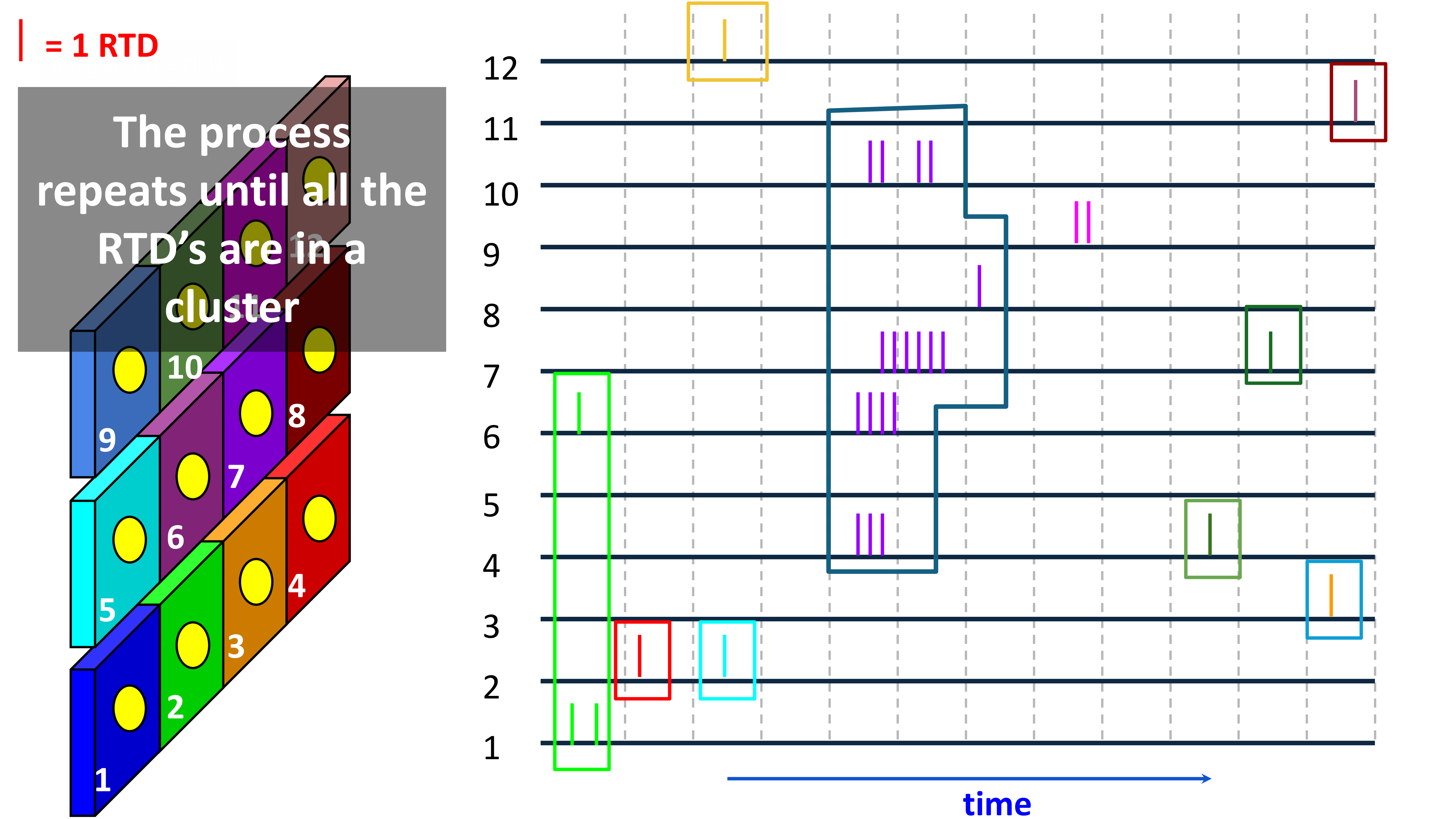


= 1 RTD
The process now repeats growing outward in time till there are no more RTD's to cluster
12
11
10
8
7
6
4
3
2
9
5
1
6
7
8
2
3
4
time



= 1 RTD
9
10
11
12
5
6
7
8
1
2
3
4
12
11
10
8
7
6
4
3
2
time


= 1 RTD
We now have a cluster with a given number of RTD's
1
2
3
4
5
6
7
8
9
10
11
12
11
10
8
7
6
4
3
2
time


= 1 RTD
The process repeats until all the RTD's are in a cluster
1
2
3
4
5
6
7
8
9
10
11
12
time