QUAC-TRNG

High-Throughput True Random Number Generation Using Quadruple Row Activation in Real DRAM Chips

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Executive Summary

- **Motivation**: DRAM-based true random number generators (TRNGs) provide **true random numbers at low cost** on **a wide range** of computing systems
- **Problem**: Prior DRAM-based TRNGs are slow:
  1. Based on fundamentally slow processes → **high latency**
  2. Cannot effectively harness entropy from DRAM rows → **low throughput**
- **Goal**: **Develop** a **high-throughput** and **low-latency** TRNG that uses **commodity DRAM** devices
- **Key Observation**: Carefully engineered sequence of DRAM commands can activate **four DRAM rows** → **QU**adruple **AC**tivation **(QUAC)**
- **Key Idea**: **Use QUAC** to activate DRAM rows that are initialized with **conflicting data** (e.g., two '1's and two '0's) to generate random values
- **QUAC-TRNG:** DRAM-based TRNG that generates true random numbers at **high-throughput** and **low-latency** by **repeatedly performing QUAC operations**
- **Results:** We evaluate QUAC-TRNG using **136** real DDR4 chips
  1. **5.4 Gb/s** maximum (**3.4 Gb/s** average) TRNG throughput per DRAM channel
  2. Outperforms existing DRAM-based TRNGs by **15.08x** (base), and **1.41x** (enhanced)
  3. Low TRNG latency: **256-bit RN** in **274 ns**
  4. Passes **all 15** NIST randomness tests

Outline

True Random Number Generation

DRAM Background

QUadruple ACtivation (QUAC)

QUAC-TRNG

Evaluation

Random Numbers

Sequence of bits without any discernible pattern

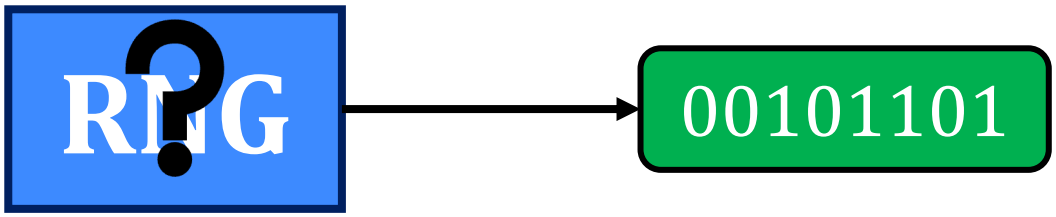
Random Number Candidates

00001111	**Pattern exists**
01010101	**Pattern exists**
00101101	**Pattern does not seem to exist**

Producing Random Numbers

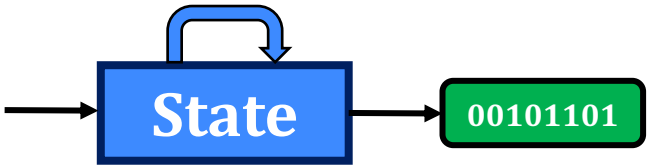
Random Number Generator (RNG)

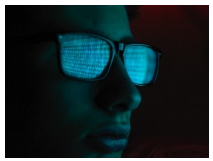
A device/program that generates random numbers



Pseudo-Random Number Generator (PRNG)

Arithmetic Transform





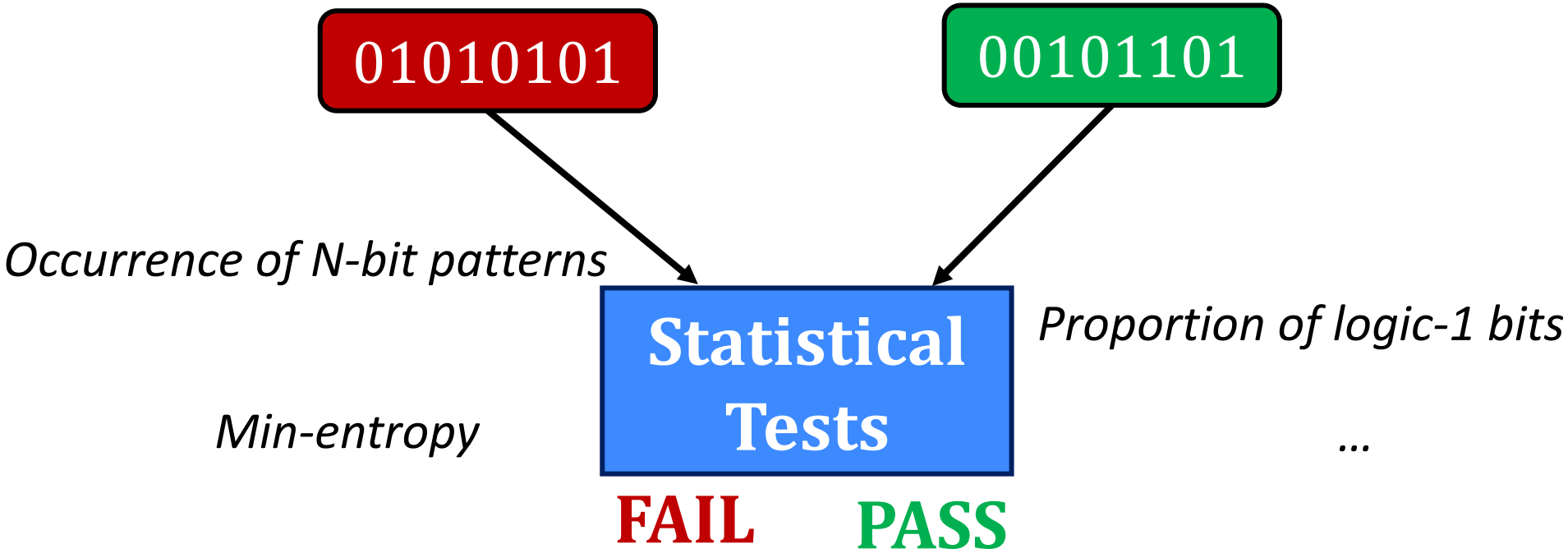
If seed is compromised
random number sequence can be regenerated

True Random Number Generator (TRNG)

TRNG output cannot be regenerated
from the physical process

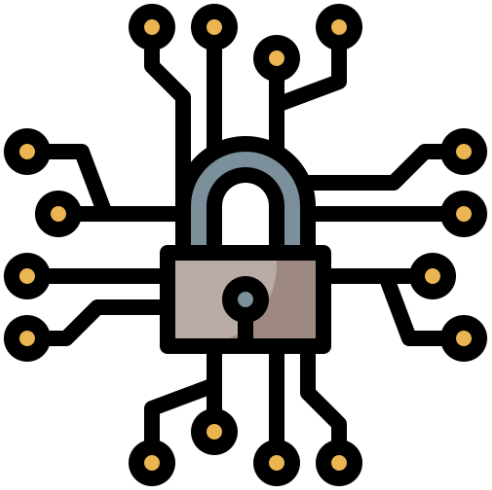
Assesing the Quality of a TRNG

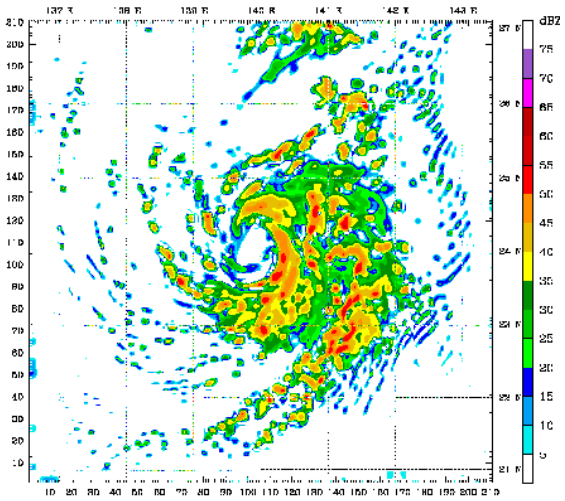
Systematically distinguish between
a low-quality and a high-quality TRNG

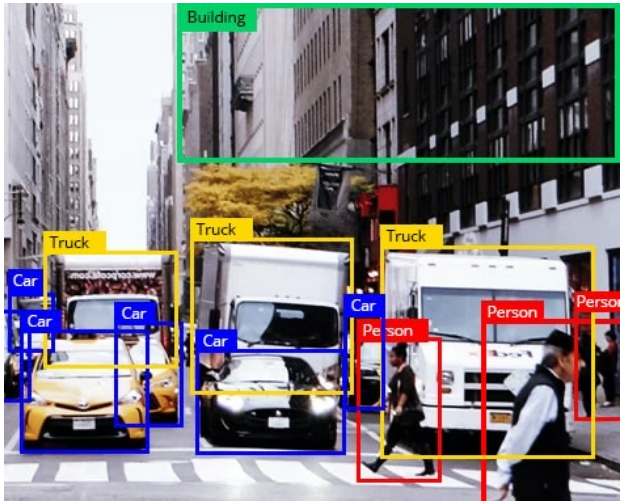


Use Cases of True Random Numbers

High-quality true random numbers are critical to many applications







- Cryptographic Key Generation
- Signature Generation
- Monte Carlo Simulations
- Randomized Training
- Genetic Algorithms

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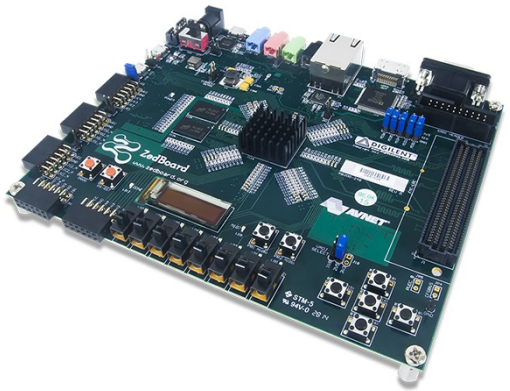
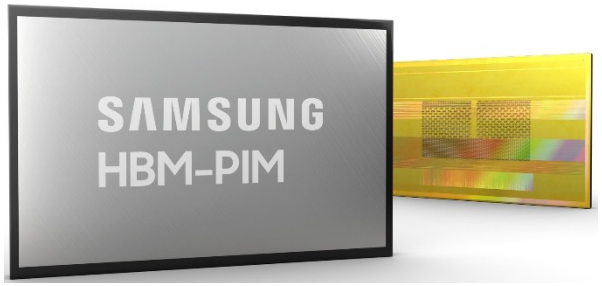
Generating True Random Numbers

True random numbers can only be obtained by sampling random physical processes

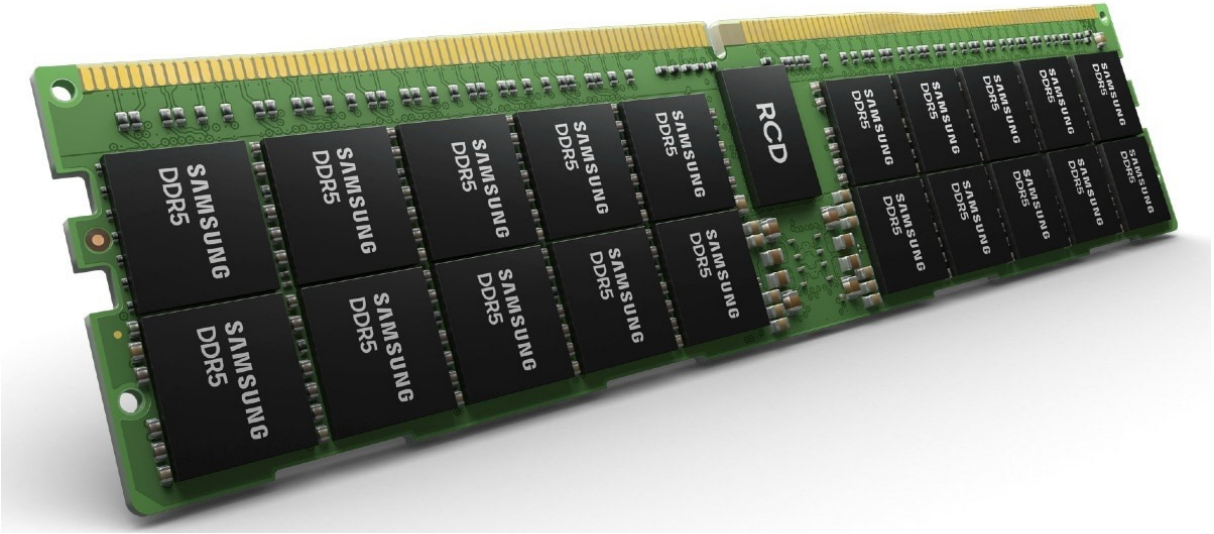
Unfortunately, not all computing systems are equipped with TRNG hardware (e.g., dedicated circuitry)





DRAM-Based TRNGs

DRAM chips are ubiquitous in modern computing platforms

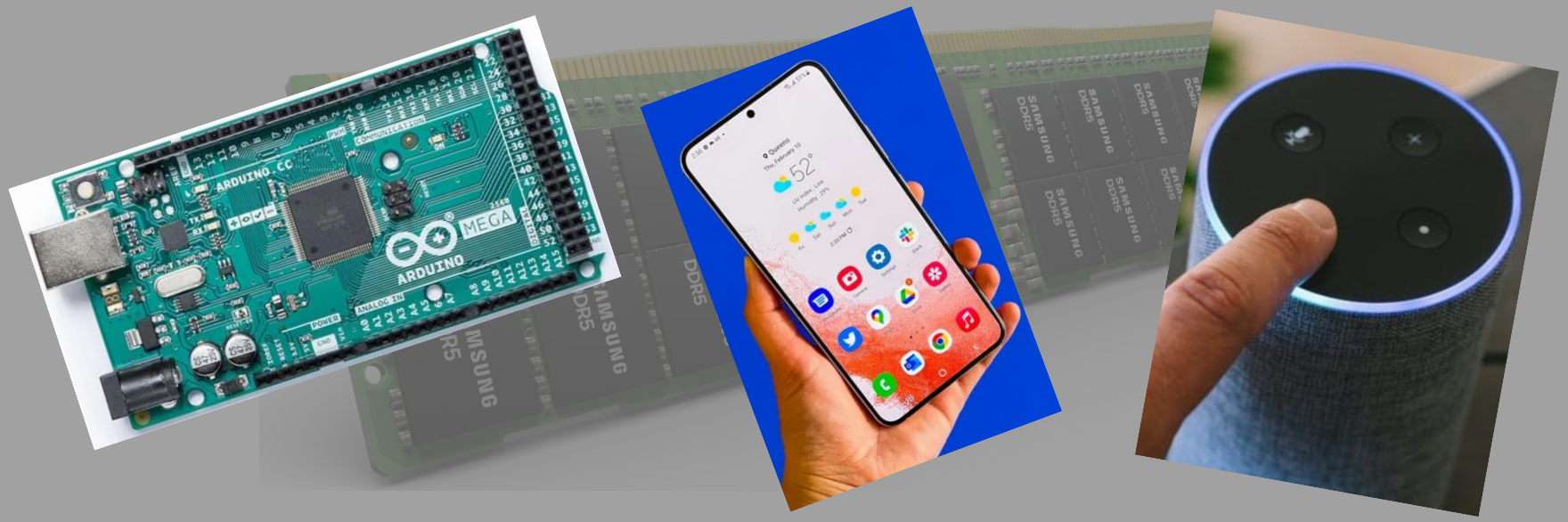


DRAM-based TRNGs enable true random number generation within DRAM chips

DRAM-Based TRNGs

Low-cost: No specialized circuitry for RNG

Beneficial for constrained systems



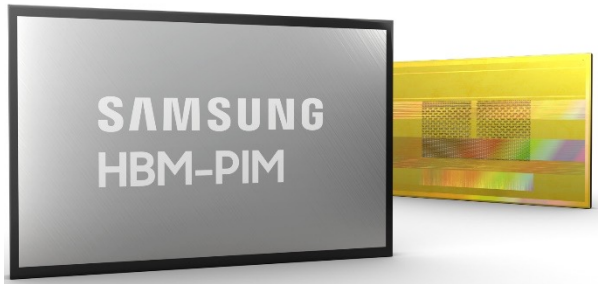
High-throughput: *> Gb/s throughput*

Enable applications that require high-throughput TRNG

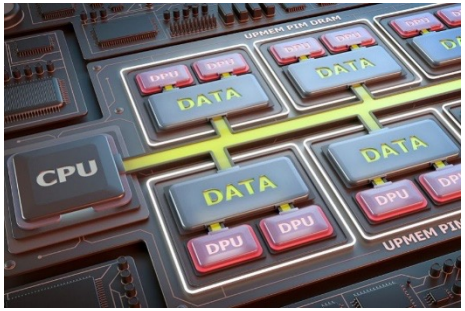
Synergy with Processing-in-Memory

Processing-in-Memory (PIM) Systems

- Perform computation directly within a memory chip
- Improve system performance by avoiding off-chip data movement



[Samsung]



[UPMEM]

True random number generation within DRAM

- Enables PIM workloads to sample true random numbers directly within the memory chip
- Avoids inefficient communication to other possible off-chip TRNG sources, enhances security & privacy

Outline

True Random Numbers in DRAM

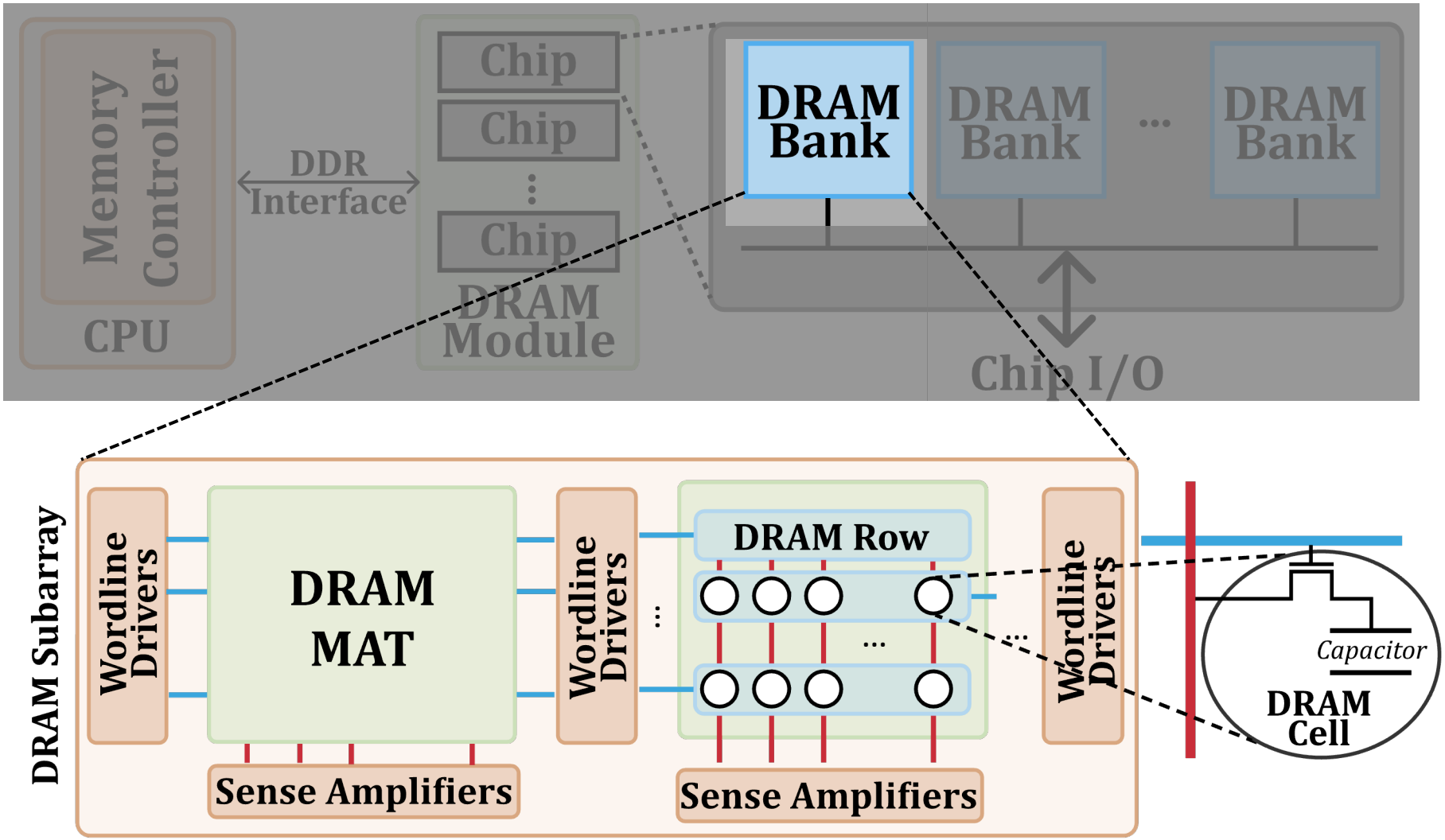
DRAM Background

QUadruple ACtivation (QUAC)

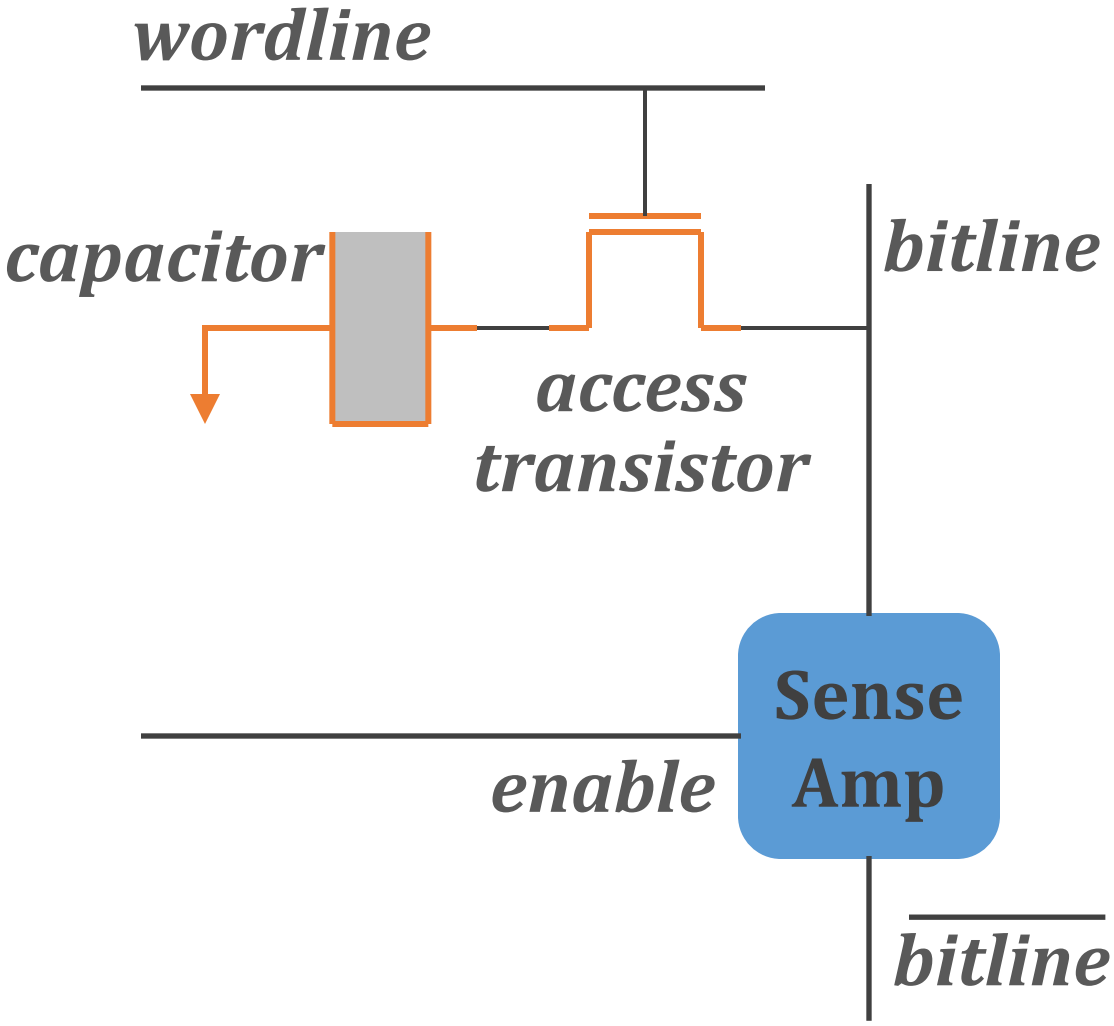
QUAC-TRNG

Evaluation

DRAM Organization



Accessing a DRAM Cell



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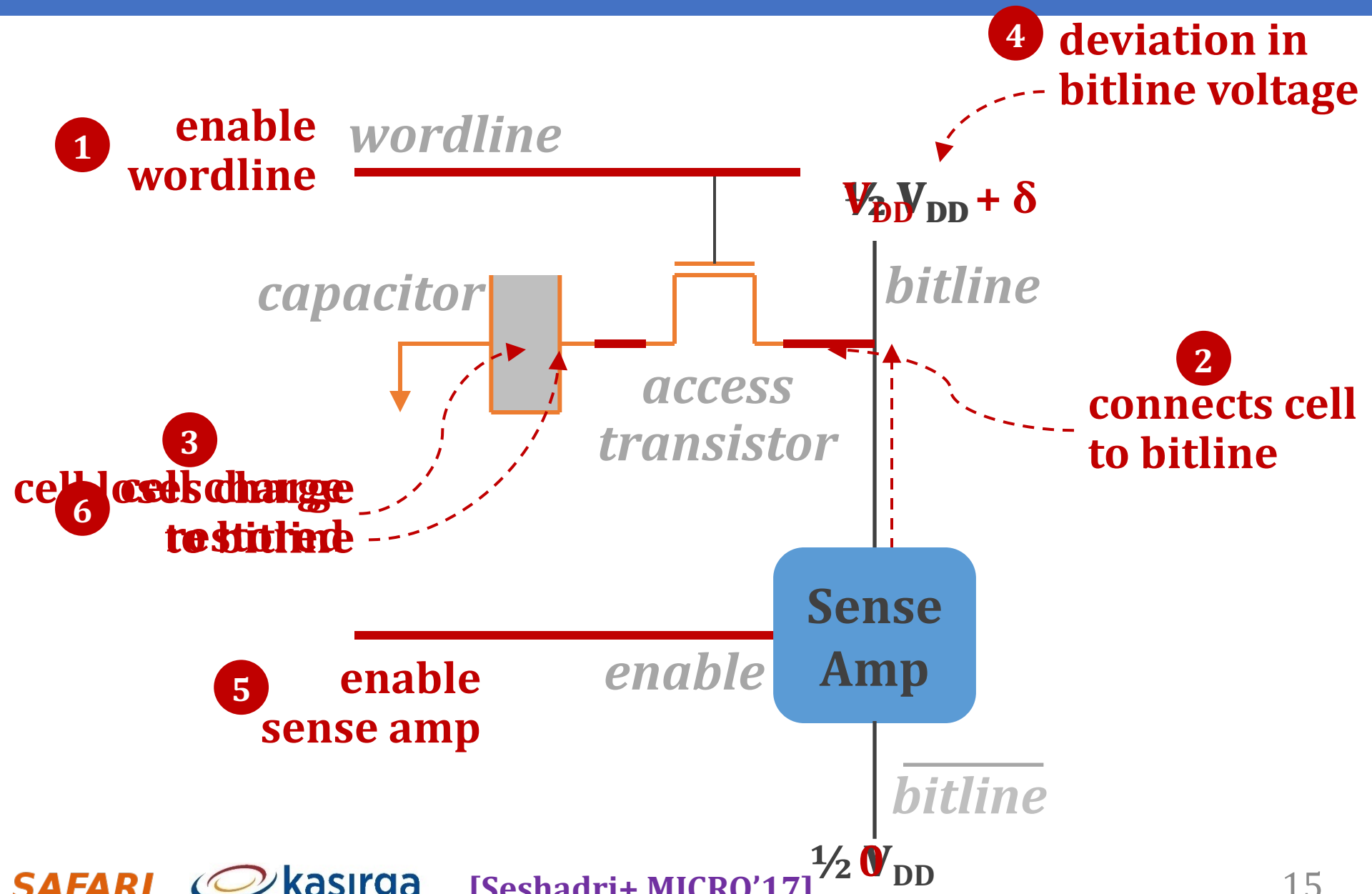
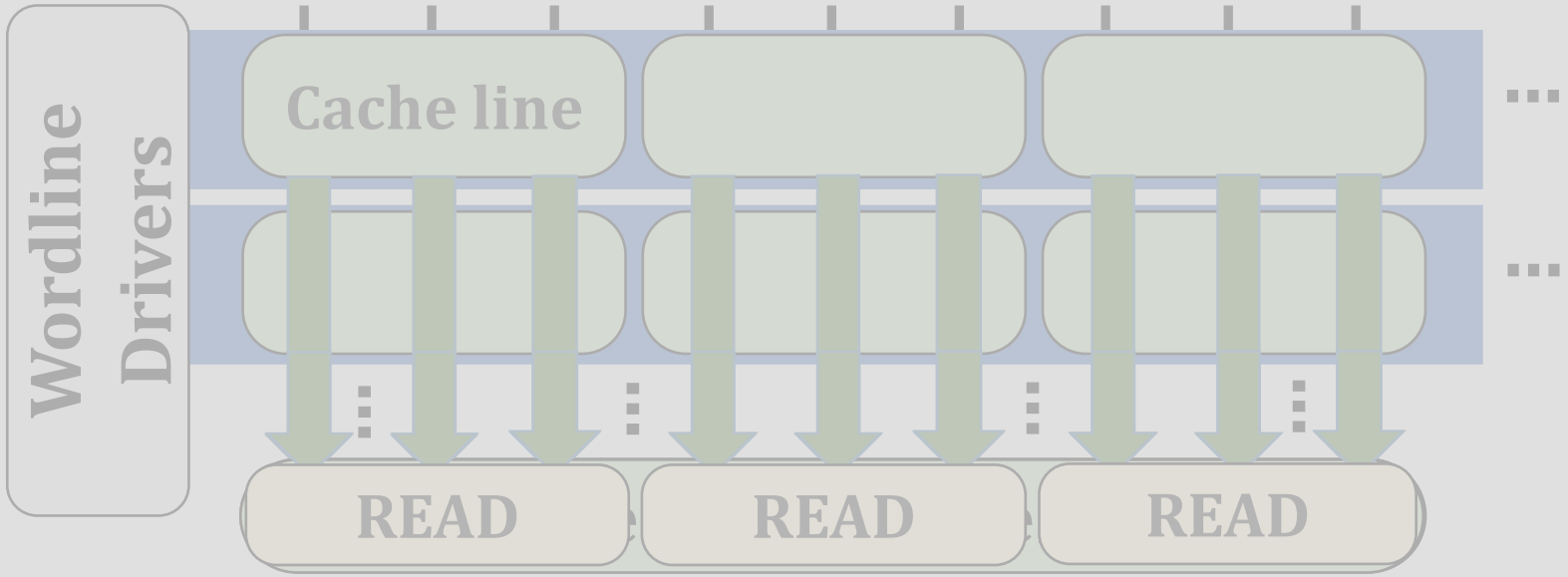
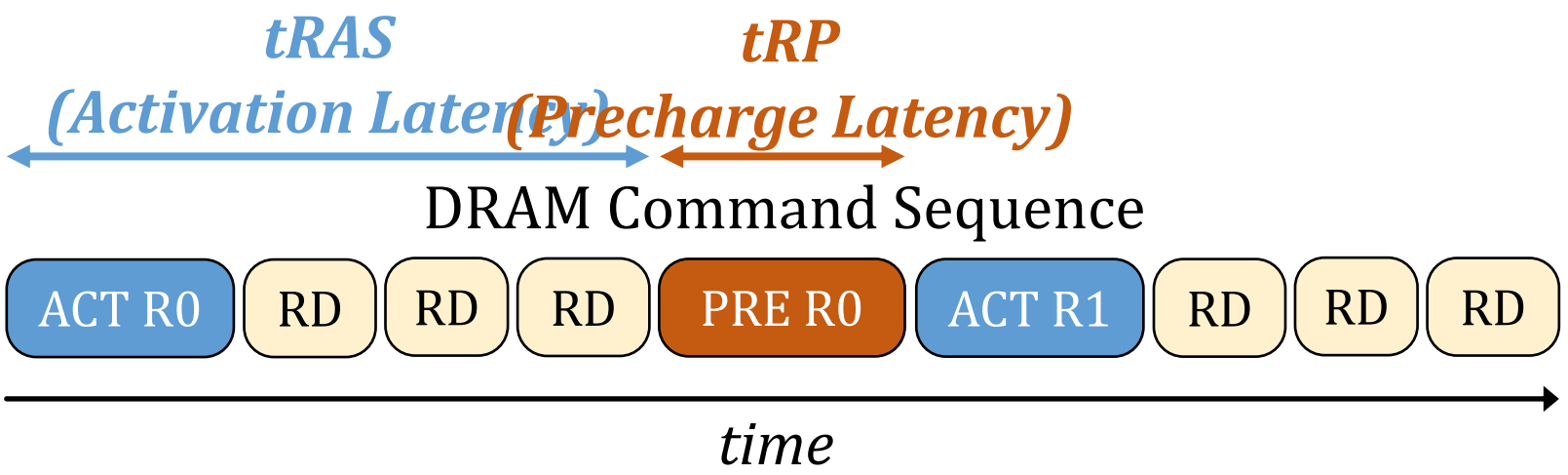


DRAM Operation





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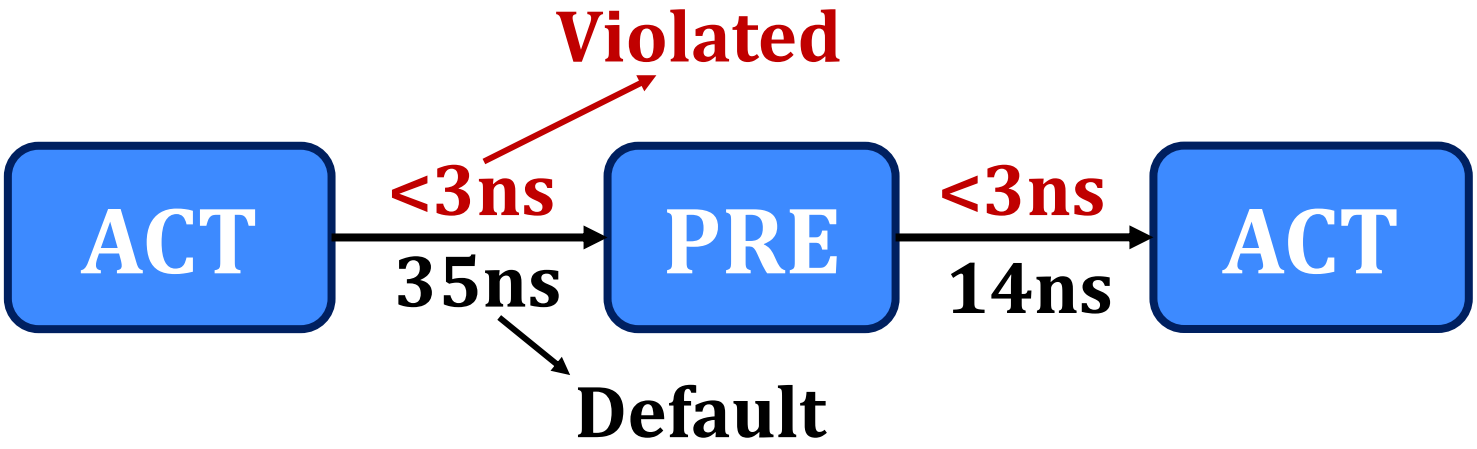
Quadruple Activation (QUAC)

New Observation

Carefully-engineered DRAM commands can activate four rows in real DRAM chips

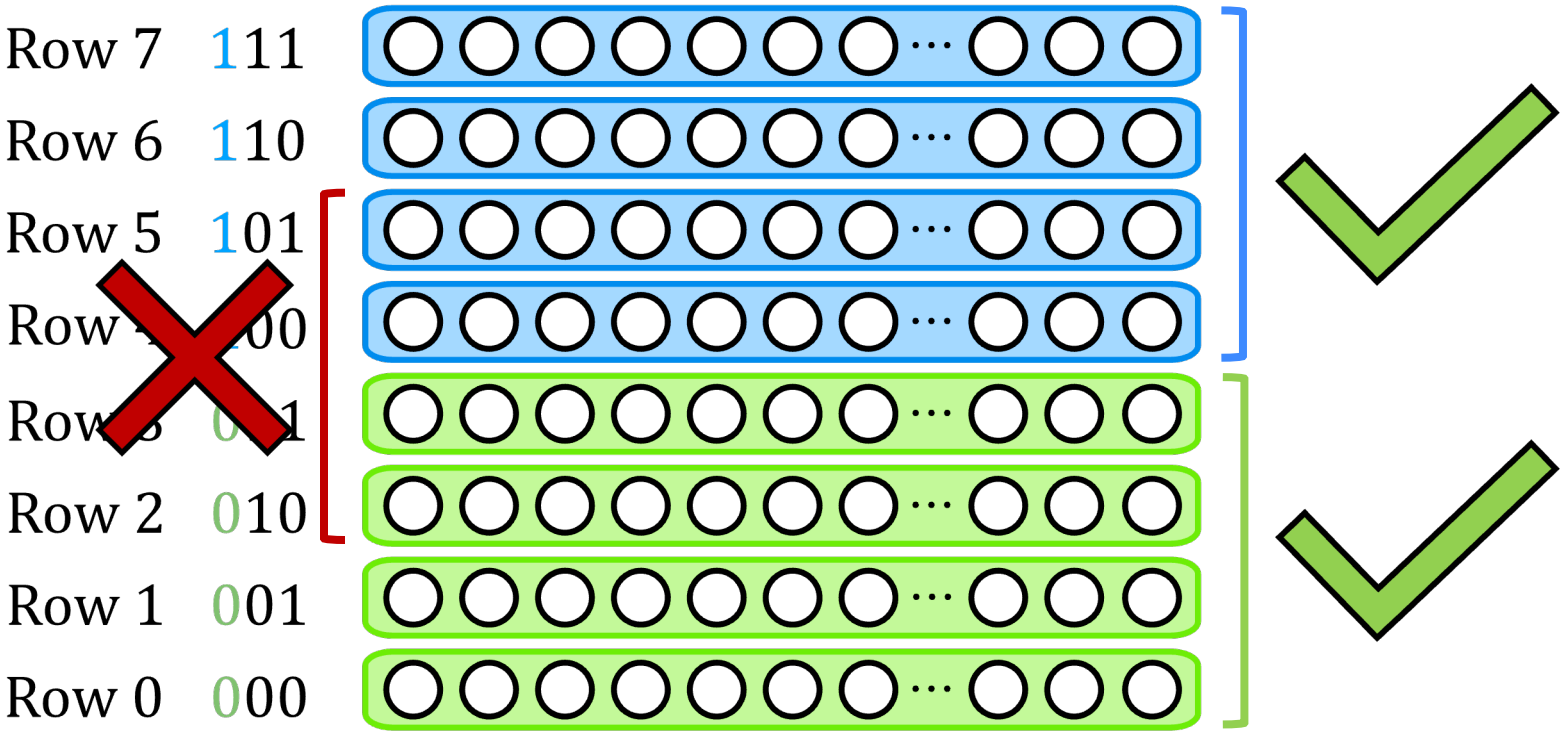


Activate four rows with two ACT commands

Quadruple Activation (QUAC)

Characteristic 1

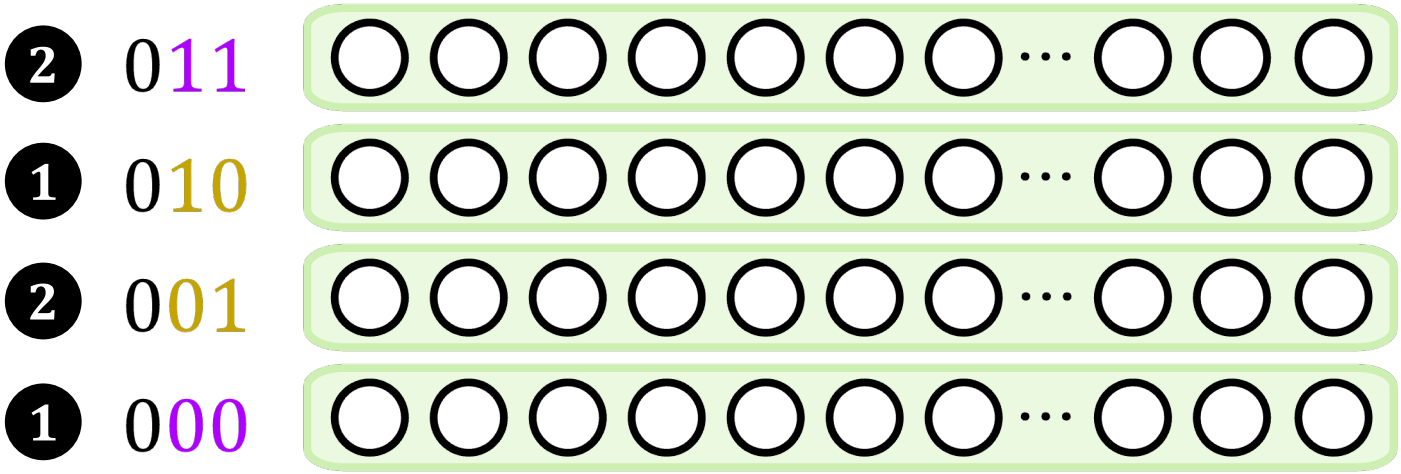
Activates a set of four DRAM rows whose addresses differ **only** in their two LSBs

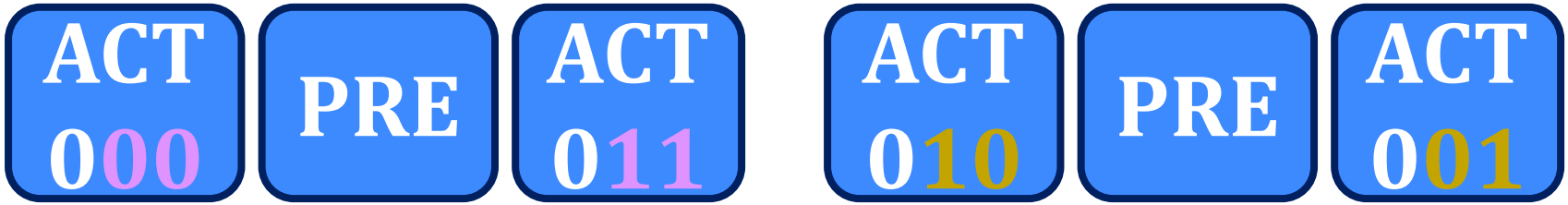


Quadruple Activation (QUAC)

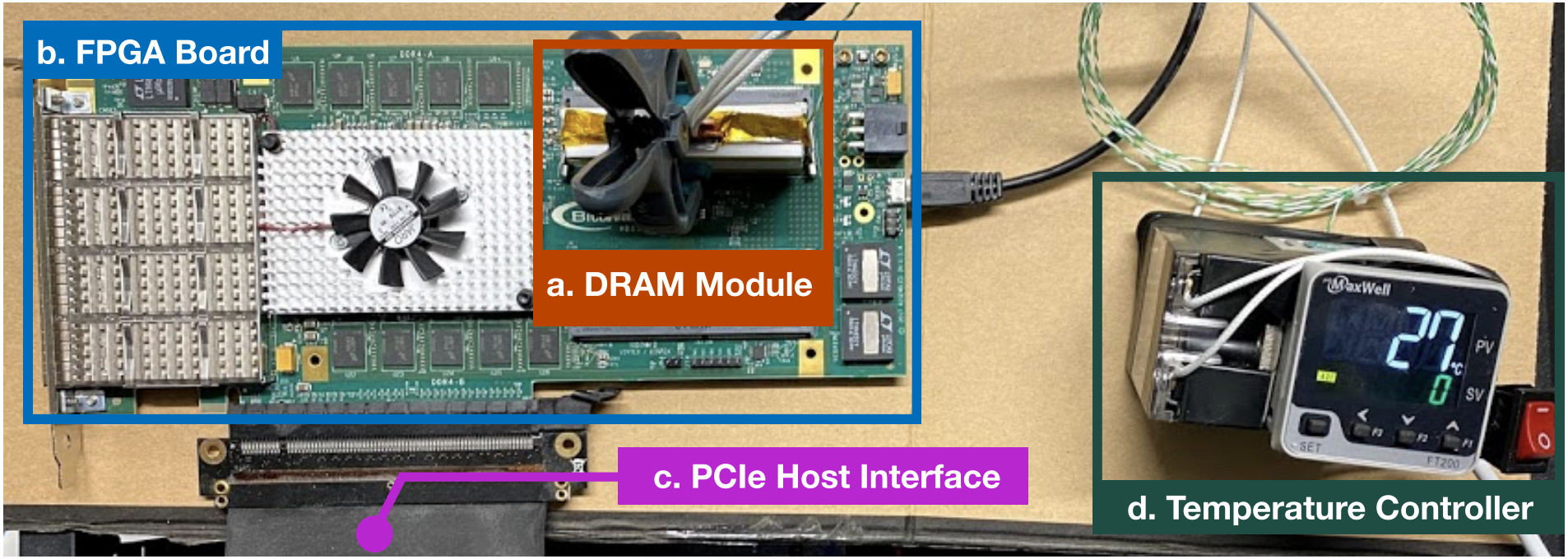
Characteristic 2

First and second ACT's addresses must have their two LSBs inverted





QUAC on Real DRAM Chips



Valid QUAC behavior on 136 DDR4 chips

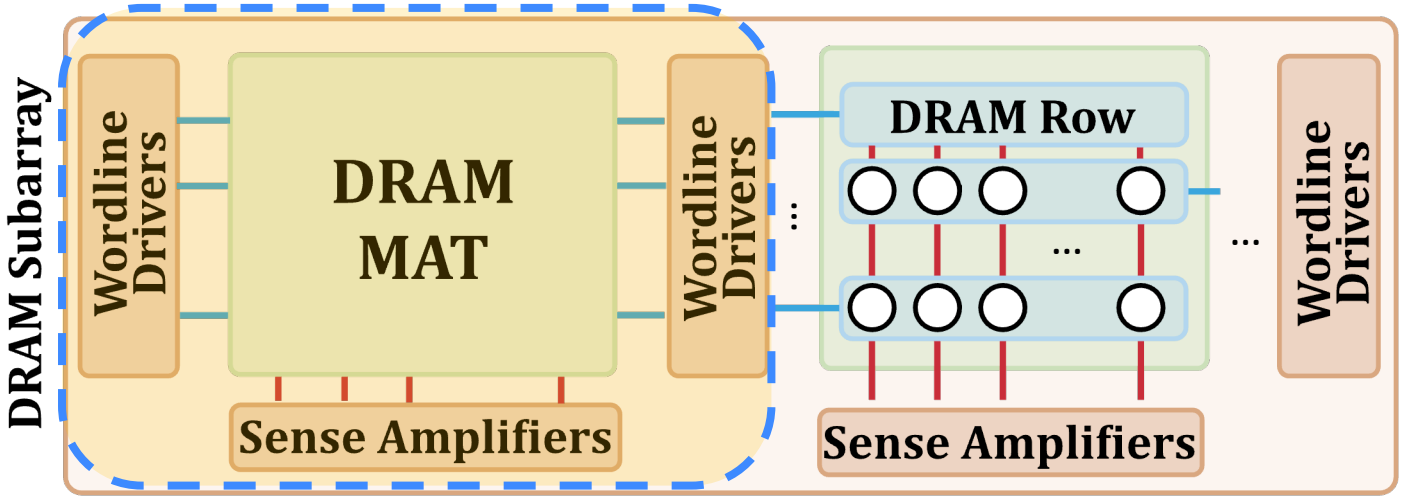
Why Does QUAC Work?

Hypothetical circuit to explain QUAC

- High *density* and *performance* requirements push for hierarchical organization
- Hierarchical organization of DRAM wordlines enable *high-density* and *low-latency* DRAM operation

Hierarchical Wordlines

A master wordline drives multiple local wordlines



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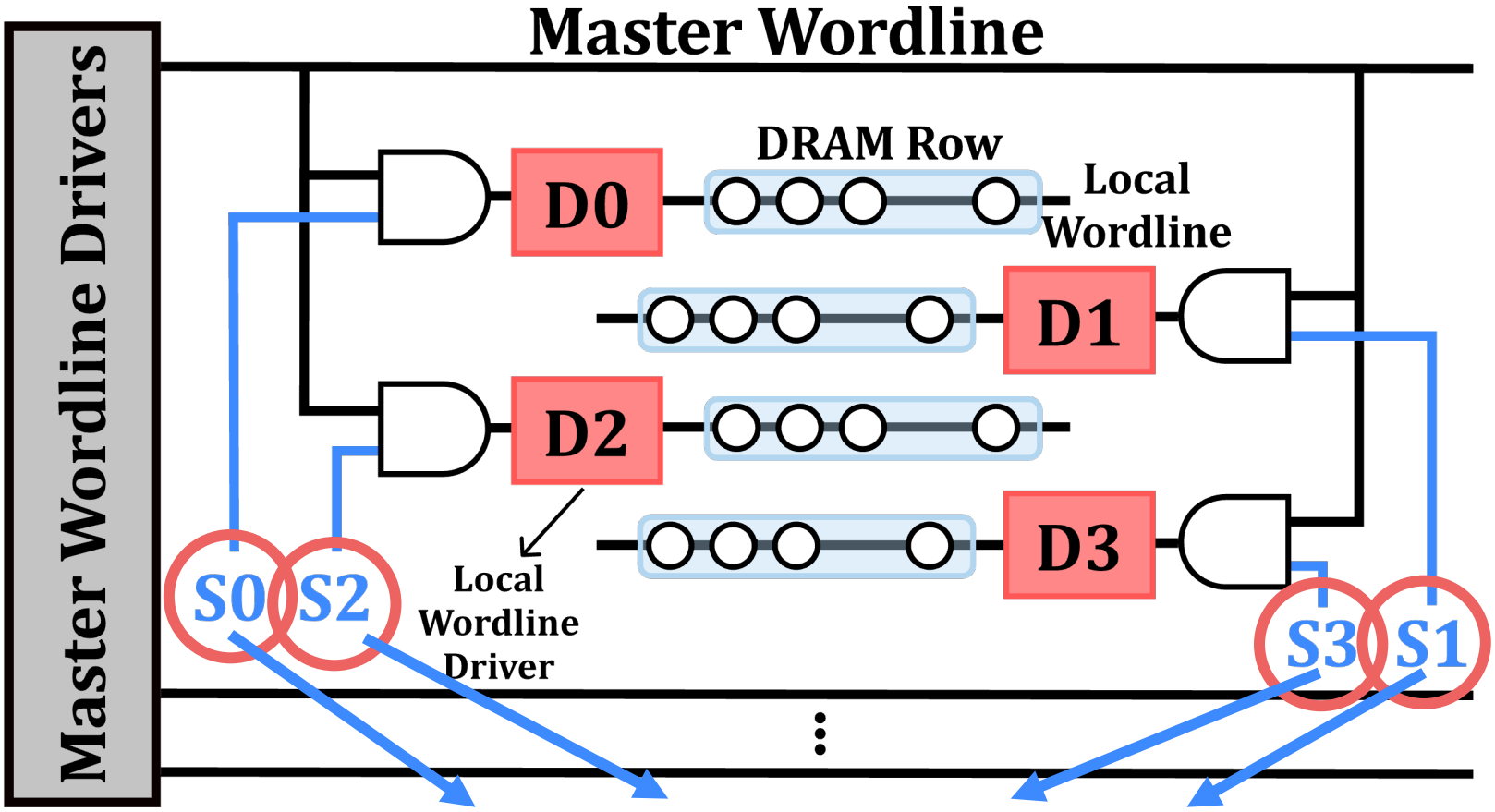
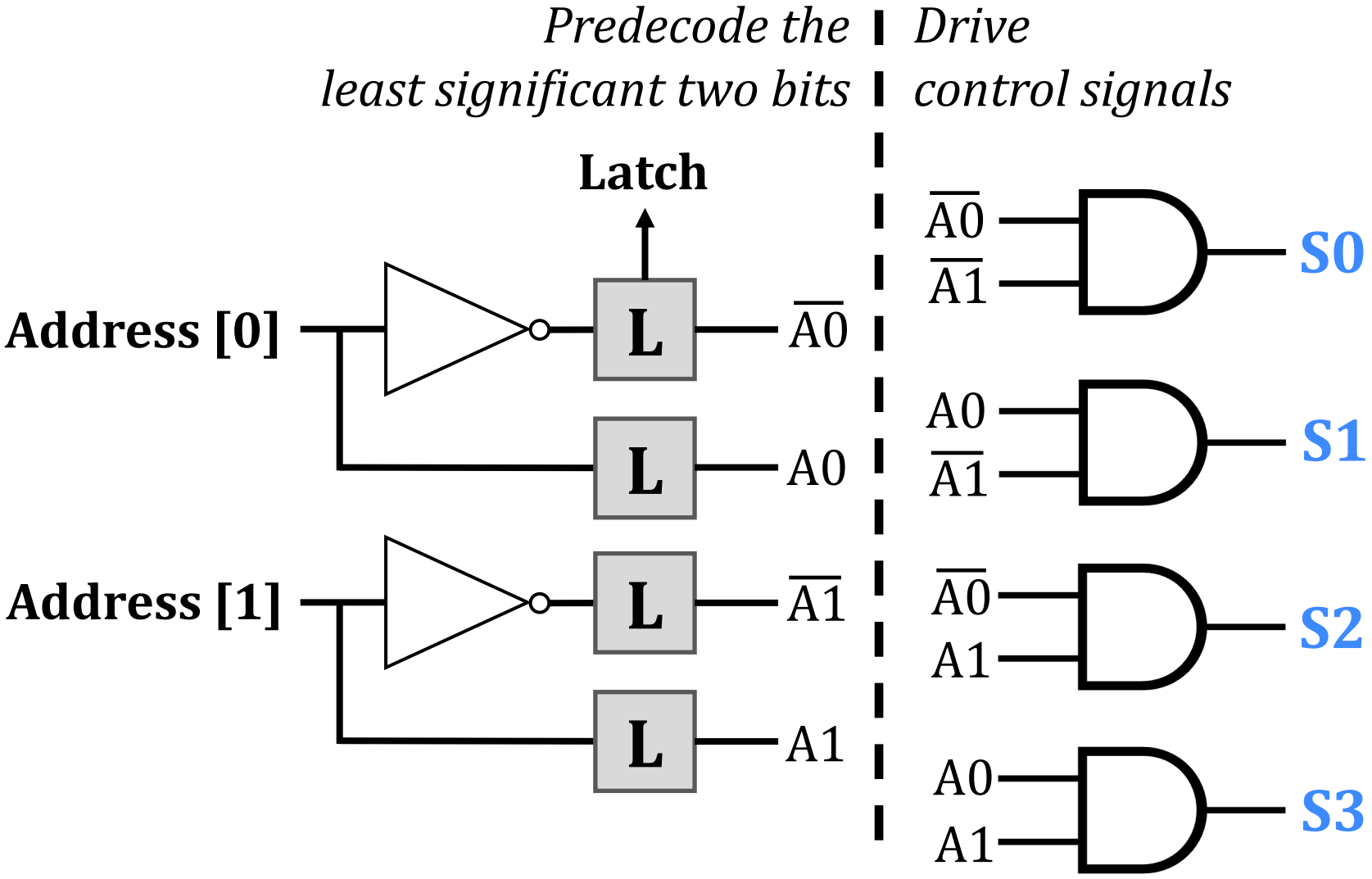
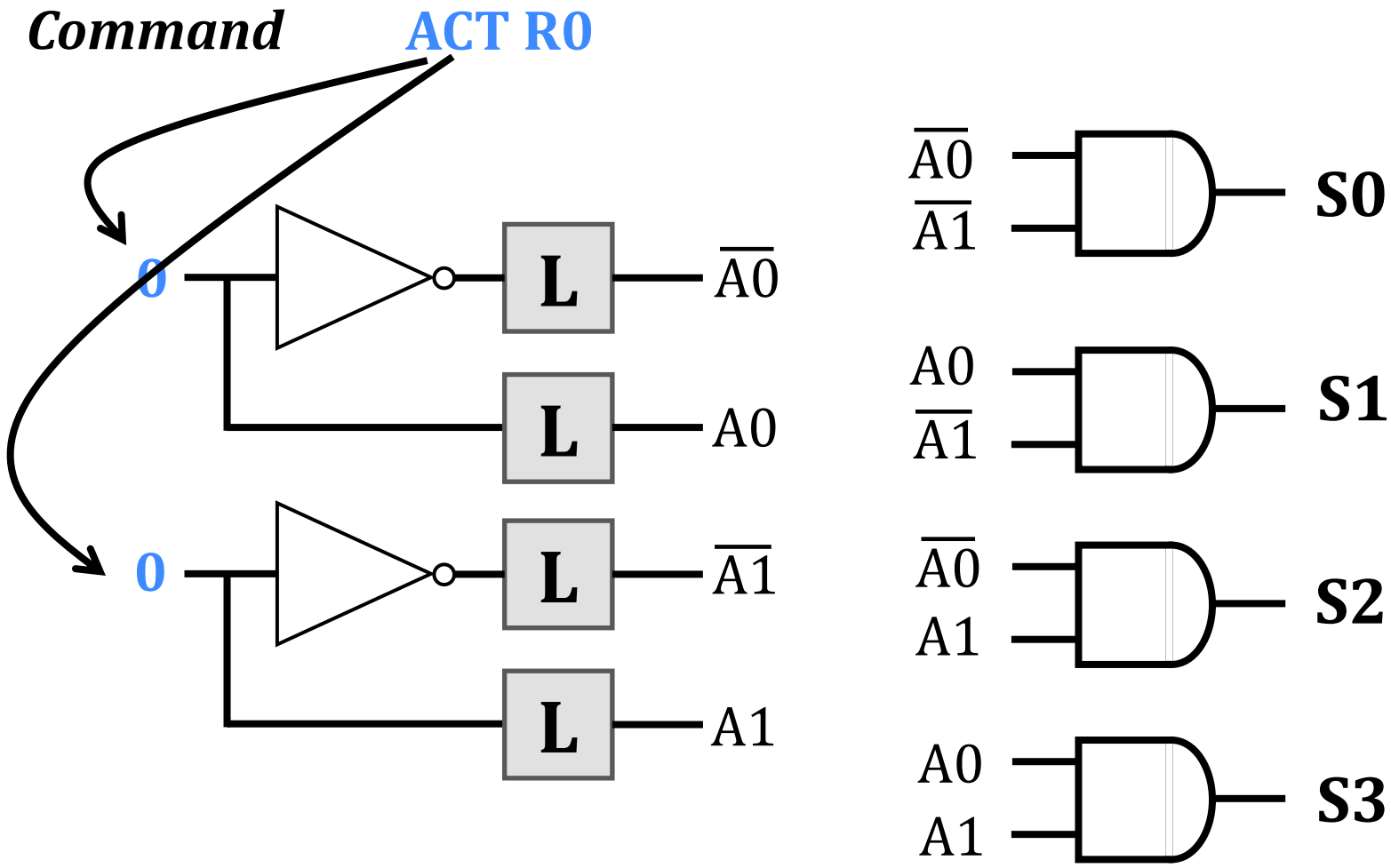


Hypothetical Row Decoder



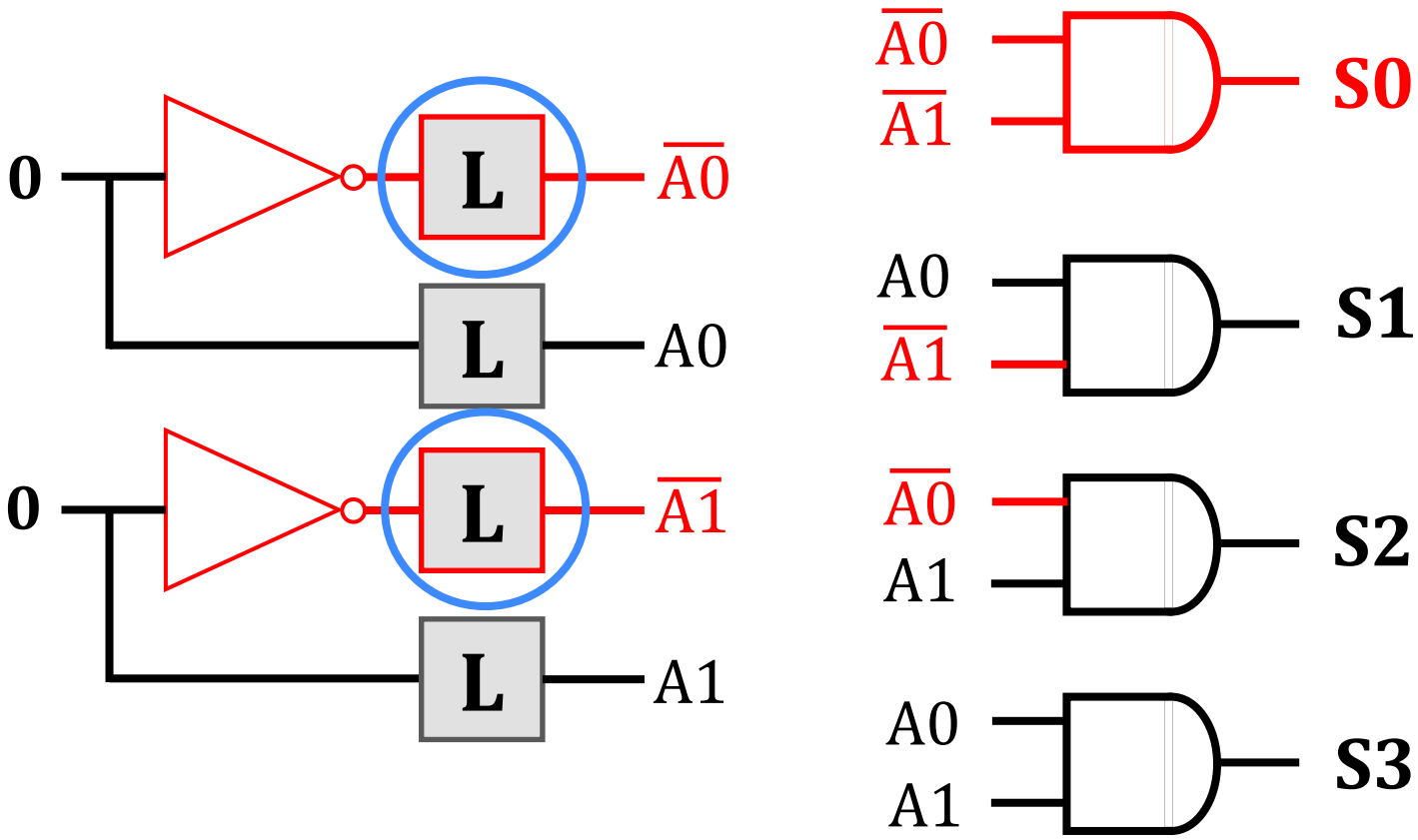
Hypothetical Row Decoder



First ACT command drives a single wordline

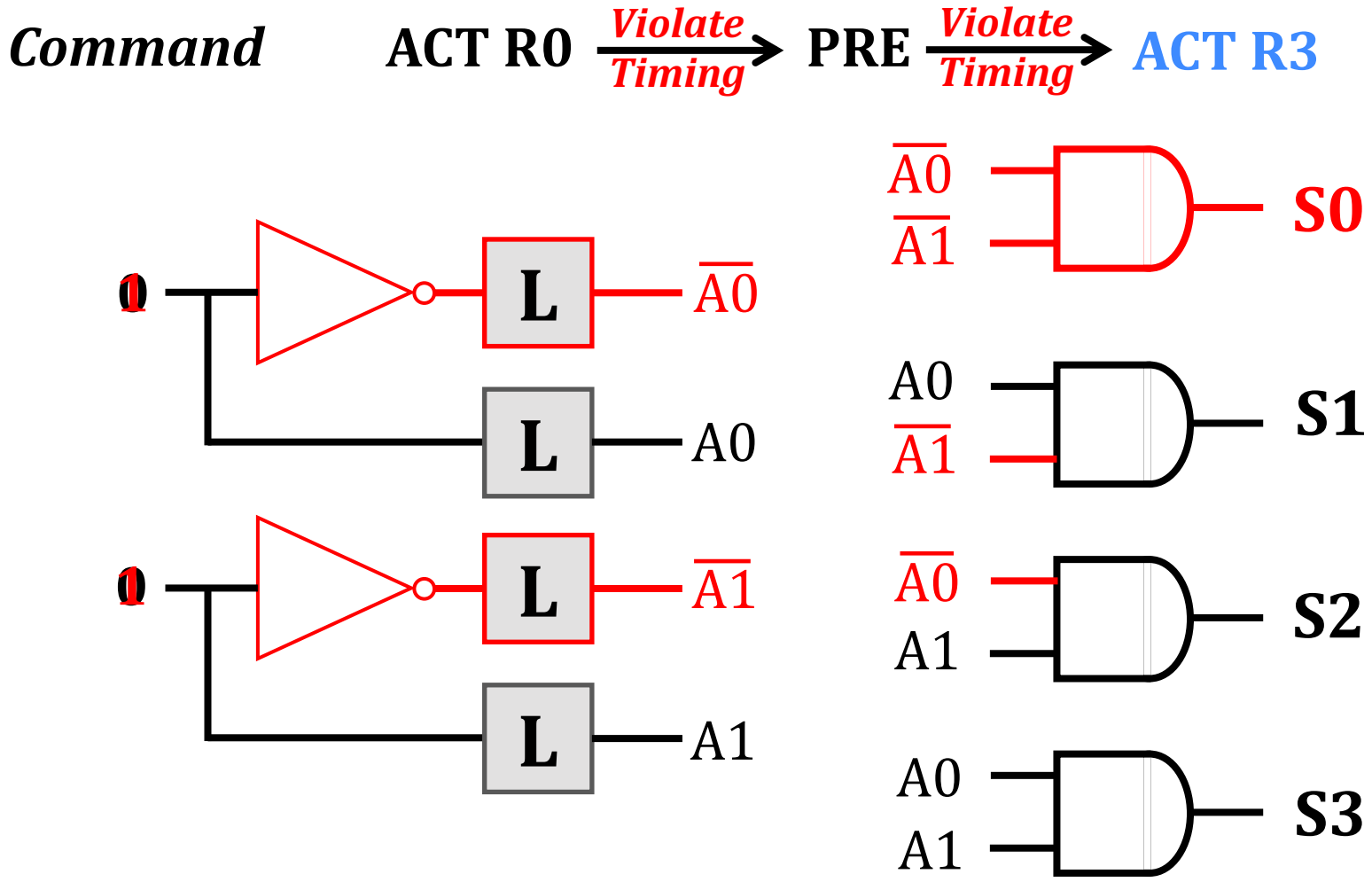
Hypothetical Row Decoder

Command **ACT R0** —*Violate Timing*→ **PRE**



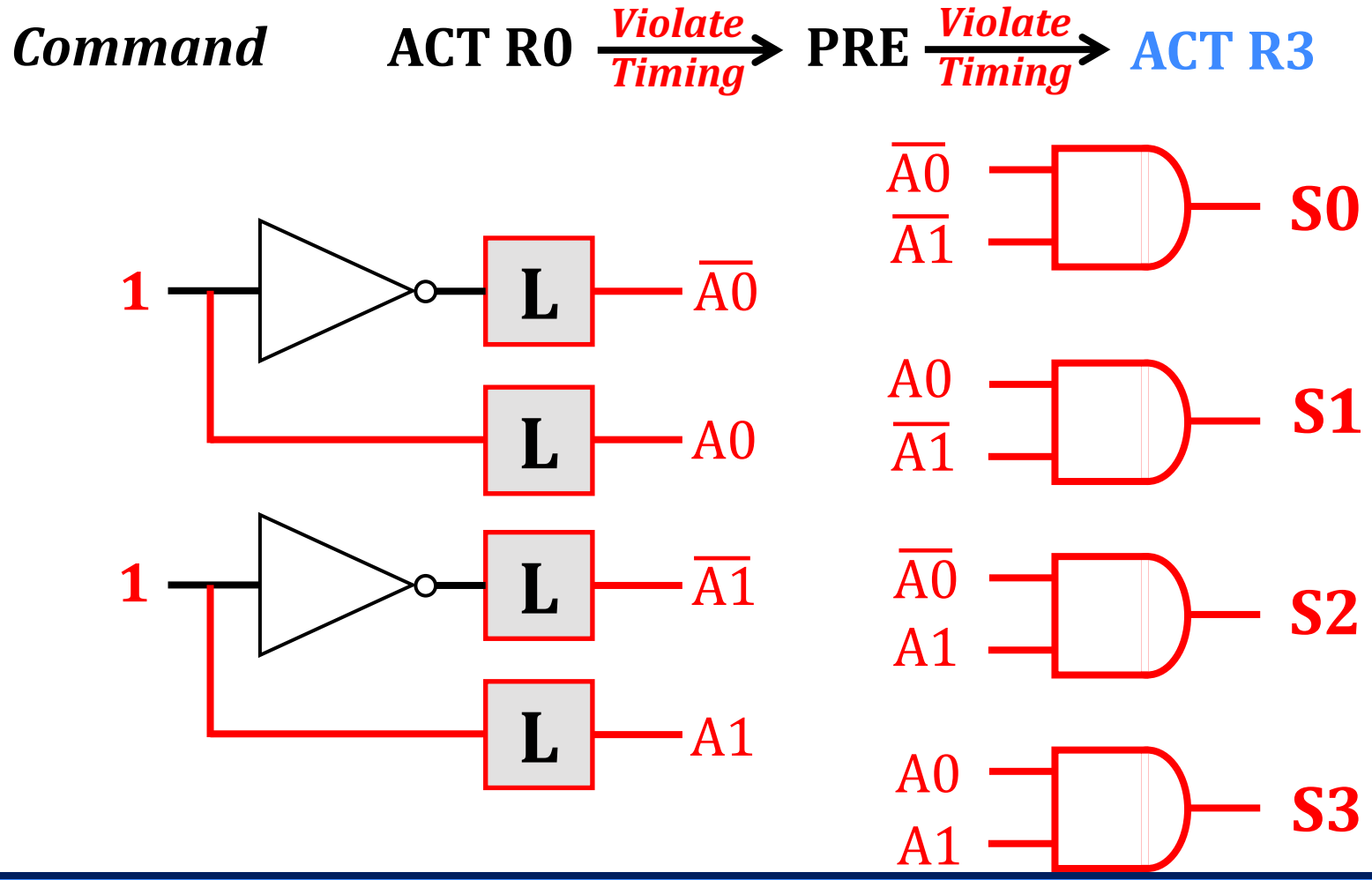
PRE command **cannot** disable latches

Hypothetical Row Decoder



Second ACT drives the **remaining three** wordlines

Hypothetical Row Decoder



All four wordlines are enabled

Quadruple Activation

Outline

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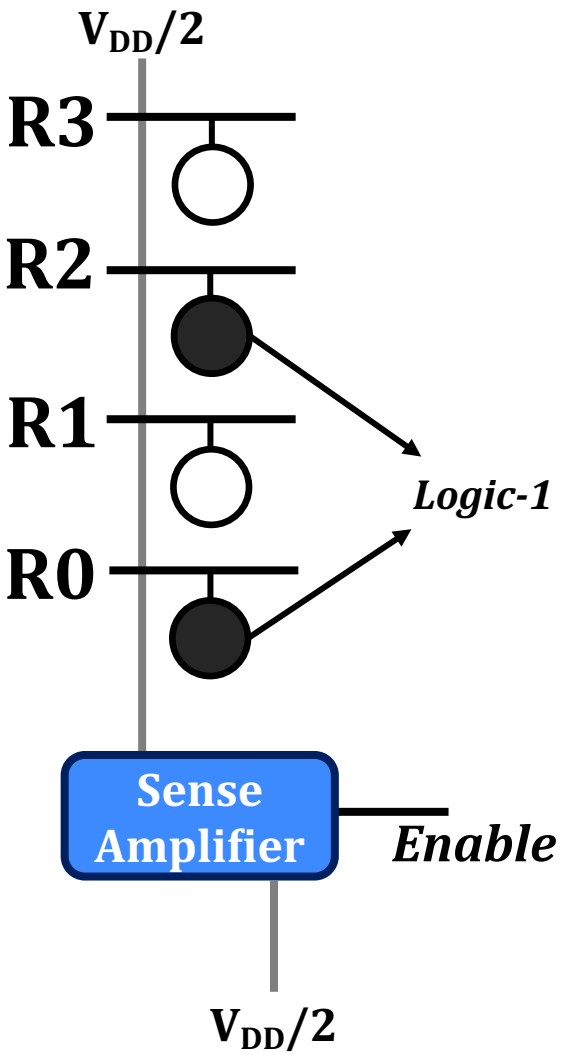
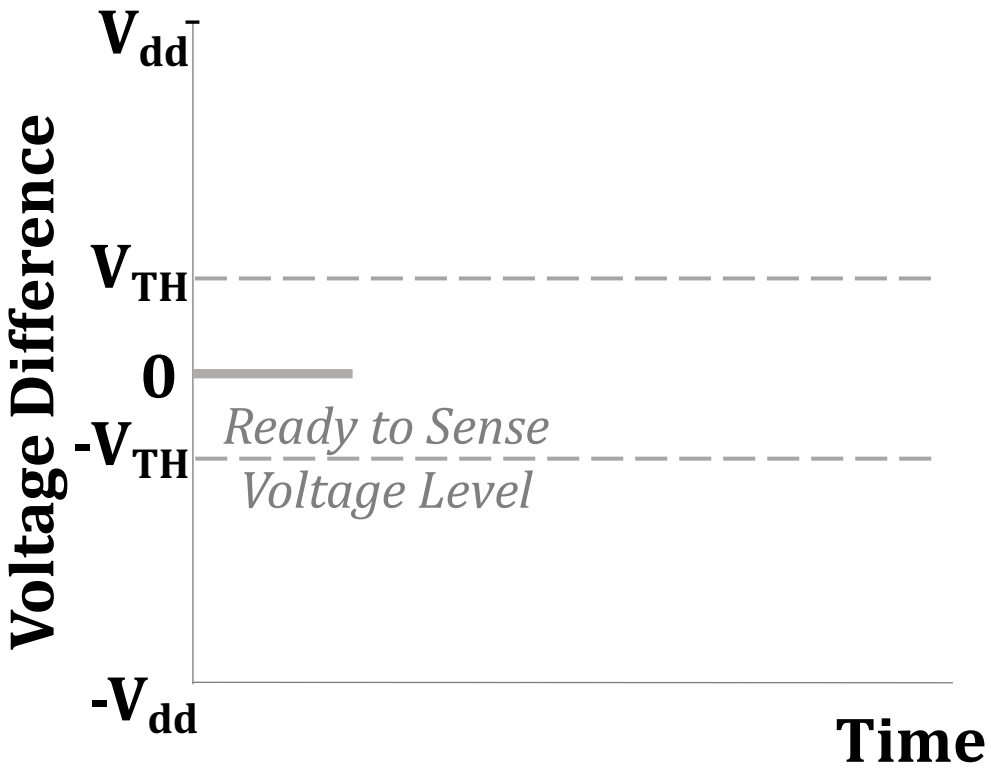
QUAC-TRNG

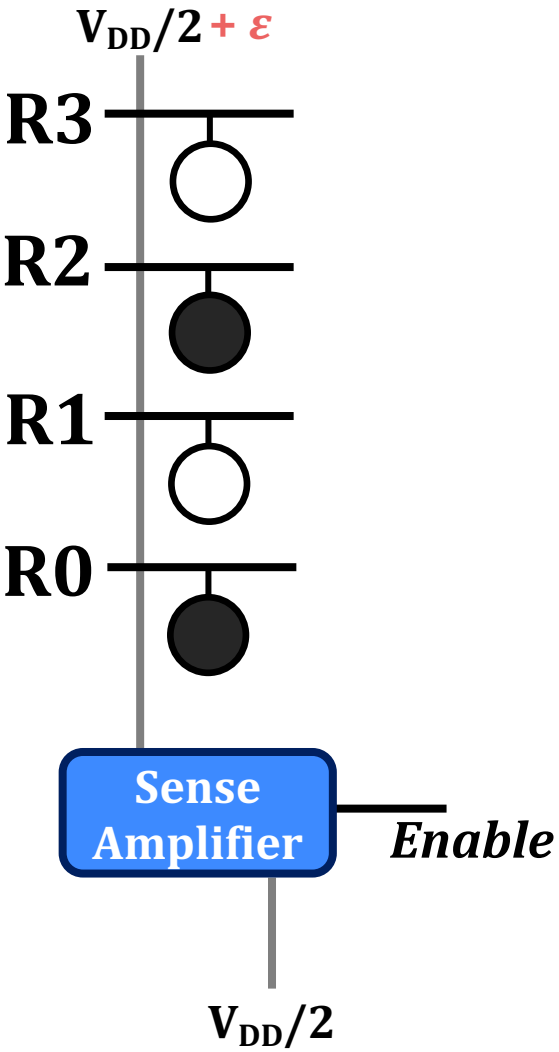
Evaluation

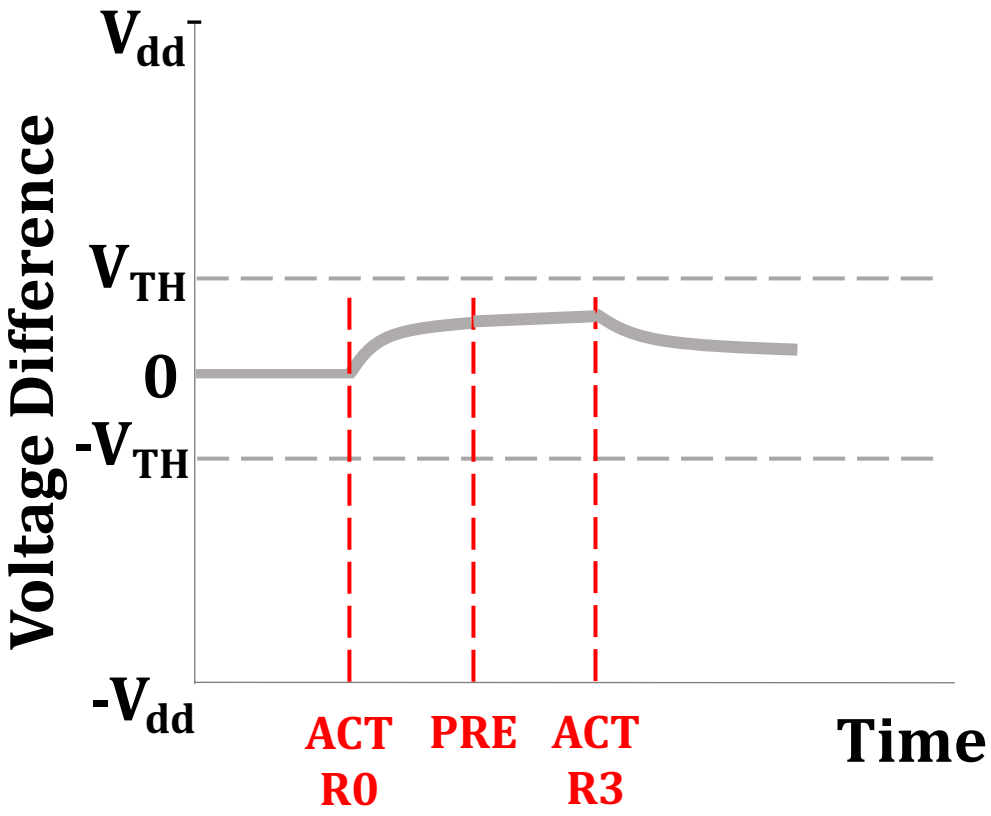
Generating Random Values via QUAC





Generating Random Values via QUAC





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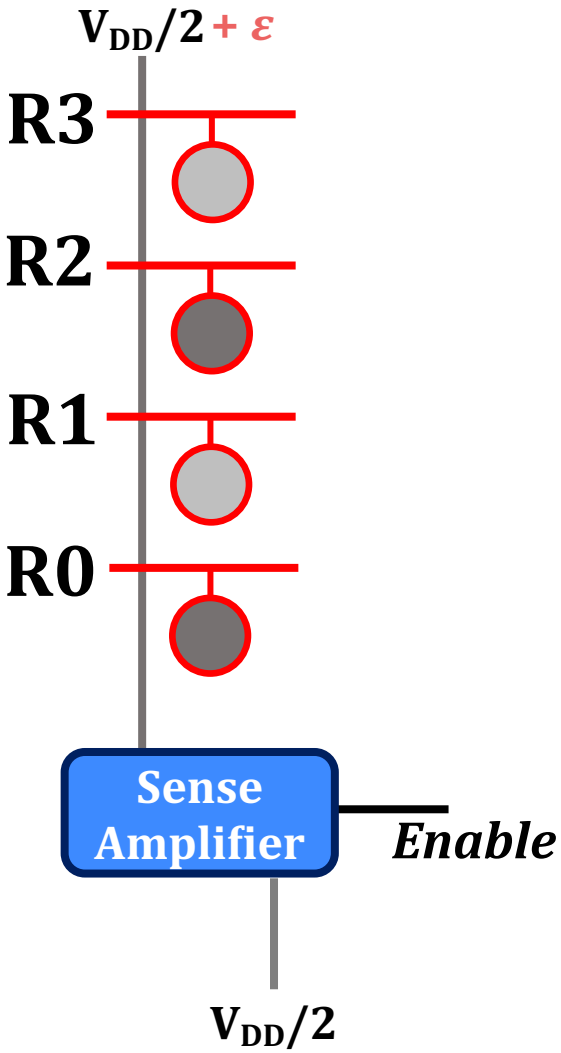
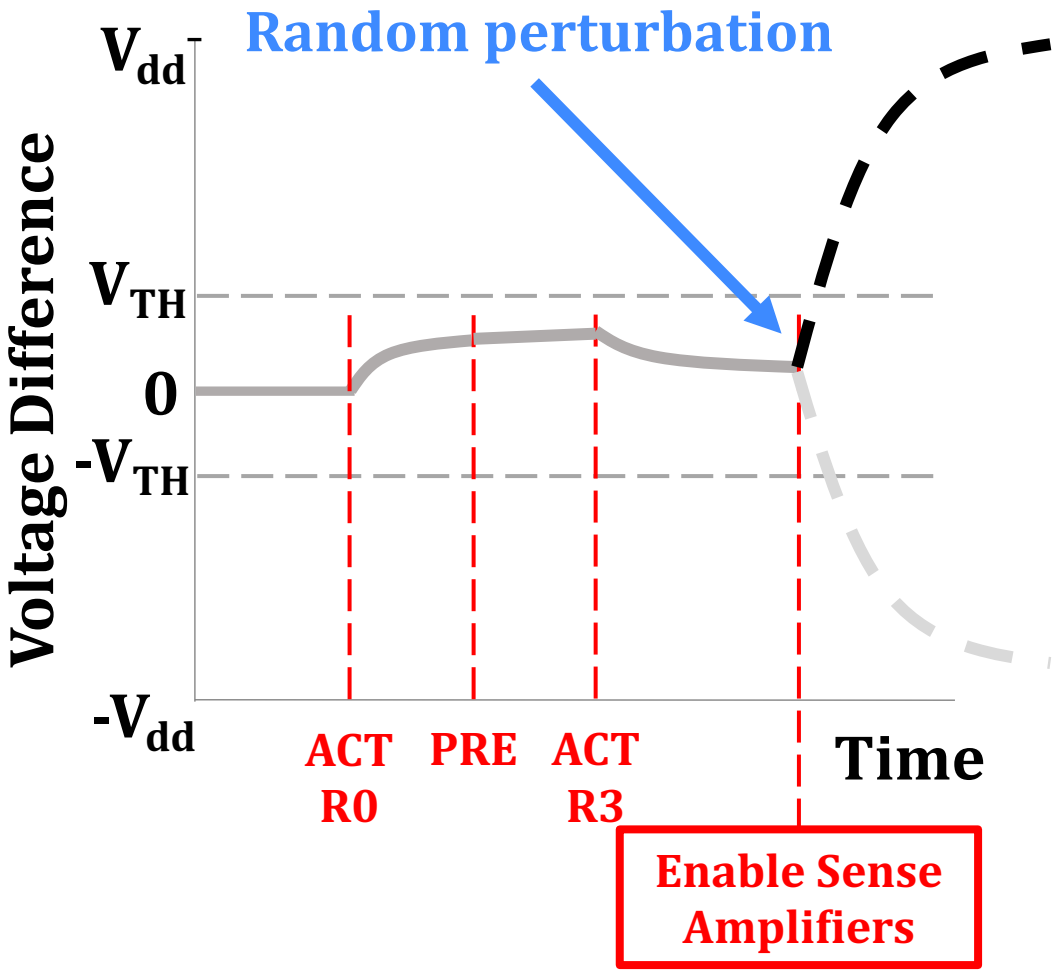
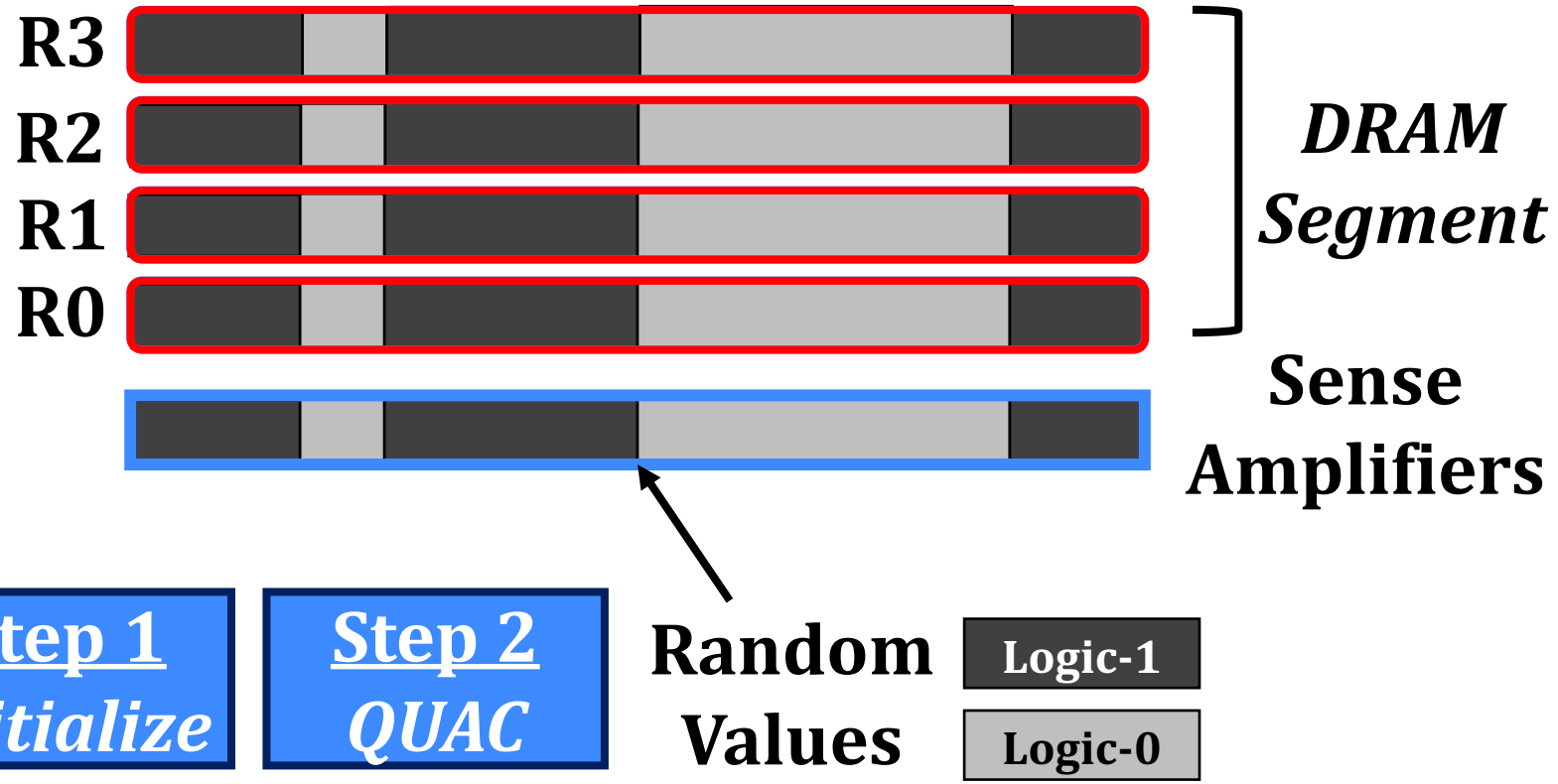




QUAC-TRNG

Key Idea: Leverage random values on sense amplifiers generated by QUAC operations as source of entropy



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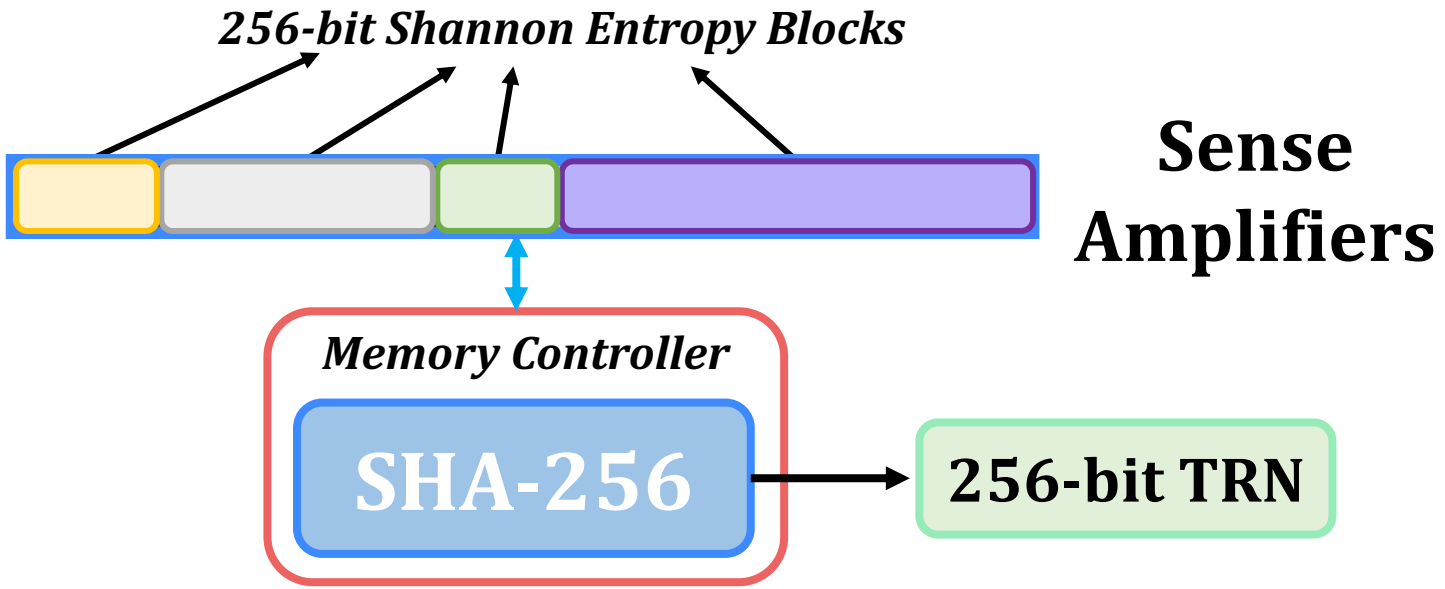

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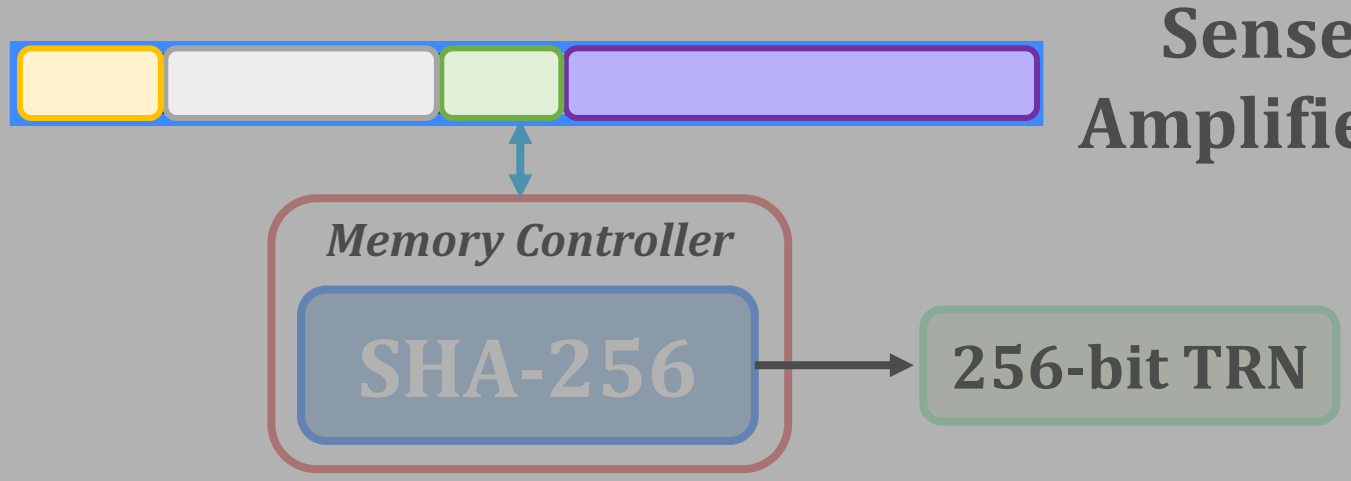


Generates a 256-bit random number **for every** 256-bit Shannon Entropy block

Outline

True Random Numbers in DRAM

DRAM Background

QUadruple ACtivation (QUAC)

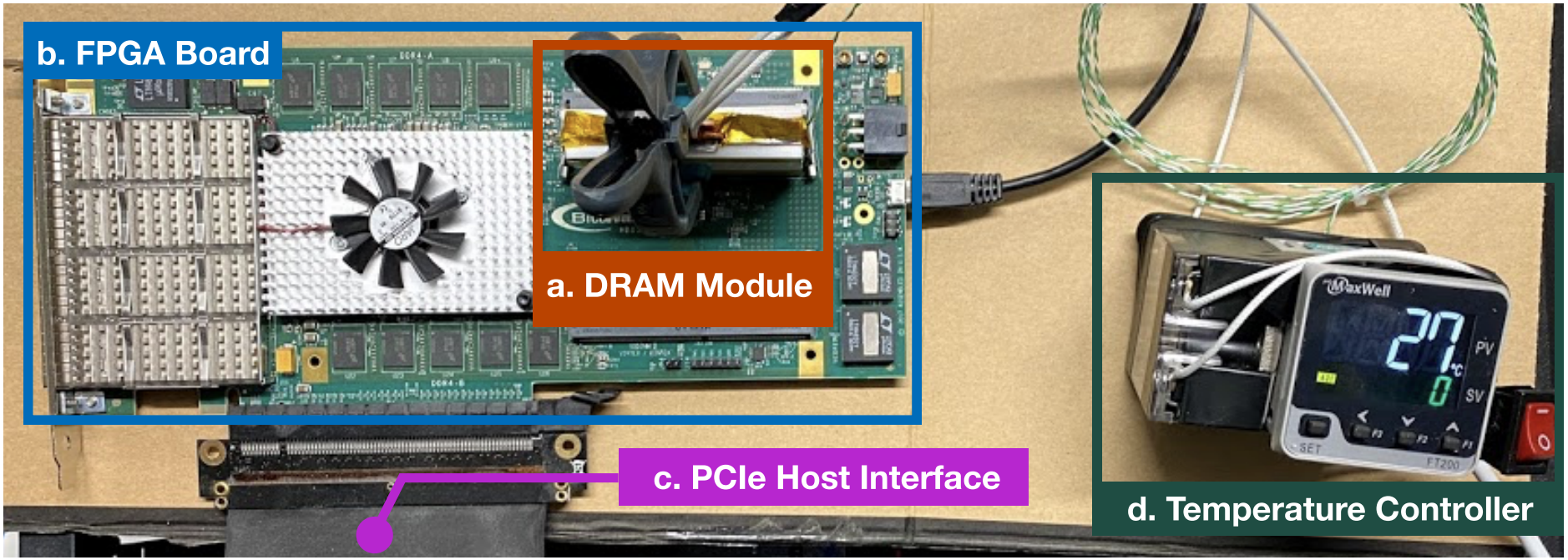
QUAC-TRNG

Evaluation

Real Chip Characterization

Experimentally study QUAC and QUAC-TRNG using 136 real DDR4 chips from SK Hynix

DDR4 DRAM Bender → DRAM Testing Infrastructure



Real Chip Characterization

Measure randomness of bitstreams using **Shannon Entropy**

$$H(x) = -\sum_{i=1}^{2} p(x_i) \log_2 p(x_i)$$

Calculating probabilities:

→ Proportion of *logic-1* and *logic-0* values in the random bitstream

Sample each bitline following QUAC *1000 times* and calculate the bitline's Shannon Entropy

SE(*1111…111*) = 0

0 < **SE(*1001…010*)** < 1

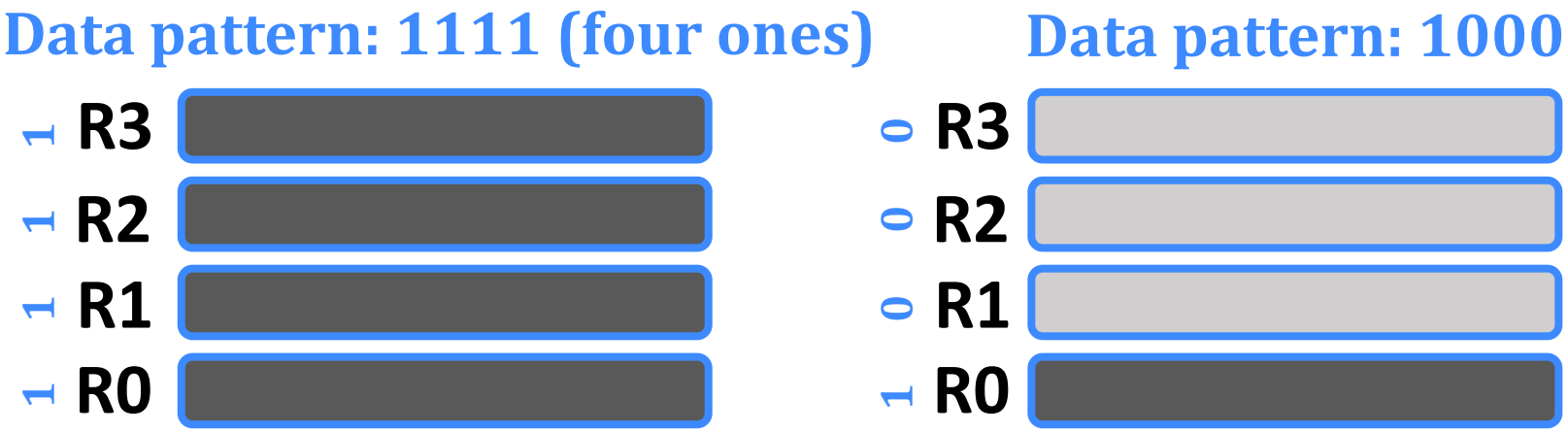
Real Chip Characterization

At 50°C and nominal voltage:

Repeatedly perform QUAC 1000 times and measure the Shannon Entropy of each bitline in

8K DRAM Segments (32K DRAM Rows),

using **all** 16 different four-bit data patterns



Data Pattern Dependence

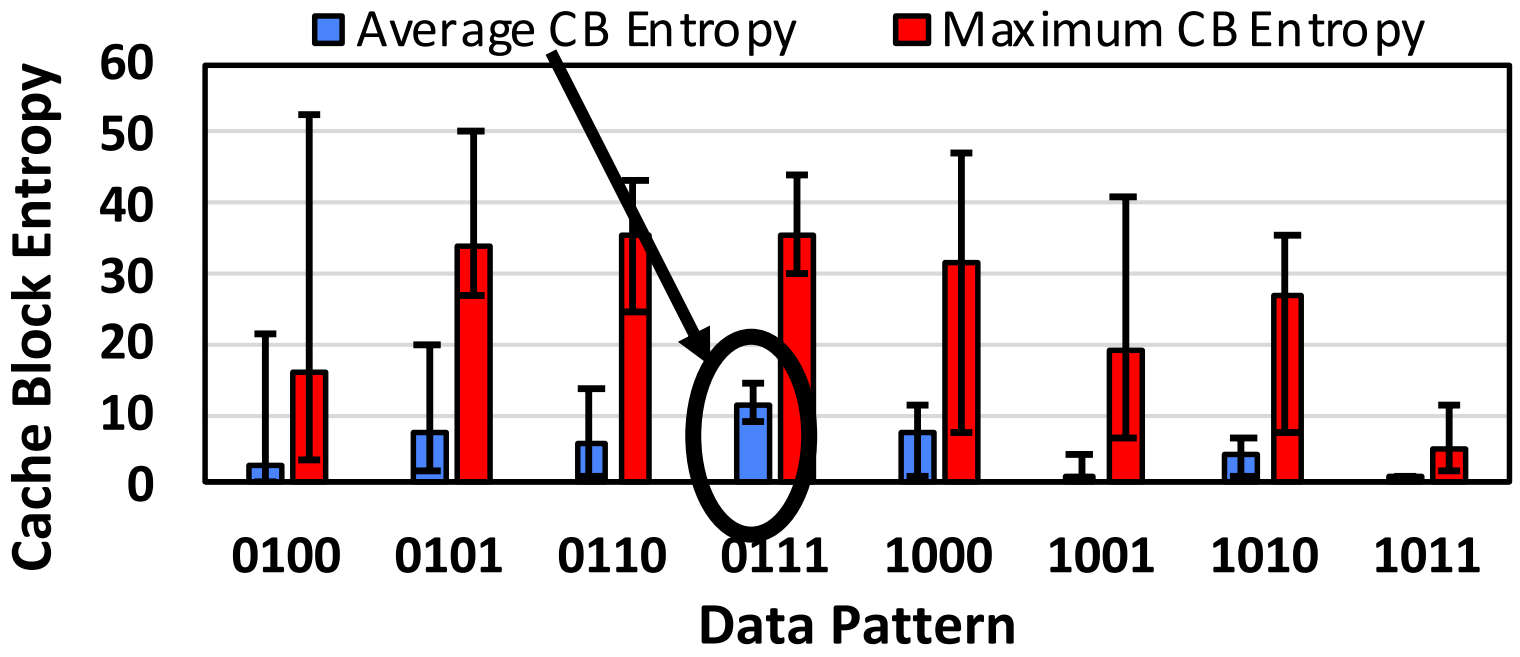
Calculate *cache block entropy (CBE)*

$$\sum \textit{all bitline entropies in the cache block}$$

Metrics based on CBE:

1. **Average CBE:** *Average* entropy across all cache blocks in a module
2. **Maximum CBE:** *Maximum* of the cache block entropies in a module

Data Pattern Dependence

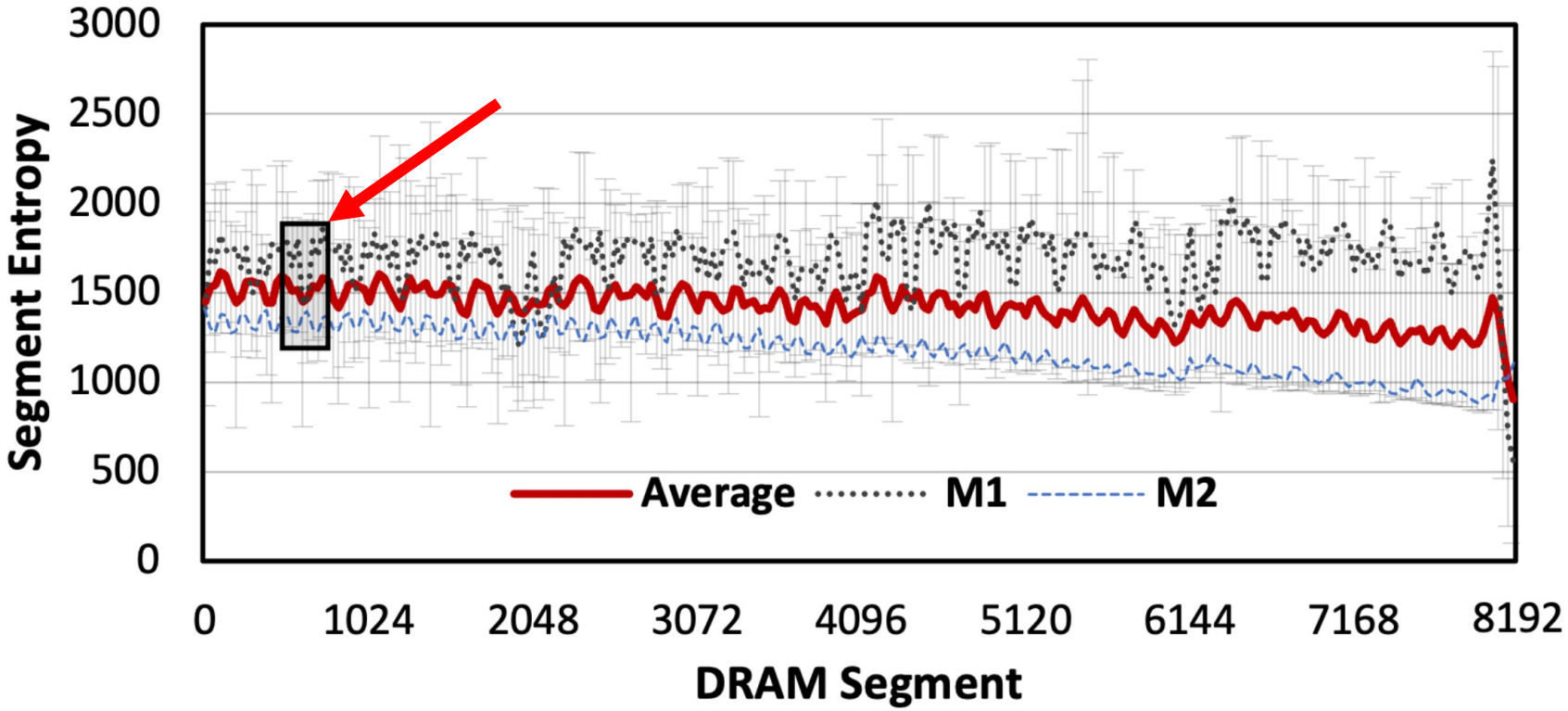


Entropy varies with data pattern

Highest average entropy with pattern "0111"

Spatial Distribution

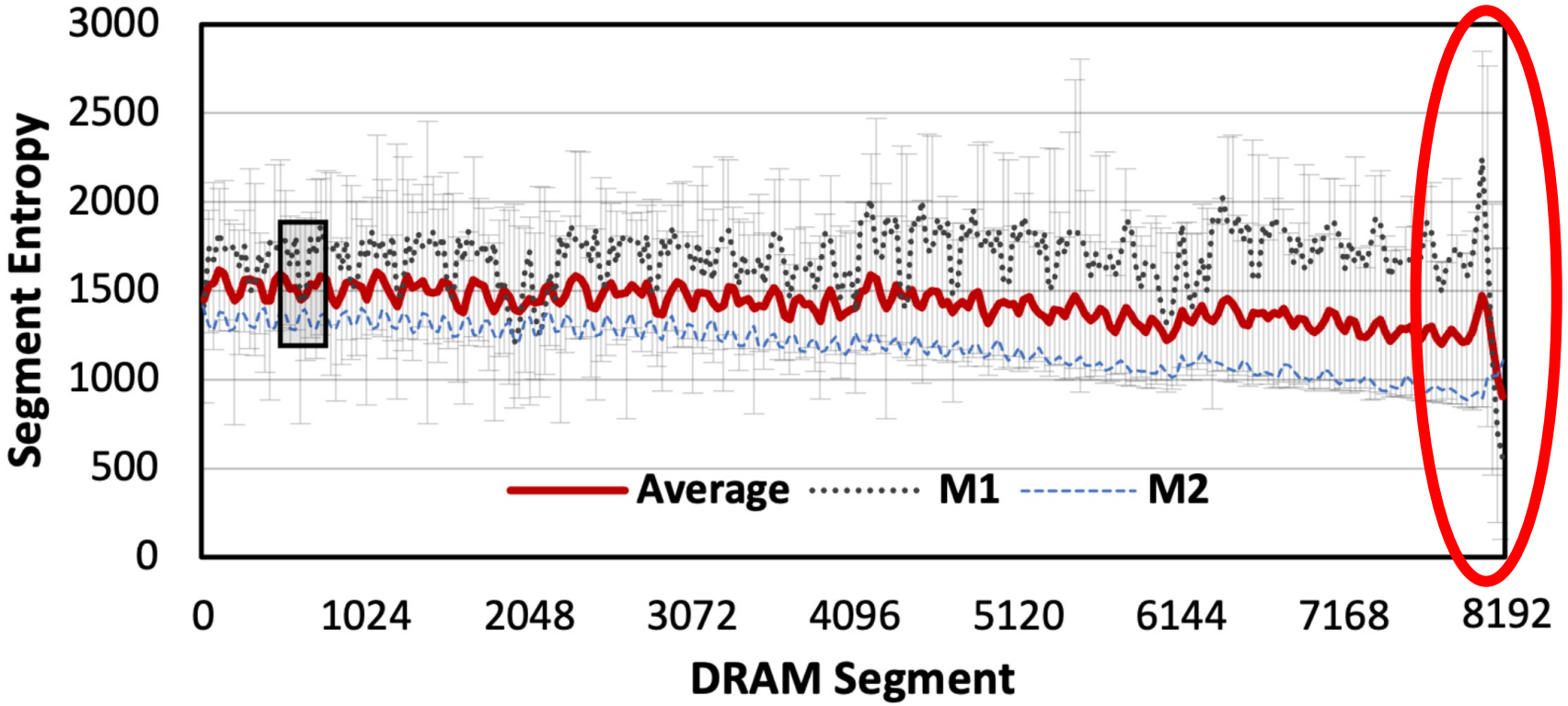
$$\text{Segment entropy} = \sum \textit{all bitline entropies in the segment}$$



Segment entropy behavior is different for different modules

Spatial Distribution

$$\text{Segment entropy} = \sum \textit{all bitline entropies in the segment}$$



Entropy significantly increases towards the end of the DRAM bank

Takeaways: QUAC Entropy

We observe that entropy resulting from QUAC operations changes according to the

- data pattern used in initialization
- physical location of DRAM segments

attributed to:

- systematic manufacturing process variation
- design-induced variation

QUAC-TRNG's Quality

Two experiments to measure quality

1. **QUAC + lightweight post-processing**

   To see if QUACs produce high-quality random values on sense amplifiers

2. **QUAC-TRNG using SHA-256**

   To evaluate QUAC-TRNG's quality

Use **NIST STS** to evaluate quality

NIST Results

Table 1: NIST STS Randomness Test Results

NIST STS Test	VNC* (p-value)	SHA-256 (p-value)
monobit	0.430	0.500
frequency_within_block	0.408	0.528
runs	0.335	0.558
longest_run_ones_in_a_block	0.564	0.533
binary_matrix_rank	0.554	0.548
dft	0.538	0.364
non_overlapping_template_matching	>0.999	0.488
overlapping_template_matching	0.513	0.410
maurers_universal	0.493	0.387
linear_complexity	0.483	0.559
serial	0.355	0.510
approximate_entropy	0.448	0.539
cumulative_sums	0.356	0.381
random_excursion	0.164	0.466
random_excursion_variant	0.116	0.510

*VNC: Von Neumann Corrector

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*VNC: Von Neumann Corrector

QUAC and QUAC-TRNG bitstreams pass all 15 NIST randomness tests

QUAC-TRNG Throughput Estimation

Estimate QUAC-TRNG's throughput according to:

$$(256 \times SIB)/(L \times 10^{-9})\ bps$$

SIB: # of **S**HA **I**nput **B**locks in the highest-entropy segment

L: **L**atency of one QUAC operation in nanoseconds

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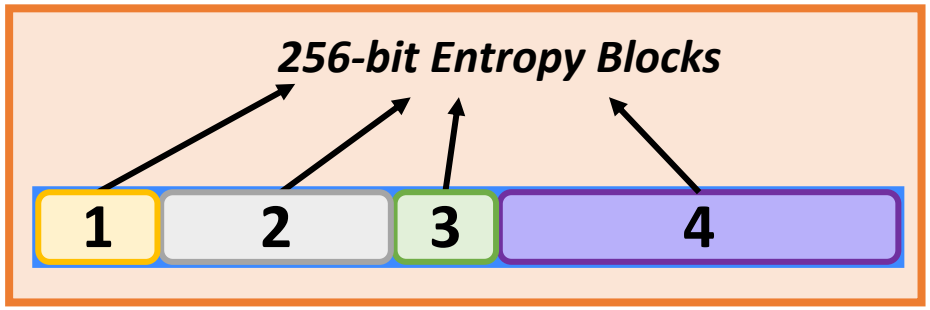
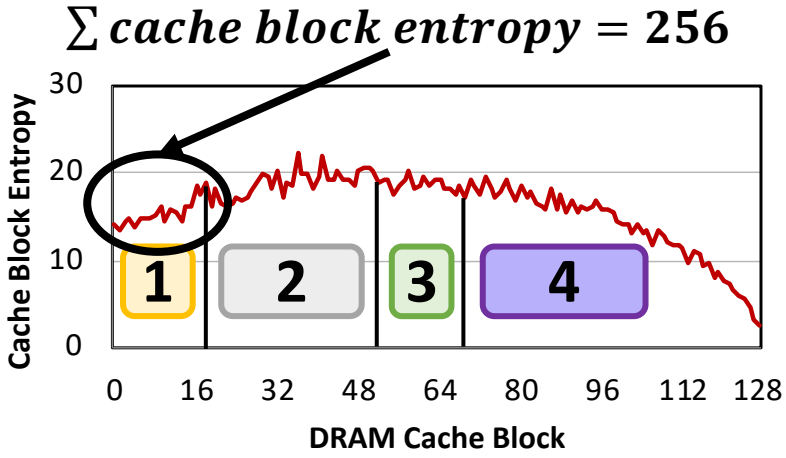




QUAC-TRNG Throughput Estimation

Estimate QUAC-TRNG's throughput according to:

$$(256 \times SIB)/(L \times 10^{-9})\ bps$$

SIB: # of **S**HA **I**nput **B**locks in the highest-entropy segment

L: Latency of one QUAC operation in nanoseconds

QUAC-TRNG Throughput Estimation

Estimate QUAC-TRNG's throughput according to:

$$(256 \times SIB)/(L \times 10^{-9})\ bps$$

SIB: # of **S**HA **I**nput **B**locks in the highest-entropy segment

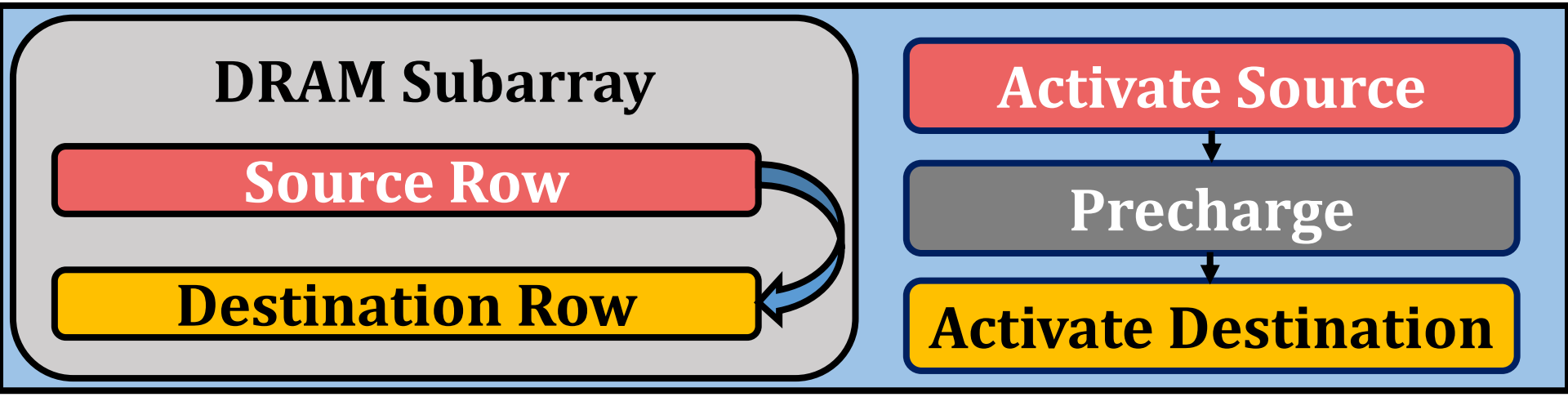
L: **L**atency of one QUAC operation in nanoseconds

QUAC-TRNG Configurations

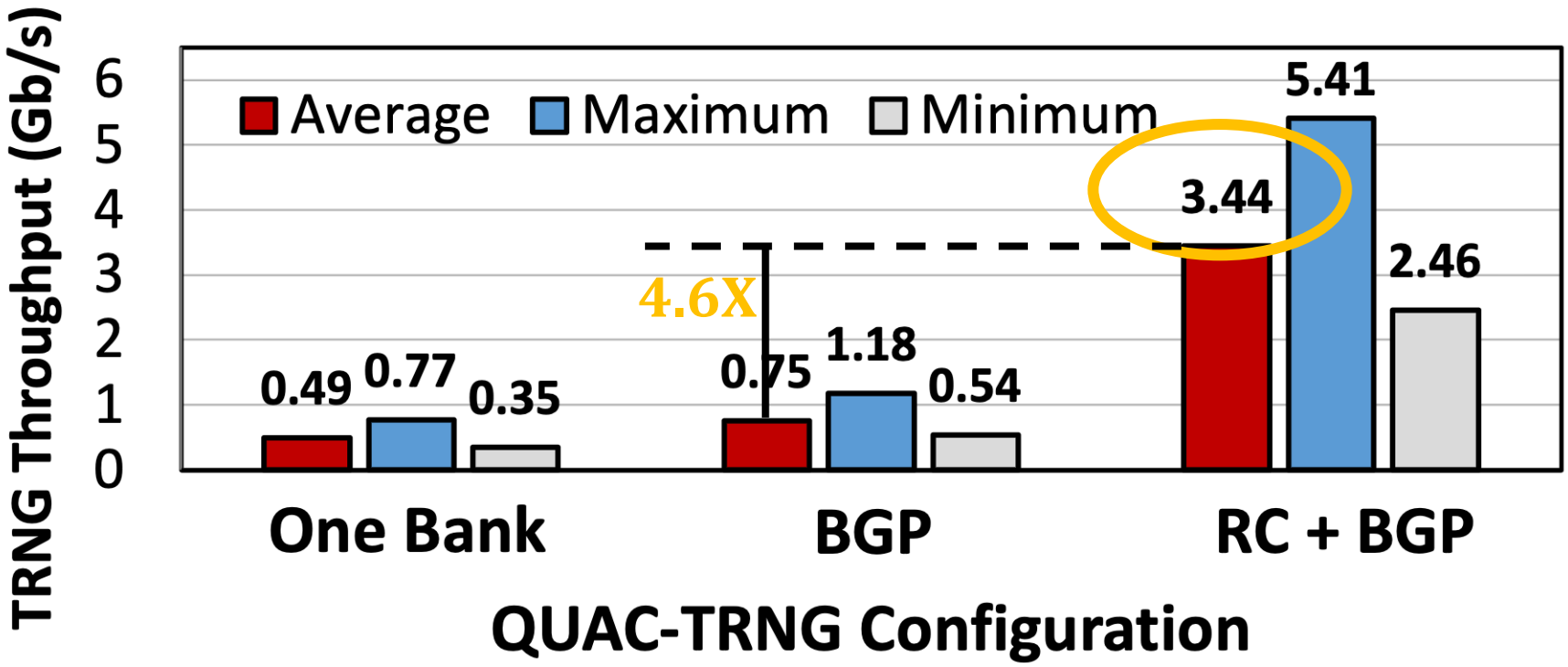
1. ***One Bank*** — Use a single DRAM bank

2. ***BGP*** — **B**ank **G**roup-Level **P**arallelism
Use four banks from different bank groups

3. ***RC + BGP*** — **R**ow**C**lone **+ BGP**
Use in-DRAM copy to initialize DRAM rows *and* use four banks from different bank groups



QUAC-TRNG Throughput



Achieves 3.44 Gb/s throughput per DRAM channel on average across all modules

In-DRAM initialization greatly improves throughput

QUAC-TRNG vs State-Of-The-Art

High-throughput DRAM-based TRNGs:

- **D-RaNGe**: Activation latency failures
- **Talukder** et. al: Precharge latency failures

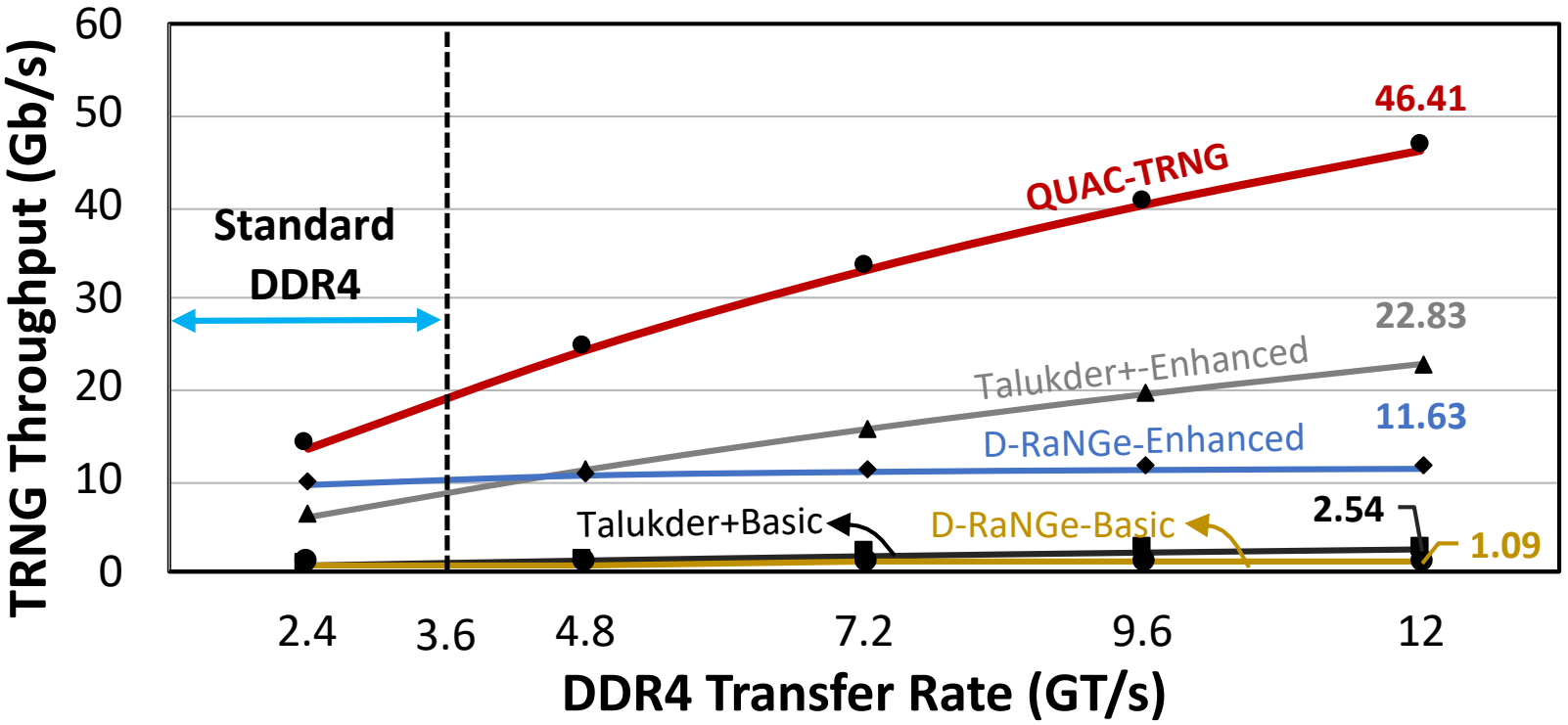
Calculate throughput by tightly scheduling the DDR4 commands required to induce failures

Evaluate two versions of these past two works:

- **Base:** As proposed
- **Enhanced (Fair):** Throughput-optimized (SHA-256)

Assume four-channel DDR4 memory

QUAC-TRNG vs State-Of-The-Art



Outperforms best prior DRAM-based TRNG

(i) "base" by 15.08x at 2.4 GT/s

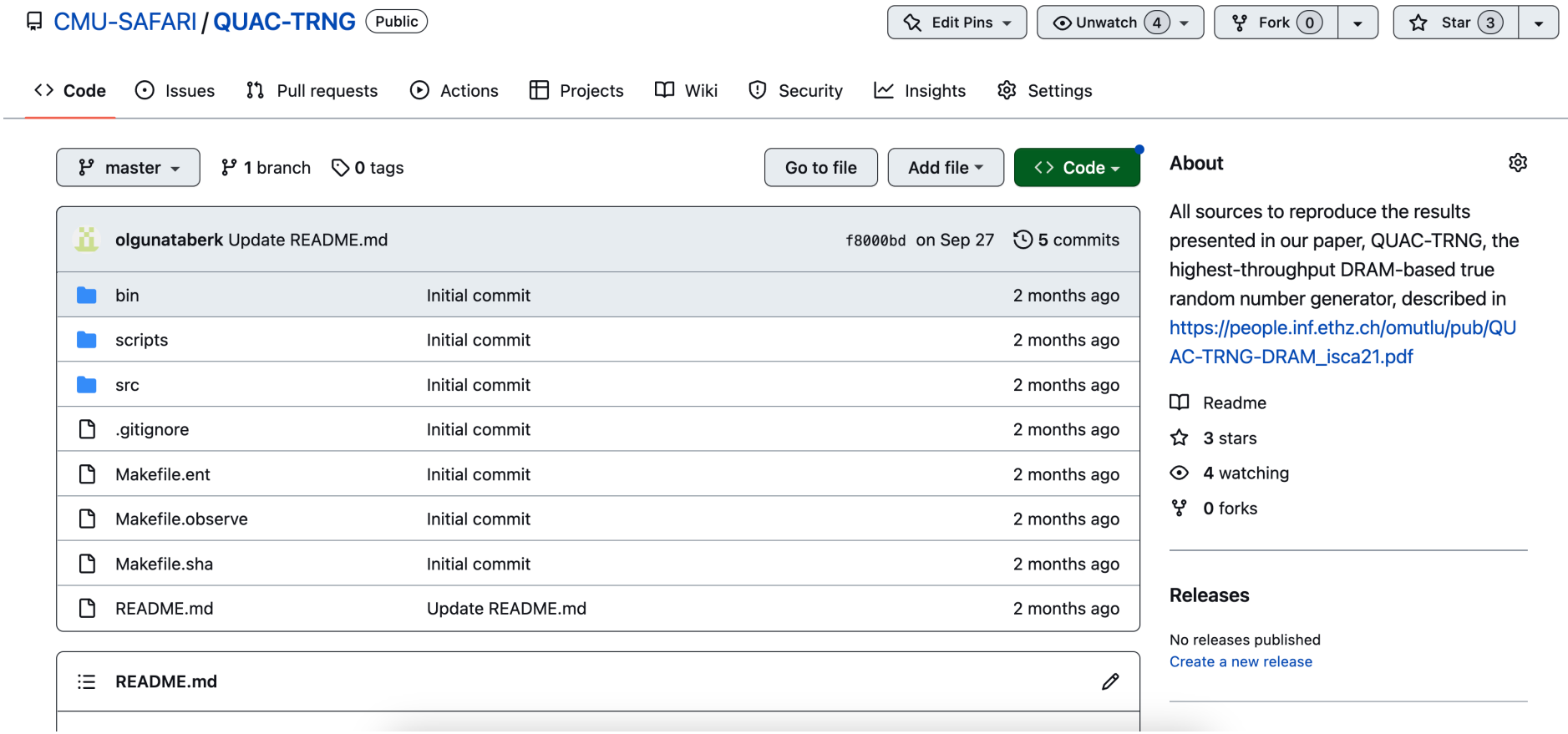
(ii) "enhanced" by 2.03x at 12 GT/s

More in the Paper

- NIST randomness tests results
- Throughput & latency comparison against four other DRAM-based TRNGs
- System Integration
  - How QUAC-TRNG can be implemented in real systems
  - System performance study
    - QUAC-TRNG's throughput with concurrently running applications
  - Area overhead: 0.04% of a contemporary CPU (7 nm)
  - Memory overhead: 0.002% of an 8 GiB DRAM module
- Sensitivity Analysis
  - Effect of temperature on QUAC's entropy
    - Entropy changes with temperature
  - Time dependence study
    - Entropy remains stable for at least up to a month

QUAC-TRNG is Open Source

https://github.com/CMU-SAFARI/QUAC-TRNG



DR-STRaNGe: End-to-End System Design for DRAM-based True Random Number Generators

F. Nisa Bostancı[†§] Ataberk Olgun[†§] Lois Orosa[§] A. Giray Yağlıkçı[§]
Jeremie S. Kim[§] Hasan Hassan[§] Oğuz Ergin[†] Onur Mutlu[§]

[†]*TOBB University of Economics and Technology* [§]*ETH Zürich*

- System Integration
  - How QUAC-TRNG can be implemented in real systems
  - System performance study
    - QUAC-TRNG's throughput with concurrently running applications
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HPCA 2022

The 28th IEEE International Symposium on High-Performance Computer Architecture (HPCA-28), Seoul, South Korea

DR-STRaNGe Talk Video

https://www.youtube.com/watch?v=mSJ7GLrCu1o

DR-STRaNGe: End-to-End System Design for DRAM-based True Random Number Generators - HPCA'22 Talk

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Executive Summary

- **Motivation**: DRAM-based true random number generators (TRNGs) provide **true random numbers at low cost** on **a wide range** of computing systems
- **Problem**: Prior DRAM-based TRNGs are slow:
  1. Based on fundamentally slow processes → **high latency**
  2. Cannot effectively harness entropy from DRAM rows → **low throughput**
- **Goal**: **Develop** a **high-throughput** and **low-latency** TRNG that uses **commodity DRAM** devices
- **Key Observation**: Carefully engineered sequence of DRAM commands can activate **four DRAM rows** → **QU**adruple **AC**tivation **(QUAC)**
- **Key Idea**: **Use QUAC** to activate DRAM rows that are initialized with **conflicting data** (e.g., two '1's and two '0's) to generate random values
- **QUAC-TRNG:** DRAM-based TRNG that generates true random numbers at **high-throughput** and **low-latency** by **repeatedly performing QUAC operations**
- **Results:** We evaluate QUAC-TRNG using **136** real DDR4 chips
  1. **5.4 Gb/s** maximum (**3.4 Gb/s** average) TRNG throughput per DRAM channel
  2. QUAC-TRNG has low TRNG latency: **256-bit RN** in **274 ns**
  3. Outperforms existing DRAM-based TRNGs by **15.08x** (base), and **1.41x** (enhanced)
  4. QUAC-TRNG passes **all 15** NIST randomness tests

QUAC-TRNG

High-Throughput True Random Number Generation Using Quadruple Row Activation in Real DRAM Chips

Ataberk Olgun

Minesh Patel A. Giray Yağlıkçı Haocong Luo

Jeremie S. Kim F. Nisa Bostancı Nandita Vijaykumar

Oğuz Ergin Onur Mutlu

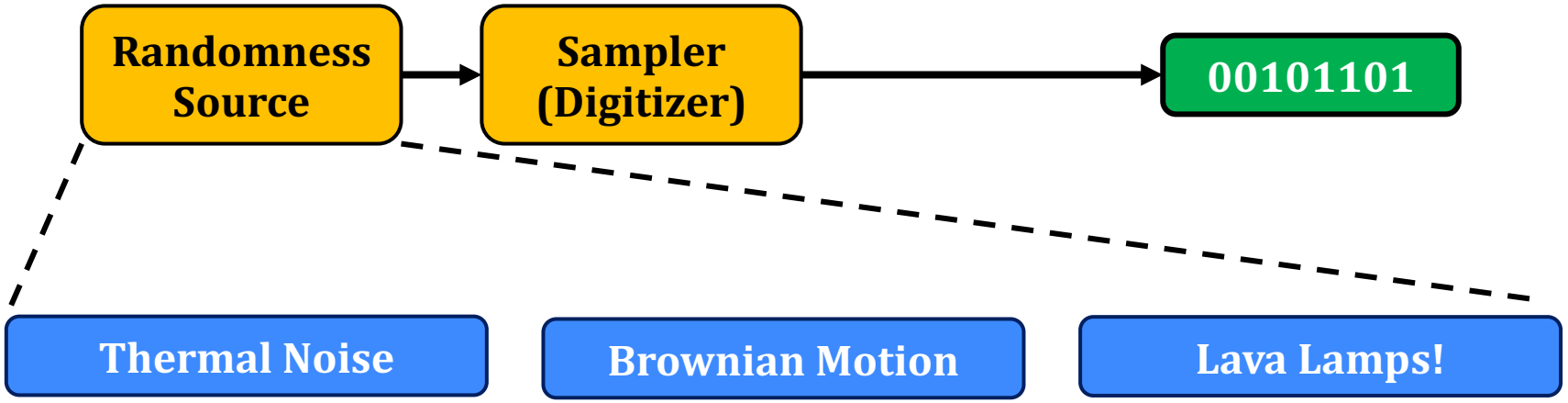
SAFARI kasırga

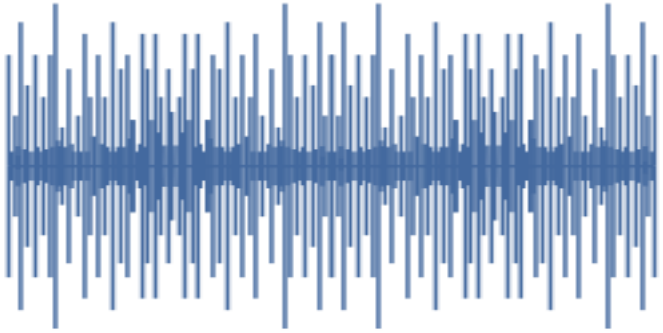
ETH zürich TOBB ETÜ University of Economics & Technology UNIVERSITY OF TORONTO

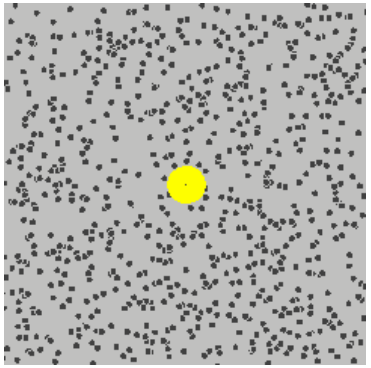
Backup Slides

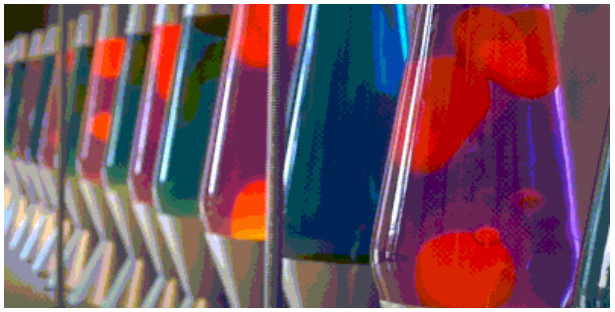
True Random Number Generators

Sample random physical phenomena

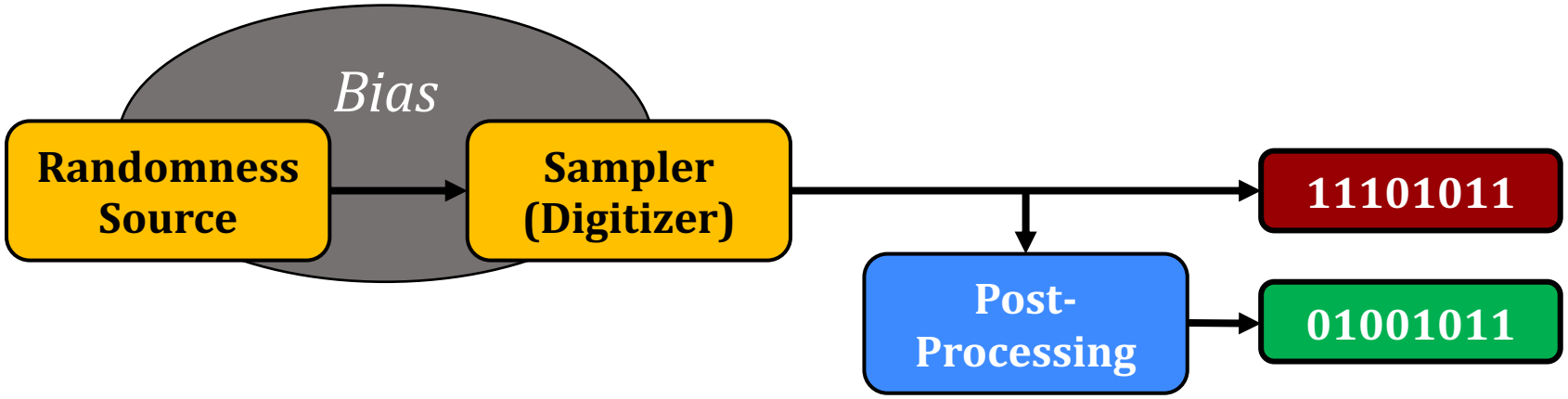








Post-processing for TRNGs



Bias in entropy source → bias in TRNG output

- Low quality (statistically) random numbers

Post-processing to remove bias

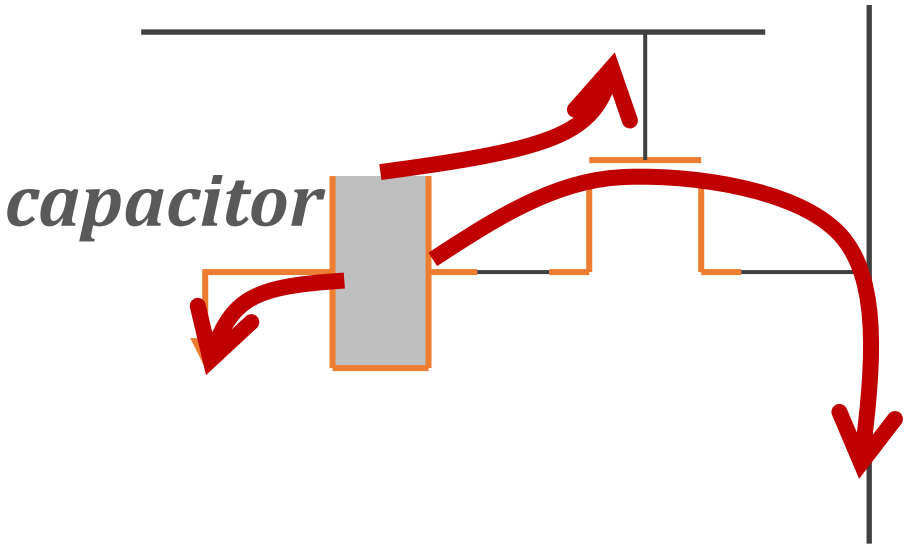
- Improve TRNG quality

Entropy Sources in DRAM

1

Retention Failures

Fundamentally Slow: cells leak charge slowly



Entropy Sources in DRAM

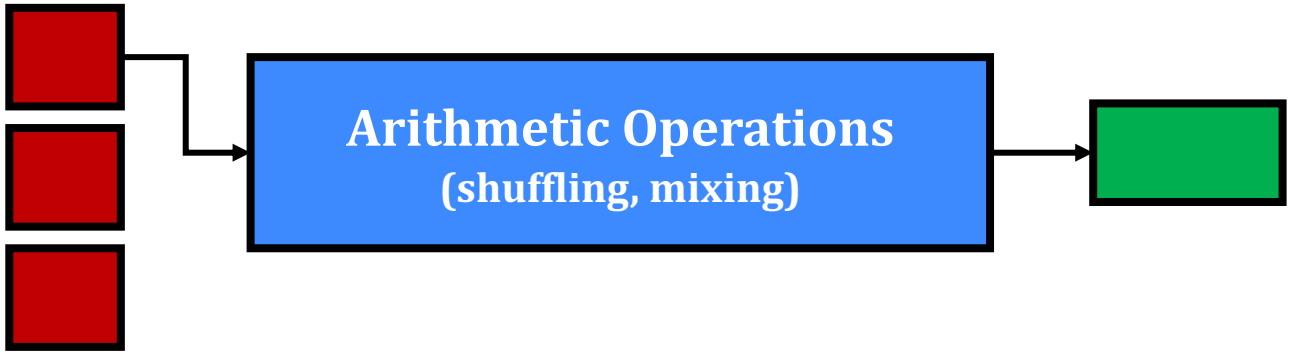
1. **Retention Failures**
   Fundamentally Slow: cells leak charge slowly

2. **Start-up Values**
   Fundamentally Slow: requires power-cycle

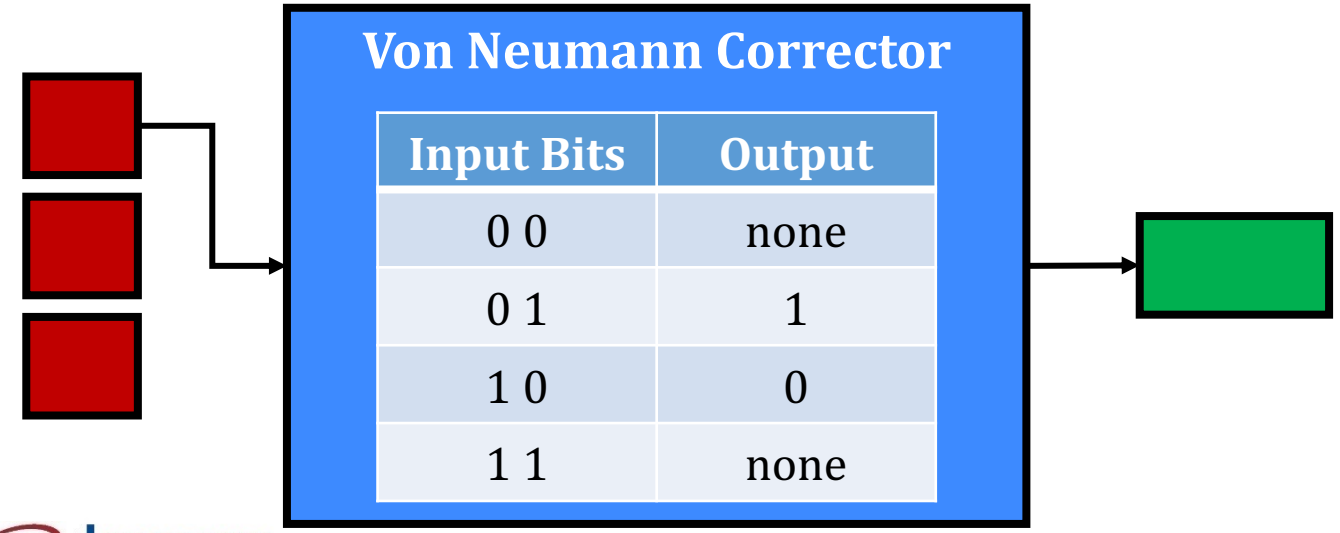
3. **Timing Failures**
   Fast: limited by DRAM command latencies

SHA-256 and Von Neumann Corrector

Cryptographic Hash Functions



Von Neumann Corrector



Input Bits	Output
0 0	none
0 1	1
1 0	0
1 1	none

Timing Failure-based TRNGs

1

D-RaNGe

Activation latency (tRCD) failures

J. S. Kim, M. Patel, H. Hassan, L. Orosa and O. Mutlu,
"D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput," HPCA, 2019

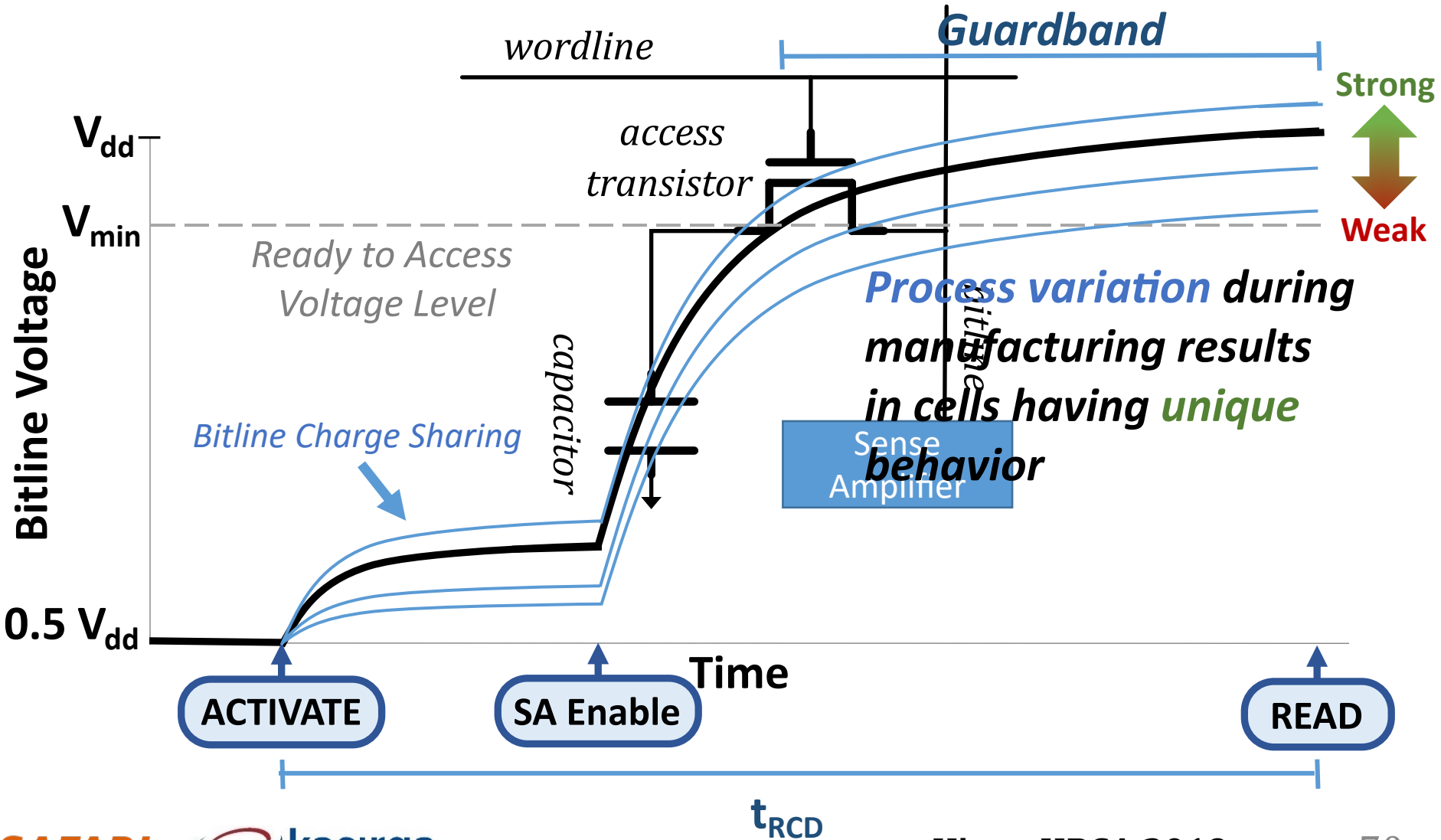
2

Talukder et al.

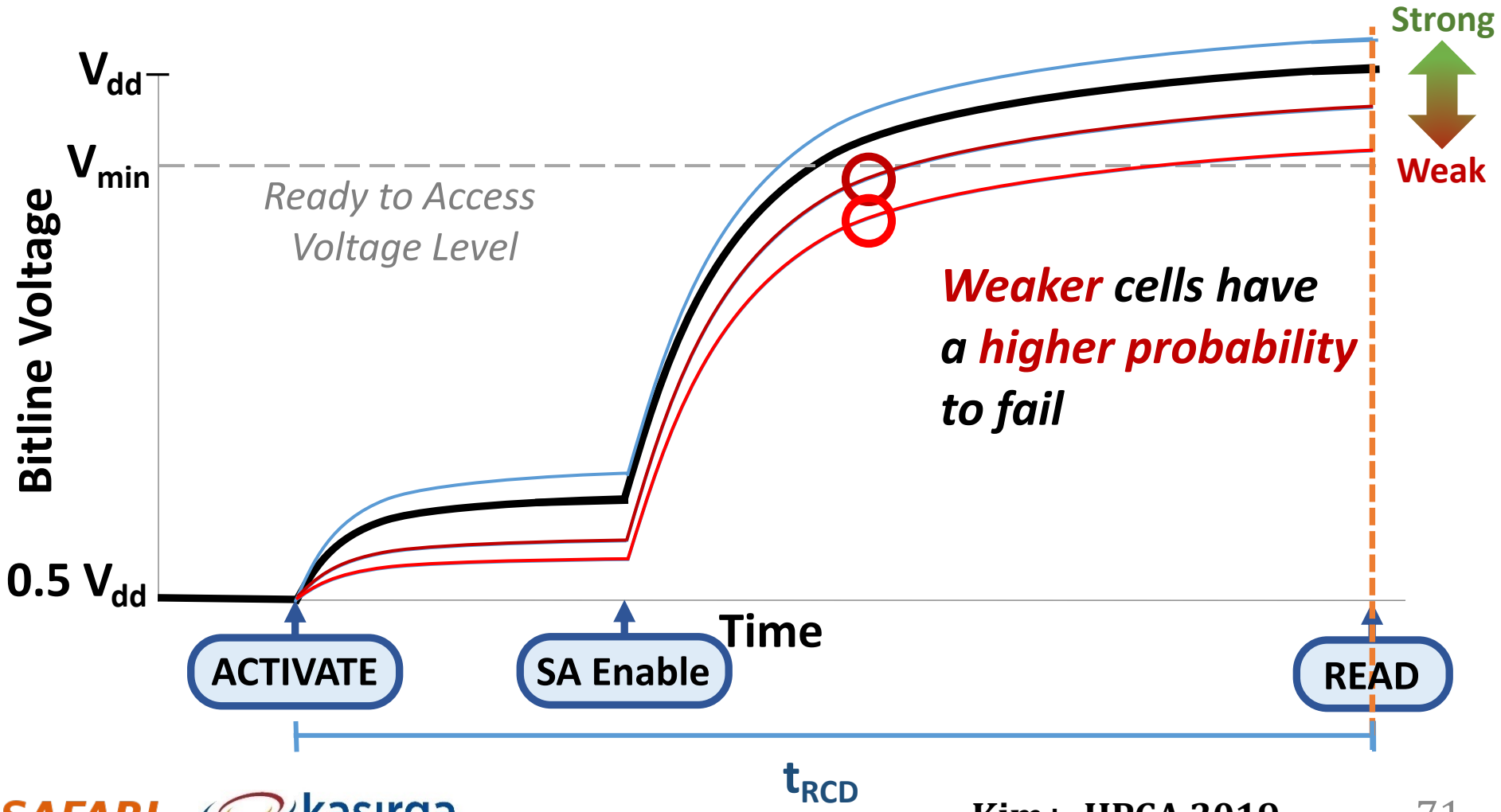
Precharge latency (tRP) failures

B. M. S. Bahar Talukder, J. Kerns, B. Ray, T. Morris and M. T. Rahman,
"Exploiting DRAM Latency Variations for Generating True Random Numbers," ICCE, 2019

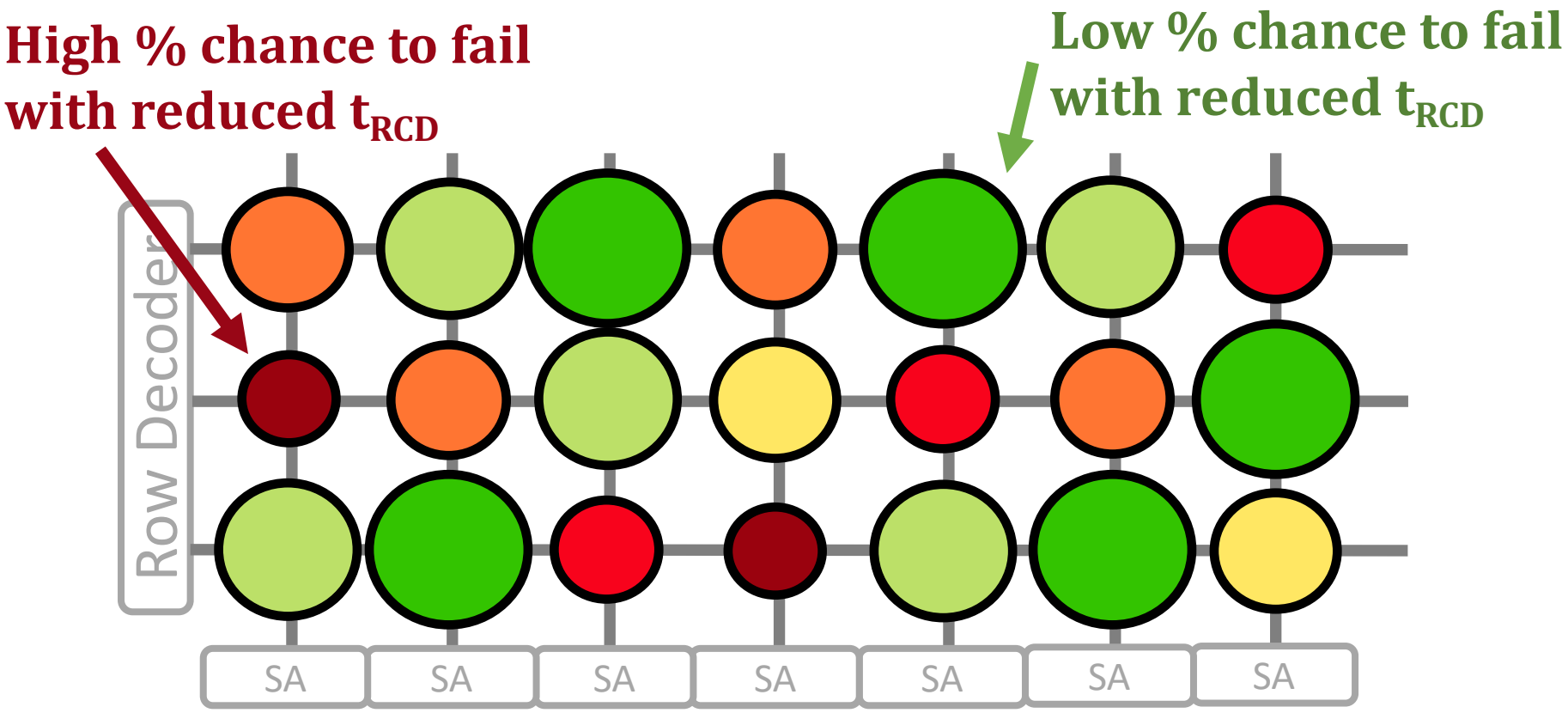
D-RaNGe: Accessing a Cell



D-RaNGe: Accessing a Cell



D-RaNGe Key Idea

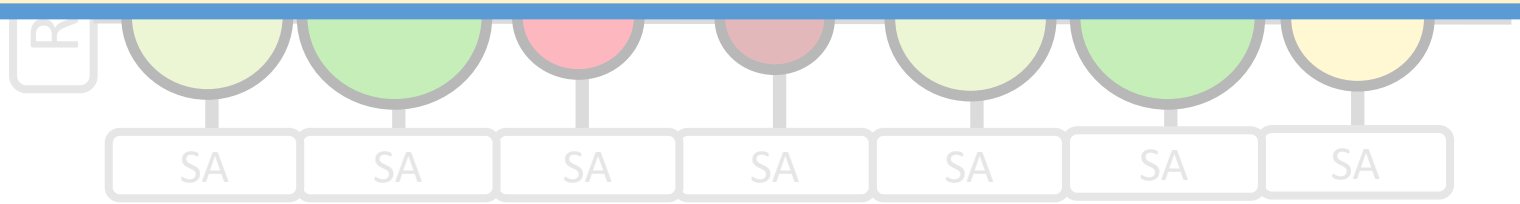


D-RaNGe Key Idea

High % chance to fail

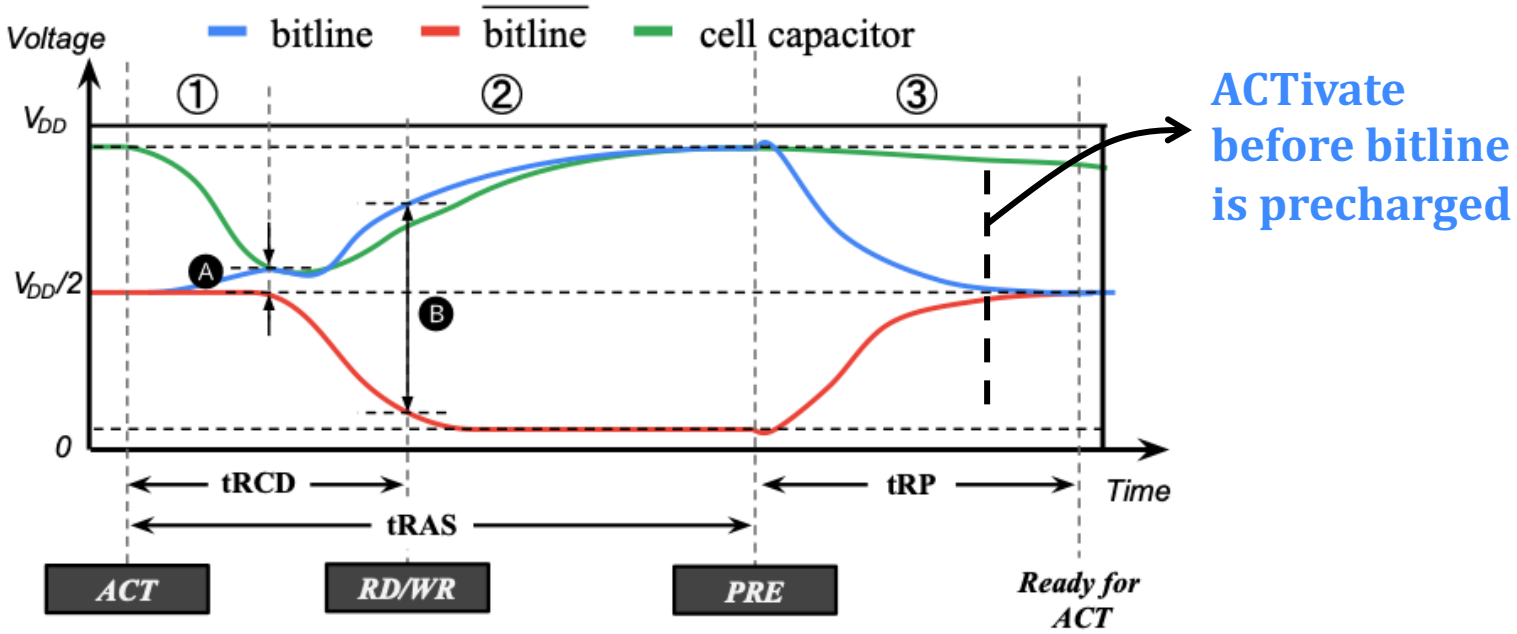
Low % chance to fail

The key idea is to extract random values by sampling DRAM cells that fail truly randomly



Talukder et al.

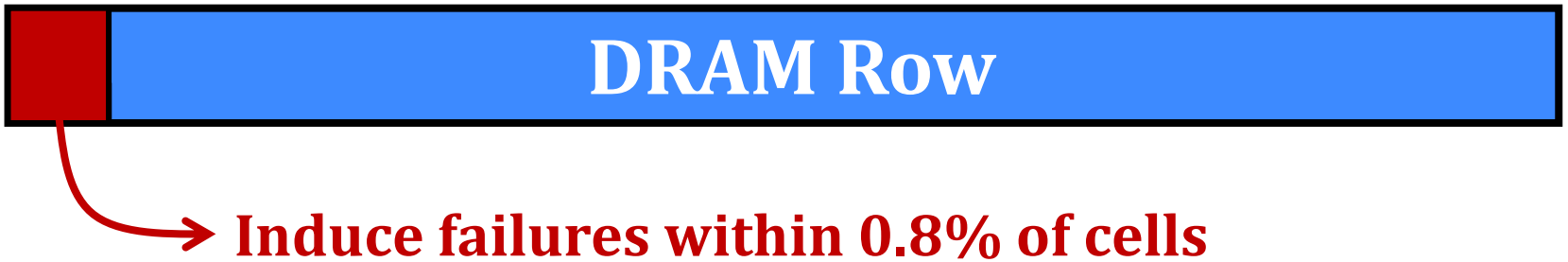
Key Idea: Sample DRAM cells that fail randomly, but with reduced tRP



Limitations of State-of-the-art

D-RaNGe

- Poorly utilizes activation granularity

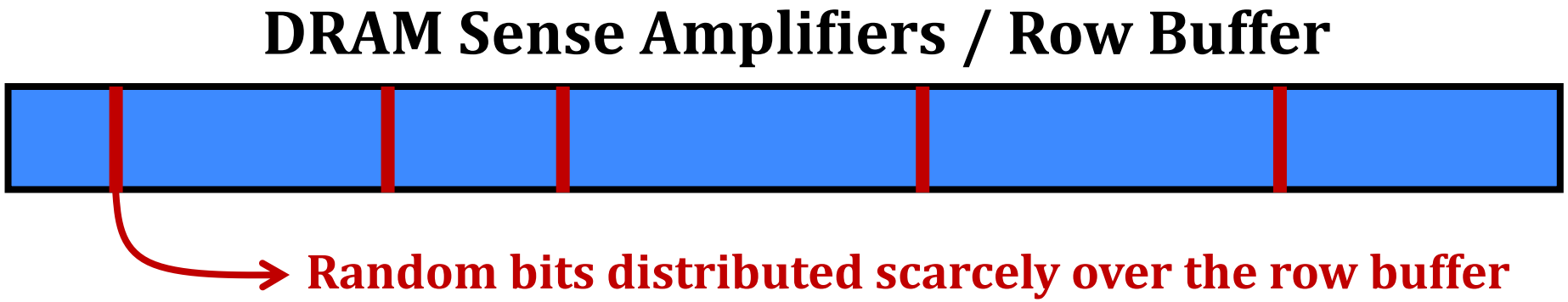


- Throughput limited by access latency

Limitations of State-of-the-art

Talukder et al.

- Well utilizes activation granularity
- *Cannot* induce metastability on many sense amplifiers



- Throughput limited by poor-quality randomness source

Limitations of State-of-the-art

Talukder et al.

- Well utilizes activation granularity
- *Cannot* induce metastability on many sense amplifiers

A **high-throughput** DRAM TRNG needs to:

(i) well utilize **activation granularity**

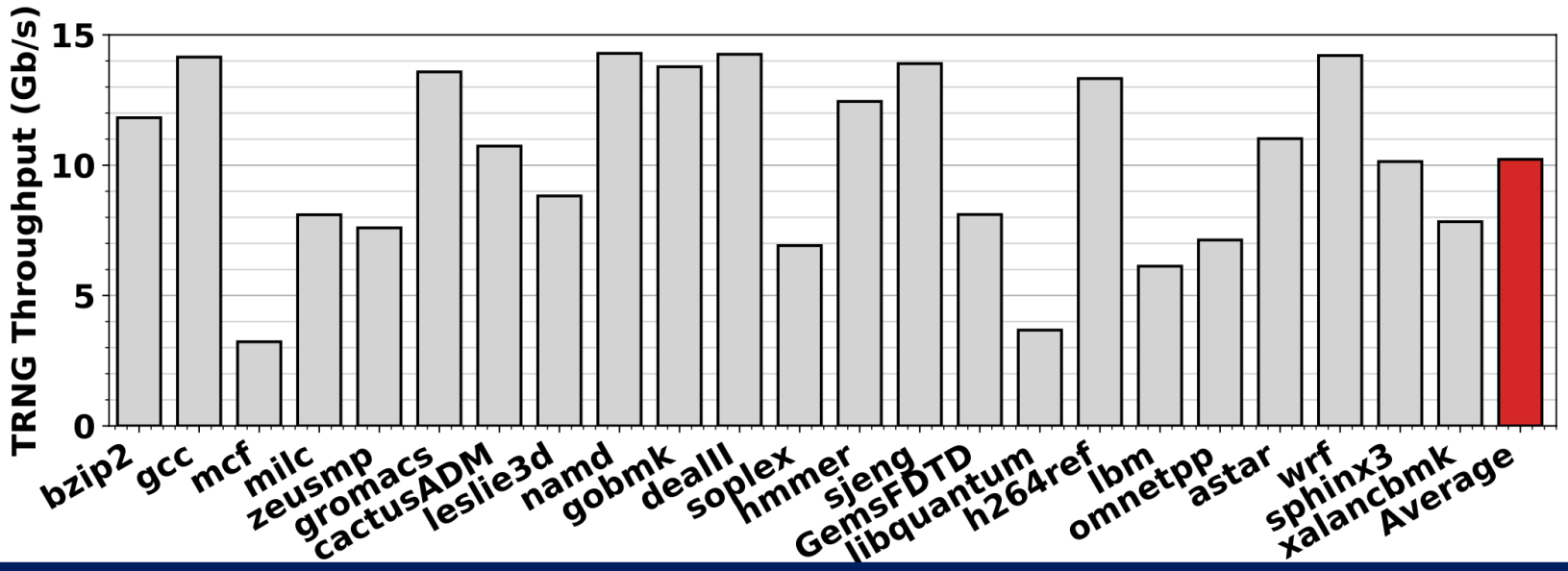
(ii) induce metastability on **many sense amplifiers**

- Throughput limited by poor-quality randomness source

System Performance Study

The maximum throughput QUAC-TRNG provides without reducing the total off-chip memory bandwidth

Ramulator: 3.2 GHz core, *four-channel* DDR4 memory



QUAC-TRNG achieves 74.1% of the empirical average throughput

Throughput & Latency Comparison

Table 2: Summary of prior DRAM-TRNGs vs QUAC-TRNG

Proposal	Entropy Source	TRNG Throughput	256-bit TRNG Latency
QUAC-TRNG	Quadruple ACT	13.76 Gb/s	274 ns
Talukder+ [15]	Precharge Failure	0.68 - 6.13 Gb/s	249 ns - 201 ns
D-RaNGe [88]	Activation Failure	0.92 - 9.73 Gb/s	260 ns - 36 ns
D-PUF [150]	Retention Failure	0.20 Mb/s	40 s
DRNG [47]	DRAM Start-up	N/A	700 µs
Keller+ [81]	Retention Failure	0.025 Mb/s	40 s
Pyo+ [126]	DRAM Cmd Schedule	2.17 Mb/s	112.5 µs

Based on fundamentally slow processes

Memory Overhead

The memory allocated for QUAC-TRNG is only 192 KiBs per DRAM module

- Four segments for QUAC (128 KiB)
- Eight DRAM rows for bulk initialization (64 KiB)
- 0.002% of the capacity of an 8 GB DDR4 DIMM.

Area Overhead

Require 326 bits of storage per DRAM channel

- Four DRAM addresses to point to segments (72 bits)
- Eight addresses to point to initialization operands (144 bits)
- 11 column addresses →
  256-bit total entropy cache block ranges (110 bits)

Model storage using CACTI:

- 0.0003 mm^2 for storage

0.0011 mm^2 for the SHA-256 engine

0.04% of a Zen 2 CPU (7 nm)

Sensitivity Study

Temperature Dependence

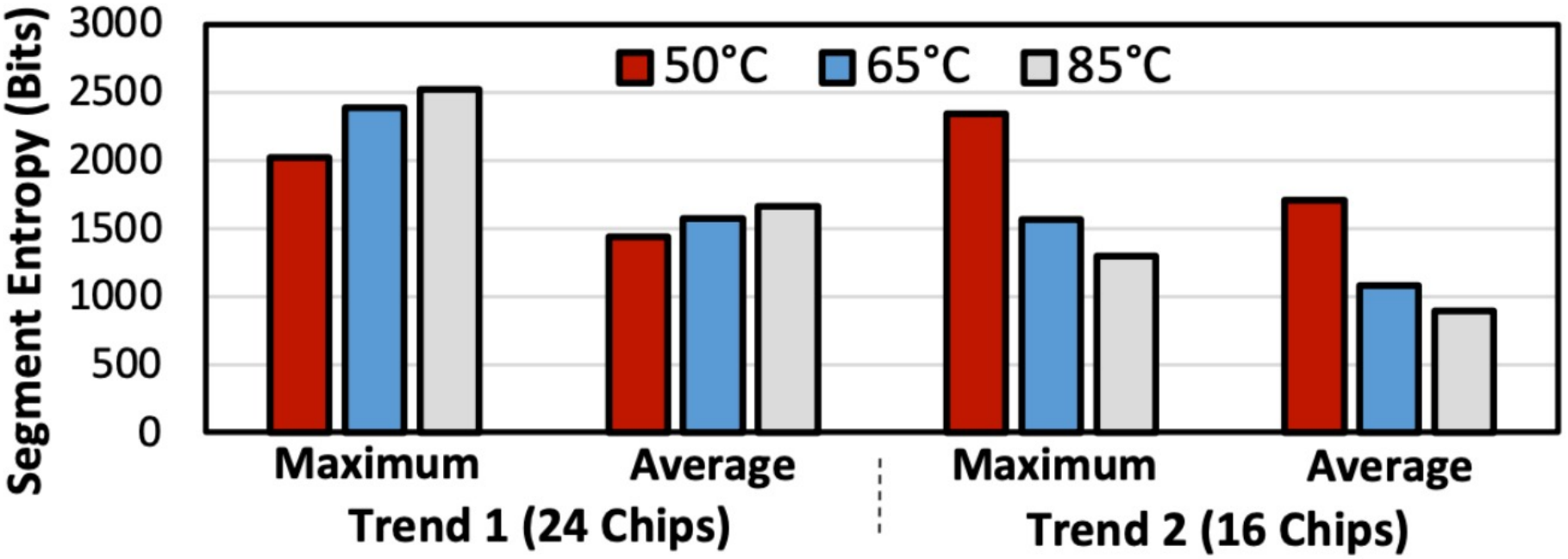
Record bitline entropy at 50, 65 and 85°C

Time Dependence

Record entropy at *the beginning* and *the end* of a 30-day period

Both studies use 5 DRAM modules and the "0111" data pattern

Temperature Dependence



Observe two temperature dependence trends

Entropy changes with temperature

Time Dependence

Entropy difference between the beginning and the end of the 30-day period:

- 2.4% average across all chips
- Maximum difference is 5.2% (minimum is 0.9%)

Characterized entropy is valid for at least 30 days

DDR4 Modules

Module	Module Identifier	Chip Identifier	Freq. (MT/s)	Organization			Segment Entropy		
				Size (GB)	Chips	Pins	Avg.	Max.†	Avg. (after 30 days)
$M1$	*Unknown*	H5AN4G8NAFR-TFC	2133	4	8	x8	1688.1	2247.4	–
$M2$	*Unknown*	*Unknown*	2133	4	8	x8	1180.4	1406.1	–
$M3$	*Unknown*	H5AN4G8NAFR-TFC	2133	4	8	x8	1205.0	1858.3	1192.9
$M4$	76TT21NUS1R8-4G	H5AN4G8NAFR-TFC	2133	4	8	x8	1608.1	2406.5	1588.0
$M5$	*Unknown*	T4D5128HT-21	2133	4	8	x8	1618.2	2121.6	–
$M6$	TLRD44G2666HC18F-SBK	H5AN4G8NMFR-VKC	2666	4	8	x8	1211.5	1444.6	–
$M7$	TLRD44G2666HC18F-SBK	H5AN4G8NMFR-VKC	2666	4	8	x8	1177.7	1404.4	–
$M8$	TLRD44G2666HC18F-SBK	H5AN4G8NMFR-VKC	2666	4	8	x8	1332.9	1600.9	1407.0
$M9$	TLRD44G2666HC18F-SBK	H5AN4G8NMFR-VKC	2666	4	8	x8	1137.1	1370.9	–
$M10$	TLRD44G2666HC18F-SBK	H5AN4G8NMFR-VKC	2666	4	8	x8	1208.5	1473.2	1251.8
$M11$	TLRD44G2666HC18F-SBK	H5AN4G8NMFR-VKC	2666	4	8	x8	1176.0	1382.9	1165.1
$M12$	TLRD44G2666HC18F-SBK	H5AN4G8NMFR-VKC	2666	4	8	x8	1485.0	1740.6	–
$M13$	KSM32RD8/16HDR	H5AN4G8NAFA-UHC	2400	4	8	x8	1853.5	2849.6	–
$M14$	F4-2400C17S-8GNT	H5AN4G8NMFR-UHC	2400	8	8	x8	1369.3	1942.2	–
$M15$	F4-2400C17S-8GNT	H5AN4G8NMFR-UHC	3200	8	8	x8	1545.8	2147.2	–
$M16$	KSM32RD8/16HDR	H5AN8G8NDJR-XNC	3200	16	8	x8	1634.4	1944.6	–
$M17$	KSM32RD8/16HDR	H5AN8G8NDJR-XNC	3200	16	8	x8	1664.7	2016.6	–

†The maximum possible entropy in a DRAM segment is 64K (65,536) bits.

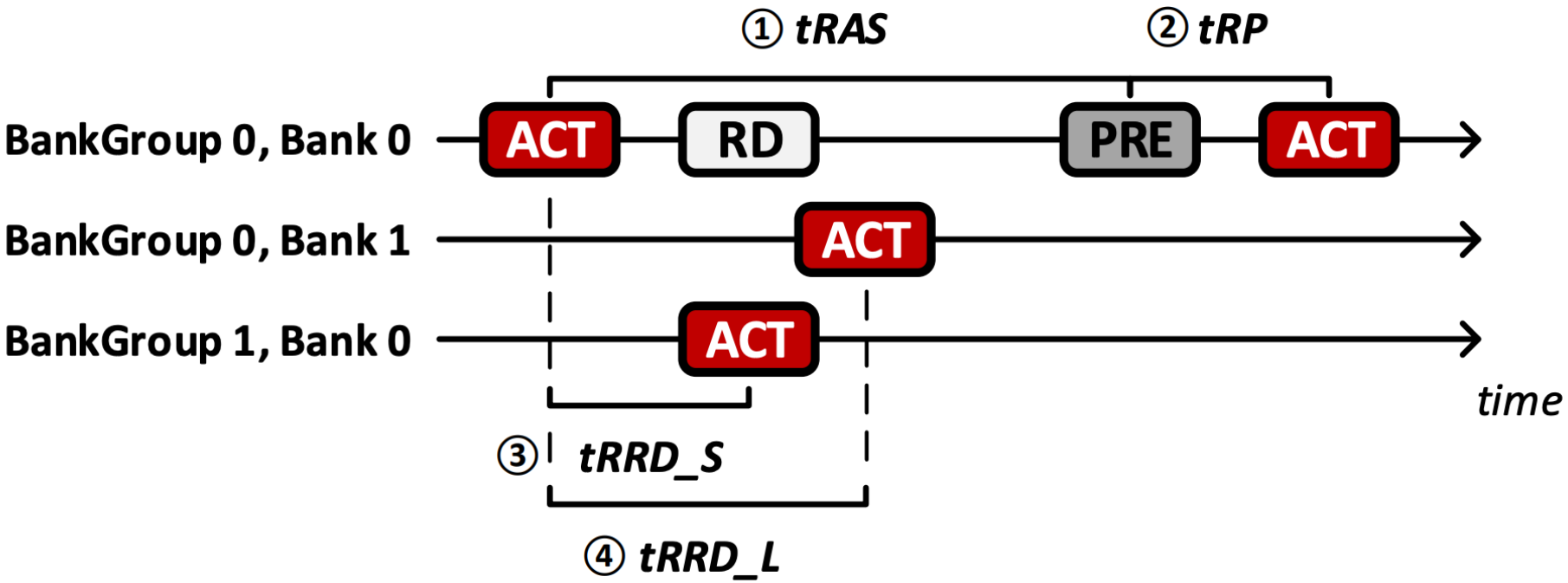


Figure 2: Timeline of key DDR4 commands.

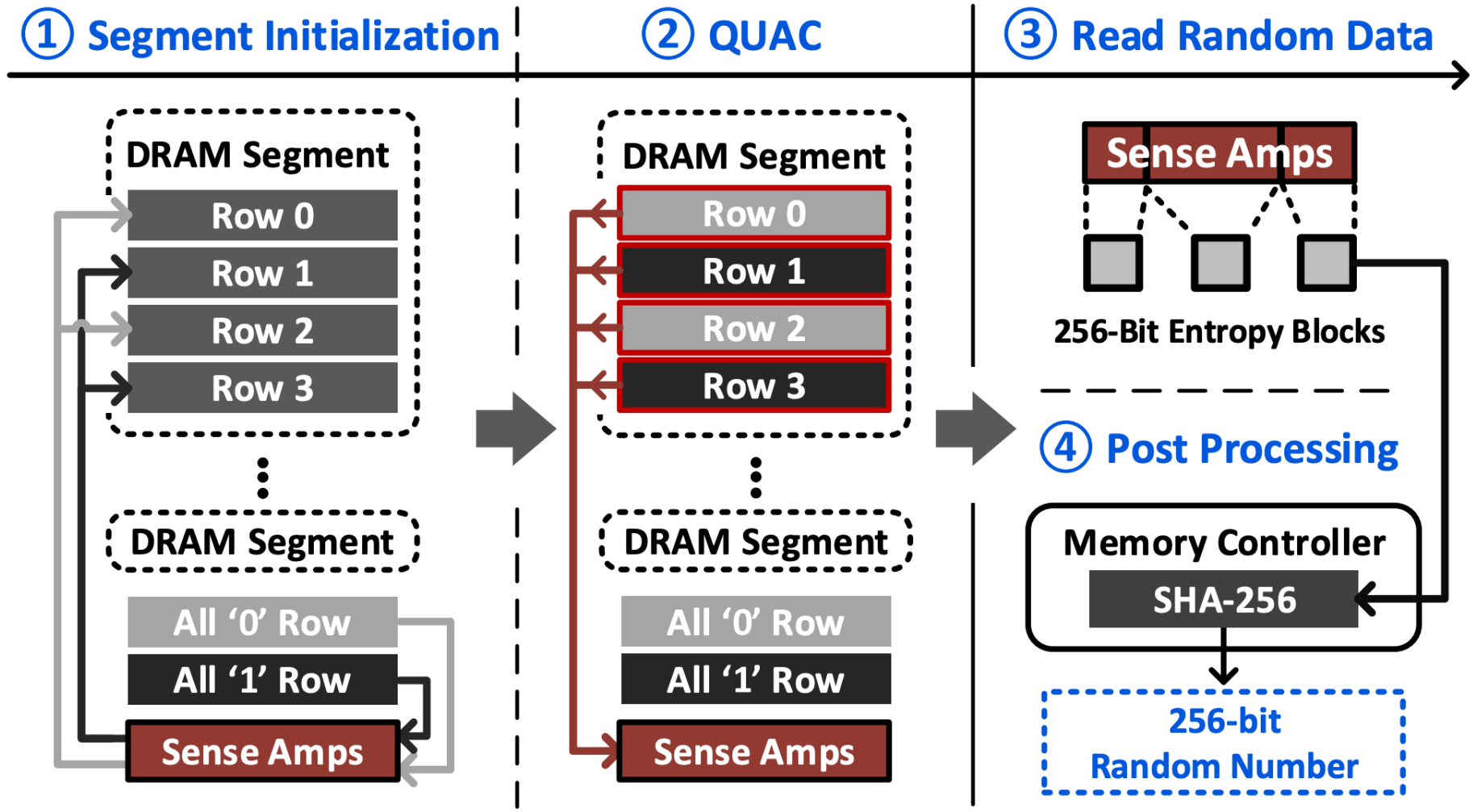


Figure 6: QUAC-TRNG mechanism.