Four Key Current Directions

- Fundamentally Secure/Reliable/Safe Architectures

- Fundamentally Energy-Efficient Architectures
  - Memory-centric (Data-centric) Architectures

- Fundamentally Low-Latency and Predictable Architectures

- Architectures for AI/ML, Genomics, Medicine, Health, ...
Two Major Sources of Latency Inefficiency

- Modern DRAM is not designed for low latency
  - Main focus is cost-per-bit (capacity)

- Modern DRAM latency is determined by worst case conditions and worst case devices
  - Much of memory latency is unnecessary

Our Goal: Reduce Memory Latency at the Source of the Problem
Why the Long Memory Latency?

**Reason 1: Design of DRAM Micro-architecture**
- Goal: Maximize capacity/area, not minimize latency

**Reason 2: “One size fits all” approach to latency specification**
- Same latency parameters for all temperatures
- Same latency parameters for all DRAM chips
- Same latency parameters for all parts of a DRAM chip
- Same latency parameters for all supply voltage levels
- Same latency parameters for all application data
- ...
More on TL-DRAM

- Donghyuk Lee, Yoongu Kim, Vivek Seshadri, Jamie Liu, Lavanya Subramanian, and Onur Mutlu,
  "Tiered-Latency DRAM: A Low Latency and Low Cost DRAM Architecture"
  Proceedings of the 19th International Symposium on High-Performance Computer Architecture (HPCA), Shenzhen, China, February 2013. Slides (pptx)

Tiered-Latency DRAM: A Low Latency and Low Cost DRAM Architecture

Donghyuk Lee  Yoongu Kim  Vivek Seshadri  Jamie Liu  Lavanya Subramanian  Onur Mutlu
Carnegie Mellon University
LISA: Low-Cost Inter-Linked Subarrays
[HPCA 2016]
Problem: Inefficient Bulk Data Movement

Bulk data movement is a key operation in many applications – `memmove` & `memcpy`: 5% cycles in Google’s datacenter [Kanev+ ISCA’15]

Long latency and high energy
Moving Data Inside DRAM?

Goal: Provide a new substrate to enable wide connectivity between subarrays.
Key Idea and Applications

• **Low-cost Inter-linked subarrays (LISA)**
  - Fast bulk data movement between subarrays
  - **Wide datapath via isolation transistors:** 0.8% DRAM chip area

• **LISA is a versatile substrate** → new applications
  - **Fast bulk data copy:** Copy latency 1.363ms → 0.148ms (9.2x)
    → 66% speedup, -55% DRAM energy
  - **In-DRAM caching:** Hot data access latency 48.7ns → 21.5ns (2.2x)
    → 5% speedup
  - **Fast precharge:** Precharge latency 13.1ns → 5.0ns (2.6x)
    → 8% speedup
New DRAM Command to Use LISA

**Row Buffer Movement (RBM):** Move a row of data in an activated row buffer to a precharged one.

RBM transfers an entire row b/w subarrays.
RBM Analysis

• The range of RBM depends on the DRAM design
  – Multiple RBMs to move data across > 3 subarrays

![Diagram showing subarrays and data flow]

• Validated with SPICE using worst-case cells
  – NCSU FreePDK 45nm library

• **4KB data in 8ns** (w/ 60% guardband)
  → **500 GB/s**, **26x** bandwidth of a DDR4-2400 channel

• **0.8%** DRAM chip area overhead [O+ ISCA’14]
1. Rapid Inter-Subarray Copying (RISC)

- **Goal:** Efficiently copy a row across subarrays
- **Key idea:** Use *RBM* to form a new command sequence

1. **Activate** `src` row

2. **RBM** `SA1 → SA2`

Reduces row-copy latency by 9.2x, DRAM energy by 48.1x
2. Variable Latency DRAM (VILLA)

- **Goal**: Reduce DRAM latency with low area overhead
- **Motivation**: Trade-off between area and latency

- **Long Bitline (DDRx)**
- **Short Bitline (RLDRAM)**

  **Shorter bitlines → faster activate and precharge time**

  **High area overhead: >40%**
### 2. Variable Latency DRAM (VILLA)

- **Key idea**: Reduce access latency of hot data via a heterogeneous DRAM design [Lee+ HPCA’13, Son+ ISCA’13]
- **VILLA**: Add fast subarrays as a *cache* in each bank

- Reduces hot data access latency by 2.2x at only 1.6% area overhead

-Challenge: VILLA cache requires frequent movement of data rows
3. Linked Precharge (LIP)

- **Problem**: The precharge time is limited by the strength of one precharge unit
- **Linked Precharge (LIP)**: LISA precharges a subarray using multiple precharge units

Reduces precharge latency by 2.6x (43% guardband)
More on LISA

Kevin K. Chang, Prashant J. Nair, Saugata Ghose, Donghyuk Lee, Moinuddin K. Qureshi, and Onur Mutlu,
"Low-Cost Inter-Linked Subarrays (LISA): Enabling Fast Inter-Subarray Data Movement in DRAM"
[Slides (pptx) (pdf)]
[Source Code]

Low-Cost Inter-Linked Subarrays (LISA):
Enabling Fast Inter-Subarray Data Movement in DRAM

Kevin K. Chang†, Prashant J. Nair*, Donghyuk Lee†, Saugata Ghose†, Moinuddin K. Qureshi*, and Onur Mutlu†
†Carnegie Mellon University  *Georgia Institute of Technology
CROW: The Copy Row Substrate
[ISCA 2019]
Challenges of DRAM Scaling

1. access latency
2. refresh overhead
3. exposure to vulnerabilities
Conventional DRAM

DRAM Subarray

row decoder

sense amplifier
Copy Row DRAM (CROW)

Row copy

Multiple row activation

DRAM Subarray

DRAM

SA
SA
SA
SA
SA
SA

Regular rows

Copy rows

Sense amplifier
Use Cases of CROW

- **CROW-cache**
  - ✓ reduces access latency

- **CROW-ref**
  - ✓ reduces DRAM refresh overhead

- A mechanism for protecting against RowHammer
Key Results

CROW-cache + CROW-ref

• 20% speedup
• 22% less DRAM energy

Hardware Overhead

• 0.5% DRAM chip area
• 1.6% DRAM capacity
• 11.3 KiB memory controller storage
More on CROW

- Hasan Hassan, Minesh Patel, Jeremie S. Kim, A. Giray Yaglikci, Nandita Vijaykumar, Nika Mansourighiasi, Saugata Ghose, and Onur Mutlu,

"CROW: A Low-Cost Substrate for Improving DRAM Performance, Energy Efficiency, and Reliability"

[Slides (pptx) (pdf)]
[Lightning Talk Slides (pptx) (pdf)]
[Poster (pptx) (pdf)]
[Lightning Talk Video (3 minutes)]
[Full Talk Video (16 minutes)]
[Source Code for CROW (Ramulator and Circuit Modeling)]

CROW: A Low-Cost Substrate for Improving DRAM Performance, Energy Efficiency, and Reliability

Hasan Hassan† Minesh Patel† Jeremie S. Kim†§ A. Giray Yaglikci†
Nandita Vijaykumar†§ Nika Mansouri Ghiasi† Saugata Ghose§ Onur Mutlu†§

†ETH Zürich §Carnegie Mellon University
CLR-DRAM: Capacity-Latency Reconfigurability


[Slides (pptx) (pdf)]
[Lightning Talk Slides (pptx) (pdf)]
[Talk Video (20 minutes)]
[Lightning Talk Video (3 minutes)]
CLR-DRAM: Capacity-Latency
Reconfigurable DRAM [ISCA 2020]
CLR-DRAM: A Low-Cost DRAM Architecture Enabling Dynamic Capacity-Latency Trade-off

Haocong Luo  Taha Shahroodi  Hasan Hassan  Minesh Patel
A. Giray Yaglıkçı  Lois Orosa  Jisung Park  Onur Mutlu

ETH Zürich  SAFARI Research Group  ShanghaiTech University
Motivation & Goal

- Workloads and systems have **varying** main memory capacity and latency demands.
- Existing commodity DRAM makes **static** capacity-latency trade-off at **design time**.
- Systems miss opportunities to improve performance by adapting to changes in main memory capacity and latency demands.
- **Goal**: Design a low-cost DRAM architecture that can be **dynamically** configured to have high capacity or low latency at a fine granularity (i.e., at the granularity of a row).
CLR-DRAM (Capacity-Latency-Reconfigurable DRAM)

- **CLR-DRAM (Capacity-Latency-Reconfigurable DRAM):**
  - A low cost DRAM architecture that enables a single DRAM row to dynamically switch between max-capacity mode or high-performance mode.

- **Key Idea:**
  *Dynamically* configure the connections between DRAM cells and sense amplifiers in the density-optimized open-bitline architecture.

---

**SAFARI**

Open-bitline (Baseline)  CLR-DRAM
CLR-DRAM (Capacity-Latency-Reconfigurable DRAM)

- **Max-capacity mode**

  - The same storage capacity as the conventional open-bitline architecture

- **High-performance mode**

  - Reduced latency and refresh overhead via coupled cell/SA operation

  *mimics the cell-to-SA connections as in the open-bitline architecture*
Key Results

- **DRAM Latency Reduction:**
  - Activation latency (tRCD) by 60.1%
  - Restoration latency (tRAS) by 64.2%
  - Precharge latency (tRP) by 46.4%
  - Write-recovery latency (tWR) by 35.2%

- **System-level Benefits:**
  - Performance improvement: 18.6%
  - DRAM energy reduction: 29.7%
  - DRAM refresh energy reduction: 66.1%

We hope that CLR-Dram can be exploited to develop more flexible systems that can adapt to the diverse and changing DRAM capacity and latency demands of workloads.
More on CLR-DRAM


[Slides (pptx) (pdf)]
[Lightning Talk Slides (pptx) (pdf)]
[Talk Video (20 minutes)]
[Lightning Talk Video (3 minutes)]
SALP: Reducing DRAM Bank Conflict Impact

Kim, Seshadri, Lee, Liu, Mutlu
*A Case for Exploiting Subarray-Level Parallelism (SALP) in DRAM*
ISCA 2012.
SALP: Problem, Goal, Observations

- **Problem:** Bank conflicts are costly for performance and energy
  - serialized requests, wasted energy (thrashing of row buffer, busy wait)
- **Goal:** Reduce bank conflicts without adding more banks (low cost)
- **Observation 1:** A DRAM bank is divided into subarrays and each subarray has its own local row buffer
Observation 2: **Subarrays are mostly independent**
- Except when sharing **global structures** to reduce cost

**Key Idea of SALP:** Minimally reduce sharing of global structures

- Reduce the sharing of...
  - Global decoder → Enables almost parallel access to subarrays
  - Global row buffer → Utilizes multiple local row buffers
SALP: Reduce Sharing of Global Decoder

Instead of a global latch, have *per-subarray latches*.
SALP: Reduce Sharing of Global Row-Buffer

Selectively connect local row-buffers to global row-buffer using a **Designated** single-bit latch.
SALP: Baseline Bank Organization

Global Decoder

Global bitlines

Latch

Local row-buffer

Local row-buffer

Global row-buffer
**SALP: Proposed Bank Organization**

- **Global Decoder**
- **Local row-buffer**
- **Global bitlines**
- **Local row-buffer**

**Overhead of SALP in DRAM chip:** 0.15%

1. Global latch → per-subarray local latches
2. Designated bit latches and wire to selectively enable a subarray
SALP: Results

- Wide variety of systems with different #channels, banks, ranks, subarrays
- Server, streaming, random-access, SPEC workloads

- Dynamic DRAM energy reduction: 19%
  - DRAM row hit rate improvement: 13%

- System performance improvement: 17%
  - Within 3% of ideal (all independent banks)

- DRAM die area overhead: 0.15%
  - vs. 36% overhead of independent banks

![Graph showing IPC increase and die-size comparison]
More on SALP

- Yoongu Kim, Vivek Seshadri, Donghyuk Lee, Jamie Liu, and Onur Mutlu, "A Case for Exploiting Subarray-Level Parallelism (SALP) in DRAM"

Proceedings of the 39th International Symposium on Computer Architecture (ISCA), Portland, OR, June 2012. Slides (pptx)
More on SALP

DRAM Process Scaling Challenges

- Refresh
  - Difficult to build high-aspect ratio cell capacitors decreasing cell capacitance

THE MEMORY FORUM 2014

Co-Architecting Controllers and DRAM to Enhance DRAM Process Scaling

Uksong Kang, Hak-soo Yu, Churoo Park, *Hongzhong Zheng,
**John Halbert, **Kuljit Bains, SeongJin Jang, and Joo Sun Choi

Samsung Electronics, Hwasung, Korea / *Samsung Electronics, San Jose / **Intel
More on SALP

Sub-array Level Parallelism with tWR Relaxation

- **tWR relaxation**
  - Relaxing tWR results in DRAM yield improvement but can degrade performance requiring new compensating features
  - By increasing tWR 5X (from 15ns to 75ns), fail bit counts are expected to reduce by 1 to 2 orders of magnitudes

- **Sub-array level parallelism (SALP)**
  - Allows a page in another sub-array in the same bank to be opened in parallel with the currently activated sub-array
  - Results in performance gain by increasing the row access parallelism within a bank
  ⇒ Used to compensate for the performance loss caused by tWR relaxation

More on SALP

Performance Impact of SALP and tWR relaxation

- Performance simulations run for various workloads when tWR is relaxed by 2X and 3X, and when SALP is applied with 2 sub-banks

- Results show that performance is reduced by ~5% and ~2% in average if tWR is relaxed by 3X and 2X, respectively

- Results also show that performance is compensated, and even improved to up to ~3% in average when SALP is applied, even with tWR relaxed by 3X

[Graph showing performance impact]

Why the Long Memory Latency?

- **Reason 1: Design of DRAM Micro-architecture**
  - Goal: Maximize capacity/area, not minimize latency

- **Reason 2: “One size fits all” approach to latency specification**
  - Same latency parameters for all temperatures
  - Same latency parameters for all DRAM chips
  - Same latency parameters for all parts of a DRAM chip
  - Same latency parameters for all supply voltage levels
  - Same latency parameters for all application data
  - ...

Tackling the Fixed Latency Mindset

- Reliable operation latency is actually very heterogeneous
  - Across temperatures, chips, parts of a chip, voltage levels, ...

- Idea: Dynamically find out and use the lowest latency one can reliably access a memory location with
  - Adaptive-Latency DRAM [HPCA 2015]
  - Flexible-Latency DRAM [SIGMETRICS 2016]
  - Design-Induced Variation-Aware DRAM [SIGMETRICS 2017]
  - Voltron [SIGMETRICS 2017]
  - DRAM Latency PUF [HPCA 2018]
  - Solar DRAM [ICCD 2018]
  - DRAM Latency True Random Number Generator [HPCA 2019]
  - ...

- We would like to find sources of latency heterogeneity and exploit them to minimize latency (or create other benefits)
Latency Variation in Memory Chips

Heterogeneous manufacturing & operating conditions → latency variation in timing parameters
Why is Latency High?

- **DRAM latency**: Delay as specified in DRAM standards
  - Doesn’t reflect true DRAM device latency
- Imperfect manufacturing process $\rightarrow$ latency variation
- **High standard latency** chosen to increase yield

![Image of DRAM latency variation](image.png)
What Causes the Long Memory Latency?

- **Conservative timing margins!**

- **DRAM timing parameters are set to cover the worst case**

- **Worst-case temperatures**
  - 85 degrees vs. common-case
  - to enable a wide range of operating conditions

- **Worst-case devices**
  - DRAM cell with smallest charge across any acceptable device
  - to tolerate process variation at acceptable yield

- **This leads to large timing margins for the common case**
Understanding and Exploiting Variation in DRAM Latency
DRAM Stores Data as Charge

Three steps of charge movement

1. Sensing
2. Restore
3. Precharge
Why does DRAM need the extra timing margin?
Two Reasons for Timing Margin

1. Process Variation
   - DRAM cells are not equal
   - Leads to extra timing margin for a cell that can store a large amount of charge

2. Temperature Dependence
DRAM Cells are Not Equal

Ideal

Real

Large variation in cell size
Large variation in charge
Large variation in access latency
Process Variation

- Cell Capacitance
- Contact Resistance
- Transistor Performance

Small cell can store small charge

- Small cell capacitance
- High contact resistance
- Slow access transistor

High access latency
Two Reasons for Timing Margin

1. *Process Variation*
   - DRAM cells are not equal
   - Leads to *extra timing margin* for a cell that can store a large amount of charge

2. *Temperature Dependence*
   - DRAM leaks more charge at higher temperature
   - Leads to extra timing margin for cells that operate at low temperature
Charge Leakage vs. Temperature

**Cells store small charge at high temperature and large charge at low temperature**

→ Large variation in access latency
DRAM Timing Parameters

• **DRAM timing parameters are dictated by the worst-case**
  - The smallest cell with the smallest charge in all DRAM products
  - Operating at the highest temperature

• **Large timing margin for the common-case**
Adaptive-Latency DRAM [HPCA 2015]

- Idea: Optimize DRAM timing for the common case
  - Current temperature
  - Current DRAM module

- Why would this reduce latency?
  - A DRAM cell can store much more charge in the common case (low temperature, strong cell) than in the worst case
  - More charge in a DRAM cell
    → Faster sensing, charge restoration, precharging
    → Faster access (read, write, refresh, ...)

Extra Charge $\rightarrow$ Reduced Latency

1. Sensing
   Sense **cells with extra charge** faster
   $\rightarrow$ Lower sensing latency

2. Restore
   No need to fully restore **cells with extra charge**
   $\rightarrow$ Lower restoration latency

3. Precharge
   No need to fully precharge bitlines for **cells with extra charge**
   $\rightarrow$ Lower precharge latency
DRAM Characterization Infrastructure

DRAM Characterization Infrastructure


- Flexible
- Easy to Use (C++ API)
- Open-source
  
github.com/CMU-SAFARI/SoftMC
SoftMC: Open Source DRAM Infrastructure

https://github.com/CMU-SAFARI/SoftMC

SoftMC: A Flexible and Practical Open-Source Infrastructure for Enabling Experimental DRAM Studies

Hasan Hassan\textsuperscript{1,2,3} Nandita Vijaykumar\textsuperscript{3} Samira Khan\textsuperscript{4,3} Saugata Ghose\textsuperscript{3} Kevin Chang\textsuperscript{3} Gennady Pekhimenko\textsuperscript{5,3} Donghyuk Lee\textsuperscript{6,3} Oguz Ergin\textsuperscript{2} Onur Mutlu\textsuperscript{1,3}

\textsuperscript{1}ETH Zürich \quad \textsuperscript{2}TOBB University of Economics & Technology \quad \textsuperscript{3}Carnegie Mellon University \\
\textsuperscript{4}University of Virginia \quad \textsuperscript{5}Microsoft Research \quad \textsuperscript{6}NVIDIA Research
Observation 1. Faster Sensing

Typical DIMM at Low Temperature

- More Charge
- Strong Charge Flow
- Faster Sensing

Timing (tRCD)

17% ↓
No Errors

115 DIMM Characterization

Typical DIMM at Low Temperature

⇒ More charge ⇒ Faster sensing
Observation 2. Reducing Restore Time

**Typical DIMM at Low Temperature**

Less Leakage ➔ Extra Charge

No Need to Fully Restore Charge

**115 DIMM Characterization**

Read (t_{RAS})

37% ↓

Write (t_{WR})

54% ↓

No Errors

Typical DIMM at lower temperature

➔ More charge ➔ Restore time reduction
AL-DRAM

- **Key idea**
  - Optimize DRAM timing parameters online

- **Two components**
  - DRAM manufacturer provides multiple sets of reliable DRAM timing parameters at different temperatures for each DIMM
  - System monitors DRAM temperature & uses appropriate DRAM timing parameters

---

DRAM Temperature

- **DRAM temperature measurement**
  - Server cluster: Operates at under 34°C
  - Desktop: Operates at under 50°C
  - **DRAM standard optimized for 85 °C**

**DRAM operates at low temperatures in the common-case**

- Previous works – Maintain low DRAM temperature
  - David+ ICAC 2011
  - Liu+ ISCA 2007
  - Zhu+ IThERM 2008
Latency Reduction Summary of 115 DIMMs

• *Latency reduction for read & write (55°C)*
  – Read Latency: **32.7%**
  – Write Latency: **55.1%**

• *Latency reduction for each timing parameter (55°C)*
  – Sensing: **17.3%**
  – Restore: **37.3%** (read), **54.8%** (write)
  – Precharge: **35.2%**
AL-DRAM: Real System Evaluation

- **System**
  - CPU: AMD 4386 (8 Cores, 3.1GHz, 8MB LLC)

---

**D18F2x200_dct[0]_mp[1:0] DDR3 DRAM Timing 0**

Reset: 0F05_0505h. See 2.9.3 [DCT Configuration Registers].

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<th>Description</th>
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</thead>
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<td>31:30</td>
<td>Reserved.</td>
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<tr>
<td>29:24</td>
<td><strong>Tras:</strong> row active strobe. Read-write. BIOS: See 2.9.7.5 [SPD ROM-Based Configuration]. Specifies the minimum time in memory clock cycles from an activate command to a precharge command, both to the same chip select bank.</td>
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<table>
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<th>Bits</th>
<th>Description</th>
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<tr>
<td>07h-00h</td>
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</tr>
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<td>2Ah-08h</td>
<td>&lt;Tras&gt; clocks</td>
</tr>
<tr>
<td>3Fh-2Bh</td>
<td>Reserved</td>
</tr>
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</table>

| 23:21  | Reserved.                   |

| 20:16  | **Trp:** row precharge time. Read-write. BIOS: See 2.9.7.5 [SPD ROM-Based Configuration]. Specifies the minimum time in memory clock cycles from a precharge command to an activate command or auto refresh command, both to the same bank. |

<table>
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<th>Bits</th>
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<td>&lt;Trp&gt; clocks</td>
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<tr>
<td>5:2</td>
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<td>1:0</td>
<td>Reserved.</td>
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AL-DRAM improves performance on a real system
AL-DRAM: Multi-Core Evaluation

Performance Improvement

Average Improvement

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<th>Workload</th>
<th>Single Core</th>
<th>Multi Core</th>
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<tbody>
<tr>
<td>soplex</td>
<td>14.0%</td>
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</tr>
<tr>
<td>mcf</td>
<td>2.9%</td>
<td>10.4%</td>
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<tr>
<td>all-workload</td>
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<td></td>
<td>10.4%</td>
</tr>
</tbody>
</table>

AL-DRAM provides higher performance for multi-programmed & multi-threaded workloads
Reducing Latency Also Reduces Energy

- AL-DRAM reduces DRAM power consumption by 5.8%
- Major reason: reduction in row activation time
AL-DRAM: Advantages & Disadvantages

- **Advantages**
  + Simple mechanism to reduce latency
  + Significant system performance and energy benefits
    + Benefits higher at low temperature
  + Low cost, low complexity

- **Disadvantages**
  - Need to determine reliable operating latencies for different temperatures and different DIMMs → higher testing cost
    (might not be that difficult for low temperatures)
More on AL-DRAM

- Donghyuk Lee, Yoongu Kim, Gennady Pekhimenko, Samira Khan, Vivek Seshadri, Kevin Chang, and Onur Mutlu,

"Adaptive-Latency DRAM: Optimizing DRAM Timing for the Common-Case"


[Slides (pptx) (pdf)] [Full data sets]

Adaptive-Latency DRAM: Optimizing DRAM Timing for the Common-Case

Donghyuk Lee  Yoongu Kim  Gennady Pekhimenko
Samira Khan  Vivek Seshadri  Kevin Chang  Onur Mutlu

Carnegie Mellon University
Different Types of Latency Variation

- AL-DRAM exploits latency variation
  - Across time (different temperatures)
  - Across chips

- Is there also latency variation within a chip?
  - Across different parts of a chip
Why the Long Memory Latency?

- **Reason 1: Design of DRAM Micro-architecture**
  - Goal: Maximize capacity/area, not minimize latency

- **Reason 2: “One size fits all” approach to latency specification**
  - Same latency parameters for all **temperatures**
  - Same latency parameters for all **DRAM chips**
  - **Same latency parameters for all parts of a DRAM chip**
  - Same latency parameters for all **supply voltage levels**
  - Same latency parameters for all **application data**
  - ...

SAFARI
Variation in Activation Errors

Results from 7500 rounds over 240 chips

Modern DRAM chips exhibit significant variation in activation latency
Spatial Locality of Activation Errors

Activation errors are concentrated at certain columns of cells
 Mechanism to Reduce DRAM Latency

- **Observation:** DRAM timing errors (slow DRAM cells) are concentrated in certain DRAM regions

- **Flexible-Latency (FLY) DRAM**
  - A software-transparent design that reduces latency

- **Key idea:**
  1) Divide memory into regions of different latencies
  2) *Memory controller:* Use lower latency for regions without slow cells; higher latency for other regions

**FLY-DRAM Configurations**

<table>
<thead>
<tr>
<th>Fraction of Cells</th>
<th>100%</th>
<th>80%</th>
<th>60%</th>
<th>40%</th>
<th>20%</th>
<th>0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (DDR3)</td>
<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

- **tRCD**
  - 13ns
  - 10ns
  - 7.5ns

- **tRP**
  - 13ns
  - 10ns
  - 7.5ns

Chang+, “**Understanding Latency Variation in Modern DRAM Chips: Experimental Characterization, Analysis, and Optimization**”, SIGMETRICS 2016.
Results

FLY-DRAM improves performance by exploiting spatial latency variation in DRAM

FLY-DRAM: Advantages & Disadvantages

- **Advantages**
  - Reduces latency significantly
  - Exploits significant within-chip latency variation

- **Disadvantages**
  - Need to determine reliable operating latencies for different parts of a chip → higher testing cost
  - More complicated controller
Analysis of Latency Variation in DRAM Chips

- Kevin Chang, Abhijith Kashyap, Hasan Hassan, Samira Khan, Kevin Hsieh, Donghyuk Lee, Saugata Ghose, Gennady Pekhimenko, Tianshi Li, and Onur Mutlu,

"Understanding Latency Variation in Modern DRAM Chips: Experimental Characterization, Analysis, and Optimization"

[Slides (pptx) (pdf)]
[Source Code]
Putting It All Together: Solar-DRAM
Solar-DRAM: Putting It Together


Solar-DRAM: Reducing DRAM Access Latency by Exploiting the Variation in Local Bitlines

Jeremie S. Kim‡§ Minesh Patel§ Hasan Hassan§ Onur Mutlu‡†
‡Carnegie Mellon University §ETH Zürich
More on Solar DRAM

Spatial Distribution of Failures

How are activation failures spatially distributed in DRAM?

1024
512

DRAM Row (number)

DRAM Column (number)

Subarray Edge

Activation failures are **highly constrained** to local bitlines (i.e., subarrays)

Solar-DRAM: Reducing DRAM Access Latency by Exploiting the Variation in Local Bitlines - ICCD 2018

https://www.youtube.com/watch?v=WPmDIx1mKrU
Why Is There Spatial Latency Variation Within a Chip?
What Is Design-Induced Variation?

Systematic variation in cell access times caused by the physical organization of DRAM

Inherently fast

Inherently slow

across row
distance from sense amplifier

across column
distance from wordline driver
DIVA Online Profiling

Design-Induced-Variation-Aware

Profile only slow regions to determine min. latency → Dynamic & low cost latency optimization
**DIVA Online Profiling**

**Design-Induced-Variation-Aware**

- slow cells
- process variation
- random error
- inherently slow design-induced variation
- localized error
- error-correcting code
- online profiling

Combine **error-correcting codes & online profiling** → **Reliably** reduce DRAM latency
DIVA-DRAM reduces latency more aggressively and uses ECC to correct random slow cells.
DIVA-DRAM: Advantages & Disadvantages

- **Advantages**
  
  ++ Automatically finds the lowest reliable operating latency at system runtime (lower production-time testing cost)
  
  + Reduces latency more than prior methods (w/ ECC)
  
  + Reduces latency at high temperatures as well

- **Disadvantages**

  - Requires knowledge of inherently-slow regions
  
  - Requires ECC (Error Correcting Codes)
  
  - Imposes overhead during runtime profiling
  
  - More complicated memory controller (capable of profiling)
Design-Induced Latency Variation in DRAM

- Donghyuk Lee, Samira Khan, Lavanya Subramanian, Saugata Ghose, Rachata Ausavarungnirun, Gennady Pekhimenko, Vivek Seshadri, and Onur Mutlu,

"Design-Induced Latency Variation in Modern DRAM Chips: Characterization, Analysis, and Latency Reduction Mechanisms"


Design-Induced Latency Variation in Modern DRAM Chips: Characterization, Analysis, and Latency Reduction Mechanisms

Donghyuk Lee, NVIDIA and Carnegie Mellon University
Samira Khan, University of Virginia
Lavanya Subramanian, Saugata Ghose, Rachata Ausavarungnirun, Carnegie Mellon University
Gennady Pekhimenko, Vivek Seshadri, Microsoft Research
Onur Mutlu, ETH Zürich and Carnegie Mellon University
Why the Long Memory Latency?

- **Reason 1:** Design of DRAM Micro-architecture
  - Goal: Maximize capacity/area, not minimize latency

- **Reason 2:** “One size fits all” approach to latency specification
  - Same latency parameters for all temperatures
  - Same latency parameters for all DRAM chips
  - Same latency parameters for all parts of a DRAM chip
  - Same latency parameters for all supply voltage levels
  - Same latency parameters for all application data
  - ...
Data-Aware DRAM Latency for DNN Inference

- Deep Neural Network evaluation is very DRAM-intensive (especially for large networks)

1. Some data and layers in DNNs are very tolerant to errors

2. Reduce DRAM latency and voltage on such data and layers

3. While still achieving a user-specified DNN accuracy target by making training DRAM-error-aware

Data-aware management of DRAM latency and voltage for Deep Neural Network Inference
Example DNN Data Type to DRAM Mapping

Mapping example of ResNet-50:

Map more error-tolerant DNN layers to DRAM partitions with lower voltage/latency

4 DRAM partitions with different error rates
Key idea: Enable **accurate, efficient** DNN inference using approximate DRAM

**EDEN** is an **iterative** process that has **3 key steps**
CPU: DRAM Energy Evaluation

Average **21%** DRAM energy reduction maintaining accuracy within 1% of original
CPU: Performance Evaluation

Average **8%** system speedup
Some workloads achieve **17%** speedup

EDEN achieves **close to the ideal** speedup possible via tRCD scaling
GPU, Eyeriss, and TPU: Energy Evaluation

- **GPU**: average 37% energy reduction
- **Eyeriss**: average 31% energy reduction
- **TPU**: average 32% energy reduction
EDEN: Data-Aware Efficient DNN Inference

- Skanda Koppula, Lois Orosa, A. Giray Yaglikci, Roknoddin Azizi, Taha Shahroodi, Konstantinos Kanellopoulos, and Onur Mutlu,

"EDEN: Enabling Energy-Efficient, High-Performance Deep Neural Network Inference Using Approximate DRAM"

Proceedings of the 52nd International Symposium on Microarchitecture (MICRO), Columbus, OH, USA, October 2019.

[Lightning Talk Slides (pptx) (pdf)]
[Lightning Talk Video (90 seconds)]
EDEN: Overview

Key idea: Enabling accurate, efficient DNN inference using approximate DRAM

EDEN is an iterative process that has 3 key steps:

1. Boosting DNN Error Tolerance
2. DNN Error Tolerance Characterization
3. DNN to DRAM Mapping

More on EDEN
Exploiting Memory Error Tolerance with Hybrid Memory Systems

Vulnerable data

Tolerant data

Reliable memory

Low-cost memory

On Microsoft’s Web Search workload
Reduces server hardware cost by 4.7 %
Achieves single server availability target of 99.90 %

Heterogeneous-Reliability Memory [DSN 2014]
Heterogeneous-Reliability Memory

Step 1: Characterize and classify application memory error tolerance

Step 2: Map application data to the HRM system enabled by SW/HW cooperative solutions

Reliable memory
Parity memory + software recovery (Par+R)
Low-cost memory
More on Heterogeneous-Reliability Memory

- Yixin Luo, Sriram Govindan, Bikash Sharma, Mark Santaniello, Justin Meza, Aman Kansal, Jie Liu, Badriddine Khessib, Kushagra Vaid, and Onur Mutlu,

"Characterizing Application Memory Error Vulnerability to Optimize Data Center Cost via Heterogeneous-Reliability Memory"

Proceedings of the 44th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Atlanta, GA, June 2014. [Summary] [Slides (pptx) (pdf)] [Coverage on ZDNet]
Why the Long Memory Latency?

- **Reason 1: Design of DRAM Micro-architecture**
  - Goal: Maximize capacity/area, not minimize latency

- **Reason 2: “One size fits all” approach to latency specification**
  - Same latency parameters for all temperatures
  - Same latency parameters for all DRAM chips
  - Same latency parameters for all parts of a DRAM chip
  - **Same latency parameters for all supply voltage levels**
  - Same latency parameters for all application data
  - ...
Understanding & Exploiting the Voltage-Latency-Reliability Relationship
Analysis of Latency-Voltage in DRAM Chips

Kevin Chang, A. Giray Yaglikci, Saugata Ghose, Aditya Agrawal, Niladrish Chatterjee, Abhijith Kashyap, Donghyuk Lee, Mike O'Connor, Hasan Hassan, and Onur Mutlu,
"Understanding Reduced-Voltage Operation in Modern DRAM Devices: Experimental Characterization, Analysis, and Mechanisms"

Understanding Reduced-Voltage Operation in Modern DRAM Chips: Characterization, Analysis, and Mechanisms

Kevin K. Chang† Abdullah Giray Yaglıkçı† Saugata Ghose† Aditya Agrawal§ Niladrish Chatterjee§
Abhijith Kashyap† Donghyuk Lee¶ Mike O’Connor¶, ‡ Hasan Hassan§ Onur Mutlu§, †
†Carnegie Mellon University ‡NVIDIA ¶The University of Texas at Austin $ETH Zürich

SAFARI
High DRAM Power Consumption

- **Problem**: High DRAM (memory) power in today’s systems

>40% in POWER7 \(^{(\text{Ware+}, \text{HPCA’10})}\) >40% in GPU \(^{(\text{Paul+}, \text{ISCA’15})}\)
Key Questions

• How does reducing voltage affect reliability (errors)?

• How does reducing voltage affect DRAM latency?

• How do we design a new DRAM energy reduction mechanism?
Supply Voltage Control on DRAM

Adjust the supply voltage to every chip on the same module.
Custom Testing Platform

**SoftMC** [Hassan+, HPCA’17]: FPGA testing platform to

1) **Adjust supply voltage** to DRAM modules
2) **Schedule DRAM commands** to DRAM modules

Existing systems: DRAM commands not exposed to users

[Diagram showing FPGA, DRAM module, and Voltage controller]

https://github.com/CMU-SAFARI/DRAM-Voltage-Study
Tested DRAM Modules

- **124 DDR3L** (low-voltage) DRAM chips
  - 31 SO-DIMMs
  - **1.35V** (DDR3 uses 1.5V)
  - Density: 4Gb per chip
  - Three major vendors/manufacturers

- Iteratively read every bit in each 4Gb chip under a wide range of supply voltage levels: 1.35V to 1.0V (-26%)
Reliability Worsens with Lower Voltage

Errors induced by reduced-voltage operation

Reducing voltage below $V_{\text{min}}$ causes an increasing number of errors
Source of Errors

Detailed circuit simulations (SPICE) of a DRAM cell array to model the behavior of DRAM operations

https://github.com/CMU-SAFARI/DRAM-Voltage-Study

Reliable low-voltage operation requires higher latency
DIMMs Operating at Higher Latency

Measured minimum latency that does not cause errors in DRAM modules

- Measured Minimum Activate Latency (ns)
  - 8
  - 10
  - 12
  - 14

- 40% of modules
- 100% of modules

Distribution of latency in the total population

DRAM requires longer latency to access data without errors at lower voltage
Spatial Locality of Errors

A module under 1.175V (12% voltage reduction)

Errors concentrate in certain regions
Voltron Overview

How do we predict performance loss due to increased latency under low DRAM voltage?

User specifies the performance loss target

Voltron

Select the **minimum** DRAM voltage without violating the target
Linear Model to Predict Performance

User specifies the performance loss target

Select the minimum DRAM voltage without violating the target

Application’s characteristics

[1.3V, 1.25V, ...] DRAM Voltage

Linear regression model

[-1%, -3%, ...] Predicted performance loss

Min. Voltage

Target

Final Voltage
Energy Savings with Bounded Performance

[Graph showing energy savings and performance loss with labels for CPU+DRAM energy savings and memory intensity, with data points for MemDVFS and Voltron. The graph indicates that Voltron offers more savings for high bandwidth applications, with a 7.3% savings compared to MemDVFS.]

More savings for high bandwidth applications

MemDVFS    Voltron
[David+, ICAC’11]

Performance target:
-1.6%    -1.8%
Voltron: Advantages & Disadvantages

- **Advantages**
  + Can trade-off between voltage and latency to improve energy or performance
  + Can exploit the high voltage margin present in DRAM

- **Disadvantages**
  - Requires finding the reliable operating voltage for each chip → higher testing cost
  - More complicated memory controller
More on Voltron

https://www.youtube.com/watch?v=F17sytMs80o&list=PL5Q2soXY2Zi-DyoI3HbqcdtUm9YWRR_z&index=17
Reducing Memory Latency to Support Security Primitives
Using Memory for Security

- **Generating True Random Numbers (using DRAM)**
  - Kim et al., HPCA 2019
  - Olgun et al., ISCA 2021

- **Evaluating Physically Unclonable Functions (using DRAM)**
  - Kim et al., HPCA 2018

- **Quickly Destroying In-Memory Data (using DRAM)**
  - Orosa et al., arxiv 2019 + ISCA 2021
DRAM Latency PUFs

- Jeremie S. Kim, Minesh Patel, Hasan Hassan, and Onur Mutlu,
  "The DRAM Latency PUF: Quickly Evaluating Physical Unclonable Functions by Exploiting the Latency-Reliability Tradeoff in Modern DRAM Devices"

[Lightning Talk Video]
[Slides (pptx) (pdf)] [Lightning Session Slides (pptx) (pdf)]
[Full Talk Lecture Video] (28 minutes)

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**The DRAM Latency PUF:**
Quickly Evaluating Physical Unclonable Functions by Exploiting the Latency-Reliability Tradeoff in Modern Commodity DRAM Devices

Jeremie S. Kim$^\dagger$§, Minesh Patel§, Hasan Hassan§, Onur Mutlu$^\dagger$§

$\dagger$Carnegie Mellon University  §ETH Zürich
More on DRAM Latency PUFs

A cell's latency failure probability is inherently related to random process variation from manufacturing.

We can provide repeatable and unique device signatures using latency error patterns.

High % chance to fail with reduced $t_{RCD}$.
DRAM Latency True Random Number Generator

- Jeremie S. Kim, Minesh Patel, Hasan Hassan, Lois Orosa, and Onur Mutlu, "D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput"  

[Slides (pptx) (pdf)]  
[Full Talk Video (21 minutes)]  
[Full Talk Lecture Video (27 minutes)]  

Top Picks Honorable Mention by IEEE Micro.

D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput

Jeremie S. Kim‡$  
Minesh Patel$  
Hasan Hassan$  
Lois Orosa$  
Onur Mutlu$‡

‡Carnegie Mellon University  
$ETH Zürich

SAFARI
D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput

Jeremie S. Kim    Minesh Patel
Hasan Hassan      Lois Orosa    Onur Mutlu

SAFARI

HPCA 2019

ETH Zürich
Carnegie Mellon
**D-RaNGe Executive Summary**

- **Motivation**: High-throughput true random numbers enable system security and various randomized algorithms.
  - Many systems (e.g., IoT, mobile, embedded) do not have dedicated True Random Number Generator (TRNG) hardware but have DRAM devices.

- **Problem**: Current DRAM-based TRNGs either
  1. do not sample a fundamentally non-deterministic entropy source
  2. are too slow for continuous high-throughput operation

- **Goal**: A novel and effective TRNG that uses existing commodity DRAM to provide random values with 1) high-throughput, 2) low latency and 3) no adverse effect on concurrently running applications.

- **D-RaNGe**: Reduce DRAM access latency below reliable values and exploit DRAM cells’ failure probabilities to generate random values.

- **Evaluation**:
  1. Experimentally characterize 282 real LPDDR4 DRAM devices
  2. D-RaNGe (717.4 Mb/s) has significantly higher throughput (211x)
  3. D-RaNGe (100ns) has significantly lower latency (180x)
DRAM Latency Characterization of 282 LPDDR4 DRAM Devices

• Latency failures come from accessing DRAM with reduced timing parameters.

• Key Observations:
  1. A cell’s latency failure probability is determined by random process variation
  2. Some cells fail randomly
Process variation during manufacturing results in cells having unique behavior.
DRAM Accesses and Failures

Weaker cells have a higher probability to fail.

$V_{dd}$

$V_{min}$

Ready to Access Voltage Level

0.5 $V_{dd}$

$V_{dd}$

Weaker cells have a higher probability to fail.
D-RaNGe Key Idea

High % chance to fail with reduced $t_{RCD}$

Low % chance to fail with reduced $t_{RCD}$

Fails randomly with reduced $t_{RCD}$
D-RaNGe Key Idea

We refer to cells that fail randomly when accessed with a reduced $t_{RCD}$ as RNG cells.

High % chance to fail with reduced $t_{RCD}$

Low % chance to fail with reduced $t_{RCD}$

Fails randomly with reduced $t_{RCD}$
Our D-RaNGe Evaluation

• We generate random values by repeatedly accessing RNG cells and aggregating the data read

• The random data satisfies the NIST statistical test suite for randomness

• The D-RaNGe generates random numbers
  - Throughput: 717.4 Mb/s
  - Latency: 64 bits in <1us
  - Power: 4.4 nJ/bit
D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput

Jeremie S. Kim  Minesh Patel  Hasan Hassan  Lois Orosa  Onur Mutlu

SAFARI  HPCA 2019

ETH Zürich  Carnegie Mellon
More on D-RaNGe

- Jeremie S. Kim, Minesh Patel, Hasan Hassan, Lois Orosa, and Onur Mutlu, "D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput"


[Slides (pptx) (pdf)]
[Full Talk Video (21 minutes)]
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D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput

Jeremie S. Kim‡§ Minesh Patel§ Hasan Hassan§ Lois Orosa§ Onur Mutlu§‡

‡Carnegie Mellon University §ETH Zürich
More on DRAM Latency TRNGs

D-RaNGe: Extracting Random Values

Identify all DRAM cells that fail randomly when accessed with a reduced $t_{RCD}$ (RNG Cell)
- When accessing an RNG Cell with a reduced $t_{RCD}$, the values read will be truly random values

RNG Cell

0110100110011101000110101
In-DRAM True Random Number Generation


[Slides (pptx) (pdf)]
[Short Talk Slides (pptx) (pdf)]
[Talk Video (25 minutes)]
[SAFARI Live Seminar Video (1 hr 26 mins)]

QUAC-TRNG: High-Throughput True Random Number Generation Using Quadruple Row Activation in Commodity DRAM Chips

Ataberk Olgun$\dagger$, Minesh Patel§, A. Giray Yağlıkçı§, Haocong Luo§, Jeremie S. Kim§, F. Nisa Bostancı$\dagger$, Nandita Vijaykumar§, Oğuz Ergin$\dagger$, Onur Mutlu§

§ETH Zürich, $\dagger$TOBB University of Economics and Technology, ○University of Toronto
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  kasrırga
ETHzürich  University of Economics & Technology  UNIVERSITY OF TORONTO
Use Cases of True Random Numbers

High-quality true random numbers are critical to many applications

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

Not all computing systems are equipped with TRNG hardware (e.g., dedicated circuitry)
DRAM-Based TRNGs

**DRAM** is ubiquitous in modern computing platforms

DRAM-based TRNGs enable **low-cost** and **high-throughput** true random number generation **within** **DRAM**
- Requires no specialized hardware: Benefits constrained systems
- Open application space: Provides high-throughput TRNG

**Processing-in-Memory (PIM)** systems perform computation directly within memory
- Avoid inefficient off-chip data movement

**DRAM-based TRNGs**
- Enable PIM workloads to sample true random numbers directly within the memory chip
- Avoid communication to possible off-chip TRNG sources
Motivation and Goal

Prior DRAM-based TRNGs are slow, these TRNGs:
1. Are based on fundamentally slow physical processes
   - DRAM retention-based TRNGs
   - DRAM startup value-based TRNGs
2. Cannot effectively harness entropy from DRAM rows
   - DRAM timing failure-based TRNGs

**Goal:** Develop a high-throughput and low-latency TRNG that can be implemented using commodity DRAM devices

**Key Observation**

**QUadruple ACtivation (QUAC):** Carefully-engineered DRAM commands can activate four DRAM rows in real chips
Using QUAC to Generate Random Values

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

Sense Amplifiers

0000000000
0 Entropy

1101001001
1 Entropy

One-time Characterization

Find Shannon Entropy of Each Sense Amplifier

Sum of each bitline’s entropy = 256 bits

Memory Controller

SHA-256

256-bit True Random Number

1. Initialize Rows
2. Perform QUAC
3. Read Block
4. Post-process
Experimental Methodology

Experimentally study QUAC and QUAC-TRNG using 136 real DDR4 chips

- Spatial distribution of entropy
- Data pattern dependency of entropy

**DDR4 SoftMC ➔ DRAM Testing Infrastructure**

[SAFARI]

[Hassan+ HPCA'17]  https://github.com/CMU-SAFARI/SoftMC
Key Results

- **5.4 Gb/s TRNG throughput (3.44 Gb/s on average) per channel**
- Outperform state-of-the-art base by **15.08x** and enhanced by **1.41x**
- Low latency: Generates a **256-bit random number in 274 ns**

- **Passes all 15 standard NIST randomness tests**

- Negligible area cost: **0.04%** of a contemporary CPU
- Negligible memory overhead: **0.002%** of an 8 GiB DRAM module

- Entropy **changes with temperature**
- Entropy remains **stable for at least up to a month**
QUAC-TRNG: 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 → QUadruple Activation (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. QUAC-TRNG has low TRNG latency: 256-bit RN in 274 ns
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
More on QUAC-TRNG

Real Chip Characterization

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

DDR4 SoftMC → DRAM Testing Infrastructure

SAFARI Live Seminar: High-Throughput TRNG Using Quadruple Row Activation in Commodity DRAM Chips

https://www.youtube.com/watch?v=snvF3g3GfkI&list=PL5Q2soXY2Zi_tOTAYm--dYByNPL7JhwR9&index=6
Reducing Refresh Latency
Reducing Refresh Latency


VRL-DRAM: Improving DRAM Performance via Variable Refresh Latency

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Reducing Memory Latency by Exploiting Memory Access Patterns
ChargeCache: Exploiting Access Patterns

Hasan Hassan, Gennady Pekhimenko, Nandita Vijaykumar, Vivek Seshadri, Donghyuk Lee, Oguz Ergin, and Onur Mutlu, "ChargeCache: Reducing DRAM Latency by Exploiting Row Access Locality"
[Slides (pptx) (pdf)]
[Source Code]

ChargeCache: Reducing DRAM Latency by Exploiting Row Access Locality

Hasan Hassan†*, Gennady Pekhimenko†, Nandita Vijaykumar† Vivek Seshadri†, Donghyuk Lee†, Oguz Ergin*, Onur Mutlu†

†Carnegie Mellon University  *TOBB University of Economics & Technology
ChargeCache: Executive Summary

- **Goal**: Reduce average DRAM access latency with no modification to the existing DRAM chips

- **Observations**:
  1) A highly-charged DRAM row can be accessed with low latency
  2) A row’s charge is restored when the row is accessed
  3) A recently-accessed row is likely to be accessed again: Row Level Temporal Locality (RLTL)

- **Key Idea**: Track recently-accessed DRAM rows and use lower timing parameters if such rows are accessed again

- **ChargeCache**:
  - Low cost & no modifications to the DRAM
  - Higher performance (8.6-10.6% on average for 8-core)
  - Lower DRAM energy (7.9% on average)
Observation 1
A highly-charged DRAM row can be accessed with low latency
- tRCD: 44%
- tRAS: 37%

How does a row become highly-charged?
Partial Restoration of Cell Charge

- Yaohua Wang, Arash Tavakkol, Lois Orosa, Saugata Ghose, Nika Mansouri Ghiasi, Minesh Patel, Jeremie S. Kim, Hasan Hassan, Mohammad Sadrosadati, and Onur Mutlu,

"Reducing DRAM Latency via Charge-Level-Aware Look-Ahead Partial Restoration"


Reducing DRAM Latency via Charge-Level-Aware Look-Ahead Partial Restoration

Yaohua Wang†§, Arash Tavakkol†, Lois Orosa†*, Saugata Ghose‡, Nika Mansouri Ghiasi†, Minesh Patel†, Jeremie S. Kim‡†, Hasan Hassan†, Mohammad Sadrosadati†, Onur Mutlu†‡

†ETH Zürich  §National University of Defense Technology
‡Carnegie Mellon University  *University of Campinas
Parallelizing Refreshes and Accesses

Kevin Chang, Donghyuk Lee, Zeshan Chishti, Alaa Alameldeen, Chris Wilkerson, Yoongu Kim, and Onur Mutlu,
"Improving DRAM Performance by Parallelizing Refreshes with Accesses"

[Summary] [Slides (pptx) (pdf)]
Parallelizing Refreshes and Accesses

- Appears at MICRO 2022

HiRA: Hidden Row Activation for Reducing Refresh Latency of Off-the-Shelf DRAM Chips

A. Giray Yağlıkçı¹  Ataberk Olgun¹,²,³  Minesh Patel¹  Haocong Luo¹  Hasan Hassan¹  Lois Orosa¹,³  Oğuz Ergin²  Onur Mutlu¹

¹ETH Zürich  ²TOBB University of Economics and Technology  ³Galicia Supercomputing Center (CESGA)
On DRAM Power Consumption
Saugata Ghose, A. Giray Yaglikci, Raghav Gupta, Donghyuk Lee, Kais Kudrolli, William X. Liu, Hasan Hassan, Kevin K. Chang, Niladrish Chatterjee, Aditya Agrawal, Mike O'Connor, and Onur Mutlu,

"What Your DRAM Power Models Are Not Telling You: Lessons from a Detailed Experimental Study"


[Abstract]
[POMACS Journal Version (same content, different format)]
[Slides (pptx) (pdf)]
[VAMPIRE DRAM Power Model]
Power Measurement Platform

Keysight 34134A DC Current Probe

DDR3L SO-DIMM

Virtex 6 FPGA

JET-5467A Riser Board
Summary: Low-Latency Memory
Challenge and Opportunity for Future

Fundamentally Low Latency Computing Architectures
Summary: Tackling Long Memory Latency

- **Reason 1: Design of DRAM Micro-architecture**
  - Goal: Maximize capacity/area, not minimize latency

- **Reason 2: “One size fits all” approach to latency specification**
  - Same latency parameters for all temperatures
  - Same latency parameters for all DRAM chips (e.g., rows)
  - Same latency parameters for all parts of a DRAM chip
  - Same latency parameters for all supply voltage levels
  - Same latency parameters for all application data
  - ...
We Can Reduce Memory Latency with Change of Mindset
Takeaway II

Main Memory Needs Intelligent Controllers to Reduce Latency
Some Solution Principles

- Data-centric design
- All components intelligent
- Better cross-layer communication, better interfaces
- Better-than-worst-case design
- Heterogeneity
- Flexibility, adaptability

Open minds
Ideas Are Applicable to Other Technologies

- Jisung Park, Myungsuk Kim, Myoungjun Chun, Lois Orosa, Jihong Kim, and Onur Mutlu,

"Reducing Solid-State Drive Read Latency by Optimizing Read-Retry"


[2-page Extended Abstract] [Short Talk Slides (pptx) (pdf)] [Full Talk Slides (pptx) (pdf)] [Short Talk Video (5 mins)] [Full Talk Video (19 mins)]

Reducing Solid-State Drive Read Latency by Optimizing Read-Retry

<table>
<thead>
<tr>
<th>Jisung Park¹</th>
<th>Myungsuk Kim²,³</th>
<th>Myoungjun Chun²</th>
<th>Lois Orosa¹</th>
<th>Jihong Kim²</th>
<th>Onur Mutlu¹</th>
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<tr>
<td>ETH Zürich Switzerland</td>
<td>Seoul National University Republic of Korea</td>
<td>Kyungpook National University Republic of Korea</td>
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</table>
Four Key Current Directions

- Fundamentally **Secure/Reliable/Safe** Architectures

- Fundamentally **Energy-Efficient** Architectures
  - **Memory-centric** (Data-centric) Architectures

- Fundamentally **Low-Latency and Predictable** Architectures

- Architectures for **AI/ML, Genomics, Medicine, Health, ...**
Backup Slides
Solar-DRAM
Solar-DRAM: Putting It Together


Solar-DRAM: Reducing DRAM Access Latency by Exploiting the Variation in Local Bitlines

Jeremie S. Kim†§, Minesh Patel§, Hasan Hassan§, Onur Mutlu§†
†Carnegie Mellon University §ETH Zürich
Activation failures are highly constrained to local bitlines.

**Spatial Distribution of Failures**

How are activation failures spatially distributed in DRAM?

**Subarray Edge**

**DRAM Row (number)**

0 512 1024

**DRAM Column (number)**

0 512 1024

Activation failures are **highly constrained** to local bitlines.
Short-term Variation

Does a bitline’s probability of failure change over time?

A weak bitline is likely to remain weak and a strong bitline is likely to remain strong over time.
Short-term Variation

Does a bitline’s probability of failure change over time?

A weak bitline is likely to remain weak and a strong bitline is likely to remain strong over time.
We can reliably issue write operations with significantly reduced $t_{RCD}$ (e.g., by 77%).
Solar-DRAM

Uses a **static profile of weak subarray columns**
- Identifies subarray columns as weak or strong
- Obtained in a one-time profiling step

Three Components

1. Variable-latency cache lines (VLC)
2. Reordered subarray columns (RSC)
3. Reduced latency for writes (RLW)
Solar-DRAM

Uses a static profile of weak subarray columns
• Identifies subarray columns as weak or strong
• Obtained in a one-time profiling step

Three Components

1. Variable-latency cache lines (VLC)
2. Reordered subarray columns (RSC)
3. Reduced latency for writes (RLW)
Solar-DRAM: VLC (I)

Identify cache lines comprised of \textbf{strong bitlines}

Access such cache lines with a \textbf{reduced} $t_{RCD}$
Solar-DRAM

Uses a static profile of weak subarray columns
  • Identifies subarray columns as weak or strong
  • Obtained in a one-time profiling step

Three Components

1. Variable-latency cache lines (VLC)
2. Reordered subarray columns (RSC)
3. Reduced latency for writes (RLW)
Remap cache lines across DRAM at the memory controller level so cache line 0 will likely map to a strong cache line.
Solar-DRAM

Uses a **static profile of weak subarray columns**

- Identifies subarray columns as weak or strong
- Obtained in a one-time profiling step

**Three Components**

1. Variable-latency cache lines (VLC)
2. Reordered subarray columns (RSC)
3. Reduced latency for writes (RLW)
Solar-DRAM: Putting It Together

- Jeremie S. Kim, Minesh Patel, Hasan Hassan, and Onur Mutlu, "Solar-DRAM: Reducing DRAM Access Latency by Exploiting the Variation in Local Bitlines"
  [Slides (pptx) (pdf)]
  [Talk Video (16 minutes)]

Solar-DRAM: Reducing DRAM Access Latency by Exploiting the Variation in Local Bitlines

Jeremie S. Kim‡§ Minesh Patel§ Hasan Hassan§ Onur Mutlu§‡
‡Carnegie Mellon University §ETH Zürich
More on Solar DRAM

Spatial Distribution of Failures

How are activation failures spatially distributed in DRAM?

 Activation failures are highly constrained to local bitlines (i.e., subarrays)

Solar-DRAM: Reducing DRAM Access Latency by Exploiting the Variation in Local Bitlines - ICCD 2018

https://www.youtube.com/watch?v=WPmDIx1mKrU
Understanding & Exploiting the Voltage-Latency-Reliability Relationship
Analysis of Latency-Voltage in DRAM Chips

Kevin Chang, A. Giray Yaglikci, Saugata Ghose, Aditya Agrawal, Niladrish Chatterjee, Abhijith Kashyap, Donghyuk Lee, Mike O'Connor, Hasan Hassan, and u,

"Understanding Reduced-Voltage Operation in Modern DRAM Devices: Experimental Characterization, Analysis, and Mechanisms"

Understanding Reduced-Voltage Operation in Modern DRAM Chips: Characterization, Analysis, and Mechanisms

Kevin K. Chang† Abdullah Giray Yağlıkçı† Saugata Ghose† Aditya Agrawal¶ Niladrish Chatterjee¶
Abhijith Kashyap† Donghyuk Lee¶ Mike O’Connor¶,‡ Hasan Hassan§ Onur Mutlu§,†
†Carnegie Mellon University ‡NVIDIA ‡The University of Texas at Austin §ETH Zürich
High DRAM Power Consumption

- Problem: High DRAM (memory) power in today’s systems

>40% in POWER7 (Ware+, HPCA’10)  >40% in GPU (Paul+, ISCA’15)
Low-Voltage Memory

• Existing DRAM designs to help reduce DRAM power by lowering supply voltage conservatively
  – \( \text{Power} \propto \text{Voltage}^2 \)
• DDR3L (low-voltage) reduces voltage from 1.5V to 1.35V (-10%)
• LPDDR4 (low-power) employs low-power I/O interface with 1.2V (lower bandwidth)

Can we reduce DRAM power and energy by further reducing supply voltage?
Goals

1. Understand and characterize the various characteristics of DRAM under **reduced voltage**

2. Develop a mechanism that reduces DRAM energy by **lowering voltage** while keeping performance loss within a target
Key Questions

• How does reducing voltage affect reliability (errors)?

• How does reducing voltage affect DRAM latency?

• How do we design a new DRAM energy reduction mechanism?
Supply Voltage Control on DRAM

Adjust the supply voltage to every chip on the same module.
Custom Testing Platform

**SoftMC** [Hassan+, HPCA’17]: FPGA testing platform to
1) Adjust supply voltage to DRAM modules
2) Schedule DRAM commands to DRAM modules

Existing systems: DRAM commands not exposed to users

https://github.com/CMU-SAFARI/DRAM-Voltage-Study
Tested DRAM Modules

- **124 DDR3L** (low-voltage) DRAM chips
  - 31 SO-DIMMs
  - **1.35V** (DDR3 uses 1.5V)
  - Density: 4Gb per chip
  - Three major vendors/manufacturers

- Iteratively read every bit in each 4Gb chip under a wide range of supply voltage levels: 1.35V to 1.0V (-26%)
Reliability Worsens with Lower Voltage

Reducing voltage below $V_{\text{min}}$ causes an increasing number of errors.
Source of Errors

Detailed circuit simulations (SPICE) of a DRAM cell array to model the behavior of DRAM operations

https://github.com/CMU-SAFARI/DRAM-Voltage-Study

Circuit model

Reliable low-voltage operation requires higher latency
DIMMs Operating at Higher Latency

Measured minimum latency that does not cause errors in DRAM modules

DRAM requires longer latency to access data without errors at lower voltage
Spatial Locality of Errors

A module under 1.175V (12% voltage reduction)

Errors concentrate in certain regions
Summary of Key Experimental Observations

- Voltage-induced errors increase as voltage reduces further below $V_{\text{min}}$
- Errors exhibit spatial locality
- Increasing the latency of DRAM operations mitigates voltage-induced errors
DRAM Voltage Adjustment to Reduce Energy

- **Goal**: Exploit the trade-off between voltage and latency to reduce energy consumption

- **Approach**: Reduce DRAM voltage **reliably**
  - Performance loss due to increased latency at lower voltage

```
<table>
<thead>
<tr>
<th>Improvement Over Nominal Voltage (%)</th>
<th>Supply Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.9</td>
</tr>
<tr>
<td>Performance</td>
<td>High Power Savings</td>
</tr>
<tr>
<td>DRAM Power Savings</td>
<td>Low Power Savings</td>
</tr>
</tbody>
</table>
```

- **Bad Performance**
- **Good Performance**

SAFARI
Voltron Overview

How do we predict performance loss due to increased latency under low DRAM voltage?

User specifies the performance loss target

Select the **minimum** DRAM voltage without violating the target
Linear Model to Predict Performance

Voltron

User specifies the performance loss target

Select the minimum DRAM voltage without violating the target

Application’s characteristics

[1.3V, 1.25V, ...] DRAM Voltage

Linear regression model

[-1%, -3%, ...] Predicted performance loss

Min. Voltage Target

Final Voltage
Regression Model to Predict Performance

• **Application’s characteristics for the model:**
  – *Memory intensity*: Frequency of last-level cache misses
  – *Memory stall time*: Amount of time memory requests stall commit inside CPU

• **Handling multiple applications:**
  – Predict a performance loss for each application
  – Select the minimum voltage that satisfies the performance target for all applications
Comparison to Prior Work

- **Prior work**: Dynamically scale frequency and voltage of the entire DRAM based on bandwidth demand [David+, ICAC’11]
  - **Problem**: Lowering voltage on the peripheral circuitry decreases channel frequency (memory data throughput)
- **Voltron**: Reduce voltage to only DRAM array without changing the voltage to peripheral circuitry
Exploiting Spatial Locality of Errors

Key idea: Increase the latency only for DRAM banks that observe errors under low voltage

– Benefit: Higher performance
Voltron Evaluation Methodology

- **Cycle-level simulator:** Ramulator [CAL’15]
  - McPAT and DRAMPower for energy measurement
    https://github.com/CMU-SAFARI/ramulator

- **4-core** system with DDR3L memory

- **Benchmarks:** SPEC2006, YCSB

- **Comparison to prior work:** MemDVFS [David+, ICAC’11]
  - Dynamic DRAM frequency and voltage scaling
  - Scaling based on the *memory bandwidth consumption*
Energy Savings with Bounded Performance

More savings for high bandwidth applications

MemDVFS
Voltron

Memory Intensity

[David+, ICAC’11]

Meets performance target

Performance Target

-1.6%  -1.8%

Performance Loss (%)
Voltron: Advantages & Disadvantages

- **Advantages**
  - Can trade-off between voltage and latency to improve energy or performance
  - Can exploit the high voltage margin present in DRAM

- **Disadvantages**
  - Requires finding the reliable operating voltage for each chip → higher testing cost
Analysis of Latency-Voltage in DRAM Chips

Kevin Chang, A. Giray Yaglikci, Saugata Ghose, Aditya Agrawal, Niladrish Chatterjee, Abhijith Kashyap, Donghyuk Lee, Mike O'Connor, Hasan Hassan, and Onur Mutlu,

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Understanding Reduced-Voltage Operation in Modern DRAM Chips: Characterization, Analysis, and Mechanisms

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\textsuperscript{†}Carnegie Mellon University \textsuperscript{¶}NVIDIA \textsuperscript{‡}The University of Texas at Austin \textsuperscript{§}ETH Zürich
More on Voltron

https://www.youtube.com/watch?v=F17sytMs80o&list=PL5Q2soXY2Zi-Dyo13HbgcdUm9YWRR_z&index=17
Reducing Memory Latency to Support Security Primitives
Using Memory for Security

- Generating True Random Numbers (using DRAM)
  - Kim et al., HPCA 2019
  - Olgun et al., ISCA 2021

- Evaluating Physically Unclonable Functions (using DRAM)
  - Kim et al., HPCA 2018

- Quickly Destroying In-Memory Data (using DRAM)
  - Orosa et al., arxiv 2019 + ISCA 2021
D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput

Jeremie S. Kim  Minesh Patel
Hasan Hassan  Lois Orosa  Onur Mutlu

SAFARI

HPCA 2019

ETH Zürich  Carnegie Mellon
**Executive Summary**

**Motivation:** High-throughput true random numbers enable system security and various randomized algorithms.
- Many systems (e.g., IoT, mobile, embedded) do not have dedicated True Random Number Generator (TRNG) hardware but have DRAM devices.

**Problem:** Current DRAM-based TRNGs either
1. do not sample a fundamentally non-deterministic entropy source
2. are too slow for continuous high-throughput operation

**Goal:** A novel and effective TRNG that uses existing commodity DRAM to provide random values with 1) high-throughput, 2) low latency and 3) no adverse effect on concurrently running applications

**D-RaNGe:** Reduce DRAM access latency below reliable values and exploit DRAM cells’ failure probabilities to generate random values

**Evaluation:**
1. Experimentally characterize 282 real LPDDR4 DRAM devices
2. D-RaNGe (717.4 Mb/s) has significantly higher throughput (211x)
3. D-RaNGe (100ns) has significantly lower latency (180x)
DRAM Latency Characterization of 282 LPDDR4 DRAM Devices

• Latency failures come from accessing DRAM with reduced timing parameters.

• Key Observations:
  1. A cell’s latency failure probability is determined by random process variation
  2. Some cells fail randomly
DRAM Accesses and Failures

Process variation during manufacturing results in cells having unique behavior.

Bitline Charge Sharing

Guardband

Ready to Access Voltage Level

SAFARI
DRAM Accesses and Failures

Weaker cells have a higher probability to fail.
D-RaNGe Key Idea

High % chance to fail with reduced $t_{\text{RCD}}$

Low % chance to fail with reduced $t_{\text{RCD}}$

Fails randomly with reduced $t_{\text{RCD}}$
D-RaNGe Key Idea

High % chance to fail with reduced $t_{RCD}$

Low % chance to fail with reduced $t_{RCD}$

We refer to cells that fail randomly when accessed with a reduced $t_{RCD}$ as RNG cells
Our D-RaNGe Evaluation

• We generate **random values** by repeatedly accessing **RNG cells** and aggregating the data read.

• The random data satisfies the NIST statistical test suite for randomness.

• The **D-RaNGe** generates random numbers:
  - **Throughput**: 717.4 Mb/s
  - **Latency**: 64 bits in <1us
  - **Power**: 4.4 nJ/bit
D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput

Jeremie S. Kim  Minesh Patel
Hasan Hassan  Lois Orosa  Onur Mutlu

SAFARI  HPCA 2019

ETH Zürich  Carnegie Mellon
More on D-RaNGe

- Jeremie S. Kim, Minesh Patel, Hasan Hassan, Lois Orosa, and Onur Mutlu, "D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput"  
  [Slides (pptx) (pdf)]  
  [Full Talk Video (21 minutes)]  
  [Full Talk Lecture Video (27 minutes)]  
  Top Picks Honorable Mention by IEEE Micro.

D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput

Jeremie S. Kim†§, Minesh Patel§, Hasan Hassan§, Lois Orosa§, Onur Mutlu§†  
†Carnegie Mellon University  
§ETH Zürich
More on DRAM Latency TRNGs

D-RaNGe: Extracting Random Values

Identify all DRAM cells that fail randomly when accessed with a reduced $t_{RCD}$ (RNG Cell)

- When accessing an RNG Cell with a reduced $t_{RCD}$, the values read will be truly random values

RNG Cell

SAFARI

0110100110011101000110101
Doing Better Than D-RaNGe

- Ataberk Olgun, Minesh Patel, A. Giray Yaglikci, Haocong Luo, Jeremie S. Kim, F. Nisa Bostanci, Nandita Vijaykumar, Oguz Ergin, and Onur Mutlu,

"QUAC-TRNG: High-Throughput True Random Number Generation Using Quadruple Row Activation in Commodity DRAM Chips"


[Slides (pptx) (pdf)]
[Short Talk Slides (pptx) (pdf)]
[Talk Video (25 minutes)]
[SAFARI Live Seminar Video (1 hr 26 mins)]

QUAC-TRNG: High-Throughput True Random Number Generation Using Quadruple Row Activation in Commodity DRAM Chips

Ataberk Olgun§†, Minesh Patel§, A. Giray Yağılkçı§, Haocong Luo§, Jeremie S. Kim§, F. Nisa Bostancı§†, Nandita Vijaykumar§, Oğuz Ergin†, Onur Mutlu§

§ETH Zürich  †TOBB University of Economics and Technology  ○University of Toronto
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  kasırğa

ETH Zürich  TOBB ETÜ  University of Economics & Technology  University of Toronto
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 → QUadruple ACtivation (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. QUAC-TRNG has low TRNG latency: 256-bit RN in 274 ns
  4. QUAC-TRNG passes all 15 NIST randomness tests
Use Cases of True Random Numbers

High-quality true random numbers are critical to many applications.

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

Not all computing systems are equipped with TRNG hardware (e.g., dedicated circuitry).
DRAM-Based TRNGs

DRAM is ubiquitous in modern computing platforms.

DRAM-based TRNGs enable low-cost and high-throughput true random number generation within DRAM:
- Requires no specialized hardware: Benefits constrained systems
- Open application space: Provides high-throughput TRNG

Processing-in-Memory (PIM) systems perform computation directly within memory:
- Avoid inefficient off-chip data movement

DRAM-based TRNGs
- Enable PIM workloads to sample true random numbers directly within the memory chip
- Avoid communication to possible off-chip TRNG sources

[Samsung] [UPMEM]
Motivation and Goal

Prior DRAM-based TRNGs are slow, these TRNGs:
1. Are based on fundamentally slow physical processes
   - DRAM retention-based TRNGs
   - DRAM startup value-based TRNGs
2. Cannot effectively harness entropy from DRAM rows
   - DRAM timing failure-based TRNGs

**Goal:** Develop a high-throughput and low-latency TRNG that can be implemented using commodity DRAM devices

**Key Observation**

QUadruple ACTivation (QUAC): Carefully-engineered DRAM commands can activate four DRAM rows in real chips
Using QUAC to Generate Random Values

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

Sense Amplifiers

0000000000
0 Entropy

1101001001
1 Entropy

One-time Characterization

Find Shannon Entropy of Each Sense Amplifier

Sum of each bitline’s entropy = 256 bits

Memory Controller

SHA-256

256-bit True Random Number

1. Initialize Rows
2. Perform QUAC
3. Read Block
4. Post-process
Experimental Methodology

Experimentally study QUAC and QUAC-TRNG using 136 real DDR4 chips

- Spatial distribution of entropy
- Data pattern dependency of entropy

**DDR4 SoftMC ➔ DRAM Testing Infrastructure**

SAFARI

[Hassan+ HPCA’17]  https://github.com/CMU-SAFARI/SoftMC
Key Results

• 5.4 Gb/s TRNG throughput (3.44 Gb/s on average) per channel
• Outperform state-of-the-art base by 15.08x and enhanced by 1.41x
• Low latency: Generates a 256-bit random number in 274 ns

• Passes all 15 standard NIST randomness tests

• Negligible area cost: 0.04% of a contemporary CPU
• Negligible memory overhead: 0.002% of an 8 GiB DRAM module

• Entropy changes with temperature
• Entropy remains stable for at least up to a month
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
More on QUAC-TRNG

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

DDR4 SoftMC → DRAM Testing Infrastructure

SAFARI Live Seminar: High-Throughput TRNG Using Quadruple Row Activation in Commodity DRAM Chips

713 views • Streamed live on Sep 15, 2021

https://www.youtube.com/watch?v=snvF3q3GfkI&list=PL5Q2soXY2Zi_tOTAYm--dYByNPL7JhwR9&index=6
DRAM Latency PUFs

- Jeremie S. Kim, Minesh Patel, Hasan Hassan, and Onur Mutlu,
  "The DRAM Latency PUF: Quickly Evaluating Physical Unclonable Functions by Exploiting the Latency-Reliability Tradeoff in Modern DRAM Devices"

  [Lightning Talk Video]
  [Slides (pptx) (pdf)] [Lightning Session Slides (pptx) (pdf)]
  [Full Talk Lecture Video (28 minutes)]
The DRAM Latency PUF:

Quickly Evaluating Physical Unclonable Functions by Exploiting the Latency-Reliability Tradeoff in Modern Commodity DRAM Devices

Jeremie S. Kim  Minesh Patel
Hasan Hassan    Onur Mutlu

SAFARI

Systems@ETH Zürich

ETH Zürich

Carnegie Mellon
DL-PUF: Executive Summary

**Motivation:**
- We can authenticate a system via unique signatures if we can evaluate a Physical Unclonable Function (PUF) on it
- Signatures (PUF response) reflect inherent properties of a device
- DRAM is a promising substrate for PUFs because it is widely used

**Problem:** Current DRAM PUFs are 1) very slow, 2) require a DRAM reboot, or 3) require additional custom hardware

**Goal:** To develop a novel and effective PUF for existing commodity DRAM devices with low-latency evaluation time and low system interference across all operating temperatures

**DRAM Latency PUF:** Reduce DRAM access latency below reliable values and exploit the resulting error patterns as unique identifiers

**Evaluation:**
1. Experimentally characterize 223 real LPDDR4 DRAM devices
2. DRAM latency PUF (88.2 ms) achieves a speedup of 102x/860x at 70°C/55°C over prior DRAM PUF evaluation mechanisms
Motivation

We want a way to ensure that a system’s components are not **compromised**

- **Physical Unclonable Function (PUF):** a function we **evaluate** on a device to **generate** a **signature unique** to the device
- We refer to the unique signature as a **PUF response**
- Often used in a **Challenge-Response Protocol (CRP)**
Motivation

1. We want a **runtime-accessible** PUF
   - Should be evaluated **quickly** with **minimal** impact on concurrent applications
   - Can protect against **attacks that swap system components with malicious parts**

2. DRAM is a **promising substrate** for evaluating PUFs because it is **ubiquitous** in modern systems
   - Unfortunately, current DRAM PUFs are **slow** and get **exponentially slower** at lower temperatures
DRAM Latency Characterization of 223 LPDDR4 DRAM Devices

• Latency failures come from accessing DRAM with reduced timing parameters.

• Key Observations:
  1. A cell’s latency failure probability is determined by random process variation
  2. Latency failure patterns are repeatable and unique to a device
**DRAM Latency PUF Key Idea**

- A cell’s latency failure probability is inherently related to **random process variation** from manufacturing.
- We can provide **repeatable and unique device signatures** using latency error patterns.

High % chance to fail with reduced $t_{RCD}$

Low % chance to fail with reduced $t_{RCD}$
DRAM Latency PUF Key Idea

- A cell’s latency failure probability is inherently related to random process variation from manufacturing.
- We can provide repeatable and unique device signatures using latency error patterns.

The **key idea** is to compose a PUF response using the DRAM cells that fail with high probability.
The DRAM Latency PUF Evaluation

• We generate PUF responses using ***latency errors*** in a region of DRAM

• The latency error patterns ***satisfy PUF requirements***

• The DRAM Latency PUF ***generates PUF responses in 88.2ms***
Results – PUF Evaluation Latency

DRAM latency PUF is

1. Fast and constant latency (88.2ms)
Results – PUF Evaluation Latency

DRAM latency PUF is

1. Fast and constant latency (88.2ms)
**Results – PUF Evaluation Latency**

- **8KiB memory segment**
- **64KiB memory segment**
- **64MiB memory segment**

**DRAM Retention PUF**
- Manufacturer A
- Manufacturer B
- Manufacturer C

**DRAM Latency PUF**
- All Manufacturers

**Temperature (°C)**
- 56
- 58
- 60
- 62
- 64
- 66
- 68
- 70

**Evaluation Time (s)**
- 10^{-1}
- 10^{0}
- 10^{1}
- 10^{2}
- 10^{3}
- 10^{4}

**Evaluation Time (s)**

**Results**
- PUF Evaluation Latency
- 8KiB memory segment
- 64KiB memory segment
- 64MiB memory segment

**DRAM latency PUF is**

1. Fast and constant latency **(88.2ms)**
Results – PUF Evaluation Latency

DRAM latency PUF is

1. Fast and constant latency (88.2ms)
2. On average, 102x/860x faster than the previous DRAM PUF with the same DRAM capacity overhead (64KiB)
Other Results in the Paper

• How the **DRAM latency PUF** meets the basic requirements for an effective PUF

• A detailed analysis on:
  - Devices of **the three major DRAM manufacturers**
  - The **evaluation time** of a PUF

• Further discussion on:
  - **Optimizing** retention PUFs
  - **System interference** of DRAM retention and latency PUFs
  - Algorithm to **quickly and reliably** evaluate DRAM latency PUF
  - **Design considerations** for a DRAM latency PUF
  - The **DRAM Latency PUF overhead analysis**
The DRAM Latency PUF:
Quickly Evaluating Physical Unclonable Functions by Exploiting the Latency-Reliability Tradeoff in Modern Commodity DRAM Devices

Jeremie S. Kim, Minesh Patel, Hasan Hassan, Onur Mutlu

QR Code for the paper

HPCA 2018

Systems@ETH Zürich

Carnegie Mellon

ETH Zürich
More on DRAM Latency PUFs

- Jeremie S. Kim, Minesh Patel, Hasan Hassan, and Onur Mutlu, "The DRAM Latency PUF: Quickly Evaluating Physical Unclonable Functions by Exploiting the Latency-Reliability Tradeoff in Modern DRAM Devices"


[Lightning Talk Video]
[Slides (pptx) (pdf)] [Lightning Session Slides (pptx) (pdf)]
More on DRAM Latency PUFs

- A cell’s latency failure probability is inherently related to random process variation from manufacturing.
- We can provide repeatable and unique device signatures using latency error patterns.

High % chance to fail with reduced t_{RCD}
Reducing Memory Latency by Exploiting Memory Access Patterns
ChargeCache: Executive Summary

- **Goal:** Reduce average DRAM access latency with no modification to the existing DRAM chips

- **Observations:**
  1) A highly-charged DRAM row can be accessed with low latency
  2) A row’s charge is restored when the row is accessed
  3) A recently-accessed row is likely to be accessed again:
      Row Level Temporal Locality (RLTL)

- **Key Idea:** Track recently-accessed DRAM rows and use lower timing parameters if such rows are accessed again

- **ChargeCache:**
  - Low cost & no modifications to the DRAM
  - Higher performance (**8.6-10.6%** on average for 8-core)
  - Lower DRAM energy (**7.9%** on average)
DRAM Charge over Time

- Cell
- Sense Amplifier

- Data 0
- Data 1

- Ready to Access
- Ready to Precharge
- Ready to Access Charge Level

- Charge Level over Time

- Precharge
- Sensing
- Restore

- tRCD
- tRAS

- ACT
- R/W
- PRE

SAFARI
Accessing Highly-charged Rows

Time

Cell

Sense-Amplifier

Ready to Access

Ready to Precharge

Data 0

Data 1

charge

Sensing

Restore

Precharge

R/W

PRE

ACT

tRCD

tRAS

SAFARI
Observation 1

A highly-charged DRAM row can be accessed with low latency

- tRCD: 44%
- tRAS: 37%

How does a row become highly-charged?
How Does a Row Become Highly-Charged?

DRAM cells lose charge over time

Two ways of restoring a row’s charge:

• Refresh Operation
• Access
Observation 2

A row’s charge is restored when the row is accessed

How likely is a recently-accessed row to be accessed again?
Row Level Temporal Locality (RLTL)

A **recently-accessed** DRAM row is likely to be accessed again.

- **$t$-RLTL**: Fraction of rows that are accessed within time $t$ after their previous access.

<table>
<thead>
<tr>
<th>Fraction of Accesses</th>
<th>AVG</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>86%</td>
</tr>
<tr>
<td>20%</td>
<td>97%</td>
</tr>
<tr>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

88% $t$-RLTL for **eight** core workloads.
Key Idea

Track **recently-accessed** DRAM rows and use **lower timing parameters** if such rows are accessed again.
ChargeCache Overview

DRAM

Memory Controller

ChargeCache

Requests: A D A

ChargeCache Hit: Use Default Timings
Area and Power Overhead

• Modeled with CACTI

• Area
  – ~5KB for 128-entry ChargeCache
  – 0.24% of a 4MB Last Level Cache (LLC) area

• Power Consumption
  – 0.15 mW on average (static + dynamic)
  – 0.23% of the 4MB LLC power consumption
Methodology

• Simulator
  – DRAM Simulator (Ramulator [Kim+, CAL’15])
    https://github.com/CMU-SAFARI/ramulator

• Workloads
  – 22 single-core workloads
    • SPEC CPU2006, TPC, STREAM
  – 20 multi-programmed 8-core workloads
    • By randomly choosing from single-core workloads
  – Execute at least 1 billion representative instructions per core (Pinpoints)

• System Parameters
  – 1/8 core system with 4MB LLC
  – Default tRCD/tRAS of 11/28 cycles
ChargeCache improves single-core performance
Eight-core Performance

ChargeCache significantly improves multi-core performance
ChargeCache reduces DRAM energy
More on ChargeCache

Hasan Hassan, Gennady Pekhimenko, Nandita Vijaykumar, Vivek Seshadri, Donghyuk Lee, Oguz Ergin, and Onur Mutlu,
"ChargeCache: Reducing DRAM Latency by Exploiting Row Access Locality"
[Slides (pptx) (pdf)]
[Source Code]

ChargeCache: Reducing DRAM Latency by Exploiting Row Access Locality

Hasan Hassan†*, Gennady Pekhimenko†, Nandita Vijaykumar†
Vivek Seshadri†, Donghyuk Lee†, Oguz Ergin*, Onur Mutlu†

†Carnegie Mellon University   *TOBB University of Economics & Technology
Observation 1
A highly-charged DRAM row can be accessed with low latency
• tRCD: 44%
• tRAS: 37%

How does a row become highly-charged?
Partial Restoration of Cell Charge

- Yaohua Wang, Arash Tavakkol, Lois Orosa, Saugata Ghose, Nika Mansouri Ghiasi, Minesh Patel, Jeremie S. Kim, Hasan Hassan, Mohammad Sadrosadati, and Onur Mutlu,

"Reducing DRAM Latency via Charge-Level-Aware Look-Ahead Partial Restoration"


Reducing DRAM Latency via Charge-Level-Aware Look-Ahead Partial Restoration

Yaohua Wang†§ Arash Tavakkol† Lois Orosa†* Saugata Ghose‡ Nika Mansouri Ghiasi†
Minesh Patel† Jeremie S. Kim‡‡ Hasan Hassan† Mohammad Sadrosadati† Onur Mutlu†‡

†ETH Zürich §National University of Defense Technology
‡Carnegie Mellon University *University of Campinas

SAFARI
On DRAM Power Consumption
VAMPIRE DRAM Power Model

- Saugata Ghose, A. Giray Yaglikci, Raghav Gupta, Donghyuk Lee, Kais Kudrolli, William X. Liu, Hasan Hassan, Kevin K. Chang, Niladrish Chatterjee, Aditya Agrawal, Mike O'Connor, and Onur Mutlu,

"What Your DRAM Power Models Are Not Telling You: Lessons from a Detailed Experimental Study"


Abstract

What Your DRAM Power Models Are Not Telling You: Lessons from a Detailed Experimental Study

Saugata Ghose† Abdullah Giray Yağlıkçı‡† Raghav Gupta† Donghyuk Lee§
Kais Kudrolli† William X. Liu† Hasan Hassan‡ Kevin K. Chang†
Niladrish Chatterjee§ Aditya Agrawal§ Mike O’Connor§‖ Onur Mutlu‡†

†Carnegie Mellon University ‡ETH Zürich §NVIDIA ‖University of Texas at Austin
Power Measurement Platform

- Keysight 34134A DC Current Probe
- DDR3L SO-DIMM
- Virtex 6 FPGA
- JET-5467A Riser Board
Power Measurement Methodology

- **SoftMC: an FPGA-based memory controller** [Hassan+ HPCA ’17]
  - Modified to repeatedly loop commands
  - Open-source: [https://github.com/CMU-SAFARI/SoftMC](https://github.com/CMU-SAFARI/SoftMC)

- **Measure current consumed by a module during a SoftMC test**

- **Tested 50 DDR3L DRAM modules** (200 DRAM chips)
  - Supply voltage: 1.35 V
  - **Three major vendors:** A, B, C
  - Manufactured between 2014 and 2016

- **For each experimental test that we perform**
  - 10 runs of each test per module
  - At least 10 current samples per run
1. Real DRAM Power Varies Widely from IDD Values

- Different vendors have very different margins (i.e., guardbands)
- Low variance among different modules from same vendor

Current consumed by real DRAM modules varies significantly for all IDD values that we measure.
2. DRAM Power is Dependent on Data Values

- Some variation due to infrastructure – can be subtracted
- Without infrastructure variation: up to 230 mA of change
- Toggle affects power consumption, but < 0.15 mA per bit

DRAM power consumption depends *strongly* on the data value
3. Structural Variation Affects DRAM Power Usage

- **Vendor C**: variation in idle current across banks
- **All vendors**: variation in read current across banks
- **All vendors**: variation in activation based on row address

**Significant structural variation:**
DRAM power varies systematically by bank and row
4. Generational Savings Are Smaller Than Expected

- Similar trends for idle and read currents

- Actual power savings of newer DRAM is much lower than the savings indicated in the datasheets.
Summary of New Observations on DRAM Power

1. Real DRAM modules often consume less power than vendor-provided IDD values state.

2. DRAM power consumption is dependent on the data value that is read/written.

3. Across banks and rows, structural variation affects power consumption of DRAM.

4. Newer DRAM modules save less power than indicated in datasheets by vendors.

Detailed observations and analyses in the paper.
A New Variation-Aware DRAM Power Model

- **VAMPIRE**: Variation-Aware model of Memory Power Informed by Real Experiments

**Inputs**
(from memory system simulator)
- Trace of DRAM commands, timing
- Data that is being written

**VAMPIRE**
- Read/Write and Data-Dependent Power Modeling
- Idle/Activate/Precharge Power Modeling
- Structural Variation Aware Power Modeling

**Outputs**
- Per-vendor power consumption
- Range for each vendor (optional)

- **VAMPIRE** and raw characterization data are open-source: https://github.com/CMU-SAFARI/VAMPIRE
VAMPIRE Has Lower Error Than Existing Models

- Validated using new power measurements: details in the paper

VAMPIRE has very low error for all vendors: 6.8%
Much more accurate than prior models
VAMPIRE Enables Several New Studies

- Taking advantage of structural variation to perform variation-aware physical page allocation to reduce power

- Smarter DRAM power-down scheduling

- Reducing DRAM energy with data-dependency-aware cache line encodings
  - 23 applications from the SPEC 2006 benchmark suite
  - Traces collected using Pin and Ramulator

- We expect there to be many other new studies in the future
VAMPIRE DRAM Power Model

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[POMACS Journal Version (same content, different format)]
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