

Memory Systems and Memory-Centric Computing

Lecture 4.2: Memory Robustness

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18 July 2024

HiPEAC ACACES Summer School 2024

SAFARI

ETH zürich

Agenda For Today

- Memory Systems and Memory-Centric Computing
 - July 15-19, 2024
- Topic 1: Memory Trends, Challenges, Opportunities, Basics
- Topic 2: Memory-Centric Computing
- Topic 3: Memory Robustness: RowHammer, RowPress & Beyond
- Topic 4: Machine Learning Driven Memory Systems
- Topic 5 (another course): Architectures for Genomics and ML
- Topic 6 (unlikely): Non-Volatile Memories and Storage
- Topic 7 (unlikely): Memory Latency, Predictability & QoS
- Major Overview Reading:
 - Mutlu et al., “A Modern Primer on Processing in Memory,” Book Chapter on Emerging Computing and Devices, 2022.

How Reliable/Secure/Safe is This Bridge?



Collapse of the “Galloping Gertie”



How Safe & Secure Are These People?



Security is about preventing unforeseen consequences

How Safe & Secure Are Our Platforms?



Security is about preventing unforeseen consequences

What Is RowHammer?

- One can **predictably induce bit flips** in commodity DRAM chips
 - All recent DRAM chips are fundamentally vulnerable
- First example of how a **simple hardware failure mechanism** can create a **widespread system security vulnerability**

WIRED

Forget Software—Now Hackers Are Exploiting Physics

BUSINESS

CULTURE

DESIGN

GEAR

SCIENCE

SHARE

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TWEET

ANDY GREENBERG

SECURITY

08.31.16

7:00 AM

FORGET SOFTWARE—NOW
HACKERS ARE EXPLOITING
PHYSICS

An “Early” Position Paper [IMW’13]

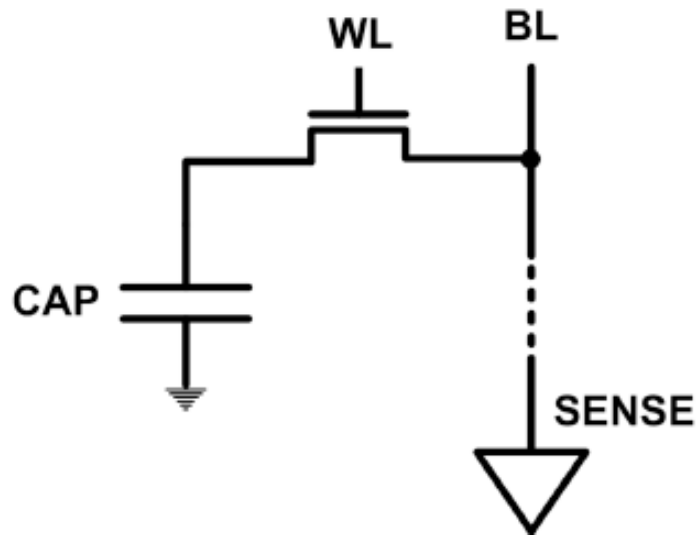
- Onur Mutlu,
"Memory Scaling: A Systems Architecture Perspective"
*Proceedings of the 5th International Memory Workshop (**IMW**), Monterey, CA, May 2013. Slides
(pptx) (pdf)
EETimes Reprint*

Memory Scaling: A Systems Architecture Perspective

Onur Mutlu
Carnegie Mellon University
onur@cmu.edu
<http://users.ece.cmu.edu/~omutlu/>

The DRAM Scaling Problem

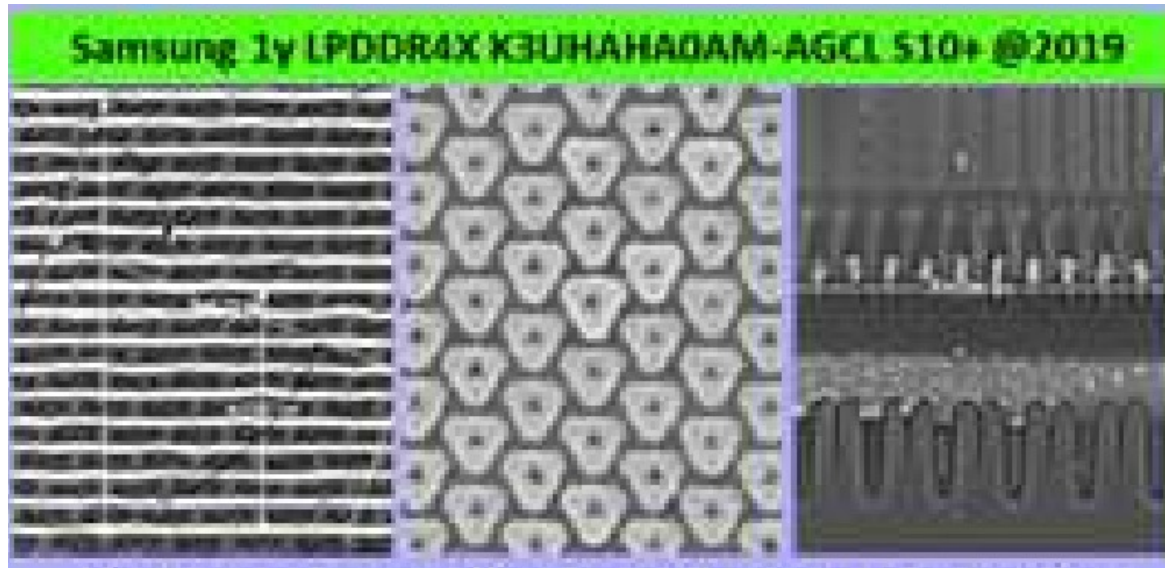
- DRAM stores charge in a capacitor (charge-based memory)
 - Capacitor must be large enough for reliable sensing
 - Access transistor should be large enough for low leakage and high retention time
 - Scaling beyond 40-35nm (2013) is challenging [ITRS, 2009]



- DRAM capacity, cost, and energy/power hard to scale

The DRAM Scaling Problem

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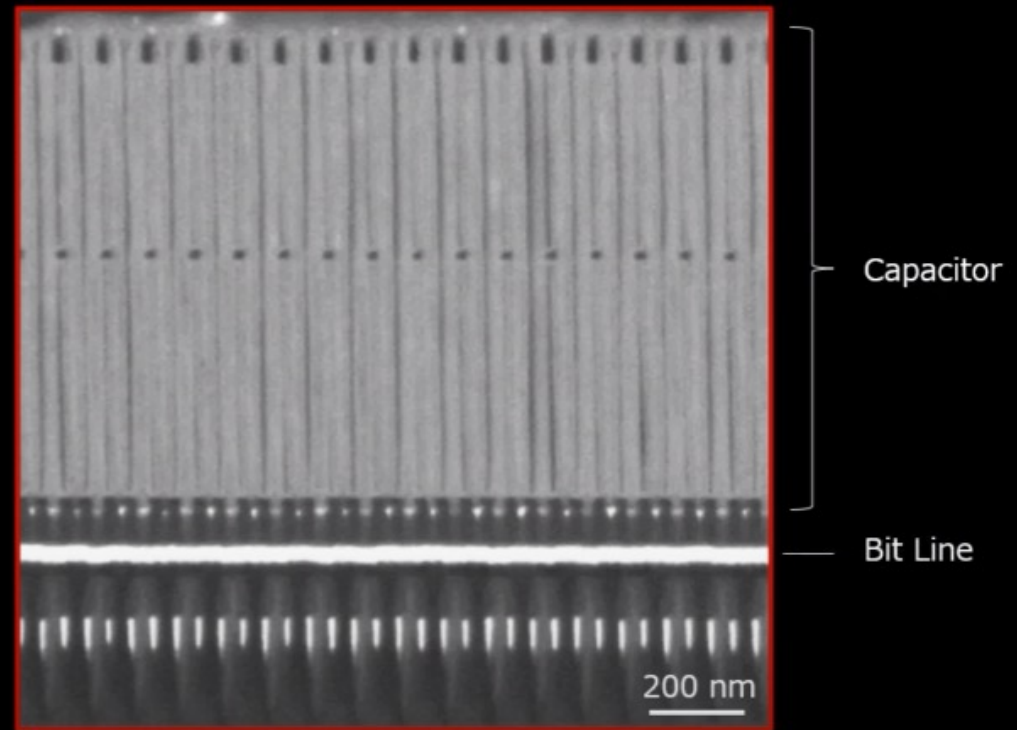
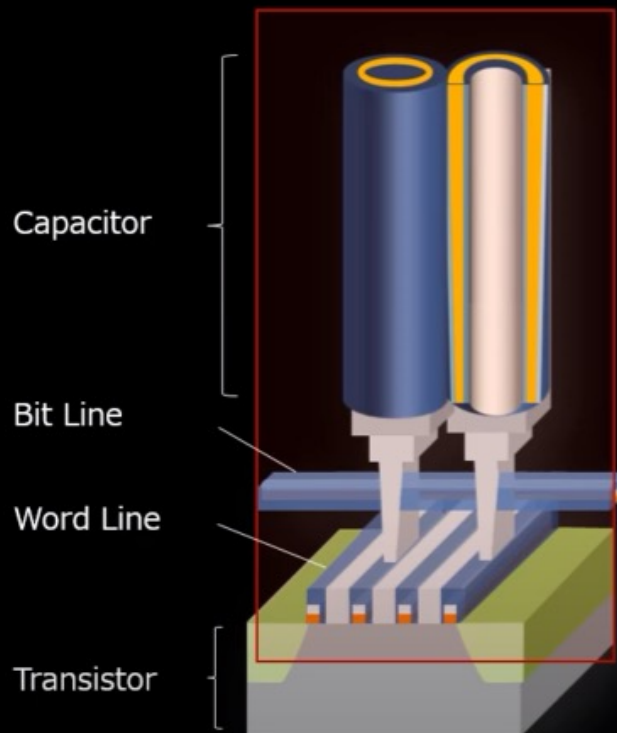
- DRAM capacity, cost, and energy/power hard to scale

The DRAM Scaling Problem

Cross-sectional SEM of DDR5* DRAM

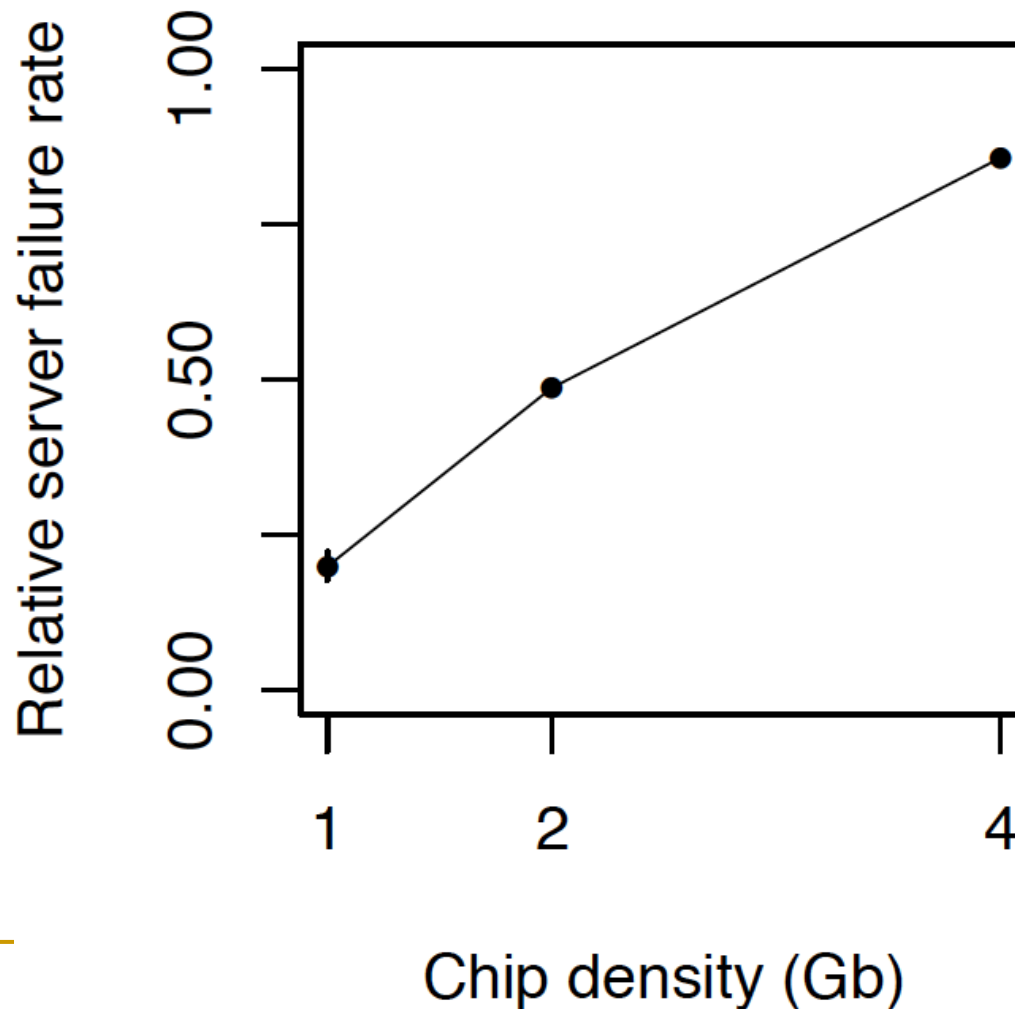
*Double Data Rate 5

(1y nm generation)



As Memory Scales, It Becomes Unreliable

- Data from all of Facebook's servers worldwide
- Meza+, "Revisiting Memory Errors in Large-Scale Production Data Centers," DSN'15.



*Intuition:
quadratic
increase
in
capacity*

Large-Scale Failure Analysis of DRAM Chips

- Analysis and modeling of memory errors found in all of Facebook's server fleet
- Justin Meza, Qiang Wu, Sanjeev Kumar, and Onur Mutlu,
"Revisiting Memory Errors in Large-Scale Production Data Centers: Analysis and Modeling of New Trends from the Field"
Proceedings of the 45th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Rio de Janeiro, Brazil, June 2015.
[[Slides \(pptx\)](#)] [[pdf](#)] [[DRAM Error Model](#)]

Revisiting Memory Errors in Large-Scale Production Data Centers: Analysis and Modeling of New Trends from the Field

Justin Meza Qiang Wu* Sanjeev Kumar* Onur Mutlu
Carnegie Mellon University * Facebook, Inc.

Infrastructures to Understand Such Issues



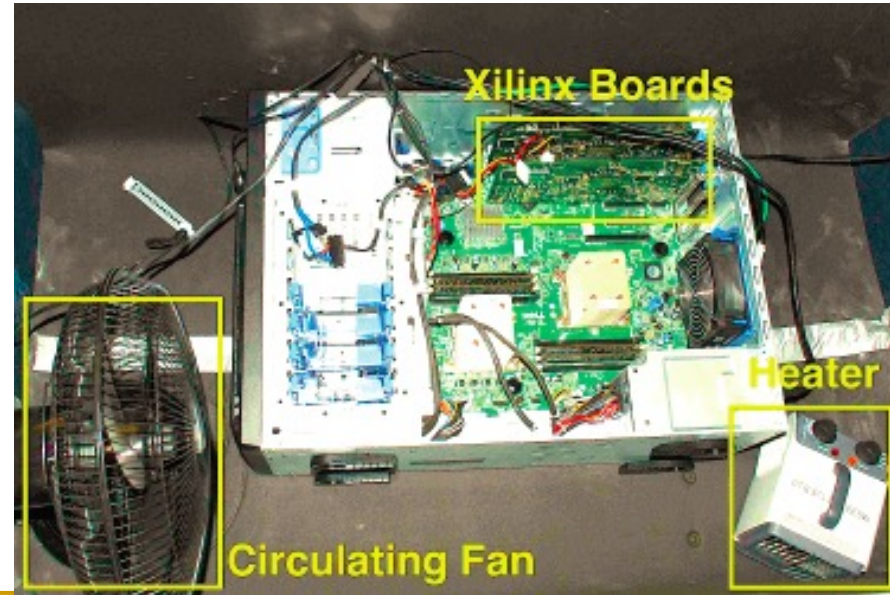
An Experimental Study of Data Retention Behavior in Modern DRAM Devices: Implications for Retention Time Profiling Mechanisms (Liu et al., ISCA 2013)

The Efficacy of Error Mitigation Techniques for DRAM Retention Failures: A Comparative Experimental Study (Khan et al., SIGMETRICS 2014)

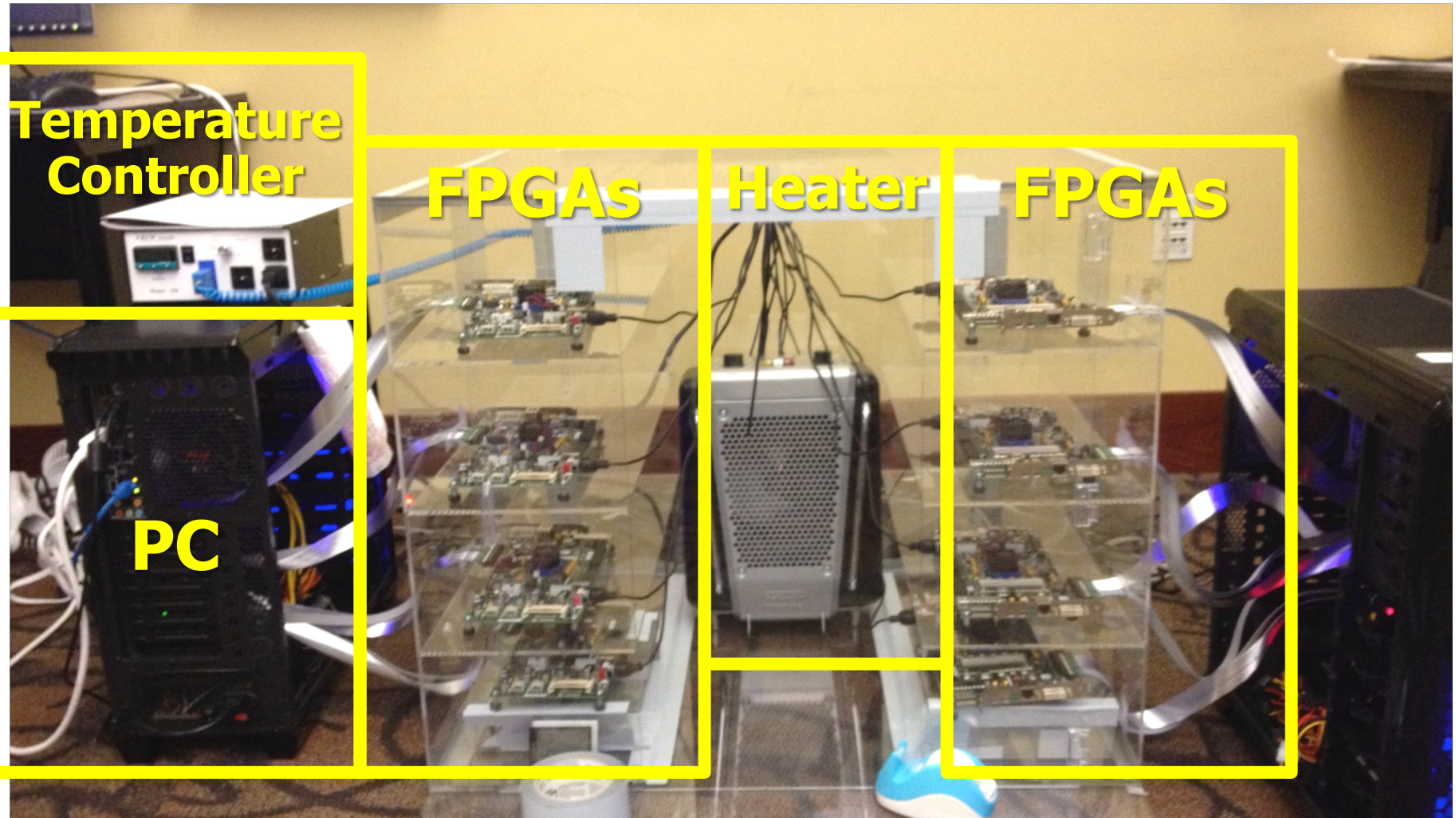
Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors (Kim et al., ISCA 2014)

Adaptive-Latency DRAM: Optimizing DRAM Timing for the Common-Case (Lee et al., HPCA 2015)

AVATAR: A Variable-Retention-Time (VRT) Aware Refresh for DRAM Systems (Qureshi et al., DSN 2015)



Infrastructures to Understand Such Issues



SoftMC: Open Source DRAM Infrastructure

- Hasan Hassan et al., “**SoftMC: A Flexible and Practical Open-Source Infrastructure for Enabling Experimental DRAM Studies**,” HPCA 2017.
- Flexible
- Easy to Use (C++ API)
- Open-source
github.com/CMU-SAFARI/SoftMC



SoftMC: Open Source DRAM Infrastructure

- Hasan Hassan, Nandita Vijaykumar, Samira Khan, Saugata Ghose, Kevin Chang, Gennady Pekhimenko, Donghyuk Lee, Oguz Ergin, and Onur Mutlu,

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

Proceedings of the 23rd International Symposium on High-Performance Computer Architecture (HPCA), Austin, TX, USA, February 2017.

[Slides (pptx) (pdf)] [Lightning Session Slides (pptx) (pdf)]

[Full Talk Lecture (39 minutes)]

[Source Code]

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

Hasan Hassan^{1,2,3} Nandita Vijaykumar³ Samira Khan^{4,3} Saugata Ghose³ Kevin Chang³
Gennady Pekhimenko^{5,3} Donghyuk Lee^{6,3} Oguz Ergin² Onur Mutlu^{1,3}

¹ETH Zürich ²TOBB University of Economics & Technology ³Carnegie Mellon University
⁴University of Virginia ⁵Microsoft Research ⁶NVIDIA Research

DRAM Bender

- Ataberk Olgun, Hasan Hassan, A Giray Yağlıkçı, Yahya Can Tuğrul, Lois Orosa, Haocong Luo, Minesh Patel, Oğuz Ergin, and Onur Mutlu,
"DRAM Bender: An Extensible and Versatile FPGA-based Infrastructure to Easily Test State-of-the-art DRAM Chips"
IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (TCAD), 2023.
[[Extended arXiv version](#)]
[[DRAM Bender Source Code](#)]
[[DRAM Bender Tutorial Video](#) (43 minutes)]

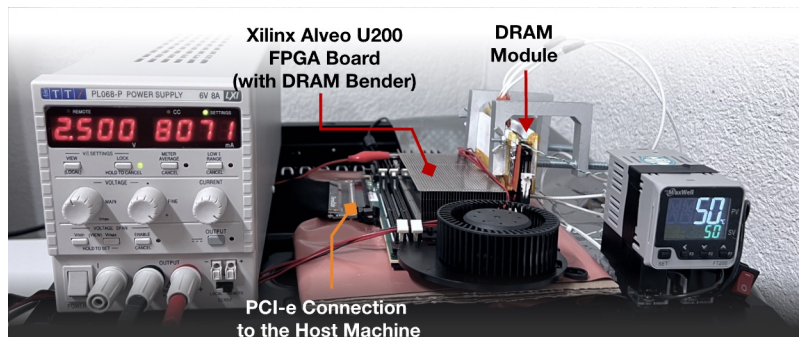
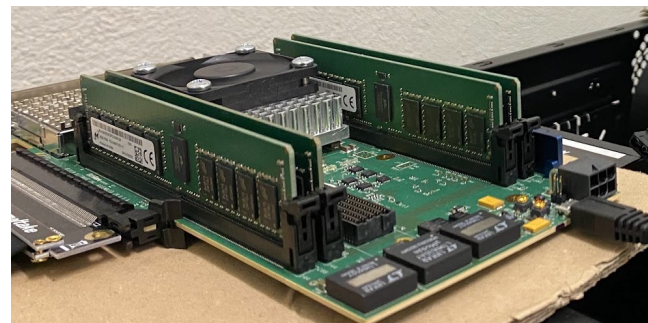
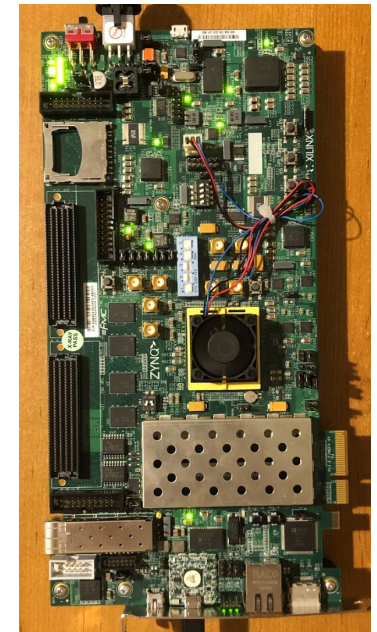
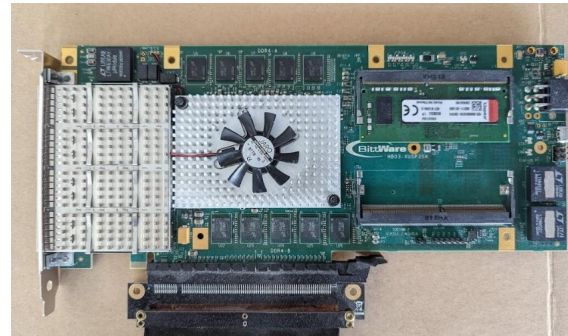
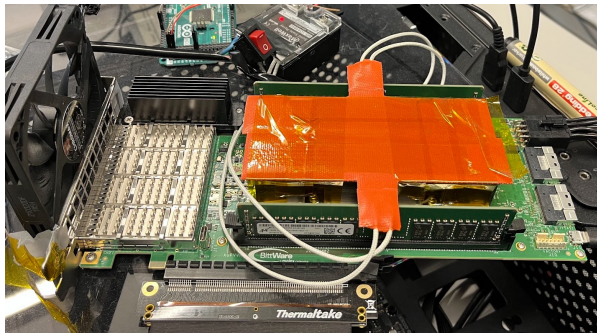
DRAM Bender: An Extensible and Versatile FPGA-based Infrastructure to Easily Test State-of-the-art DRAM Chips

Ataberk Olgun[§] Hasan Hassan[§] A. Giray Yağlıkçı[§] Yahya Can Tuğrul^{§†}
Lois Orosa^{§⊙} Haocong Luo[§] Minesh Patel[§] Oğuz Ergin[†] Onur Mutlu[§]
 [§]*ETH Zürich* [†]*TOBB ETÜ* [⊙]*Galician Supercomputing Center*

DRAM Bender: Prototypes

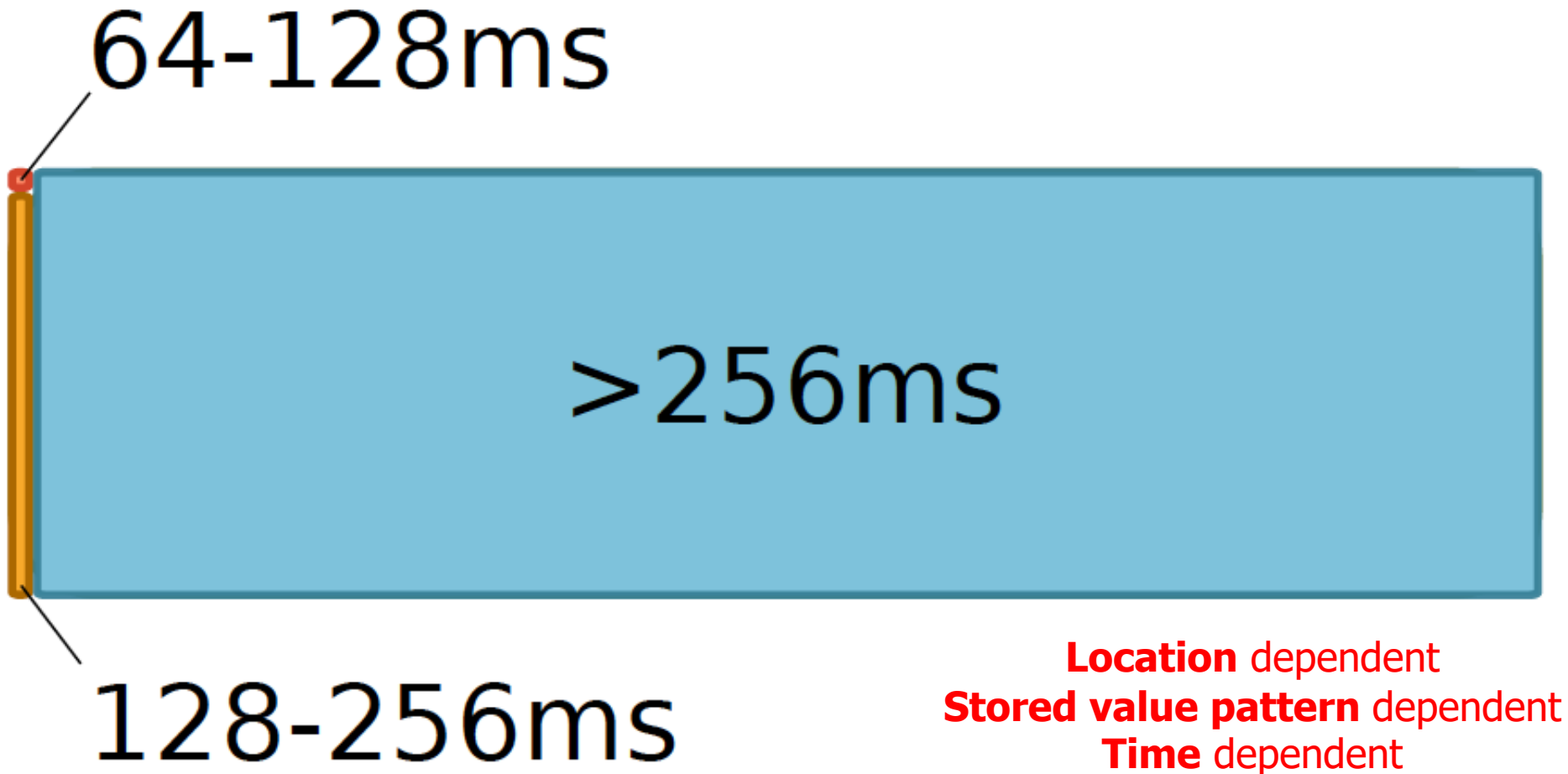
Testing Infrastructure	Protocol Support	FPGA Support
SoftMC [134]	DDR3	One Prototype
LiteX RowHammer Tester (LRT) [17]	DDR3/4, LPDDR4	Two Prototypes
DRAM Bender (this work)	DDR3/DDR4	Five Prototypes

Five out of the box FPGA-based prototypes



Data Retention in Memory [Liu et al., ISCA 2013]

- Retention Time Profile of DRAM looks like this:



RAIDR: Heterogeneous Refresh [ISCA'12]

- Jamie Liu, Ben Jaiyen, Richard Veras, and Onur Mutlu,
"RAIDR: Retention-Aware Intelligent DRAM Refresh"
Proceedings of the 39th International Symposium on Computer Architecture (ISCA), Portland, OR, June 2012. Slides (pdf)
[Invited Retrospective at 50 Years of ISCA, 2023 (pdf)]
Selected to the ISCA-50 25-Year Retrospective Issue covering 1996-2020 in 2023 (Retrospective (pdf) Full Issue).

RAIDR: Retention-Aware Intelligent DRAM Refresh

Jamie Liu Ben Jaiyen Richard Veras Onur Mutlu
Carnegie Mellon University

Analysis of Data Retention Failures [ISCA'13]

- Jamie Liu, Ben Jaiyen, Yoongu Kim, Chris Wilkerson, and Onur Mutlu,
"An Experimental Study of Data Retention Behavior in Modern DRAM Devices: Implications for Retention Time Profiling Mechanisms"
Proceedings of the 40th International Symposium on Computer Architecture (ISCA), Tel-Aviv, Israel, June 2013. [Slides \(ppt\)](#) [Slides \(pdf\)](#)
[Invited Retrospective at 50 Years of ISCA, 2023 (pdf)]
Selected to the ISCA-50 25-Year Retrospective Issue covering 1996-2020 in 2023 (Retrospective (pdf) Full Issue).

An Experimental Study of Data Retention Behavior in Modern DRAM Devices: Implications for Retention Time Profiling Mechanisms

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Infrastructure for Testing NAND Flash Chips



[DATE 2012, ICCD 2012, DATE 2013, ITJ 2013, ICCD 2013, SIGMETRICS 2014, HPCA 2015, DSN 2015, MSST 2015, JSAC 2016, HPCA 2017, DFRWS 2017, PIEEE 2017, HPCA 2018, SIGMETRICS 2018]

NAND Daughter Board

Cai+, "Error Characterization, Mitigation, and Recovery in Flash Memory Based Solid State Drives," Proc. IEEE 2017.

Analysis of NAND Flash Errors [DATE'12]

- Yu Cai, Erich F. Haratsch, Onur Mutlu, and Ken Mai, **"Error Patterns in MLC NAND Flash Memory: Measurement, Characterization, and Analysis"**
*Proceedings of the Design, Automation, and Test in Europe Conference (**DATE**), Dresden, Germany, March 2012. Slides (ppt)*

Error Patterns in MLC NAND Flash Memory: Measurement, Characterization, and Analysis

Yu Cai¹, Erich F. Haratsch², Onur Mutlu¹ and Ken Mai¹

¹Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA

²LSI Corporation, 1110 American Parkway NE, Allentown, PA

¹{yucai, onur, kenmai}@andrew.cmu.edu, ²erich.haratsch@lsi.com

Analysis of NAND Flash Errors [ITJ'13]

- Yu Cai, Gulay Yalcin, Onur Mutlu, Erich F. Haratsch, Adrian Cristal, Osman Unsal, and Ken Mai,
"Error Analysis and Retention-Aware Error Management for NAND Flash Memory"
Intel Technology Journal (ITJ) Special Issue on Memory Resiliency, Vol. 17, No. 1, May 2013.

Intel® Technology Journal | Volume 17, Issue 1, 2013

ERROR ANALYSIS AND RETENTION-AWARE ERROR MANAGEMENT
FOR NAND FLASH MEMORY



Proceedings of the IEEE, Sept. 2017



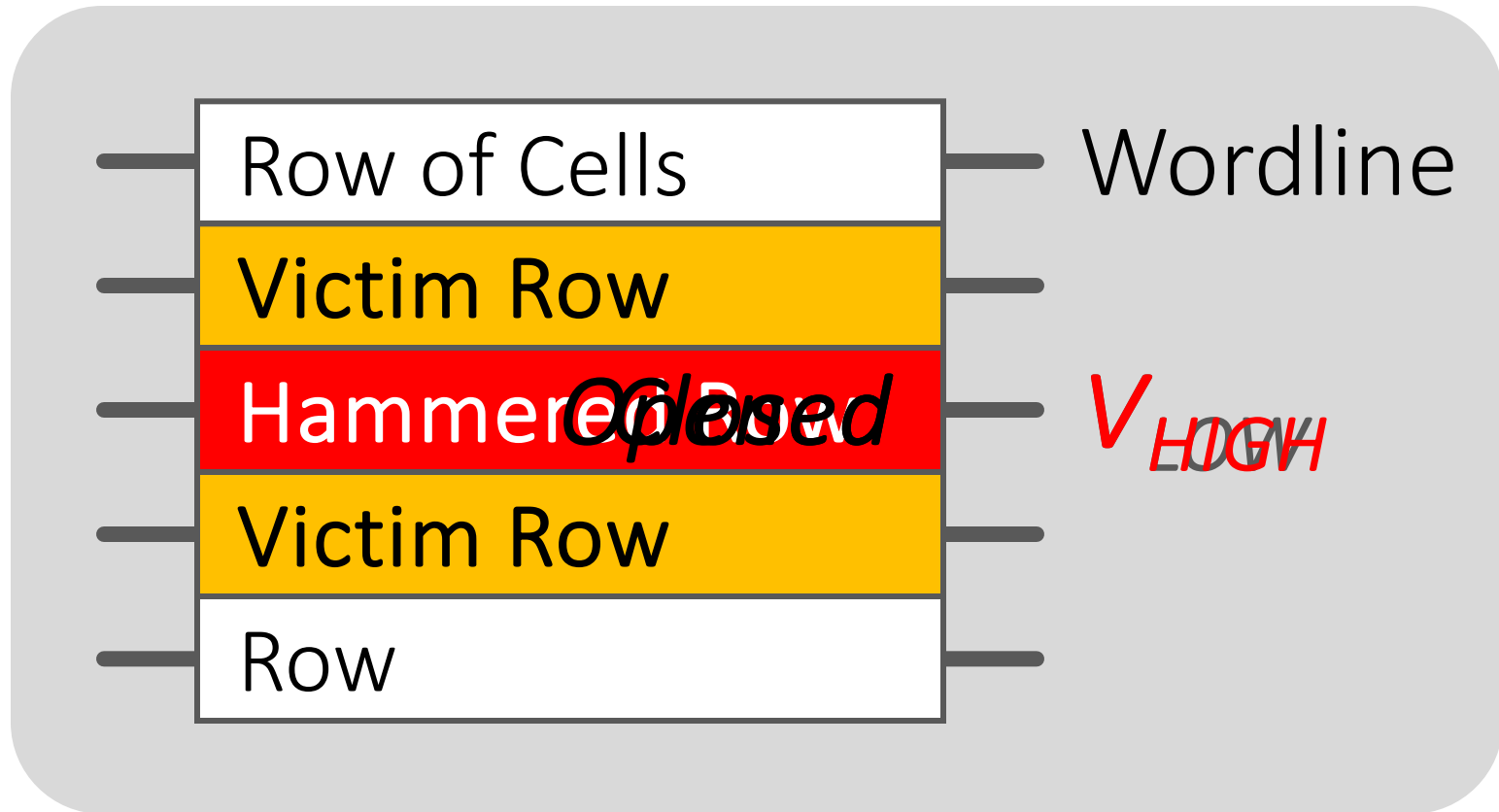
Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

This paper reviews the most recent advances in solid-state drive (SSD) error characterization, mitigation, and data recovery techniques to improve both SSD's reliability and lifetime.

By YU CAI, SAUGATA GHOSE, ERICH F. HARATSCH, YIXIN LUO, AND ONUR MUTLU

A Curious Phenomenon

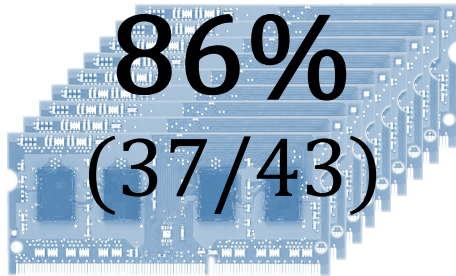
Modern DRAM is Prone to Disturbance Errors



Repeatedly reading a row enough times (before memory gets refreshed) induces **disturbance errors** in adjacent rows in **most real DRAM chips you can buy today**

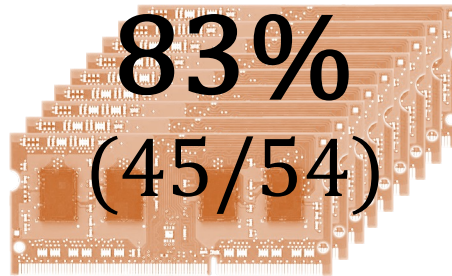
Most DRAM Modules Are Vulnerable

A company



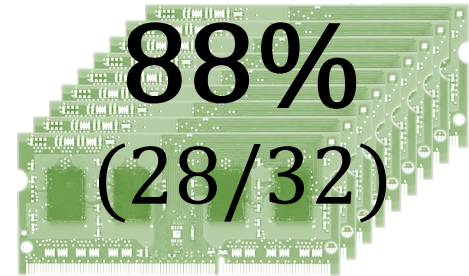
Up to
 1.0×10^7
errors

B company



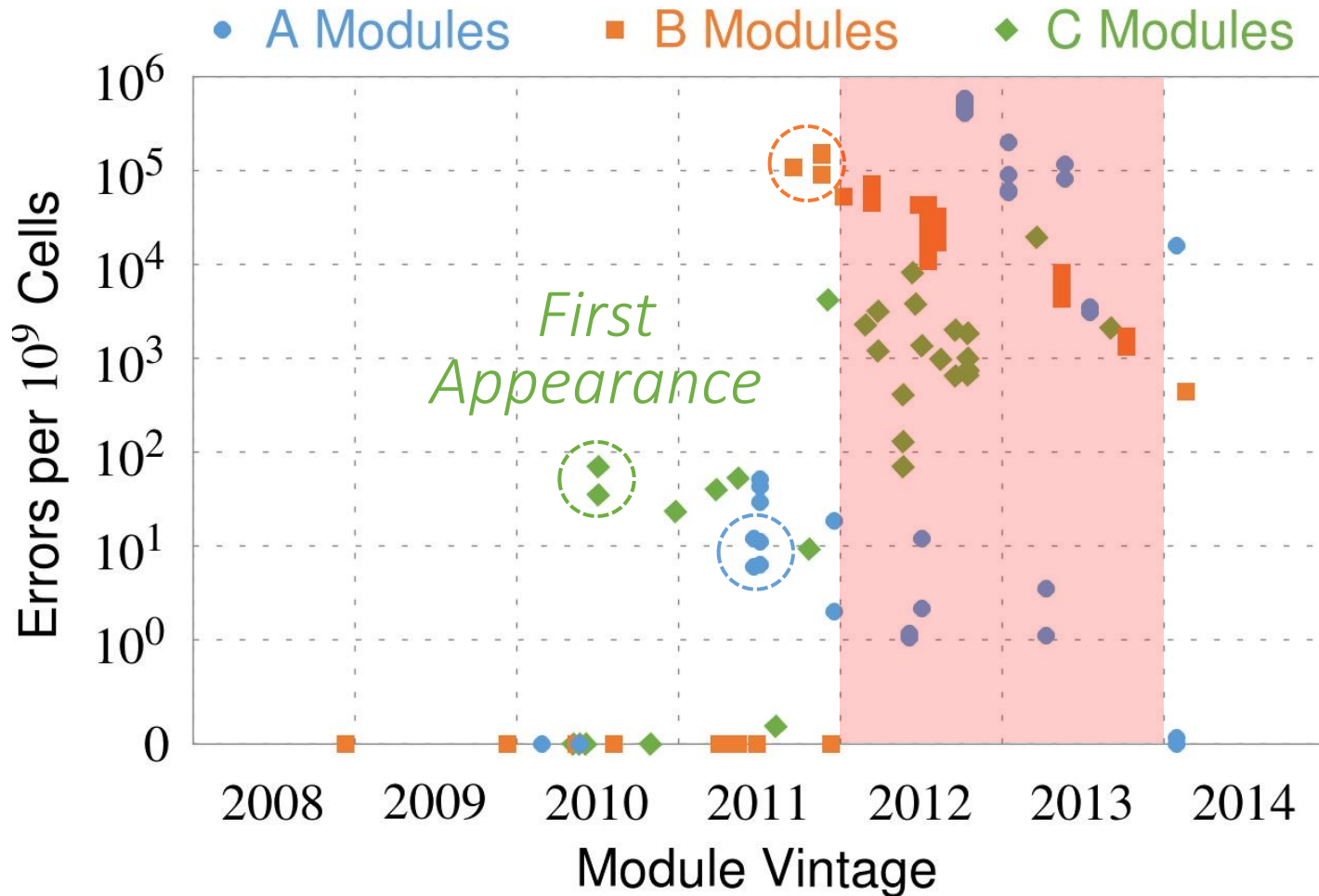
Up to
 2.7×10^6
errors

C company



Up to
 3.3×10^5
errors

Recent DRAM Is More Vulnerable



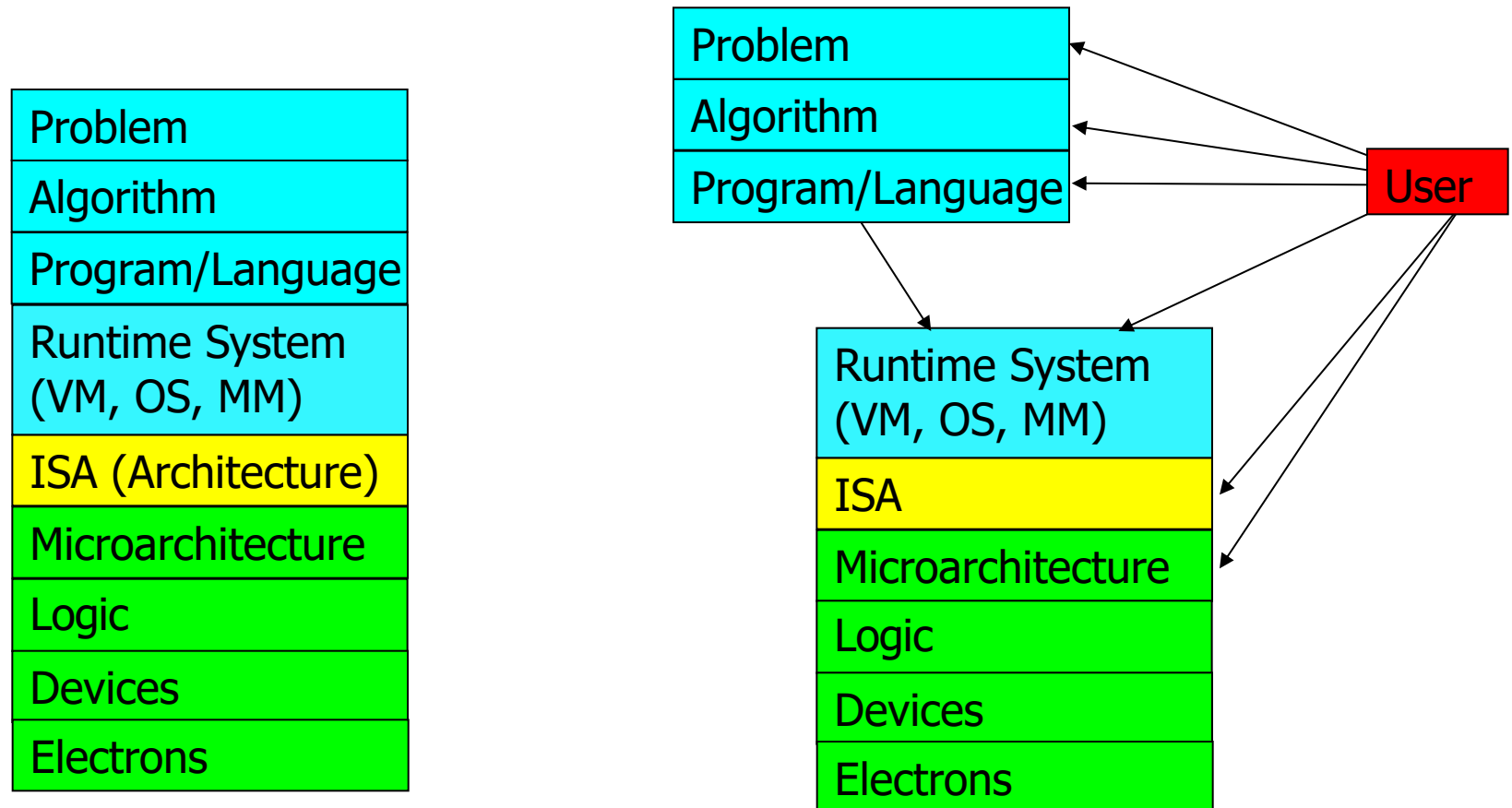
All modules from 2012-2013 are vulnerable

Why Is This Happening?

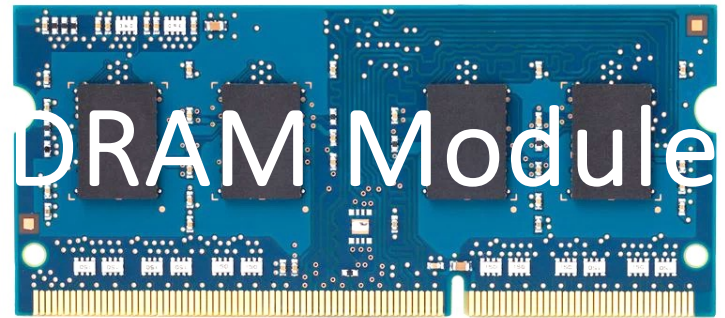
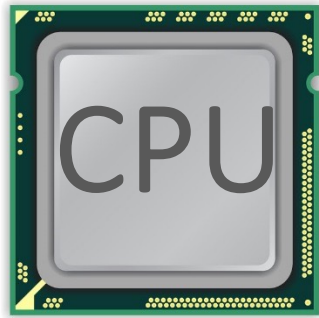
- DRAM cells are too close to each other!
 - They are not electrically isolated from each other
- Access to one cell affects the value in nearby cells
 - due to **electrical interference** between
 - the cells
 - wires used for accessing the cells
 - Also called cell-to-cell coupling/interference
- Example: When we activate (apply high voltage) to a row, an adjacent row gets slightly activated as well
 - Vulnerable cells in that slightly-activated row lose a little bit of charge
 - If RowHammer happens enough times, charge in such cells gets drained

Higher-Level Implications

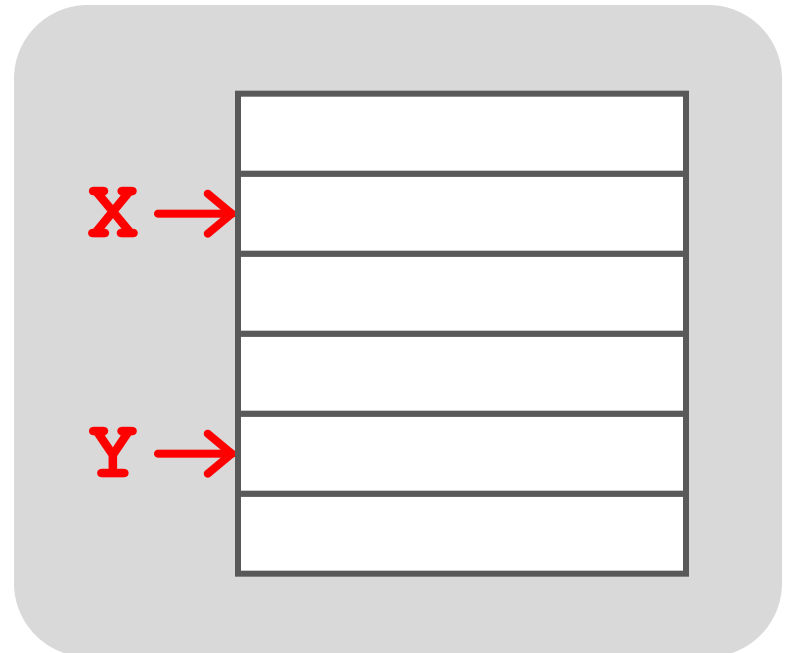
- This simple circuit level failure mechanism has enormous implications on upper layers of the transformation hierarchy



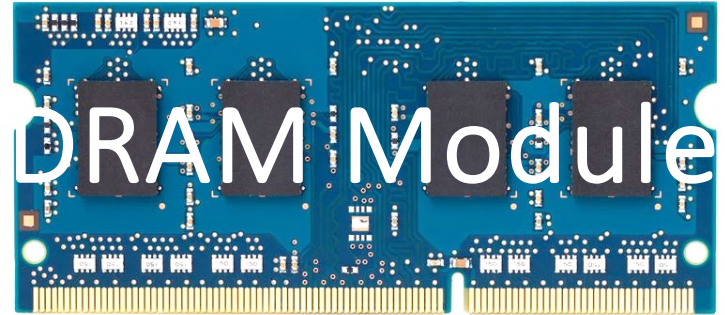
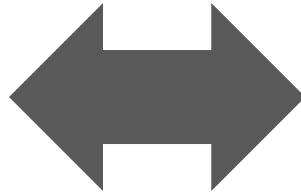
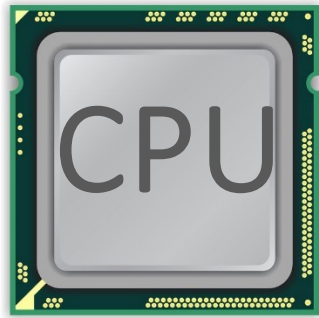
A Simple Program Can Induce Many Errors



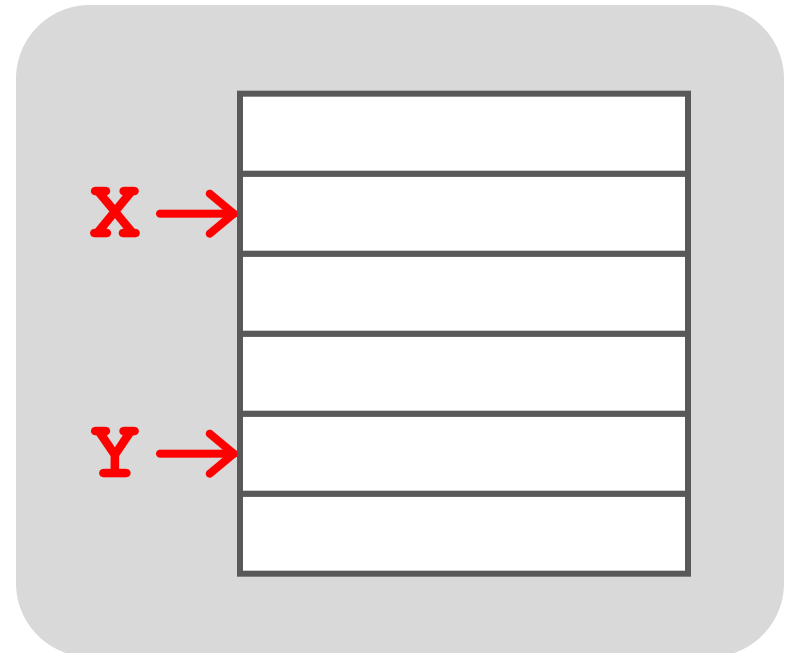
```
loop:  
  mov  (X), %eax  
  mov  (Y), %ebx  
  clflush (X)  
  clflush (Y)  
  mfence  
  jmp  loop
```



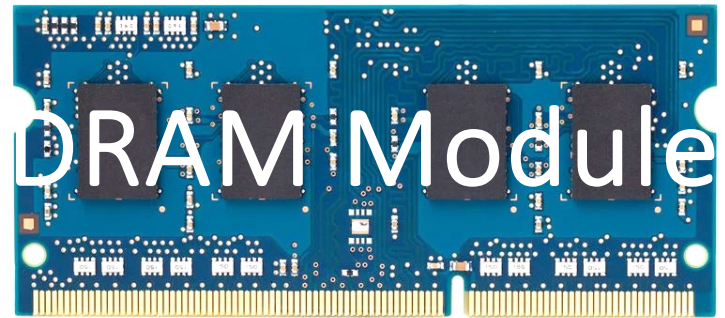
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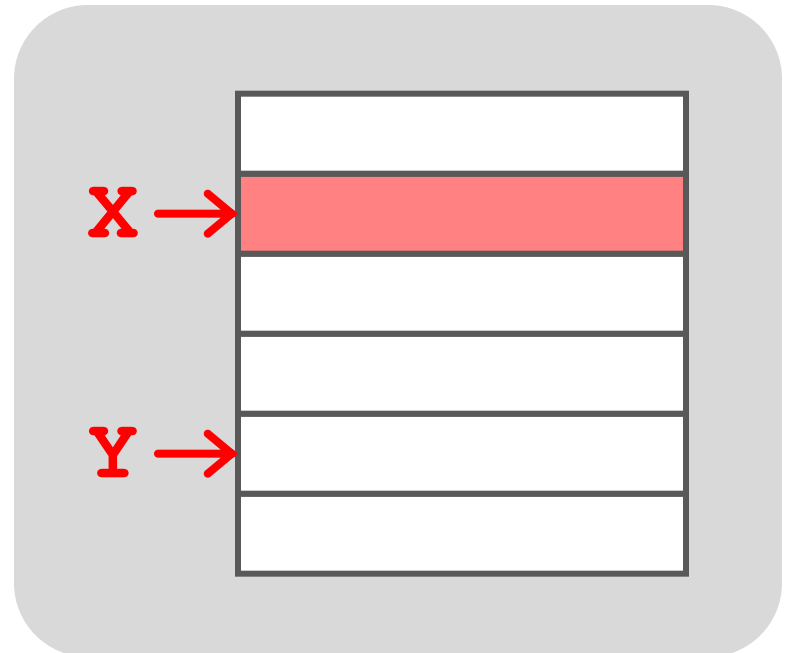
1. Avoid *cache hits*
 - Flush **X** from cache
2. Avoid *row hits* to **X**
 - Read **Y** in another row



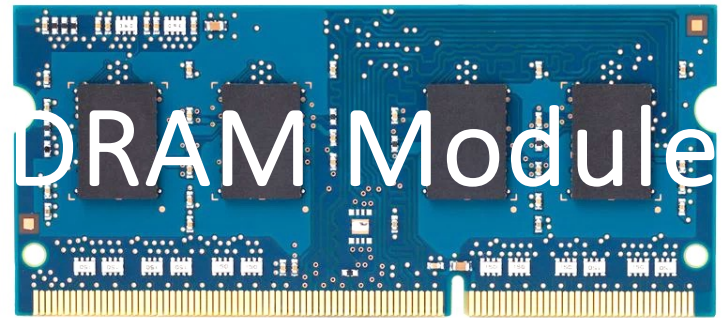
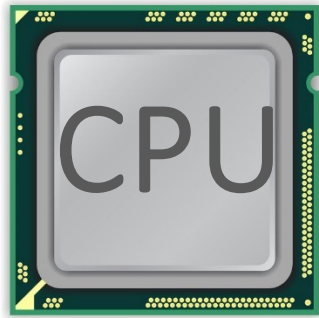
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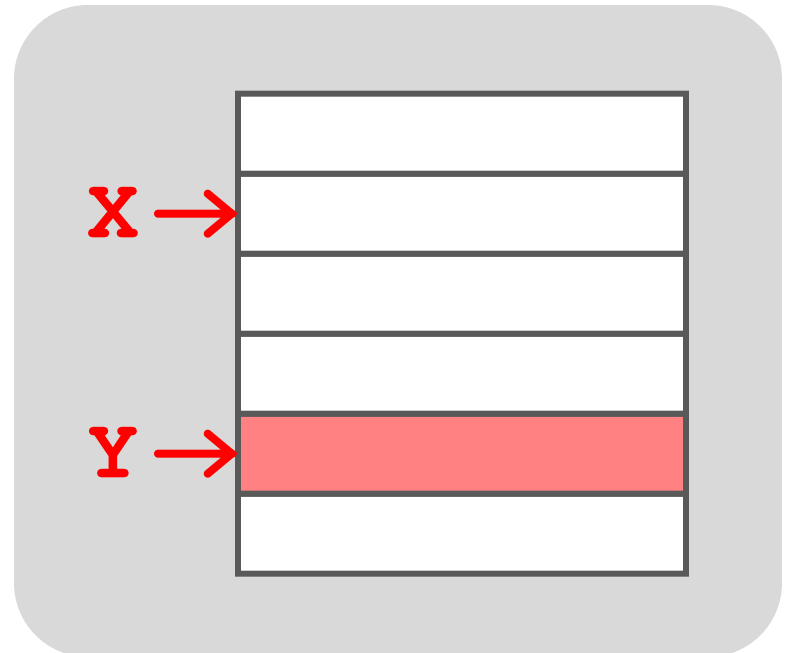
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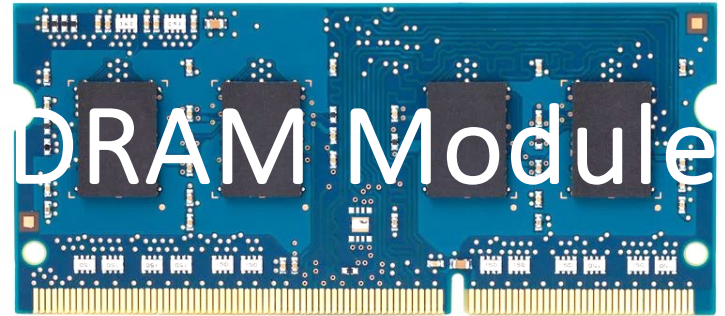
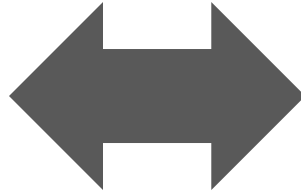
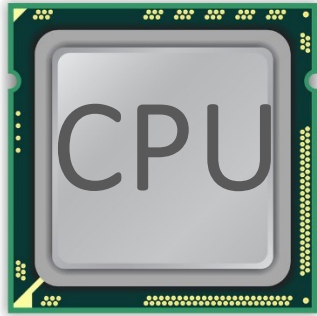
A Simple Program Can Induce Many Errors



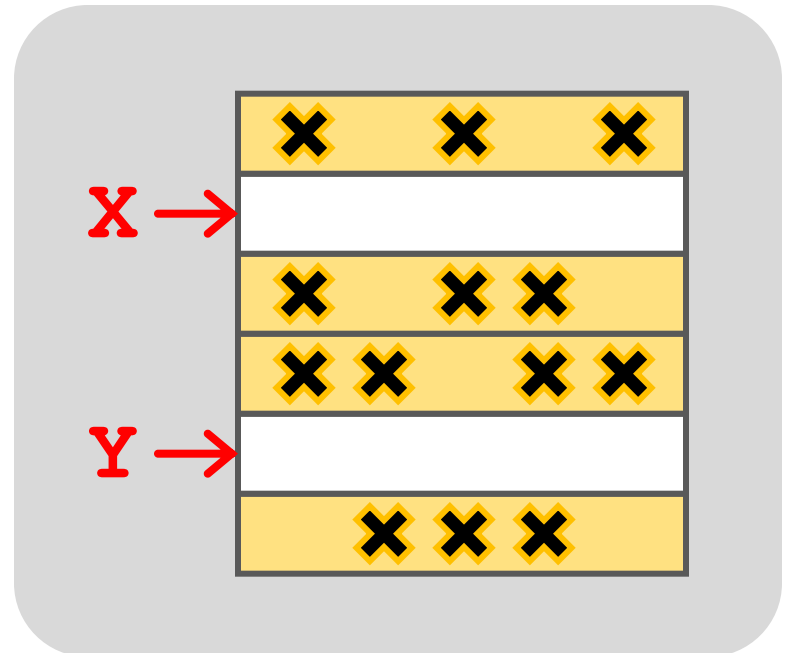
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  mov  (Y), %ebx  
  clflush (X)  
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  mfence  
  jmp  loop
```



A Simple Program Can Induce Many Errors



```
loop:  
  mov  (X), %eax  
  mov  (Y), %ebx  
  clflush (X)  
  clflush (Y)  
  mfence  
  jmp  loop
```



Observed Errors in Real Systems

CPU Architecture	Errors	Access-Rate
Intel Haswell (2013)	22.9K	12.3M/sec
Intel Ivy Bridge (2012)	20.7K	11.7M/sec
Intel Sandy Bridge (2011)	16.1K	11.6M/sec
AMD Piledriver (2012)	59	6.1M/sec

A real robustness issue
(including reliability, security, safety)

First Adopters: Memory Testing Software

- PassMark Software, memtest86, since 2014
 - <https://www.memtest86.com/troubleshooting.htm#hammer>

Why am I only getting errors during Test 13 Hammer Test?

The Hammer Test is designed to detect RAM modules that are susceptible to disturbance errors caused by charge leakage. This phenomenon is characterized in the research paper **Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors** by Yoongu Kim et al. According to the research, a significant number of RAM modules manufactured 2010 or newer are affected by this defect. In simple terms, susceptible RAM modules can be subjected to disturbance errors when repeatedly accessing addresses in the same memory bank but different rows in a short period of time. Errors occur when the repeated access causes charge loss in a memory cell, before the cell contents can be refreshed at the next DRAM refresh interval.

Starting from MemTest86 v6.2, the user may see a warning indicating that the RAM may be vulnerable to high frequency row hammer bit flips. This warning appears when errors are detected during the first pass (maximum hammer rate) but no errors are detected during the second pass (lower hammer rate). See **MemTest86 Test Algorithms** for a description of the two passes that are performed during the Hammer Test (Test 13). When performing the second pass, address pairs are hammered only at the rate deemed as the maximum allowable by memory vendors (200K accesses per 64ms). Once this rate is exceeded, the integrity of memory contents may no longer be guaranteed. If errors are detected in both passes, errors are reported as normal.

The errors detected during Test 13, albeit exposed only in extreme memory access cases, are most certainly real errors. During typical home PC usage (eg. web browsing, word processing, etc.), it is less likely that the memory usage pattern will fall into the extreme case that make it vulnerable to disturbance errors. It may be of greater concern if you were running highly sensitive equipment such as medical equipment, aircraft control systems, or bank database servers. It is impossible to predict with any accuracy if these errors will occur in real life applications. One would need to do a major scientific study of 1000 of computers and their usage patterns, then do a forensic analysis of each application to study how it makes use of the RAM while it executes. To date, we have only seen 1-bit errors as a result of running the Hammer Test.

First Adopters: Memory Testing Software

- PassMark Software, memtest86, since 2014
 - <https://www.memtest86.com/troubleshooting.htm#hammer>

Detection and mitigation of row hammer errors

The ability of MemTest86 to detect and report on row hammer errors depends on several factors and what mitigations are in place. To generate errors adjacent memory rows must be repeatedly accessed. But hardware features such as multiple channels, interleaving, **scrambling**, Channel Hashing, NUMA & XOR schemes make it nearly impossible (for an arbitrary CPU & RAM stick) to know which memory addresses correspond to which rows in the RAM. Various mitigations might also be in place. Different BIOS firmware might set the refresh interval to different values (tREFI). The shorter the interval the more resistant the RAM will be to errors. But shorter intervals result in higher power consumption and increased processing overhead. Some CPUs also support pseudo target row refresh (pTRR) that can be used in combination with pTRR-compliant RAM. This field allows the RAM stick to indicate the MAC (Maximum Active Count) level which is the RAM can support. A typical value might be 200,000 row activations. Some CPUs also support the Joint Electron Design Engineering Council (JEDEC) Targeted Row Refresh (TRR) algorithm. The TRR is an improved version of the previously implemented pTRR algorithm and does not inflict any performance drop or additional power usage. As a result the row hammer test implemented in MemTest86 maybe not be the worst case possible and vulnerabilities in the underlying RAM might be undetectable due to the mitigations in place in the BIOS and CPU.



One Can Take Over an Otherwise-Secure System

Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors

Abstract. Memory isolation is a key property of a reliable and secure computing system — an access to one memory address should not have unintended side effects on data stored in other addresses. However, as DRAM process technology

Project Zero

Flipping Bits in Memory Without Accessing Them:
An Experimental Study of DRAM Disturbance Errors
(Kim et al., ISCA 2014)

News and updates from the Project Zero team at Google

Exploiting the DRAM rowhammer bug to
gain kernel privileges (Seaborn, 2015)

Monday, March 9, 2015

Exploiting the DRAM rowhammer bug to gain kernel privileges

Many RowHammer Security Exploits

- One can exploit RowHammer to
- Take over a system
- Read data they do not have access to
- Break out of virtual machine sandboxes
- Corrupt important data → e.g., render ML inference useless
- Steal secret data (e.g., crypto keys & ML model parameters)

RowHammer Security Attack Example

- “Rowhammer” is a problem with some recent DRAM devices in which repeatedly accessing a row of memory can cause bit flips in adjacent rows (Kim et al., ISCA 2014).
 - Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors (Kim et al., ISCA 2014)
- We tested a selection of laptops and found that a subset of them exhibited the problem.
- We built two working privilege escalation exploits that use this effect.
 - Exploiting the DRAM rowhammer bug to gain kernel privileges (Seaborn+, 2015)
- One exploit uses rowhammer-induced bit flips to gain kernel privileges on x86-64 Linux when run as an unprivileged userland process.
- When run on a machine vulnerable to the rowhammer problem, the process was able to induce bit flips in page table entries (PTEs).
- It was able to use this to gain write access to its own page table, and hence gain read-write access to all of physical memory.

Security Implications



Security Implications



It's like breaking into an apartment by repeatedly slamming a neighbor's door until the vibrations open the door you were after

More Security Implications (I)

“We can gain unrestricted access to systems of website visitors.”

www.iaik.tugraz.at ■

Not there yet, but ...



ROOT privileges for web apps!

29

Daniel Gruss (@lavados), Clémentine Maurice (@BloodyTangerine),
December 28, 2015 — 32c3, Hamburg, Germany



GATED
COMMUNITIES

Rowhammer.js: A Remote Software-Induced Fault Attack in JavaScript (DIMVA'16)

More Security Implications (II)

"Can gain control of a smart phone deterministically"



Drammer: Deterministic Rowhammer
Attacks on Mobile Platforms, CCS'16 ⁴⁷

More Security Implications (III)

- Using an integrated GPU in a mobile system to remotely escalate privilege via the WebGL interface. [IEEE S&P 2018](#)



TECHNICA

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"GRAND PWINING UNIT" —

Drive-by Rowhammer attack uses GPU to compromise an Android phone

JavaScript based GLitch pwns browsers by flipping bits inside memory chips.

DAN GOODIN - 5/3/2018, 12:00 PM

Grand Pwning Unit: Accelerating Microarchitectural Attacks with the GPU

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More Security Implications (IV)

- Rowhammer over RDMA (I) [USENIX ATC 2018](#)

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THROWHAMMER —

Packets over a LAN are all it takes to trigger serious Rowhammer bit flips

The bar for exploiting potentially serious DDR weakness keeps getting lower.

DAN GOODIN - 5/10/2018, 5:26 PM

Throwhammer: Rowhammer Attacks over the Network and Defenses

Andrei Tatar
VU Amsterdam

Radhesh Krishnan
VU Amsterdam

Elias Athanasopoulos
University of Cyprus

Cristiano Giuffrida
VU Amsterdam

Herbert Bos
VU Amsterdam

Kaveh Razavi
VU Amsterdam

More Security Implications (V)

■ Rowhammer over RDMA (II)



Nethammer—Exploiting DRAM Rowhammer Bug Through Network Requests



Nethammer: Inducing Rowhammer Faults through Network Requests

Moritz Lipp
Graz University of Technology

Misiker Tadesse Aga
University of Michigan

Michael Schwarz
Graz University of Technology

Daniel Gruss
Graz University of Technology

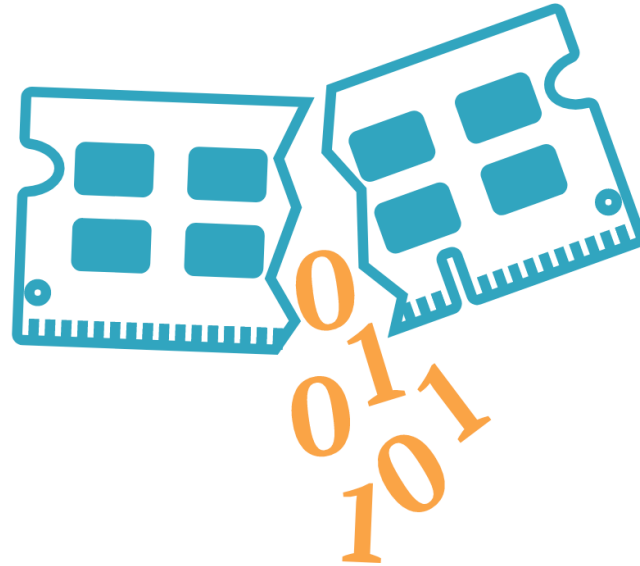
Clémentine Maurice
Univ Rennes, CNRS, IRISA

Lukas Raab
Graz University of Technology

Lukas Lamster
Graz University of Technology

More Security Implications (VI)

- IEEE S&P 2020



RAMBleed

RAMBleed: Reading Bits in Memory Without Accessing Them

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More Security Implications (VII)

■ USENIX Security 2019

Terminal Brain Damage: Exposing the Graceless Degradation in Deep Neural Networks Under Hardware Fault Attacks

Sanghyun Hong, Pietro Frigo[†], Yiğitcan Kaya, Cristiano Giuffrida[†], Tudor Dumitraş

University of Maryland, College Park

[†]Vrije Universiteit Amsterdam



A Single Bit-flip Can Cause Terminal Brain Damage to DNNs

One specific bit-flip in a DNN's representation leads to accuracy drop over 90%

Our research found that a specific bit-flip in a DNN's bitwise representation can cause the accuracy loss up to 90%, and the DNN has 40-50% parameters, on average, that can lead to the accuracy drop over 10% when individually subjected to such single bitwise corruptions...

[Read More](#)

More Security Implications (VIII)

■ USENIX Security 2020

DeepHammer: Depleting the Intelligence of Deep Neural Networks through Targeted Chain of Bit Flips

Fan Yao
University of Central Florida
fan.yao@ucf.edu

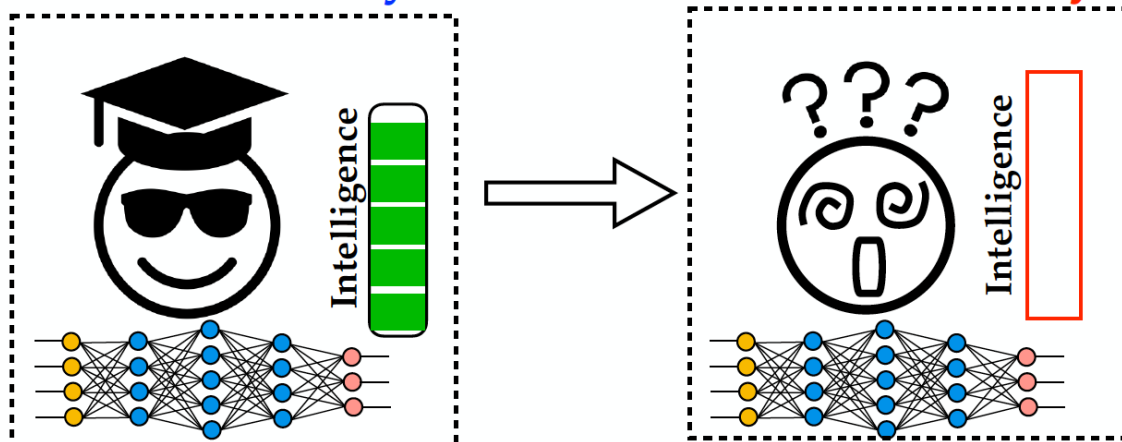
Adnan Siraj Rakin
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Degrade the inference accuracy to the level of Random Guess

Example: ResNet-20 for CIFAR-10, 10 output classes

Before attack, **Accuracy: 90.2%** After attack, **Accuracy: ~10% (1/10)**



More Security Implications (IX)

■ CHES 2020

JackHammer: Efficient Rowhammer on Heterogeneous FPGA-CPU Platforms

Zane Weissman¹, Thore Tiemann², Daniel Moghimi¹, Evan Custodio³,
Thomas Eisenbarth² and Berk Sunar¹

¹ Worcester Polytechnic Institute, MA, USA

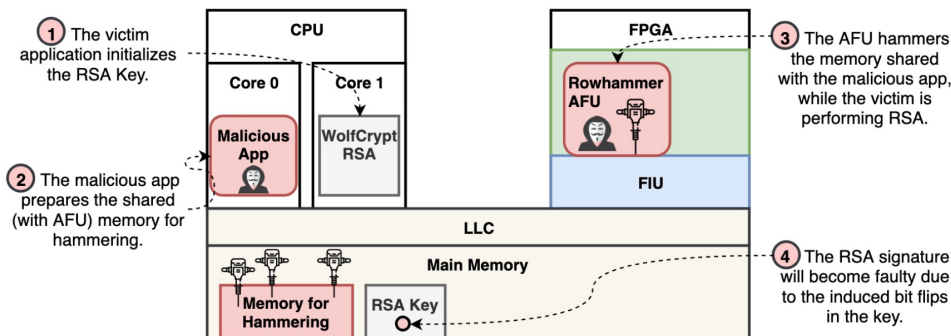
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An **FPGA-based** RowHammer attack recovering **private keys** twice as fast compared to **CPU-based** attacks

Google's Half-Double RowHammer Attack (May 2021)

Google Security Blog

The latest news and insights from Google on security and safety on the Internet

Introducing Half-Double: New hammering technique for DRAM Rowhammer bug

May 25, 2021

Research Team: Salman Qazi, Yoongu Kim, Nicolas Boichat, Eric Shiu & Mattias Nissler

Today, we are sharing details around our discovery of [Half-Double](#), a new Rowhammer technique that capitalizes on the worsening physics of some of the newer DRAM chips to alter the contents of memory.

Rowhammer is a DRAM vulnerability whereby repeated accesses to one address can tamper with the data stored at other addresses. Much like speculative execution vulnerabilities in CPUs, Rowhammer is a breach of the security guarantees made by the underlying hardware. As an electrical coupling phenomenon within the silicon itself, Rowhammer allows the potential bypass of hardware and software memory protection policies. This can allow untrusted code to break out of its sandbox and take full control of the system.

More Security Implications (X)

- **USENIX Security 2022**
- **Google's Half-Double RowHammer Attack**

Google Security Blog

The latest news and insights from Google on security and safety on the Internet

Introducing Half-Double: New hammering technique for DRAM Rowhammer bug

May 25, 2021

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Half-Double: Hammering From the Next Row Over

Andreas Kogler¹ Jonas Juffinger^{1,2} Salman Qazi³ Yoongu Kim³ Moritz Lipp^{4*}
Nicolas Boichat³ Eric Shiu⁵ Mattias Nissler³ Daniel Gruss¹

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⁴*Amazon Web Services* ⁵*Rivos*

More Security Implications?



A RowHammer Survey Across the Stack

- Onur Mutlu and Jeremie Kim,
[**"RowHammer: A Retrospective"**](#)
IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (TCAD) Special Issue on Top Picks in Hardware and Embedded Security, 2019.
[[Preliminary arXiv version](#)]
[[Slides from COSADE 2019 \(pptx\)](#)]
[[Slides from VLSI-SOC 2020 \(pptx\) \(pdf\)](#)]
[[Talk Video](#) (1 hr 15 minutes, with Q&A)]

RowHammer: A Retrospective

Onur Mutlu^{§‡} Jeremie S. Kim^{‡§}
§ETH Zürich ‡Carnegie Mellon University

A RowHammer Survey: Recent Update

- Onur Mutlu, Ataberk Olgun, and A. Giray Yaglikci,
"Fundamentally Understanding and Solving RowHammer"
Invited Special Session Paper at the 28th Asia and South Pacific Design Automation Conference (ASP-DAC), Tokyo, Japan, January 2023.
[arXiv version]
[Slides (pptx) (pdf)]
[Talk Video (26 minutes)]

Fundamentally Understanding and Solving RowHammer

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<https://arxiv.org/pdf/2211.07613.pdf>

A Short Retrospective @ 50 Years of ISCA

Retrospective: Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors

Onur Mutlu
ETH Zürich

Abstract—Our ISCA 2014 paper [1] provided the first scientific and detailed characterization, analysis, and real-system demonstration of what is now popularly known as the RowHammer phenomenon (or vulnerability) in modern commodity DRAM chips, which are used as main memory in almost all modern computing systems. It experimentally demonstrated that more than 80% of all DRAM modules we tested from the three major DRAM vendors were vulnerable to the RowHammer read disturbance phenomenon; one can predictably induce bitflips (i.e., data corruption) in real DRAM modules by repeatedly accessing a DRAM row and thus causing electrical disturbance to physically nearby rows. We showed that a simple unprivileged user-level program induced RowHammer bitflips in multiple real systems and suggested that a security attack can be built using this proof-of-concept to hijack control of the system or cause other harm. To solve the RowHammer problem, our paper examined seven different approaches (including a novel probabilistic approach that has very low cost), some of which influenced or were adopted in different industrial products.

Many later works from various research communities examined RowHammer, building real security attacks, proposing new defenses, further analyzing the problem at various (e.g., device/circuit, architecture, and system) levels, and exploiting RowHammer for various purposes (e.g., to reverse-engineer DRAM chips). Industry has worked to mitigate the problem, changing both memory controllers and DRAM standards/chips. Two major DRAM vendors finally wrote papers on the topic in 2023, describing their current approaches to mitigate RowHammer. Research & development on RowHammer in both academia & industry continues to be very active and fascinating.

This short retrospective provides a brief analysis of our ISCA 2014 paper and its impact. We describe the circumstances that led to our paper, mention its influence on later works and products, describe the change we believe it has helped enable in hardware security, and discuss our predictions for future.

I. BACKGROUND AND CIRCUMSTANCES

Our stumbling on the RowHammer problem and creation of its first scientific analysis happened as a result of a confluence of multiple factors. First, my group was working on DRAM technology scaling issues since late 2010. We were very interested in failure mechanisms that appear or worsen due to aggressive technology scaling. To study such issues (e.g., data retention errors [2]), we built an FPGA-based DRAM testing infrastructure [2] between 2011-2012, which we later open sourced as SoFIMC [3, 4] and DRAM Bender [5, 6]. Second, around the same timeframe, we were investigating similar technology scaling issues in flash memory using real NAND flash chips [7, 8]. We knew read disturbance errors were significant in NAND flash memory [7–11] and were very interested in how prevalent they were in DRAM. Third, we were collaborating with Intel (e.g., [2]) to understand and solve DRAM technology scaling problems and build our DRAM infrastructure. Three of my students and I spent the summer of 2012 at Intel to work closely with our collaborators (two are co-authors): during this time, we finalized the calibration and stabilization of our infrastructure and had significant technical discussions and experimentation on DRAM scaling problems.

Although there was awareness of the RowHammer problem in industry in 2012 (see Footnote 1 in [1]), there was no comprehensive experimental analysis and detailed real-system demonstration of it. We believed it was critical to provide a rigorous scientific analysis using a wide variety of DRAM chips and scientifically establish major characteristics and prevalence of RowHammer. Hence, in the summer of 2012, we set out to use our DRAM testing infrastructure to analyze RowHammer. Our initial results showed how widespread the read disturbance problem was across the (at the time) recent DRAM chips we tested, so we studied the problem comprehensively and developed many solutions to it. The resulting paper was submitted to MICRO in May 2013 but was rejected. We strengthened the results, especially of the mitigation mechanisms and the number of tested chips, and made the analysis

more comprehensive before it was accepted to ISCA 2014 [2] of the 6 reviewers still rejected it for interesting reasons).

II. MAJOR CONTRIBUTION AND INFLUENCE

The major contribution of our paper is the exposure and detailed analysis of a fundamental hardware failure mechanism that breaks memory isolation in real systems and thus has huge implications on system reliability, security, and safety. Our paper is a comprehensive study of a major DRAM technology scaling problem, RowHammer, including its first scientific analysis, experimental characterization, real system demonstration, and solutions with their evaluation. To our knowledge, RowHammer is the first example of a hardware failure mechanism that creates a significant and widespread system security vulnerability [12–15], as our ISCA 2014 paper suggested.

Our work has had large influence on both industry & academia. Individual follow-on works are many to list here; we refer the reader to longer invited retrospectives we wrote [12–14]. We give major examples of influence, focusing on RowHammer's effect on the collective mindset of security research and major industry milestones related to RowHammer.

RowHammer Attacks & Mindset Shift in Hardware Security. Our demonstration that one can easily and predictably induce bitflips in commodity DRAM chips using a real user-level program enabled a major mindset shift in hardware security. It showed that general-purpose hardware is fallible in a very widespread manner and its problems are exploitable. Tens of works (see [13, 14]) built directly on our work to exploit RowHammer bitflips to develop many attacks that compromise system integrity and confidentiality, starting from the first RowHammer exploit by Google Project Zero in 2015 [16, 17] to recent works in 2022-2023 (e.g., [18, 19]). These attacks showed increasingly sophisticated ways by which an unprivileged attacker can exploit RowHammer bitflips to circumvent memory protection and gain complete control of a system (e.g., [16, 20–28]), gain access to confidential data (e.g., [18, 19, 29]), or maliciously destroy the safety and accuracy of a system, e.g., an otherwise accurate machine learning inference engine (e.g., [30, 31]). The mindset enabled by RowHammer bitflips caused a renewed interest in hardware security research, enticing many researchers to deeply understand hardware's inner workings and find new vulnerabilities. Thus, hardware security issues have become mainstream discussion in top security & architecture venues, some having sessions entitled RowHammer.

RowHammer Defenses. Tens of works proposed mitigations against RowHammer, some of which were inspired by the solutions we discussed in our ISCA 2014 paper. To date, the search for more efficient and low-cost RowHammer solutions continues. We refer the reader to our prior overview papers [13, 14, 32] and more recent works in 2023 (e.g., [33–35]).

RowHammer Analyses. Our paper initiated works at both architectural & circuit/device-levels to better understand RowHammer and reverse-engineer DRAM chips, to develop better models, defenses, and attacks (see [13, 14]). Our ISCA'20 work [36] revisited RowHammer, comprehensively analyzed of 1580 DRAM chips of three different types from at least two generations, showing that RowHammer has gotten much worse with technology scaling & existing solutions are not effective at future vulnerability levels.

Industry Reaction: Attacks, Analyses, and Mitigations. Folks developing industrial memory testing programs immediately included RowHammer tests, e.g., in memtest86 [37], citing our work. Industry needed to immediately protect RowHammer-vulnerable chips already in the field, so almost all system vendors increased refresh rates; a solution we examined in our paper and deemed costly for performance and energy, yet it was the only practical lever that could be used in the field. Apple publicly acknowledged our work in their security release [38] that announced higher refresh rates

to mitigate RowHammer. Intel designed memory controllers that performed probabilistic activations (i.e., pTRR [39, 40]), similar to our PARA solution [1]. DRAM vendors modified the DRAM standard to introduce TRR (target row refresh) mechanisms [39] and claimed their new DDR4 chips to be RowHammer-free [39, 41]. This bold claim was later refuted by our TRRespass work [39] in 2020, which introduced the many-sided RowHammer attack to circumvent internal protection mechanisms added to the DRAM chips. Our later work, Uncovering TRR [41] showed that one can almost completely reverse-engineer and thus easily bypass RowHammer mitigations employed in all tested DRAM chips, i.e., RowHammer solutions in DRAM chips are broken. The industry done by our two major works in 2020 [36, 39] caused the industry to reorganize the RowHammer task group at JEDEC, which produced two white papers on mitigating RowHammer [42, 43]. Nine years after our paper, in 2023, two major DRAM vendors, SK Hynix and Samsung, finally wrote papers [44, 45] on the RowHammer problem, describing their solutions. Several of these industry solutions build on the probabilistic & access-counter-based solution approaches our ISCA 2014 paper introduced.

Major Internet and cloud systems companies also took a deep interest in RowHammer as it can greatly impact their system security, dependability, and availability. Multiple works from Google, e.g., by Google Project Zero in 2015 [16, 17] and Half Double in 2021–2022 [46] directly built on our paper to demonstrate attacks in real systems. Researchers from Microsoft have developed deeper analyses of RowHammer [47], along with new RowHammer attacks [48] and defenses (e.g., [48–51]).

III. SUMMARY AND FUTURE OUTLOOK

Since 2012-2014, RowHammer vulnerability has become much worse due to technology scaling: without mitigation, one can now induce RowHammer bitflips with orders of magnitude smaller number of activations (e.g., ~10K) and cause much higher rates of errors in cutting-edge DRAM chips [36, 41]. Sophisticated attacks are continuously developed to circumvent the mitigations employed in real DRAM chips. Fortunately, we have also come a long way in further understanding and better mitigating the RowHammer vulnerability. The industry is now (hopefully) fully aware of the importance of the problem and of avoiding bitflips. Unfortunately, an efficient and completely-secure solution is not found yet. The solution space poses a rich area of tradeoffs in terms of security, performance, power/energy, cost/complexity. All solutions forego some desirable properties in favor of others. As such, a critical direction for the future is to find solutions superior to what we have today. We believe system-DRAM cooperation [14, 52] will be important to enabling complete solutions. We also believe it is critical to deeply understand the properties of RowHammer under many different conditions so that we can develop effective solutions that work under all circumstances. Unfortunately, we do not yet fully understand many facets of RowHammer (see [14, 53–55]).

DRAM technology scaling will continue to create problems that will exacerbate the bitflips and the resulting robustness (i.e., safety/security/reliability) problems. Our ISCA 2023 paper on RowPress [55] provides the first scientific and detailed characterization, analysis, and real-system demonstration of yet another read disturbance mechanism in DRAM. What other fascinating problems will we see and can we completely solve them efficiently? Will we ever be free of bitflips at the system and application levels?

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Understanding RowHammer

First Row Hammer Analysis [ISCA 2014]

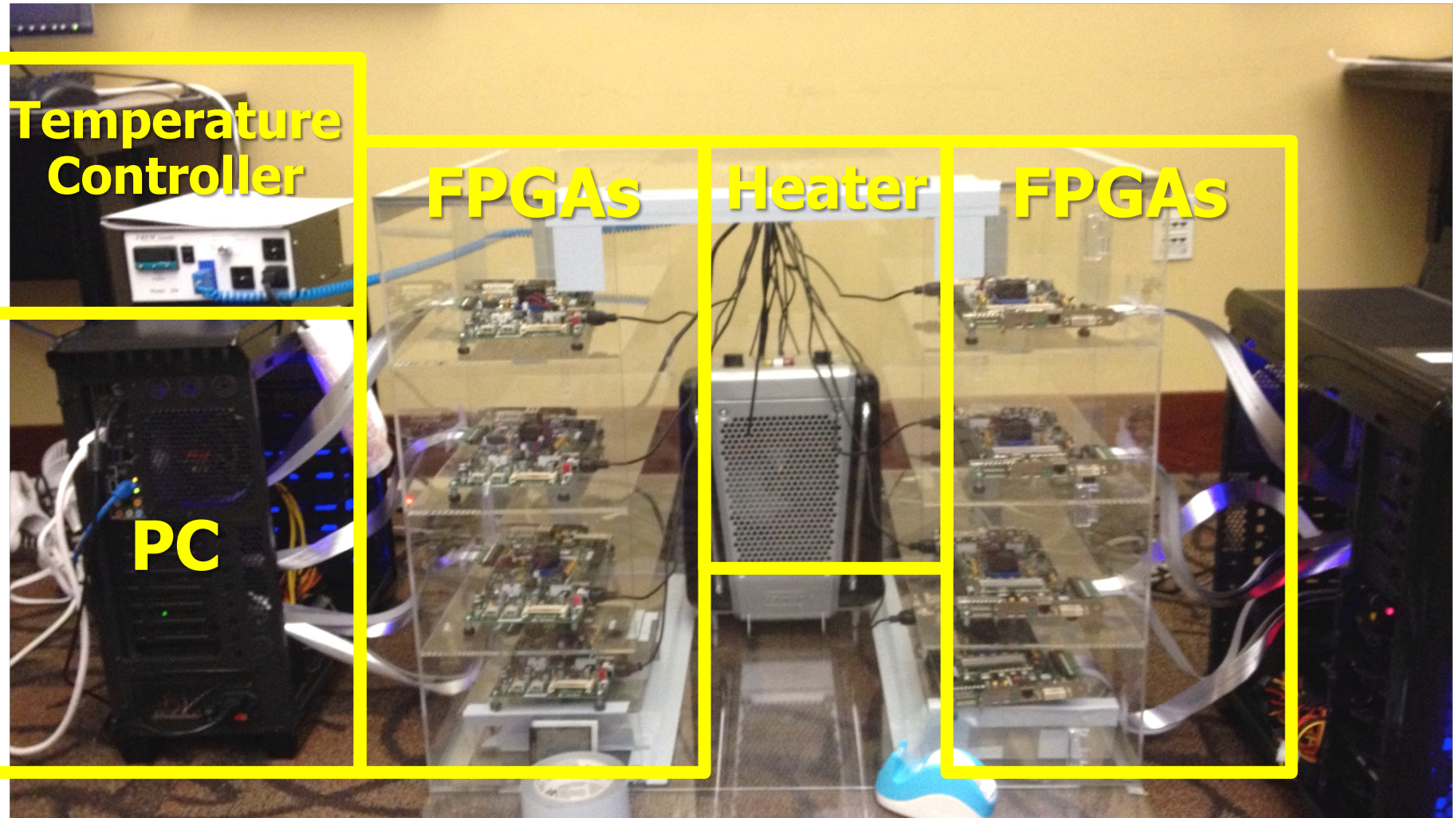
- Yoongu Kim, Ross Daly, Jeremie Kim, Chris Fallin, Ji Hye Lee, Donghyuk Lee, Chris Wilkerson, Konrad Lai, and Onur Mutlu,
"Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors"
Proceedings of the 41st International Symposium on Computer Architecture (ISCA), Minneapolis, MN, June 2014.
[[Slides \(pptx\) \(pdf\)](#)] [[Lightning Session Slides \(pptx\) \(pdf\)](#)] [[Source Code and Data](#)] [[Lecture Video](#) (1 hr 49 mins), 25 September 2020]
One of the 7 papers of 2012-2017 selected as Top Picks in Hardware and Embedded Security for IEEE TCAD ([link](#)). Selected to the ISCA-50 25-Year Retrospective Issue covering 1996-2020 in 2023 ([Retrospective \(pdf\) Full Issue](#)). Winner of the 2024 IFIP Jean-Claude Laprie Award in dependable computing ([link](#)).

Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors

Yoongu Kim¹ Ross Daly* Jeremie Kim¹ Chris Fallin* Ji Hye Lee¹
Donghyuk Lee¹ Chris Wilkerson² Konrad Lai Onur Mutlu¹

¹Carnegie Mellon University ²Intel Labs

RowHammer Infrastructure (2012-2014)



Tested DRAM Modules from 2008-2014 (129 total)

Manufacturer	Module	Date*	Timing†		Organization		Chip			Victims-per-Module			RI _{th} (ms)
		(yy-ww)	Freq (MT/s)	t _{RC} (ns)	Size (GB)	Chips	Size (Gb)‡	Pins	DieVersion§	Average	Minimum	Maximum	Min
Total of 43 Modules	A ₁	10-08	1066	50.625	0.5	4	1 × 16	B	0	0	0	–	
	A ₂	10-20	1066	50.625	1	8	1 × 8	F	0	0	0	–	
	A ₃₋₅	10-20	1066	50.625	0.5	4	1 × 16	B	0	0	0	–	
	A ₆₋₇	11-24	1066	49.125	1	4	2 × 16	D	7.8 × 10 ¹	5.2 × 10 ¹	1.0 × 10 ²	21.3	
	A ₈₋₁₂	11-26	1066	49.125	1	4	2 × 16	D	2.4 × 10 ²	5.4 × 10 ¹	4.4 × 10 ²	16.4	
	A ₁₃₋₁₄	11-50	1066	49.125	1	4	2 × 16	D	8.8 × 10 ¹	1.7 × 10 ¹	1.6 × 10 ²	26.2	
	A ₁₅₋₁₆	12-22	1600	50.625	1	4	2 × 16	D	9.5	9	1.0 × 10 ¹	34.4	
	A ₁₇₋₁₈	12-26	1600	49.125	2	8	2 × 8	M	1.2 × 10 ²	3.7 × 10 ¹	2.0 × 10 ²	21.3	
	A ₁₉₋₃₀	12-40	1600	48.125	2	8	2 × 8	K	8.6 × 10 ⁶	7.0 × 10 ⁶	1.0 × 10 ⁷	8.2	
	A ₃₁₋₃₄	13-02	1600	48.125	2	8	2 × 8	–	1.8 × 10 ⁶	1.0 × 10 ⁶	3.5 × 10 ⁶	11.5	
	A ₃₅₋₃₆	13-14	1600	48.125	2	8	2 × 8	–	4.0 × 10 ¹	1.9 × 10 ¹	6.1 × 10 ¹	21.3	
	A ₃₇₋₃₈	13-20	1600	48.125	2	8	2 × 8	K	1.7 × 10 ⁶	1.4 × 10 ⁶	2.0 × 10 ⁶	9.8	
	A ₃₉₋₄₀	13-28	1600	48.125	2	8	2 × 8	K	5.7 × 10 ⁴	5.4 × 10 ⁴	6.0 × 10 ⁴	16.4	
	A ₄₁	14-04	1600	49.125	2	8	2 × 8	–	2.7 × 10 ⁵	2.7 × 10 ⁵	2.7 × 10 ⁵	18.0	
	A ₄₂₋₄₃	14-04	1600	48.125	2	8	2 × 8	K	0.5	0	1	62.3	
Total of 54 Modules	B ₁	08-49	1066	50.625	1	8	1 × 8	D	0	0	0	–	
	B ₂	09-49	1066	50.625	1	8	1 × 8	E	0	0	0	–	
	B ₃	10-19	1066	50.625	1	8	1 × 8	F	0	0	0	–	
	B ₄	10-31	1333	49.125	2	8	2 × 8	C	0	0	0	–	
	B ₅	11-13	1333	49.125	2	8	2 × 8	C	0	0	0	–	
	B ₆	11-16	1066	50.625	1	8	1 × 8	F	0	0	0	–	
	B ₇	11-19	1066	50.625	1	8	1 × 8	F	0	0	0	–	
	B ₈	11-25	1333	49.125	2	8	2 × 8	C	0	0	0	–	
	B ₉	11-37	1333	49.125	2	8	2 × 8	D	1.9 × 10 ⁶	1.9 × 10 ⁶	1.9 × 10 ⁶	11.5	
	B ₁₀₋₁₂	11-46	1333	49.125	2	8	2 × 8	D	2.2 × 10 ⁶	1.5 × 10 ⁶	2.7 × 10 ⁶	11.5	
	B ₁₃	11-49	1333	49.125	2	8	2 × 8	C	0	0	0	–	
	B ₁₄	12-01	1866	47.125	2	8	2 × 8	D	9.1 × 10 ⁵	9.1 × 10 ⁵	9.1 × 10 ⁵	9.8	
	B ₁₅₋₃₁	12-10	1866	47.125	2	8	2 × 8	D	9.8 × 10 ⁵	7.8 × 10 ⁵	1.2 × 10 ⁶	11.5	
	B ₃₂	12-25	1600	48.125	2	8	2 × 8	E	7.4 × 10 ⁵	7.4 × 10 ⁵	7.4 × 10 ⁵	11.5	
	B ₃₃₋₄₂	12-28	1600	48.125	2	8	2 × 8	E	5.2 × 10 ⁵	1.9 × 10 ⁵	7.3 × 10 ⁵	11.5	
Total of 32 Modules	C ₁	10-18	1333	49.125	2	8	2 × 8	A	0	0	0	–	
	C ₂	10-20	1066	50.625	2	8	2 × 8	A	0	0	0	–	
	C ₃	10-22	1066	50.625	2	8	2 × 8	A	0	0	0	–	
	C ₄₋₅	10-26	1333	49.125	2	8	2 × 8	B	8.9 × 10 ²	6.0 × 10 ²	1.2 × 10 ³	29.5	
	C ₆	10-43	1333	49.125	1	8	1 × 8	T	0	0	0	–	
	C ₇	10-51	1333	49.125	2	8	2 × 8	B	4.0 × 10 ²	4.0 × 10 ²	4.0 × 10 ²	29.5	
	C ₈	11-12	1333	46.25	2	8	2 × 8	B	6.9 × 10 ²	6.9 × 10 ²	6.9 × 10 ²	21.3	
	C ₉	11-19	1333	46.25	2	8	2 × 8	B	9.2 × 10 ²	9.2 × 10 ²	9.2 × 10 ²	27.9	
	C ₁₀	11-31	1333	49.125	2	8	2 × 8	B	3	3	3	39.3	
	C ₁₁	11-42	1333	49.125	2	8	2 × 8	B	1.6 × 10 ²	1.6 × 10 ²	1.6 × 10 ²	39.3	
	C ₁₂	11-48	1600	48.125	2	8	2 × 8	C	7.1 × 10 ⁴	7.1 × 10 ⁴	7.1 × 10 ⁴	19.7	
	C ₁₃	12-08	1333	49.125	2	8	2 × 8	C	3.9 × 10 ⁴	3.9 × 10 ⁴	3.9 × 10 ⁴	21.3	
	C ₁₄₋₁₅	12-12	1333	49.125	2	8	2 × 8	C	3.7 × 10 ⁴	2.1 × 10 ⁴	5.4 × 10 ⁴	21.3	
	C ₁₆₋₁₈	12-20	1600	48.125	2	8	2 × 8	C	3.5 × 10 ³	1.2 × 10 ³	7.0 × 10 ³	27.9	
	C ₁₉	12-23	1600	48.125	2	8	2 × 8	E	1.4 × 10 ⁵	1.4 × 10 ⁵	1.4 × 10 ⁵	18.0	
	C ₂₀	12-24	1600	48.125	2	8	2 × 8	C	6.5 × 10 ⁴	6.5 × 10 ⁴	6.5 × 10 ⁴	21.3	
	C ₂₁	12-26	1600	48.125	2	8	2 × 8	C	2.3 × 10 ⁴	2.3 × 10 ⁴	2.3 × 10 ⁴	24.6	
	C ₂₂	12-32	1600	48.125	2	8	2 × 8	C	1.7 × 10 ⁴	1.7 × 10 ⁴	1.7 × 10 ⁴	22.9	
	C ₂₃₋₂₄	12-37	1600	48.125	2	8	2 × 8	C	2.3 × 10 ⁴	1.1 × 10 ⁴	3.4 × 10 ⁴	18.0	
	C ₂₅₋₃₀	12-41	1600	48.125	2	8	2 × 8	C	2.0 × 10 ⁴	1.1 × 10 ⁴	3.2 × 10 ⁴	19.7	
	C ₃₁	13-11	1600	48.125	2	8	2 × 8	C	3.3 × 10 ⁵	3.3 × 10 ⁵	3.3 × 10 ⁵	14.7	
	C ₃₂	13-35	1600	48.125	2	8	2 × 8	C	3.7 × 10 ⁴	3.7 × 10 ⁴	3.7 × 10 ⁴	21.3	

* We report the manufacture date marked on the chip packages, which is more accurate than other dates that can be gleaned from a module.

† We report timing constraints stored in the module's on-board ROM [33], which is read by the system BIOS to calibrate the memory controller.

‡ The maximum DRAM chip size supported by our testing platform is 2Gb.

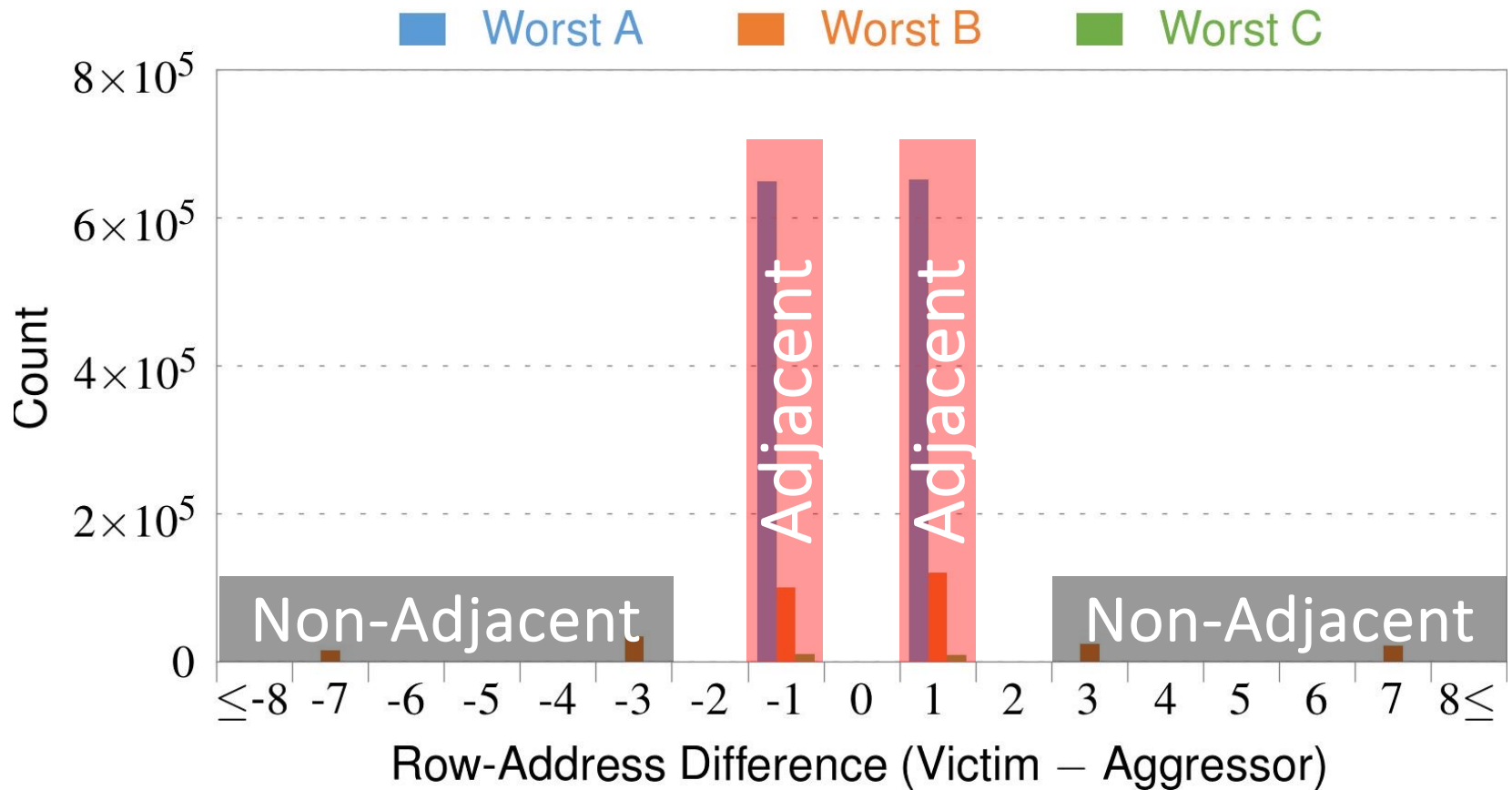
§ We report DRAM die versions marked on the chip packages, which typically progress in the following manner: $\mathcal{M} \rightarrow \mathcal{A} \rightarrow \mathcal{B} \rightarrow \mathcal{C} \rightarrow \dots$.

Table 3. Sample population of 129 DDR3 DRAM modules, categorized by manufacturer and sorted by manufacture date

RowHammer Characterization Results

1. Most Modules Are at Risk
2. Errors vs. Vintage
3. Error = Charge Loss
4. Adjacency: Aggressor & Victim
5. Sensitivity Studies
6. Other Results in Paper
7. Solution Space

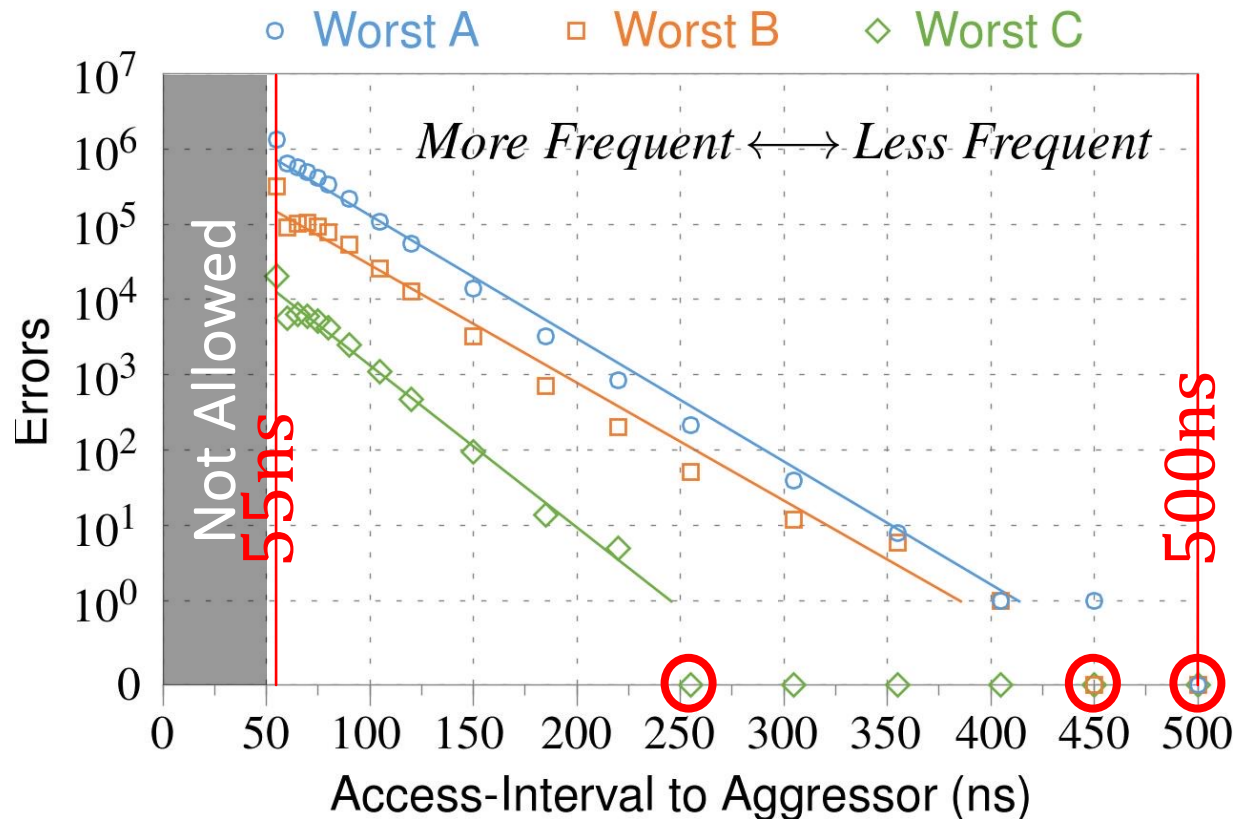
4. Adjacency: Aggressor & Victim



Note: For three modules with the most errors (only first bank)

Most aggressors & victims are adjacent

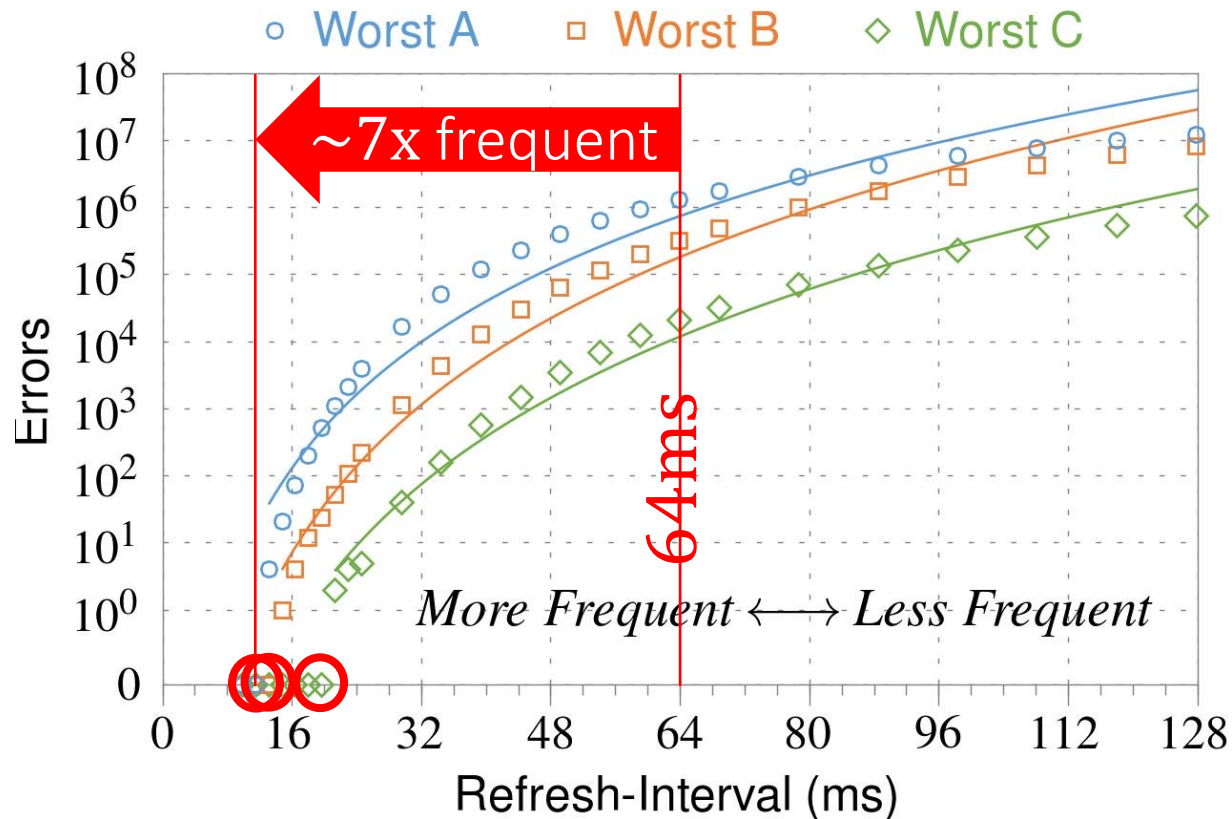
1 Access Interval (Aggressor)



Note: For three modules with the most errors (only first bank)

Less frequent accesses \rightarrow Fewer errors

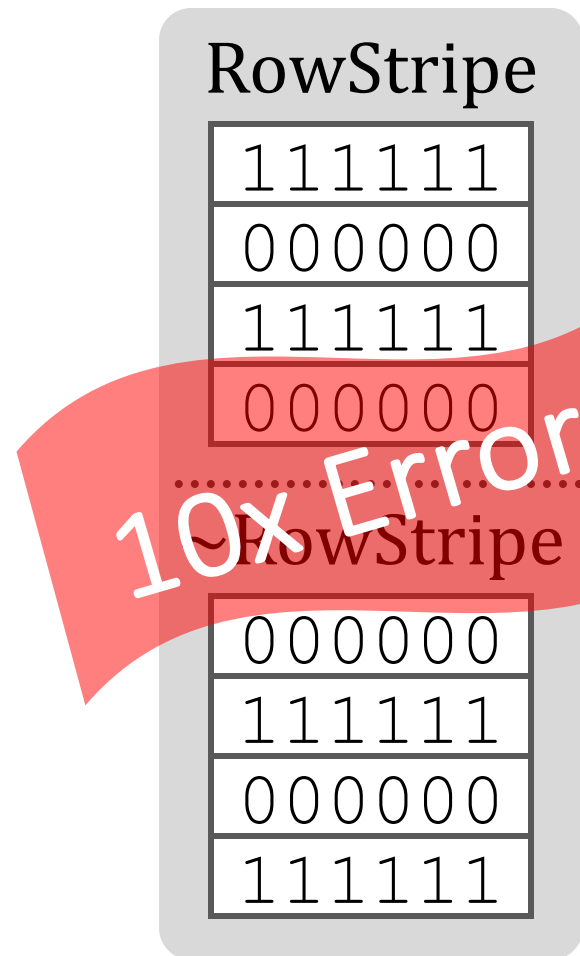
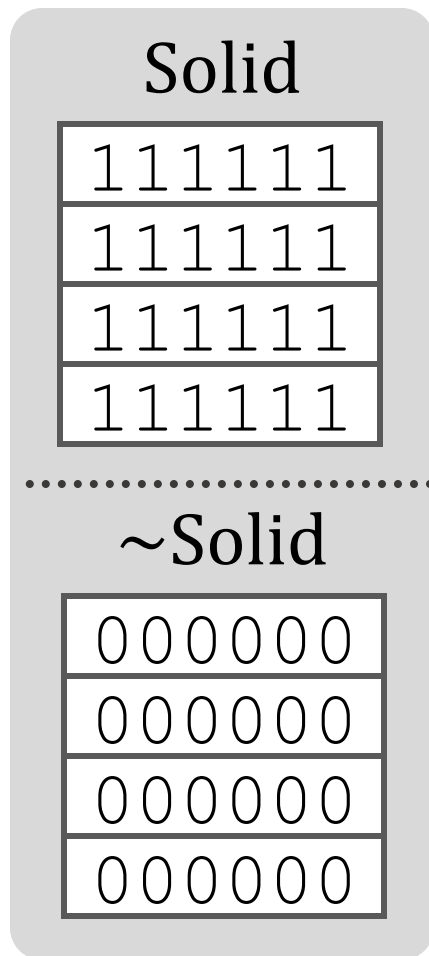
2 Refresh Interval



Note: Using three modules with the most errors (only first bank)

More frequent refreshes \rightarrow Fewer errors

3 Data Pattern



10x Errors

Errors affected by data stored in other cells

6. Other Key Observations [ISCA'14]

- *Victim Cells \neq Retention-Weak Cells*
 - Almost no overlap between them
- *Errors are repeatable*
 - Across ten iterations of testing, >70% of victim cells had errors in every iteration
- *As many as 4 errors per cache-line*
 - Simple ECC (e.g., SECDED) cannot prevent all errors
- *Cells affected by two aggressors on either side*
 - Double sided hammering

Major RowHammer Characteristics (2014)

- Yoongu Kim, Ross Daly, Jeremie Kim, Chris Fallin, Ji Hye Lee, Donghyuk Lee, Chris Wilkerson, Konrad Lai, and Onur Mutlu,
"Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors"
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RowHammer is Getting Much Worse (2020)

- Jeremie S. Kim, Minesh Patel, A. Giray Yaglikci, Hasan Hassan, Roknoddin Azizi, Lois Orosa, and Onur Mutlu,
["Revisiting RowHammer: An Experimental Analysis of Modern Devices and Mitigation Techniques"](#)
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Revisiting RowHammer: An Experimental Analysis of Modern DRAM Devices and Mitigation Techniques

Jeremie S. Kim^{§†} Minesh Patel[§] A. Giray Yağlıkçı[§]
Hasan Hassan[§] Roknoddin Azizi[§] Lois Orosa[§] Onur Mutlu^{§†}
[§]*ETH Zürich* [†]*Carnegie Mellon University*

RowHammer Has Many Dimensions (2021)

- Lois Orosa, Abdullah Giray Yaglikci, Haocong Luo, Ataberk Olgun, Jisung Park, Hasan Hassan, Minesh Patel, Jeremie S. Kim, and Onur Mutlu,
"A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses"
*Proceedings of the 54th International Symposium on Microarchitecture (**MICRO**), Virtual, October 2021.*
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Short Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
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[[Lightning Talk Video](#) (1.5 minutes)]
[[arXiv version](#)]

A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses

Lois Orosa*
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Ataberk Olgun
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Jisung Park
ETH Zürich

Hasan Hassan
ETH Zürich

Minesh Patel
ETH Zürich

Jeremie S. Kim
ETH Zürich

Onur Mutlu
ETH Zürich

RowHammer vs. Wordline Voltage (2022)

- A. Giray Yağlıkçı, Haocong Luo, Geraldo F. de Oliveira, Ataberk Olgun, Minesh Patel, Jisung Park, Hasan Hassan, Jeremie S. Kim, Lois Orosa, and Onur Mutlu, **"Understanding RowHammer Under Reduced Wordline Voltage: An Experimental Study Using Real DRAM Devices"**
Proceedings of the 52nd Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Baltimore, MD, USA, June 2022.
[[Slides \(pptx\)](#)] [[pdf](#)]
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[[Talk Video](#) (34 minutes, including Q&A)]
[[Lightning Talk Video](#) (2 minutes)]

Understanding RowHammer Under Reduced Wordline Voltage: An Experimental Study Using Real DRAM Devices

A. Giray Yağlıkçı¹ Haocong Luo¹ Geraldo F. de Oliveira¹ Ataberk Olgun¹ Minesh Patel¹
Jisung Park¹ Hasan Hassan¹ Jeremie S. Kim¹ Lois Orosa^{1,2} Onur Mutlu¹
¹*ETH Zürich* ²*Galicia Supercomputing Center (CESGA)*

RowHammer in HBM Chips (2023)

- Ataberk Olgun, Majd Osserian, A. Giray Yağlıkçı, Yahya Can Tugrul, Haocong Luo, Steve Rhyner, Behzad Salami, Juan Gomez-Luna, and Onur Mutlu, **"An Experimental Analysis of RowHammer in HBM2 DRAM Chips"**
Proceedings of the 53rd Annual IEEE/IFIP International Conference on Dependable Systems and Networks Disrupt Track (DSN Disrupt), Porto, Portugal, June 2023.
[[arXiv version](#)]
[[Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (24 minutes, including Q&A)]

An Experimental Analysis of RowHammer in HBM2 DRAM Chips

Ataberk Olgun¹ Majd Osseiran^{1,2} A. Giray Yağlıkçı¹ Yahya Can Tuğrul¹
Haocong Luo¹ Steve Rhyner¹ Behzad Salami¹ Juan Gomez Luna¹ Onur Mutlu¹
¹SAFARI Research Group, ETH Zürich ²American University of Beirut

RowHammer in HBM Chips (2024)

- **Appears at DSN 2024**

Read Disturbance in High Bandwidth Memory: A Detailed Experimental Study on HBM2 DRAM Chips

Ataberk Olgun¹ Majd Osseiran¹ A. Giray Yağlıkçı¹ Yahya Can Tuğrul¹
Haocong Luo¹ Steve Rhyner¹ Behzad Salami² Juan Gomez Luna¹ Onur Mutlu¹
¹ETH Zürich ²BSC

<https://arxiv.org/pdf/2310.14665>

RowHammer Spatial Variation Analysis (2024)

- **Appears at HPCA 2024**

Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Abdullah Giray Yağlıkçı Yahya Can Tuğrul Geraldo F. Oliveira
İsmail Emir Yüksel Ataberk Olgun Haocong Luo Onur Mutlu
ETH Zürich

<https://arxiv.org/pdf/2402.18652>

RowHammer Solutions

Two Types of RowHammer Solutions

■ Immediate

- ❑ To protect the vulnerable DRAM chips in the field
- ❑ Limited possibilities

■ Longer-term

- ❑ To protect future DRAM chips
- ❑ Wider range of protection mechanisms

■ Our ISCA 2014 paper proposes both types of solutions

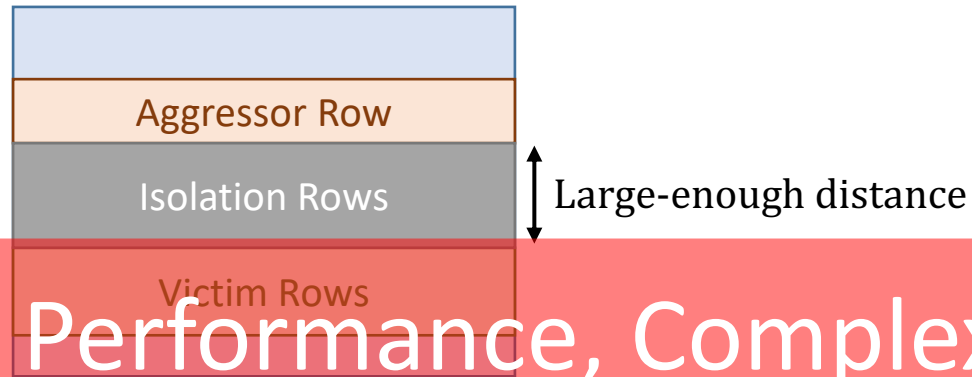
- ❑ Seven solutions in total
- ❑ PARA proposed as best solution → already employed in the field

RowHammer Solution Approaches

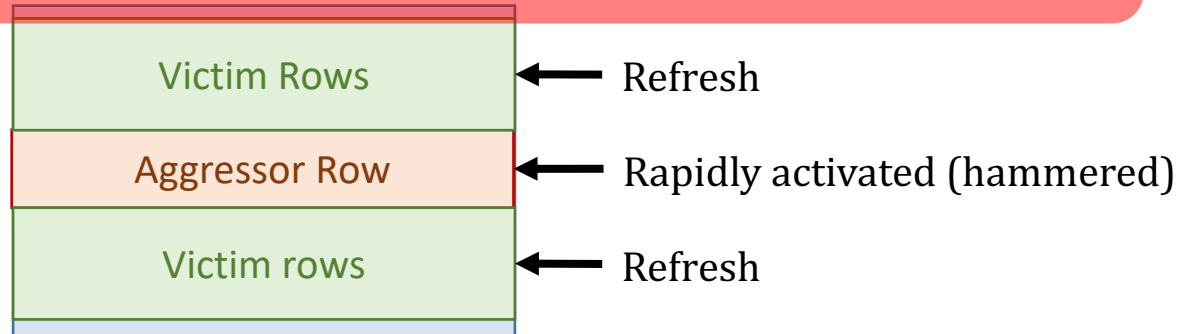
- More robust DRAM chips **and/or** error-correcting codes
- Increased refresh rate



- Physical isolation

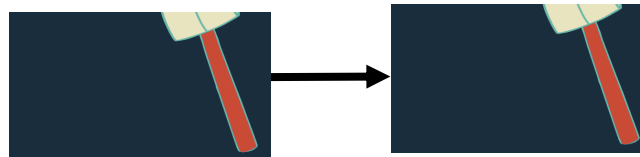


- Reactive refresh



- Proactive throttling

SAFARI



Fewer activations allowed for aggressive applications

Apple's Security Patch for RowHammer

- <https://support.apple.com/en-gb/HT204934>

Available for: OS X Mountain Lion v10.8.5, OS X Mavericks v10.9.5

Impact: A malicious application may induce memory corruption to escalate privileges

Description: A disturbance error, also known as Rowhammer, exists with some DDR3 RAM that could have led to memory corruption. This issue was mitigated by increasing memory refresh rates.

CVE-ID

CVE-2015-3693 : Mark Seaborn and Thomas Dullien of Google, working from original research by Yoongu Kim et al (2014)

HP, Lenovo, and many other vendors released similar patches

Our First Solution to RowHammer

- *PARA: Probabilistic Adjacent Row Activation*
- Key Idea
 - After closing a row, activate (i.e., refresh) its neighbors with a low probability: $p = 0.005$
- Reliability Guarantee
 - When $p=0.005$, errors in one year: 9.4×10^{-14}
 - By adjusting the value of p , we can vary the strength of protection against errors

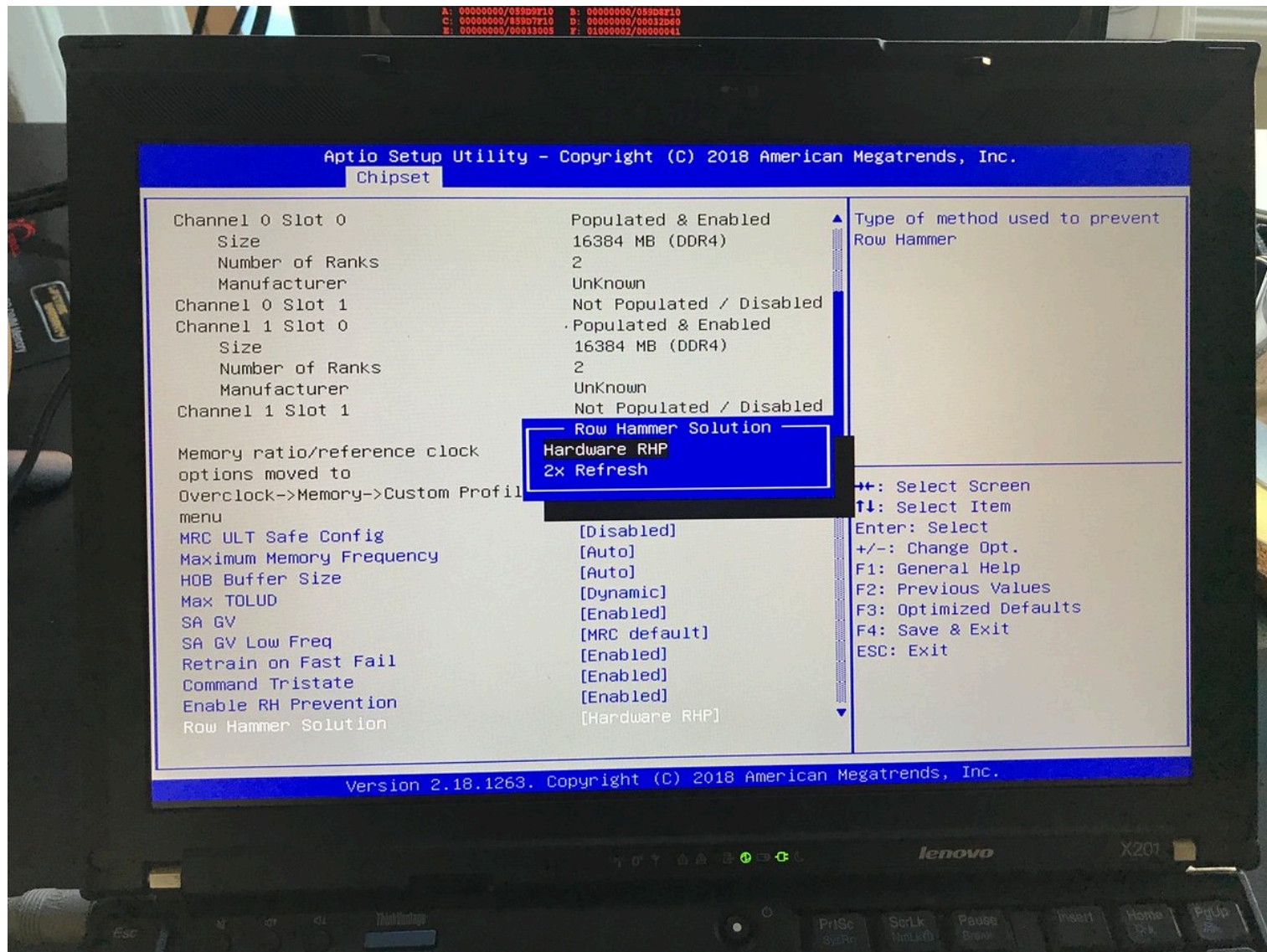
Advantages of PARA

- *PARA refreshes rows infrequently*
 - Low power
 - Low performance-overhead
 - Average slowdown: **0.20%** (for 29 benchmarks)
 - Maximum slowdown: **0.75%**
- *PARA is stateless*
 - Low cost
 - Low complexity
- *PARA is an effective and low-overhead solution to prevent disturbance errors*

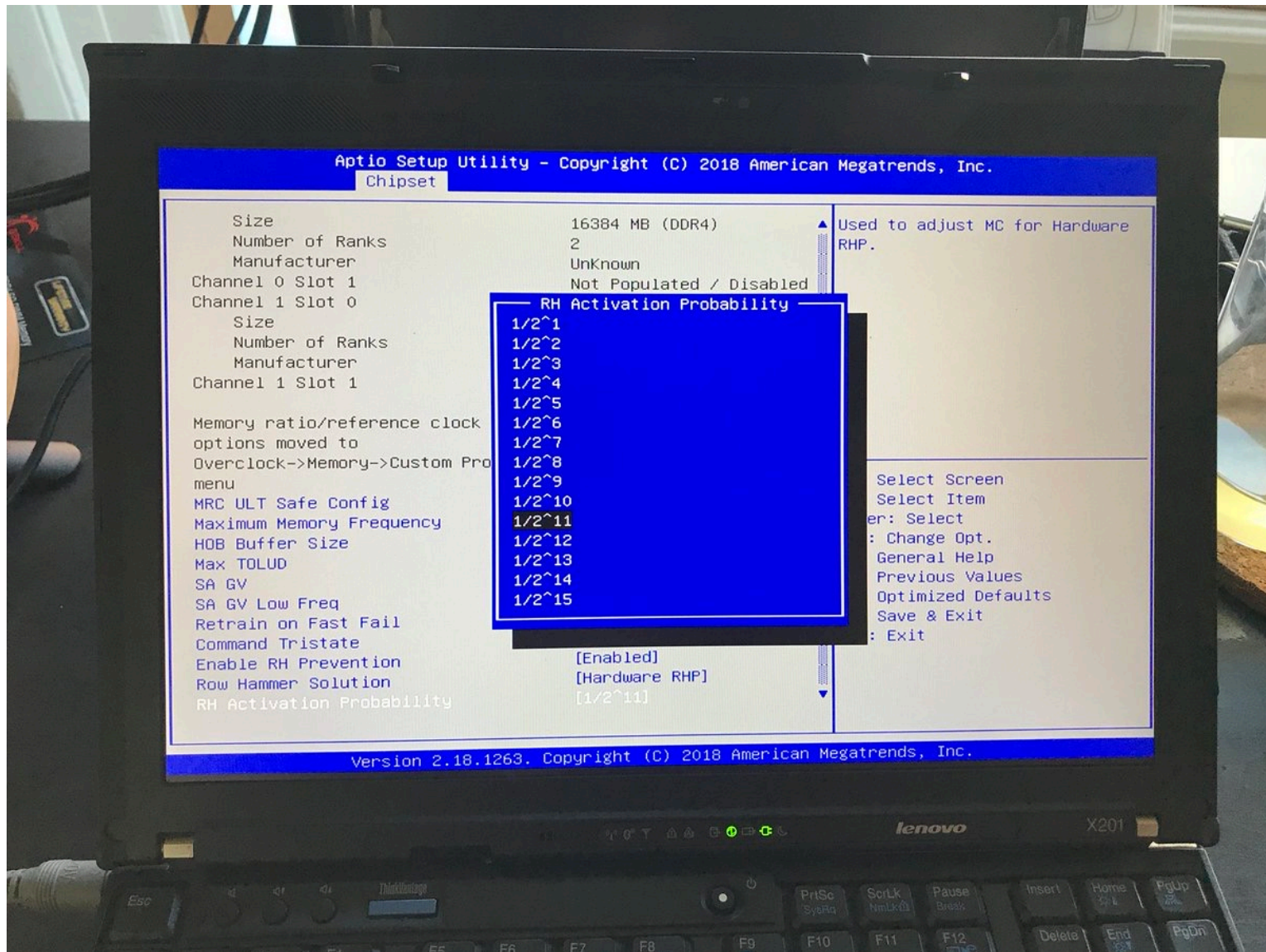
Requirements for PARA

- If implemented in **DRAM chip** (done today)
 - Enough slack in timing and refresh parameters
 - Plenty of slack today:
 - Lee et al., “**Adaptive-Latency DRAM: Optimizing DRAM Timing for the Common Case**,” HPCA 2015.
 - Chang et al., “**Understanding Latency Variation in Modern DRAM Chips**,” SIGMETRICS 2016.
 - Lee et al., “**Design-Induced Latency Variation in Modern DRAM Chips**,” SIGMETRICS 2017.
 - Chang et al., “**Understanding Reduced-Voltage Operation in Modern DRAM Devices**,” SIGMETRICS 2017.
 - Ghose et al., “**What Your DRAM Power Models Are Not Telling You: Lessons from a Detailed Experimental Study**,” SIGMETRICS 2018.
 - Kim et al., “**Solar-DRAM: Reducing DRAM Access Latency by Exploiting the Variation in Local Bitlines**,” ICCD 2018.
- If implemented in **memory controller**
 - Need coordination between controller and DRAM
 - Memory controller should know which rows are physically adjacent

Probabilistic Activation in Real Life (I)



Probabilistic Activation in Real Life (II)



Seven RowHammer Solutions Proposed

- Yoongu Kim, Ross Daly, Jeremie Kim, Chris Fallin, Ji Hye Lee, Donghyuk Lee, Chris Wilkerson, Konrad Lai, and Onur Mutlu,
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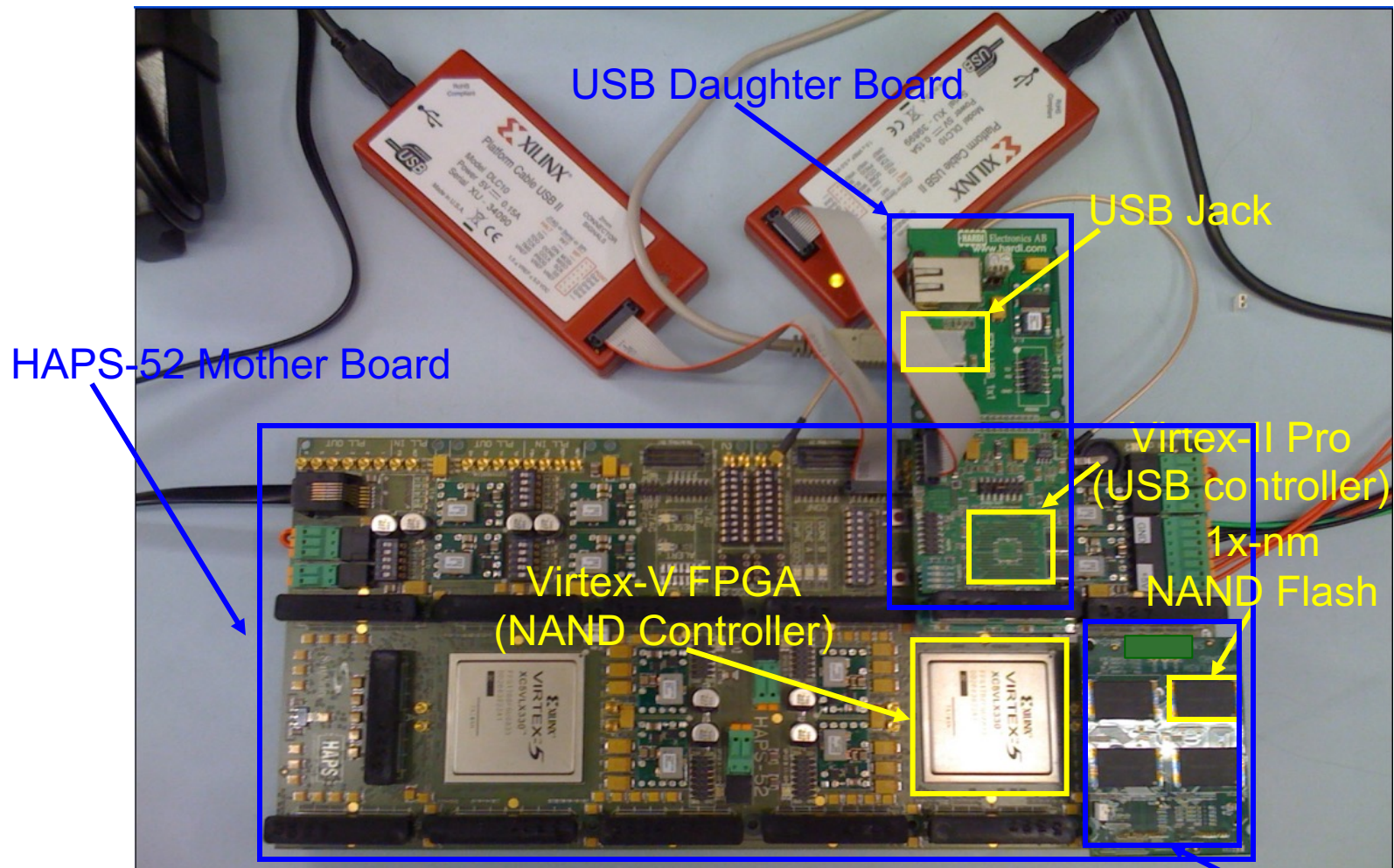
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Main Memory Needs
Intelligent Controllers
for Security, Safety,
Reliability, Scaling

Aside: Intelligent Controller for NAND Flash



[DATE 2012, ICCD 2012, DATE 2013, ITJ 2013, ICCD 2013, SIGMETRICS 2014, HPCA 2015, DSN 2015, MSST 2015, JSAC 2016, HPCA 2017, DFRWS 2017, PIEEE 2017, HPCA 2018, SIGMETRICS 2018]

Cai+, "Error Characterization, Mitigation, and Recovery in Flash Memory Based Solid State Drives," Proc. IEEE 2017.



Proceedings of the IEEE, Sept. 2017



Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

This paper reviews the most recent advances in solid-state drive (SSD) error characterization, mitigation, and data recovery techniques to improve both SSD's reliability and lifetime.

By YU CAI, SAUGATA GHOSE, ERICH F. HARATSCH, YIXIN LUO, AND ONUR MUTLU

Two Major RowHammer Directions

■ **Understanding RowHammer**

- Many effects still need to be rigorously examined
 - Aging of DRAM Chips
 - Environmental Conditions (e.g., Process, Voltage, Temperature)
 - Memory Access Patterns
 - Memory Controller & System Design Decisions
 - ...

■ **Solving RowHammer**

- Flexible and efficient solutions are necessary
 - In-field patchable / reconfigurable / programmable solutions
- Co-architecting System and Memory is important
 - To avoid performance and denial-of-service problems

RowHammer in 2020-2024

Revisiting RowHammer

RowHammer is Getting Much Worse

- Jeremie S. Kim, Minesh Patel, A. Giray Yaglikci, Hasan Hassan, Roknoddin Azizi, Lois Orosa, and Onur Mutlu,
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[§]*ETH Zürich* [†]*Carnegie Mellon University*

Key Takeaways from 1580 Chips

- **Newer DRAM chips are much more vulnerable to RowHammer (more bit flips, happening earlier)**
- There are new chips whose weakest cells fail after **only 4800 hammers**
- Chips of newer DRAM technology nodes can exhibit RowHammer bit flips 1) in **more rows** and 2) **farther away** from the victim row.
- **Existing mitigation mechanisms are NOT effective at future technology nodes**

1580 DRAM Chips Tested

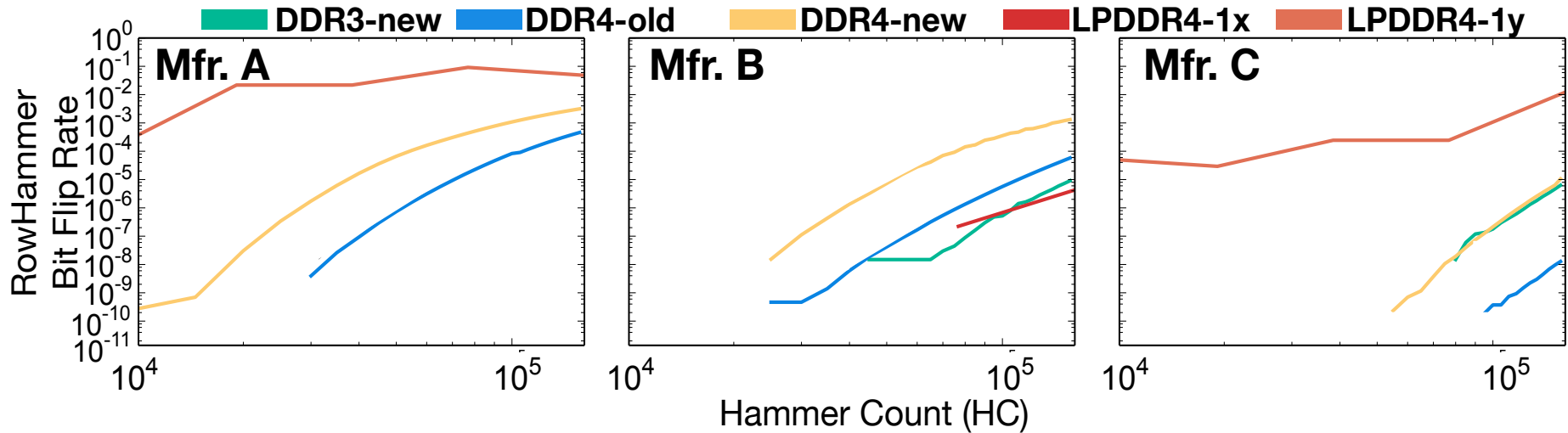
DRAM type-node	Number of Chips (Modules) Tested			
	Mfr. A	Mfr. B	Mfr. C	Total
DDR3-old	56 (10)	88 (11)	28 (7)	172 (28)
DDR3-new	80 (10)	52 (9)	104 (13)	236 (32)
DDR4-old	112 (16)	24 (3)	128 (18)	264 (37)
DDR4-new	264 (43)	16 (2)	108 (28)	388 (73)
LPDDR4-1x	12 (3)	180 (45)	N/A	192 (48)
LPDDR4-1y	184 (46)	N/A	144 (36)	328 (82)

1580 total DRAM chips tested from **300** DRAM modules

- **Three** major DRAM manufacturers {A, B, C}
- **Three** DRAM *types or standards* {DDR3, DDR4, LPDDR4}
 - LPDDR4 chips we test implement on-die ECC
- **Two** technology nodes per DRAM type {old/new, 1x/1y}
 - Categorized based on manufacturing date, datasheet publication date, purchase date, and characterization results

Type-node: configuration describing a chip's type and technology node generation: **DDR3-old/new, DDR4-old/new, LPDDR4-1x/1y**

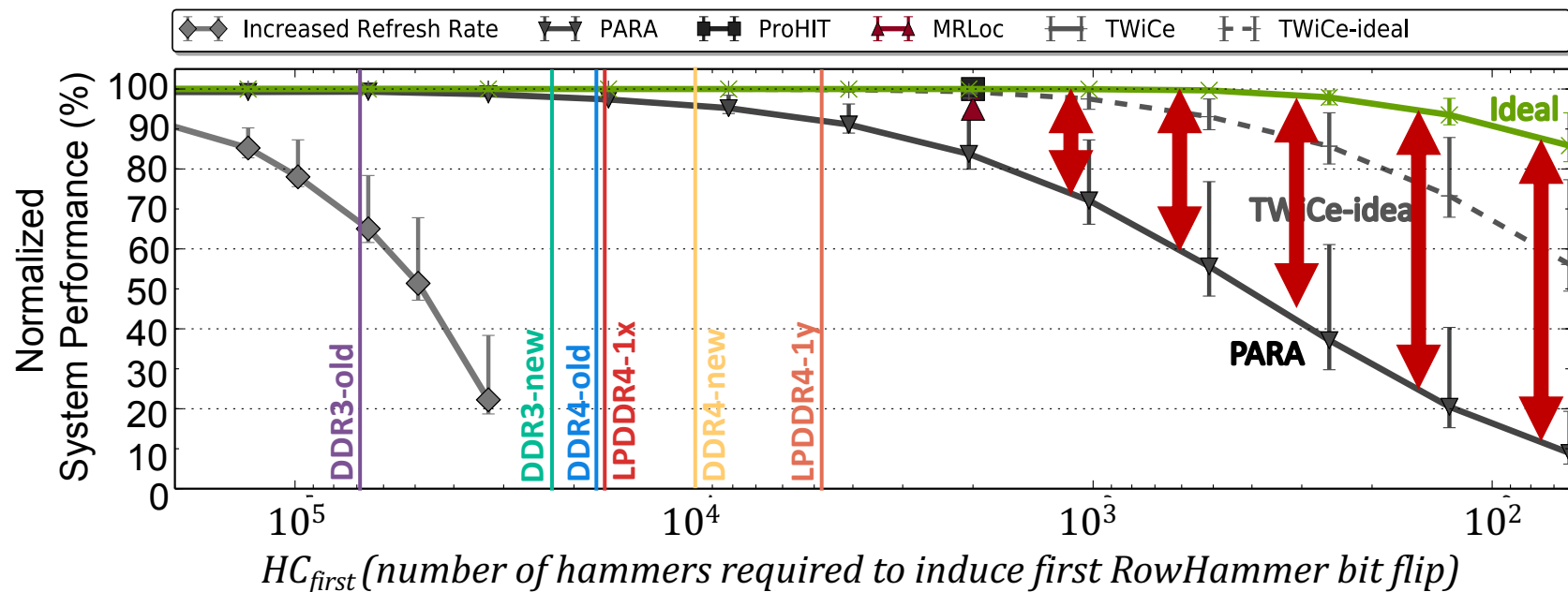
3. Hammer Count (HC) Effects



RowHammer bit flip rates **increase**
when going **from old to new** DDR4 technology node generations

**RowHammer bit flip rates (i.e., RowHammer vulnerability)
increase with technology node generation**

Mitigation Mechanism Evaluation



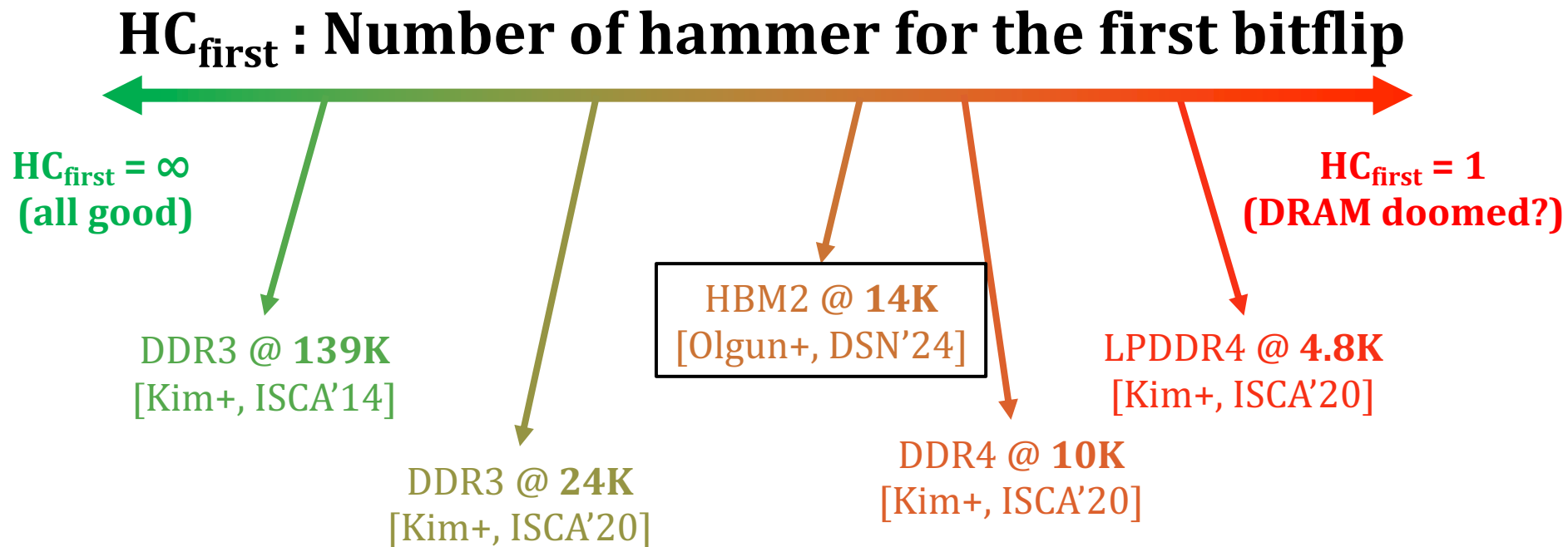
Ideal mechanism is **significantly better** than any existing mechanism for $HC_{first} < 1024$

Significant opportunity for developing a RowHammer solution with **low performance overhead** that supports low HC_{first}

RowHammer is a
technology scaling problem

Finding a good solution to
RowHammer is difficult
(and will become more so)

Reported HC_{first} Values (2012 – Now)



*Not shown: Significant variance in HC_{first} across vendors and die variations

New RowHammer Characteristics

RowHammer Has Many Dimensions

- Lois Orosa, Abdullah Giray Yaglikci, Haocong Luo, Ataberk Olgun, Jisung Park, Hasan Hassan, Minesh Patel, Jeremie S. Kim, and Onur Mutlu,
"A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses"
*Proceedings of the 54th International Symposium on Microarchitecture (**MICRO**), Virtual, October 2021.*
[[Slides \(pptx\)](#)] [[pdf](#)]
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[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (21 minutes)]
[[Lightning Talk Video](#) (1.5 minutes)]
[[arXiv version](#)]

A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses

Lois Orosa*
ETH Zürich

A. Giray Yağlıkçı*
ETH Zürich

Haocong Luo
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Ataberk Olgun
ETH Zürich, TOBB ETÜ

Jisung Park
ETH Zürich

Hasan Hassan
ETH Zürich

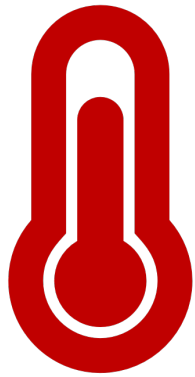
Minesh Patel
ETH Zürich

Jeremie S. Kim
ETH Zürich

Onur Mutlu
ETH Zürich

Our Goal

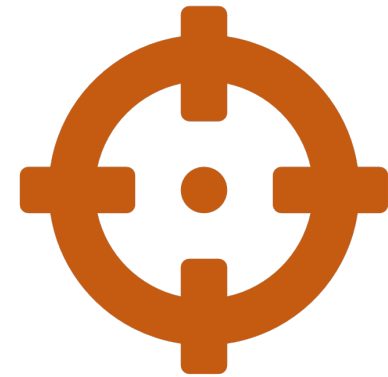
Provide insights into **three fundamental properties**



Temperature



Aggressor Row
Active Time



Victim DRAM Cell's
Physical Location

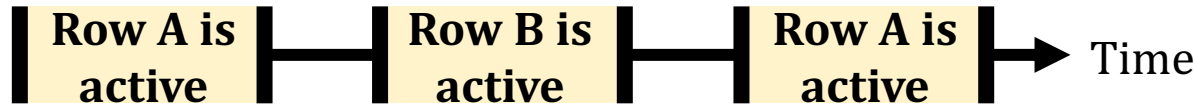
To find **effective and efficient** attacks and defenses

Summary of The Study & Key Results

- **272 DRAM chips** from **four major manufacturers**
- **6 major takeaways** from **16 novel observations**
- A RowHammer bit flip is **more likely to occur**
 - 1) in a **bounded range of temperature**
 - 2) if the aggressor row is **active for longer time**
 - 3) in **certain physical regions** of the DRAM module under attack
- Our novel observations can inspire and aid future work
 - Craft **more effective attacks**
 - Design **more effective and efficient defenses**

Example Attack Improvement 3: Bypassing Defenses with Aggressor Row Active Time

Activating aggressor rows as frequently as possible:



Keeping aggressor rows active for a longer time:

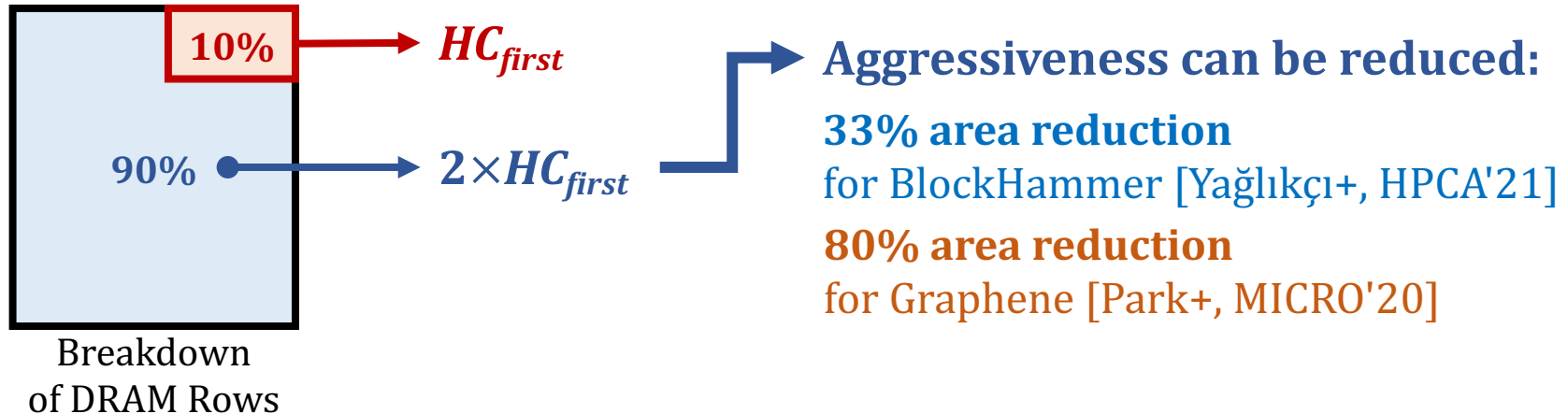


Reduces the minimum activation count to induce a bit flip **by 36%**

Bypasses defenses that do not account for this reduction

Example Defense Improvements

- **Example 1: Leveraging variation across DRAM rows**



- **Example 2: Leveraging variation with temperature**

- A DRAM cell experiences **bit flips** within a **bounded temperature range**




- A row can be **disabled** within the row's **vulnerable temperature range**




Deeper Look into RowHammer: Talk Video

Our Goal


Provide insights into **three fundamental properties**



Temperature



Aggressor Row
Active Time



Victim DRAM Cell's
Physical Location

To find **effective and efficient** attacks and defenses

SAFARI 4:11 / 21:25 • Motivation Goal >

ETH zürich
Gray Yaglicci

A Deeper Look into RowHammer's Sensitivities: Analysis, Attacks & Defenses - MICRO'21 Long Talk; 21m

Onur Mutlu Lectures
31.6K subscribers

Analytics Edit video

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More RowHammer Analysis

RowHammer vs. Wordline Voltage (2022)

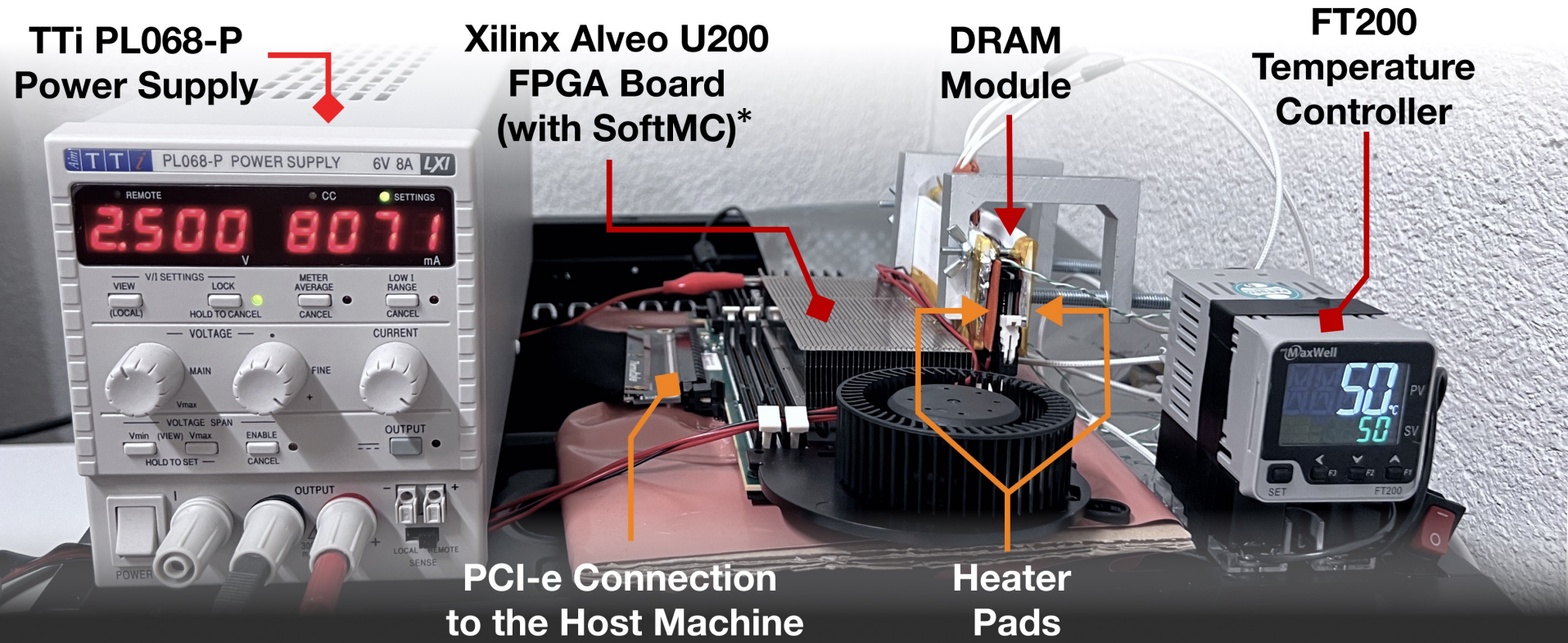
- A. Giray Yağlıkçı, Haocong Luo, Geraldo F. de Oliveira, Ataberk Olgun, Minesh Patel, Jisung Park, Hasan Hassan, Jeremie S. Kim, Lois Orosa, and Onur Mutlu, **"Understanding RowHammer Under Reduced Wordline Voltage: An Experimental Study Using Real DRAM Devices"**
Proceedings of the 52nd Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Baltimore, MD, USA, June 2022.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[arXiv version](#)]
[[Talk Video](#) (34 minutes, including Q&A)]
[[Lightning Talk Video](#) (2 minutes)]

Understanding RowHammer Under Reduced Wordline Voltage: An Experimental Study Using Real DRAM Devices

A. Giray Yağlıkçı¹ Haocong Luo¹ Geraldo F. de Oliveira¹ Ataberk Olgun¹ Minesh Patel¹
Jisung Park¹ Hasan Hassan¹ Jeremie S. Kim¹ Lois Orosa^{1,2} Onur Mutlu¹
¹*ETH Zürich* ²*Galicia Supercomputing Center (CESGA)*

Updated DRAM Testing Infrastructure

FPGA-based SoftMC (Xilinx Virtex UltraScale+ XCU200)



Fine-grained control over DRAM commands,
timing parameters ($\pm 1.5\text{ns}$), temperature ($\pm 0.1^\circ\text{C}$),
and wordline voltage ($\pm 1\text{mV}$)

Summary

We provide *the first* RowHammer characterization **under reduced wordline voltage**

Experimental results with 272 *real DRAM chips* show that **reducing wordline voltage**:

1. Reduces RowHammer vulnerability

- **Bit error rate** caused by a RowHammer attack reduces by **15.2% (66.9% max)**
- A row needs to be activated **7.4% more times (85.8% max)** to induce *the first* bit flip

2. Increases row activation latency

- More than **76%** of the tested DRAM chips **reliably operate** using **nominal** timing parameters
- Remaining **24%** **reliably operate** with **increased** (up to 24ns) row activation latency

3. Reduces data retention time

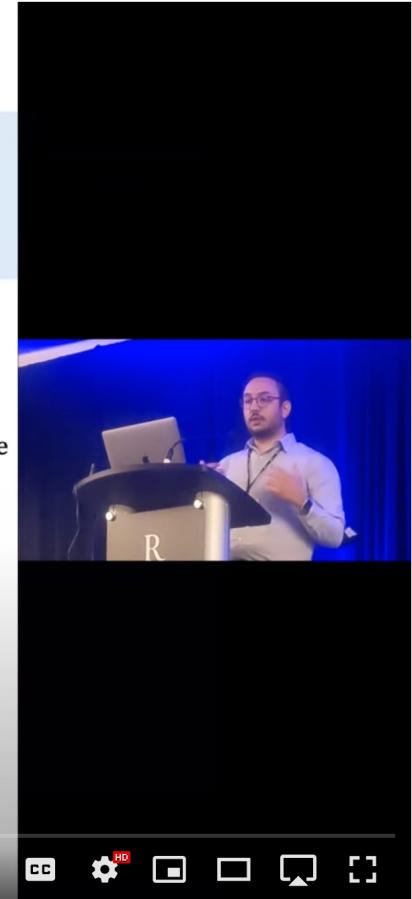
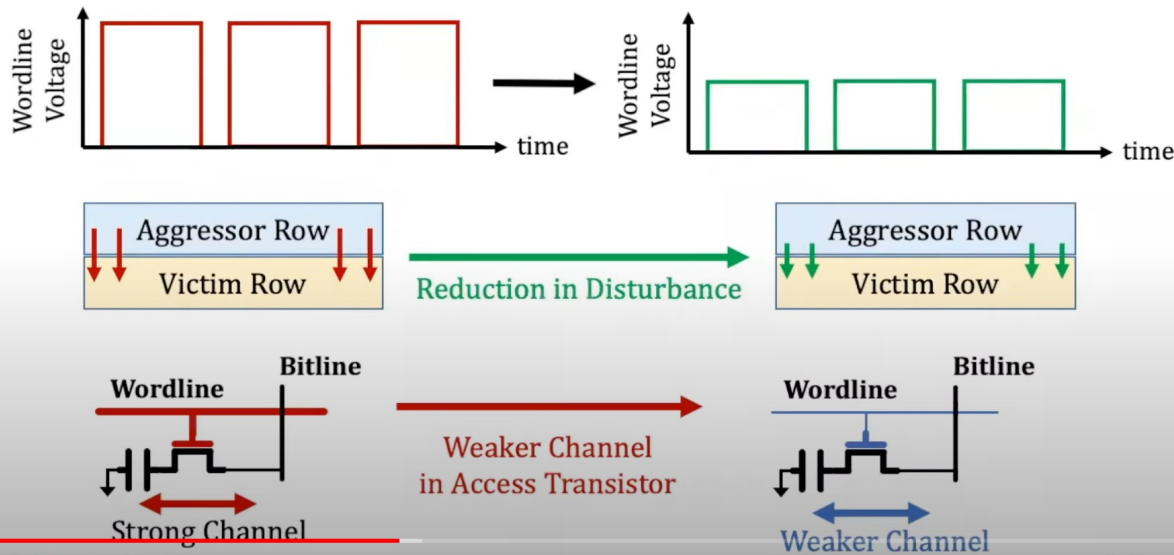
- **80%** of the tested DRAM chips **reliably operate using nominal refresh rate**
- Remaining **20%** **reliably operate** by
 - Using **single error correcting codes**
 - **Doubling the refresh rate** for **a small fraction (16.4%) of DRAM rows**

Reducing wordline voltage can **reduce RowHammer vulnerability**
without significantly affecting **reliable DRAM operation**

RowHammer vs. Wordline Voltage: Talk Video

Our Hypothesis

Reducing **wordline voltage**
can **reduce RowHammer vulnerability**
without significantly affecting **reliable DRAM operation**



Understanding RowHammer Under Reduced Wordline Voltage - Live Talk in DSN'22 by Giray Yaglikci



Onur Mutlu Lectures
30.2K subscribers



Subscribed

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RowHammer in HBM Chips (2023)

- Ataberk Olgun, Majd Osserian, A. Giray Yağlıkçı, Yahya Can Tugrul, Haocong Luo, Steve Rhyner, Behzad Salami, Juan Gomez-Luna, and Onur Mutlu, **"An Experimental Analysis of RowHammer in HBM2 DRAM Chips"**
Proceedings of the 53rd Annual IEEE/IFIP International Conference on Dependable Systems and Networks Disrupt Track (DSN Disrupt), Porto, Portugal, June 2023.
[[arXiv version](#)]
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (24 minutes, including Q&A)]

An Experimental Analysis of RowHammer in HBM2 DRAM Chips

Ataberk Olgun¹ Majd Osseiran^{1,2} A. Giray Yağlıkçı¹ Yahya Can Tuğrul¹
Haocong Luo¹ Steve Rhyner¹ Behzad Salami¹ Juan Gomez Luna¹ Onur Mutlu¹
¹SAFARI Research Group, ETH Zürich ²American University of Beirut

RowHammer in HBM Chips (2024)

- **Appears at DSN 2024**

Read Disturbance in High Bandwidth Memory: A Detailed Experimental Study on HBM2 DRAM Chips

Ataberk Olgun¹ Majd Osseiran¹ A. Giray Yağlıkçı¹ Yahya Can Tuğrul¹
Haocong Luo¹ Steve Rhyner¹ Behzad Salami² Juan Gomez Luna¹ Onur Mutlu¹
¹*ETH Zürich* ²*BSC*

<https://arxiv.org/pdf/2310.14665>

RowHammer Spatial Variation Analysis (2024)

- **Appears at HPCA 2024**

Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Abdullah Giray Yağlıkçı Yahya Can Tuğrul Geraldo F. Oliveira
İsmail Emir Yüksel Ataberk Olgun Haocong Luo Onur Mutlu
ETH Zürich

<https://arxiv.org/pdf/2402.18652>

New RowHammer Solutions

TRRespass

Industry-Adopted Solutions Do Not Work

- Pietro Frigo, Emanuele Vannacci, Hasan Hassan, Victor van der Veen, Onur Mutlu, Cristiano Giuffrida, Herbert Bos, and Kaveh Razavi,
"TRRespass: Exploiting the Many Sides of Target Row Refresh"
Proceedings of the 41st IEEE Symposium on Security and Privacy (S&P), San Francisco, CA, USA, May 2020.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Lecture Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#)] (17 minutes)
[[Lecture Video](#)] (59 minutes)
[[Source Code](#)]
[[Web Article](#)]
Best Paper Award. IEEE Micro Top Pick Honorable Mention.
Pwnie Award 2020 for Most Innovative Research. [Pwnie Awards 2020](#)

TRRespass: Exploiting the Many Sides of Target Row Refresh

Pietro Frigo^{*†} Emanuele Vannacci^{*†} Hasan Hassan[§] Victor van der Veen[¶]
Onur Mutlu[§] Cristiano Giuffrida^{*} Herbert Bos^{*} Kaveh Razavi^{*}

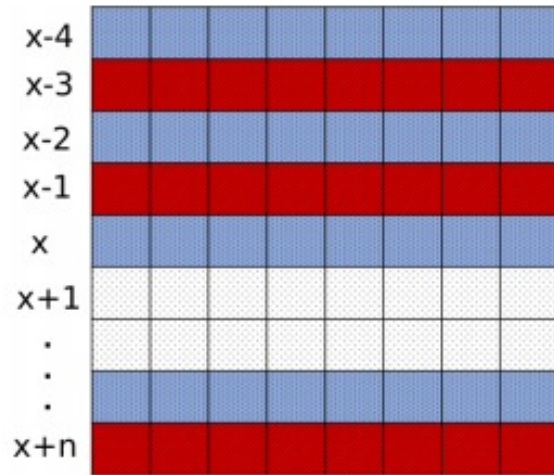
A Poor RowHammer Solution



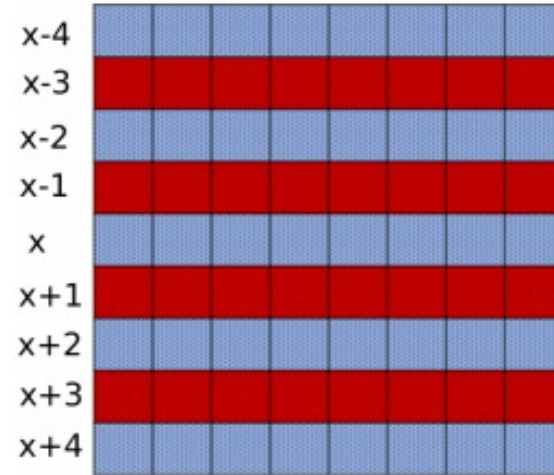
TRRespass

- First work to show that TRR-protected DRAM chips are vulnerable to RowHammer in the field
 - Mitigations advertised as secure are not secure
- Introduces the Many-sided RowHammer attack
 - Idea: Hammer many rows to bypass TRR mitigations (e.g., by overflowing proprietary TRR tables that detect aggressor rows)
- (Partially) reverse-engineers the TRR and pTRR mitigation mechanisms implemented in DRAM chips and memory controllers
- Provides an automatic tool that can effectively create many-sided RowHammer attacks in DDR4 and LPDDR4(X) chips

Example Many-Sided Hammering Patterns



(a) Assisted double-sided



(b) 4-sided

Fig. 12: Hammering patterns discovered by *TRRespass*. Aggressor rows are in red (■) and victim rows are in blue (■).

BitFlips vs. Number of Aggressor Rows

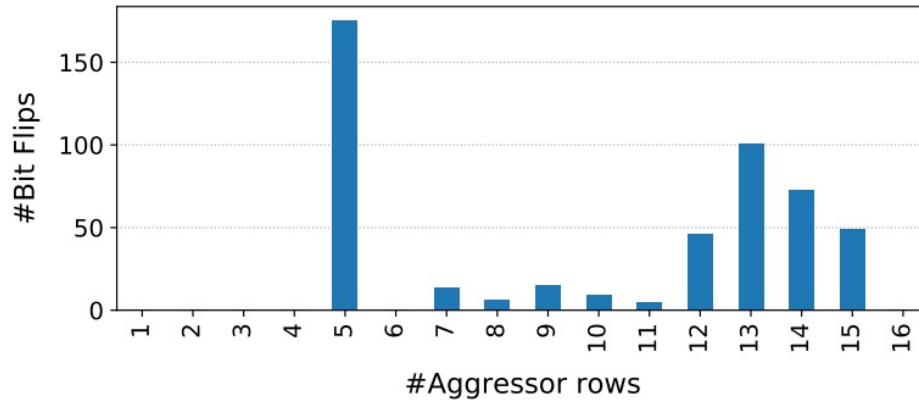


Fig. 10: Bit flips vs. number of aggressor rows. Module C_{12} : Number of bit flips in bank 0 as we vary the number of aggressor rows. Using SoftMC, we refresh DRAM with standard t_{REFI} and run the tests until each aggressor rows is hammered 500K times.

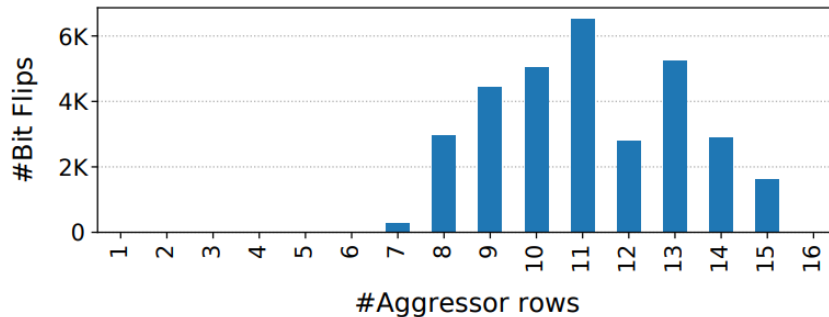


Fig. 11: Bit flips vs. number of aggressor rows. Module A_{15} : Number of bit flips in bank 0 as we vary the number of aggressor rows. Using SoftMC, we refresh DRAM with standard t_{REFI} and run the tests until each aggressor rows is hammered 500K times.

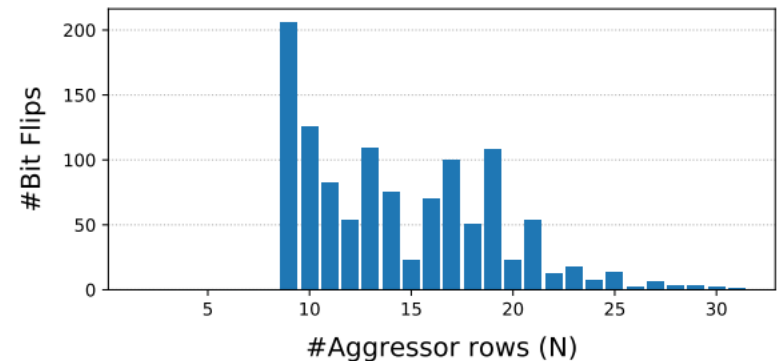


Fig. 13: Bit flips vs. number of aggressor rows. Module A_{10} : Number of bit flips triggered with N -sided RowHammer for varying number of N on Intel Core i7-7700K. Each aggressor row is one row away from the closest aggressor row (i.e., VAVAVA... configuration) and aggressor rows are hammered in a round-robin fashion.

TRRespass Vulnerable DRAM Modules

TABLE II: *TRRespass* results. We report the number of patterns found and bit flips detected for the 42 DRAM modules in our set.

Module	Date (yy-ww)	Freq. (MHz)	Size (GB)	Organization			MAC	Found Patterns	Best Pattern	Corruptions			Double Refresh
				Ranks	Banks	Pins				Total	1 → 0	0 → 1	
$\mathcal{A}_{0,1,2,3}$	16-37	2132	4	1	16	×8	UL	—	—	—	—	—	—
\mathcal{A}_4	16-51	2132	4	1	16	×8	UL	4	9-sided	7956	4008	3948	—
\mathcal{A}_5	18-51	2400	4	1	8	×16	UL	—	—	—	—	—	—
$\mathcal{A}_{6,7}$	18-15	2666	4	1	8	×16	UL	—	—	—	—	—	—
\mathcal{A}_8	17-09	2400	8	1	16	×8	UL	33	19-sided	20808	10289	10519	—
\mathcal{A}_9	17-31	2400	8	1	16	×8	UL	33	19-sided	24854	12580	12274	—
\mathcal{A}_{10}	19-02	2400	16	2	16	×8	UL	488	10-sided	11342	1809	11533	✓
\mathcal{A}_{11}	19-02	2400	16	2	16	×8	UL	523	10-sided	12830	1682	11148	✓
$\mathcal{A}_{12,13}$	18-50	2666	8	1	16	×8	UL	—	—	—	—	—	—
\mathcal{A}_{14}	19-08 [†]	3200	16	2	16	×8	UL	120	14-sided	32723	16490	16233	—
$\mathcal{A}_{15}^{\ddagger}$	17-08	2132	4	1	16	×8	UL	2	9-sided	22397	12351	10046	—
\mathcal{B}_0	18-11	2666	16	2	16	×8	UL	2	3-sided	17	10	7	—
\mathcal{B}_1	18-11	2666	16	2	16	×8	UL	2	3-sided	22	16	6	—
\mathcal{B}_2	18-49	3000	16	2	16	×8	UL	2	3-sided	5	2	3	—
\mathcal{B}_3	19-08 [†]	3000	8	1	16	×8	UL	—	—	—	—	—	—
$\mathcal{B}_{4,5}$	19-08 [†]	2666	8	2	16	×8	UL	—	—	—	—	—	—
$\mathcal{B}_{6,7}$	19-08 [†]	2400	4	1	16	×8	UL	—	—	—	—	—	—
\mathcal{B}_8^{\diamond}	19-08 [†]	2400	8	1	16	×8	UL	—	—	—	—	—	—
\mathcal{B}_9^{\diamond}	19-08 [†]	2400	8	1	16	×8	UL	2	3-sided	12	—	12	✓
$\mathcal{B}_{10,11}$	16-13 [†]	2132	8	2	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_{0,1}$	18-46	2666	16	2	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_{2,3}$	19-08 [†]	2800	4	1	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_{4,5}$	19-08 [†]	3000	8	1	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_{6,7}$	19-08 [†]	3000	16	2	16	×8	UL	—	—	—	—	—	—
\mathcal{C}_8	19-08 [†]	3200	16	2	16	×8	UL	—	—	—	—	—	—
\mathcal{C}_9	18-47	2666	16	2	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_{10,11}$	19-04	2933	8	1	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_{12}^{\ddagger}$	15-01 [†]	2132	4	1	16	×8	UT	25	10-sided	190037	63904	126133	✓
$\mathcal{C}_{13}^{\ddagger}$	18-49	2132	4	1	16	×8	UT	3	9-sided	694	239	455	—

[†] The module does not report manufacturing date. Therefore, we report purchase date as an approximation.

[‡] Analyzed using the FPGA-based SoftMC.

[◊] The system runs with double refresh frequency in standard conditions. We configured the refresh interval to be 64 *ms* in the BIOS settings.

UL = Unlimited

UT = Untested

TRRespass Vulnerable Mobile Phones

TABLE III: LPDDR4(X) results. Mobile phones tested against *TRRespass* on ARMv8 sorted by production date. We found bit flip inducing RowHammer patterns on 5 out of 13mobile phones.

<i>Mobile Phone</i>	<i>Year</i>	<i>SoC</i>	<i>Memory (GB)</i>	<i>Found Patterns</i>
Google Pixel	2016	MSM8996	4 [†]	✓
Google Pixel 2	2017	MSM8998	4	—
Samsung G960F/DS	2018	Exynos 9810	4	—
Huawei P20 DS	2018	Kirin 970	4	—
Sony XZ3	2018	SDM845	4	—
HTC U12+	2018	SDM845	6	—
LG G7 ThinQ	2018	SDM845	4 [†]	✓
Google Pixel 3	2018	SDM845	4	✓
Google Pixel 4	2019	SM8150	6	—
OnePlus 7	2019	SM8150	8	✓
Samsung G970F/DS	2019	Exynos 9820	6	✓
Huawei P30 DS	2019	Kirin 980	6	—
Xiaomi Redmi Note 8 Pro	2019	Helio G90T	6	—

[†] LPDDR4 (not LPDDR4X)

TRRespass Based RowHammer Attack

TABLE IV: Time to exploit. Time to find the first exploitable template on two sample modules from each DRAM vendor.

<i>Module</i>	τ (ms)	<i>PTE</i> [81]	<i>RSA-2048</i> [79]	<i>sudo</i> [27]
\mathcal{A}_{14}	188.7	4.9s	6m 27s	—
\mathcal{A}_4	180.8	38.8s	39m 28s	—
\mathcal{B}_1	360.7	—	—	—
\mathcal{B}_2	331.2	—	—	—
\mathcal{C}_{12}	300.0	2.3s	74.6s	54m16s
\mathcal{C}_{13}	180.9	3h 15m	—	—

τ : Time to template a single row: time to fill the victim and aggressor rows + hammer time + time to scan the row.

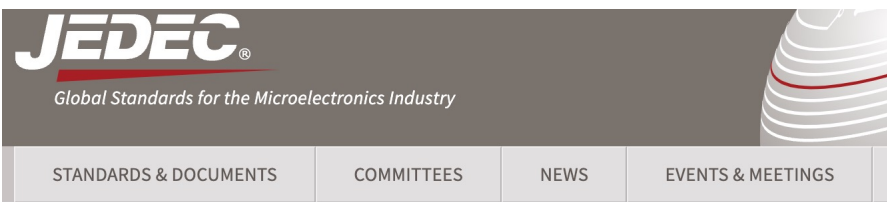
TRRespass Key Results

- 13 out of 42 tested DDR4 DRAM modules are vulnerable
 - From all 3 major manufacturers
 - 3-, 9-, 10-, 14-, 19-sided hammer attacks needed
- 5 out of 13 mobile phones tested vulnerable
 - From 4 major manufacturers
 - With LPDDR4(X) DRAM chips
- These results are scratching the surface
 - TRRespass tool is not exhaustive
 - There is a lot of room for uncovering more vulnerable chips and phones

RowHammer is still
an open problem

Security by obscurity
is likely not a good solution

Improvements in JEDEC (2020-2021)



NEAR-TERM DRAM LEVEL ROWHAMMER MITIGATION

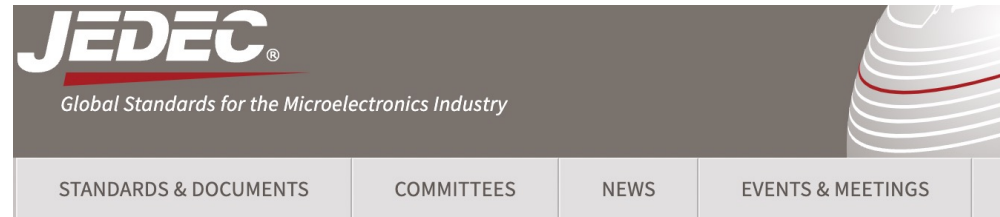
JEP300-1

Published: Mar 2021

RAM process node transistor scaling for power and DRAM capacity has made DRAM cells more sensitive to disturbances or transient faults. This sensitivity becomes much worse if external stresses are applied in a meticulously manipulated sequence, such as Rowhammer. Rowhammer related papers have been written outside of JEDEC, but some assumptions used in those papers didn't explain the problem very clearly or correctly, so the perception for this matter is not precisely understood within the industry. This publication defines the problem and recommends following mitigations to address such concerns across the DRAM industry or academia. Item 1866.01.

Committee(s): [JC-42](#)

<https://www.jedec.org/standards-documents/docs/jep300-1>



SYSTEM LEVEL ROWHAMMER MITIGATION

JEP301-1


Published: Mar 2021

A DRAM rowhammer security exploit is a serious threat to cloud service providers, data centers, laptops, smart phones, self-driving cars and IoT devices. Hardware research and development will take time. DRAM components, DRAM DIMMs, System-on-chip (SoC), chipsets and system products have their own design cycle time and overall life time. This publication recommends best practices to mitigate the security risks from rowhammer attacks. Item 1866.02.

Committee(s): [JC-42](#)

<https://www.jedec.org/standards-documents/docs/jep301-1>

Improvements in JEDEC (2024)



Global Standards for the Microelectronics Industry

STANDARDS & DOCUMENTS

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DDR5 SDRAM

JESD79-5C

Apr 2024

Release Number: Version 1.30

Version 1.30

This standard defines the DDR5 SDRAM specification, including features, functionalities, AC and DC characteristics, packages, and ball/signal assignments. The purpose of this Standard is to define the minimum set of requirements for JEDEC compliant 8 Gb through 32 Gb for x4, x8, and x16 DDR5 SDRAM devices. This standard was created based on the DDR4 standards (JESD79-4) and some aspects of the DDR, DDR2, DDR3, and LPDDR4 standards (JESD79, JESD79-2, JESD79-3, and JESD209-4).

Committee(s): [JC-42](#), [JC-42.3](#)

Uncovering TRR Almost Completely

Industry-Adopted Solutions Are Very Poor

- Hasan Hassan, Yahya Can Tugrul, Jeremie S. Kim, Victor van der Veen, Kaveh Razavi, and Onur Mutlu,
"Uncovering In-DRAM RowHammer Protection Mechanisms: A New Methodology, Custom RowHammer Patterns, and Implications"
Proceedings of the 54th International Symposium on Microarchitecture (MICRO), Virtual, October 2021.
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[[arXiv version](#)]

Uncovering In-DRAM RowHammer Protection Mechanisms: A New Methodology, Custom RowHammer Patterns, and Implications

Hasan Hassan[†]

[†]ETH Zürich

Yahya Can Tuğrul^{†‡}

Kaveh Razavi[†]
[‡]TOBB University of Economics & Technology

Jeremie S. Kim[†]

Onur Mutlu[†]

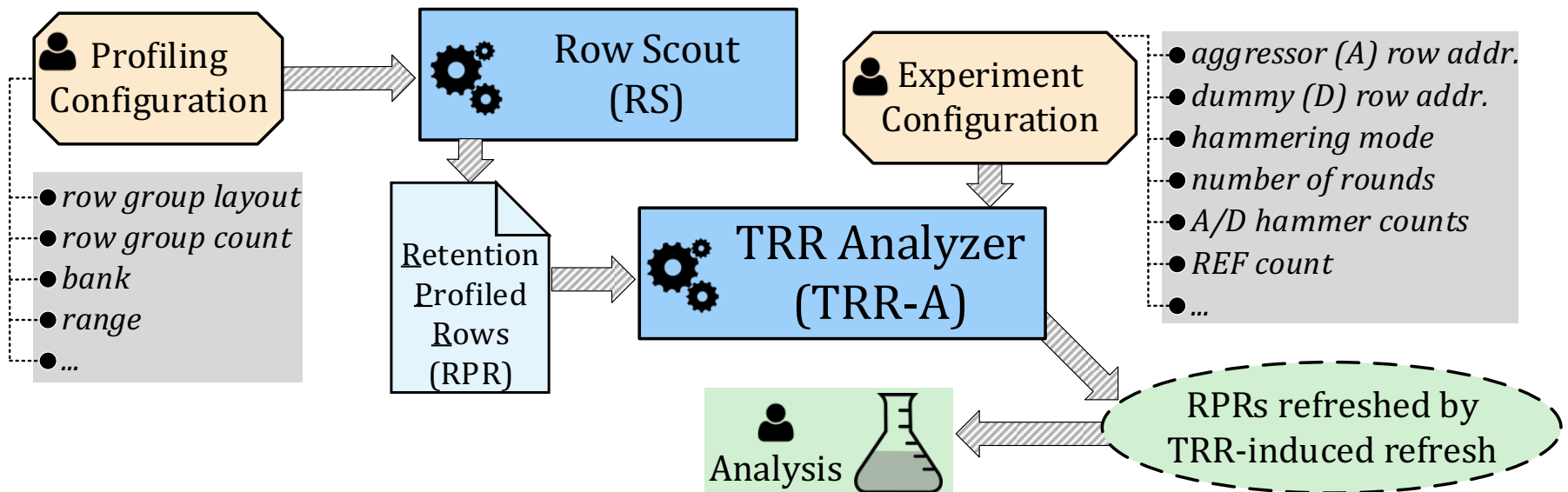
Victor van der Veen^σ

^σQualcomm Technologies Inc.

Overview of U-TRR

U-TRR: A new methodology to *uncover* the inner workings of TRR

Key idea: Use **data retention failures** as a side channel to **detect when a row is refreshed** by TRR



Key Takeaways

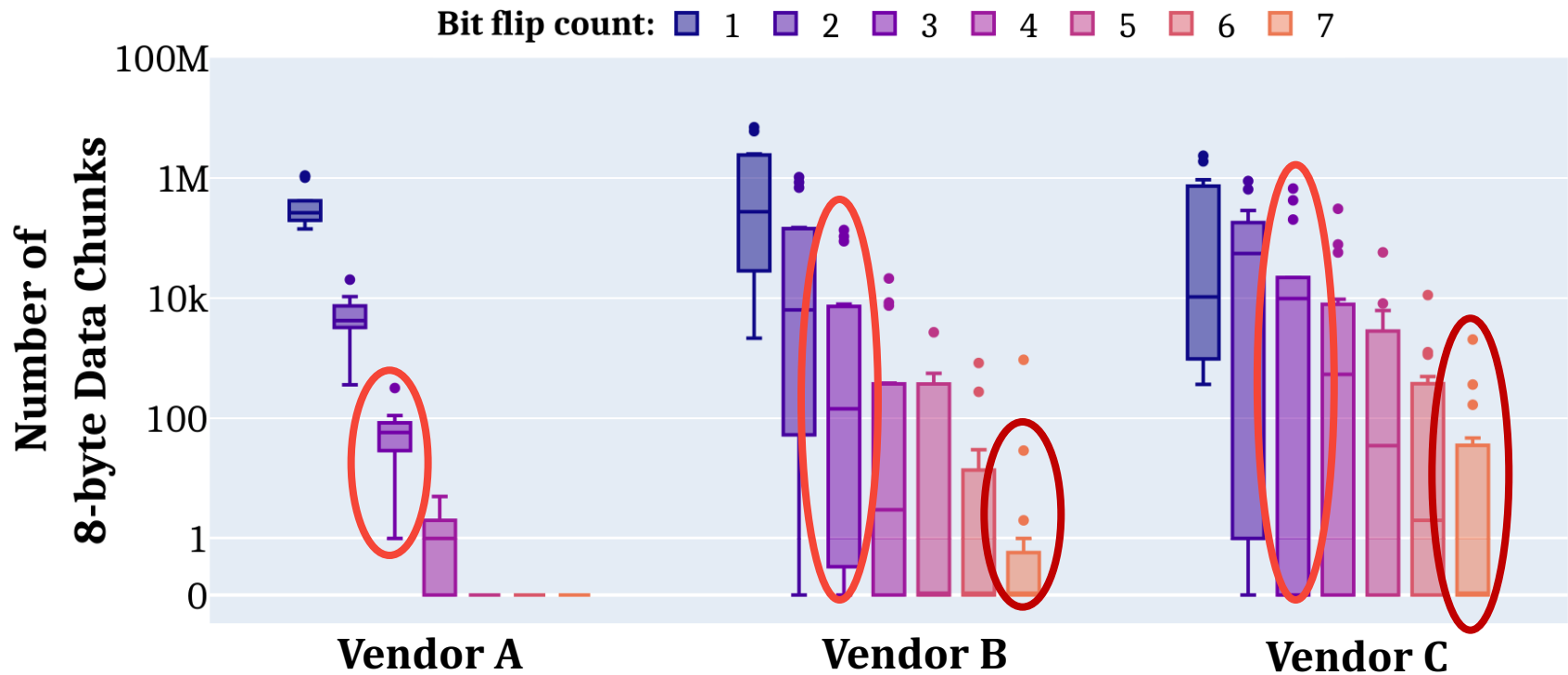
All 45 modules we test are vulnerable

99.9% of rows in a DRAM bank
experience **at least one RowHammer bit flip**

ECC is ineffective: up to **7 RowHammer bit flips**
in an 8-byte dataword

Module	Date (yy-ww)	Chip Density (Gbit)	Organization			HC_{first}^{\dagger}	Our Key TRR Observations and Results							
			Ranks	Banks	Pins		Version	Aggressor Detection	Aggressor Capacity	Per-Bank TRR	TRR-to-REF Ratio	Neighbors Refreshed	% Vulnerable DRAM Rows [†]	Max. Bit Flips per Row per Hammer [†]
A0	19-50	8	1	16	8	16K	A_{TRR1}	Counter-based	16	✓	1/9	4	73.3%	1.16
A1-5	19-36	8	1	8	16	13K-15K	A_{TRR1}	Counter-based	16	✓	1/9	4	99.2% - 99.4%	2.32 - 4.73
A6-7	19-45	8	1	8	16	13K-15K	A_{TRR1}	Counter-based	16	✓	1/9	4	99.3% - 99.4%	2.12 - 3.86
A8-9	20-07	8	1	16	8	12K-14K	A_{TRR1}	Counter-based	16	✓	1/9	4	74.6% - 75.0%	1.96 - 2.96
A10-12	19-51	8	1	16	8	12K-13K	A_{TRR1}	Counter-based	16	✓	1/9	4	74.6% - 75.0%	1.48 - 2.86
A13-14	20-31	8	1	8	16	11K-14K	A_{TRR2}	Counter-based	16	✓	1/9	2	94.3% - 98.6%	1.53 - 2.78
B0	18-22	4	1	16	8	44K	B_{TRR1}	Sampling-based	1	✗	1/4	2	99.9%	2.13
B1-4	20-17	4	1	16	8	159K-192K	B_{TRR1}	Sampling-based	1	✗	1/4	2	23.3% - 51.2%	0.06 - 0.11
B5-6	16-48	4	1	16	8	44K-50K	B_{TRR1}	Sampling-based	1	✗	1/4	2	99.9%	1.85 - 2.03
B7	19-06	8	2	16	8	20K	B_{TRR1}	Sampling-based	1	✗	1/4	2	99.9%	31.14
B8	18-03	4	1	16	8	43K	B_{TRR1}	Sampling-based	1	✗	1/4	2	99.9%	2.57
B9-12	19-48	8	1	16	8	42K-65K	B_{TRR2}	Sampling-based	1	✗	1/9	2	36.3% - 38.9%	16.83 - 24.26
B13-14	20-08	4	1	16	8	11K-14K	B_{TRR3}	Sampling-based	1	✓	1/2	4	99.9%	16.20 - 18.12
C0-3	16-48	4	1	16	x8	137K-194K	C_{TRR1}	Mix	Unknown	✓	1/17	2	1.0% - 23.2%	0.05 - 0.15
C4-6	17-12	8	1	16	x8	130K-150K	C_{TRR1}	Mix	Unknown	✓	1/17	2	7.8% - 12.0%	0.06 - 0.08
C7-8	20-31	8	1	8	x16	40K-44K	C_{TRR1}	Mix	Unknown	✓	1/17	2	39.8% - 41.8%	9.66 - 14.56
C9-11	20-31	8	1	8	x16	42K-53K	C_{TRR2}	Mix	Unknown	✓	1/9	2	99.7%	9.30 - 32.04
C12-14	20-46	16	1	8	x16	6K-7K	C_{TRR3}	Mix	Unknown	✓	1/8	2	99.9%	4.91 - 12.64

Bypassing ECC with New RowHammer Patterns



Modules from all three vendors have many **8-byte data chunks** with **3 and more (up to 7) RowHammer bit flips**

Conventional DRAM ECC **cannot protect** against our **new RowHammer access patterns**

Google's Half-Double RowHammer Attack (May 2021)

Google Security Blog

The latest news and insights from Google on security and safety on the Internet

Introducing Half-Double: New hammering technique for DRAM Rowhammer bug

May 25, 2021

Research Team: Salman Qazi, Yoongu Kim, Nicolas Boichat, Eric Shiu & Mattias Nissler

Today, we are sharing details around our discovery of [Half-Double](#), a new Rowhammer technique that capitalizes on the worsening physics of some of the newer DRAM chips to alter the contents of memory.

Rowhammer is a DRAM vulnerability whereby repeated accesses to one address can tamper with the data stored at other addresses. Much like speculative execution vulnerabilities in CPUs, Rowhammer is a breach of the security guarantees made by the underlying hardware. As an electrical coupling phenomenon within the silicon itself, Rowhammer allows the potential bypass of hardware and software memory protection policies. This can allow untrusted code to break out of its sandbox and take full control of the system.

Google's Half-Double RowHammer Attack (May 2021)



- Given three consecutive rows A, B, and C, we were able to attack C by directing a very large number of accesses to A, along with just a handful (~dozens) to B.
- Based on our experiments, accesses to B have a non-linear gating effect, in which they appear to “transport” the Rowhammer effect of A onto C.
- This is likely an indication that the electrical coupling responsible for **Rowhammer** is a property of distance, **effectively becoming stronger** and longer-ranged as cell geometries shrink down.

Google's Half-Double RowHammer Attack

- **Appears at USENIX Security 2022**

Half-Double: Hammering From the Next Row Over

Andreas Kogler¹ Jonas Juffinger^{1,2} Salman Qazi³ Yoongu Kim³ Moritz Lipp^{4*}
Nicolas Boichat³ Eric Shiu⁵ Mattias Nissler³ Daniel Gruss¹

¹*Graz University of Technology* ²*Lamarr Security Research* ³*Google*
⁴*Amazon Web Services* ⁵*Rivos*

Microsoft's MOESI-prime Work [ISCA'22]

- Introduces coherence-induced hammering
- Hammering in commodity workloads (non-malicious code)

MOESI-prime: Preventing Coherence-Induced Hammering in Commodity Workloads

Kevin Loughlin
University of Michigan

Stefan Saroiu
Microsoft

Alec Wolman
Microsoft

Yatin A. Manerkar
University of Michigan

Baris Kasikci
University of Michigan

ABSTRACT

Prior work shows that Rowhammer attacks—which flip bits in DRAM via frequent activations of the same row(s)—are viable. Adversaries typically mount these attacks via instruction sequences that are carefully-crafted to bypass CPU caches. However, we discover a novel form of hammering that we refer to as *coherence-induced hammering*, caused by Intel's implementations of cache coherent non-uniform memory access (ccNUMA) protocols. We show that this hammering *occurs in commodity benchmarks* on a major cloud provider's production hardware, the first hammering found to be generated by non-malicious code. Given DRAM's rising susceptibility to bit flips, it is paramount to prevent coherence-induced hammering to ensure reliability and security in the cloud.

1 INTRODUCTION

The threat of Rowhammer [61] bit flips (i.e., DRAM disturbances) is a widespread concern, especially in multi-tenant computing environments such as the cloud. Rowhammer arises from frequent activations—to a first approximation, accesses—of the same DRAM rows, which can disturb data in nearby rows due to electromagnetic interference. These bit flips manifest at the system level as data loss, machine failure, or system subversion.

Prior attacks and analyses [20, 22, 25, 30, 38, 39, 41, 48, 49, 51, 58, 61, 65, 70, 84, 88, 94, 95, 101, 108, 111–114, 119] confirm that malicious adversaries can trigger sufficient activations to flip bits, establishing Rowhammer as a *security* threat. At a high level, existing attacks require a carefully-crafted sequence of instructions to

BlockHammer Solution in 2021

- A. Giray Yaglikci, Minesh Patel, Jeremie S. Kim, Roknoddin Azizi, Ataberk Olgun, Lois Orosa, Hasan Hassan, Jisung Park, Konstantinos Kanellopoulos, Taha Shahroodi, Saugata Ghose, and Onur Mutlu,

"BlockHammer: Preventing RowHammer at Low Cost by Blacklisting Rapidly-Accessed DRAM Rows"

Proceedings of the 27th International Symposium on High-Performance Computer Architecture (HPCA), Virtual, February-March 2021.

[[Slides \(pptx\)](#) ([pdf](#))]

[[Short Talk Slides \(pptx\)](#) ([pdf](#))]

[[Intel Hardware Security Academic Awards Short Talk Slides \(pptx\)](#) ([pdf](#))]

[[Talk Video](#) (22 minutes)]

[[Short Talk Video](#) (7 minutes)]

[[Intel Hardware Security Academic Awards Short Talk Video](#) (2 minutes)]

[[BlockHammer Source Code](#)]

Intel Hardware Security Academic Award Finalist (one of 4 finalists out of 34 nominations)

BlockHammer: Preventing RowHammer at Low Cost by Blacklisting Rapidly-Accessed DRAM Rows

A. Giray Yağlıkçı¹ Minesh Patel¹ Jeremie S. Kim¹ Roknoddin Azizi¹ Ataberk Olgun¹ Lois Orosa¹

Hasan Hassan¹ Jisung Park¹ Konstantinos Kanellopoulos¹ Taha Shahroodi¹ Saugata Ghose² Onur Mutlu¹

¹ETH Zürich

²University of Illinois at Urbana-Champaign

Two Key Challenges

1

Scalability

with worsening RowHammer vulnerability

2

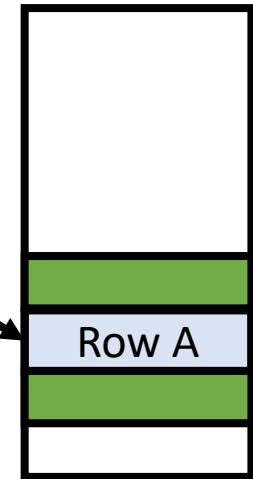
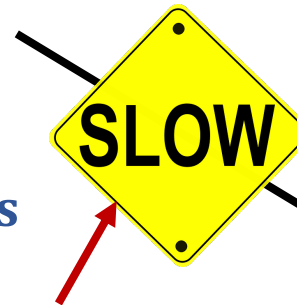
Compatibility

with commodity DRAM chips

BlockHammer: Practical Throttling-based Mechanism



- A RowHammer attack hammers Row A
- **BlockHammer** detects a RowHammer attack using **area-efficient Bloom filters**
- **BlockHammer** **selectively throttles** accesses from within **the memory controller**
- Bit flips **do not** occur
- BlockHammer can *optionally* **inform the system software** about the attack



Physical
Row Layout

BlockHammer is **compatible with commodity DRAM chips**
No need for **proprietary info** of or **modifications** to DRAM chips

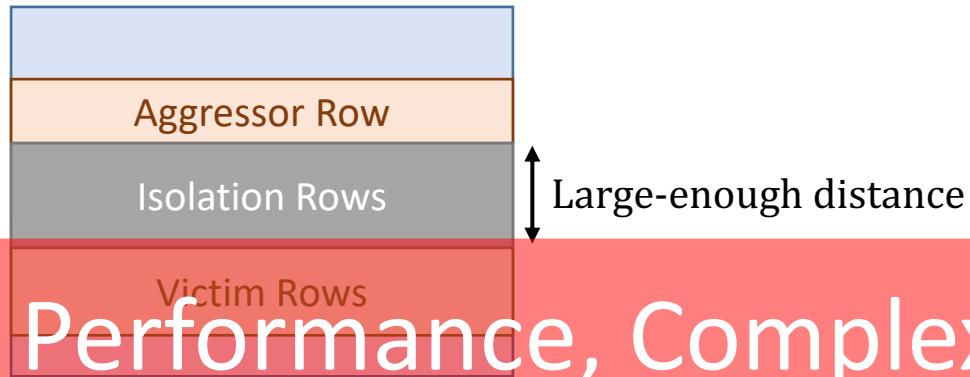
Main Memory Needs
Intelligent Controllers
for Security, Safety,
Reliability, Scaling

RowHammer Solution Approaches

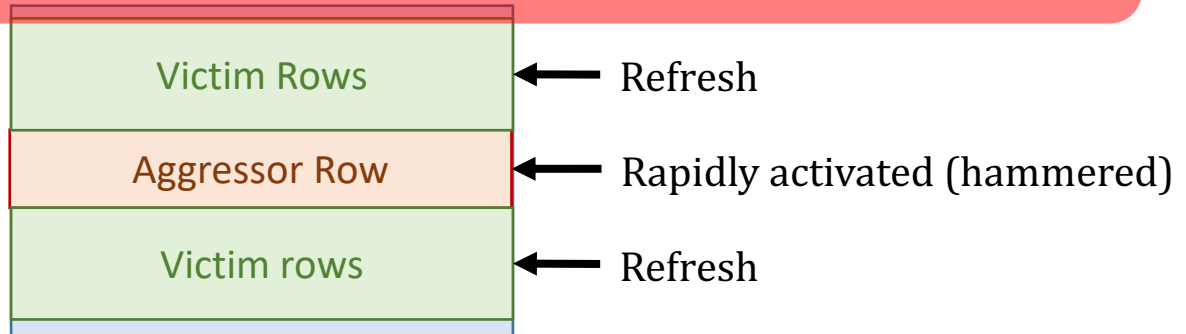
- More robust DRAM chips **and/or** error-correcting codes
- Increased refresh rate



- Physical isolation

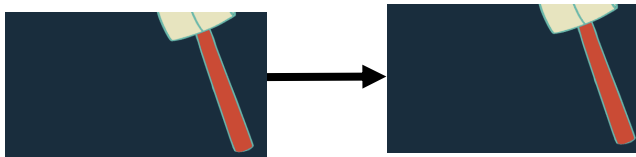


- Reactive refresh



- Proactive throttling

SAFARI



Fewer activations allowed for aggressive applications

RowHammer in 2023: SK Hynix

ISSCC 2023 / SESSION 28 / HIGH-DENSITY MEMORIES

28.8 A 1.1V 16Gb DDR5 DRAM with Probabilistic-Aggressor Tracking, Refresh-Management Functionality, Per-Row Hammer Tracking, a Multi-Step Precharge, and Core-Bias Modulation for Security and Reliability Enhancement

Woongrae Kim, Chulmoon Jung, Seongnyuh Yoo, Duckhwa Hong, Jeongjin Hwang, Jungmin Yoon, Ohyong Jung, Joonwoo Choi, Sanga Hyun, Mankeun Kang, Sangho Lee, Dohong Kim, Sanghyun Ku, Donhyun Choi, Nogeun Joo, Sangwoo Yoon, Junseok Noh, Byeongyong Go, Cheolhoe Kim, Sunil Hwang, Mihyun Hwang, Seol-Min Yi, Hyungmin Kim, Sanghyuk Heo, Yeonsu Jang, Kyoungchul Jang, Shinho Chu, Yoonna Oh, Kwidong Kim, Junghyun Kim, Soohwan Kim, Jeongtae Hwang, Sangil Park, Junphyo Lee, Inchul Jeong, Joohwan Cho, Jonghwan Kim

SK hynix Semiconductor, Icheon, Korea

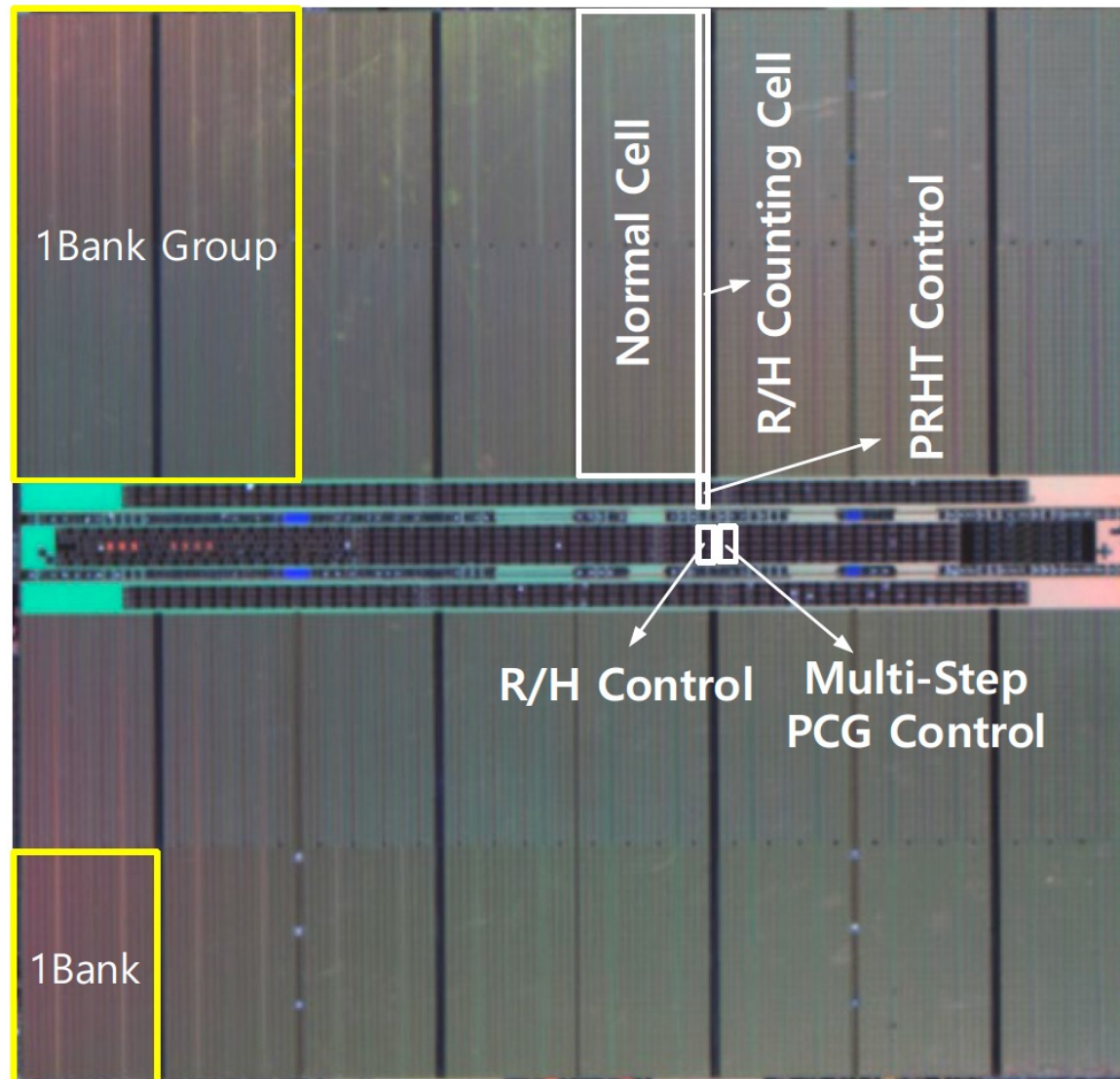


Industry's RowHammer Solutions (I)

SK hynix Semiconductor, Icheon, Korea

DRAM products have been recently adopted in a wide range of high-performance computing applications: such as in cloud computing, in big data systems, and IoT devices. This demand creates larger memory capacity requirements, thereby requiring aggressive DRAM technology node scaling to reduce the cost per bit [1,2]. However, DRAM manufacturers are facing technology scaling challenges due to row hammer and refresh retention time beyond 1a-nm [2]. Row hammer is a failure mechanism, where repeatedly activating a DRAM row disturbs data in adjacent rows. Scaling down severely threatens reliability since a reduction of DRAM cell size leads to a reduction in the intrinsic row hammer tolerance [2,3]. To improve row hammer tolerance, there is a need to probabilistically activate adjacent rows with carefully sampled active addresses and to improve intrinsic row hammer tolerance [2]. In this paper, row-hammer-protection and refresh-management schemes are presented to guarantee DRAM security and reliability despite the aggressive scaling from 1a-nm to sub 10-nm nodes. The probabilistic-aggressor-tracking scheme with a refresh-management function (RFM) and per-row hammer tracking (PRHT) improve DRAM resilience. A multi-step precharge reinforces intrinsic row-hammer tolerance and a core-bias modulation improves retention time: even in the face of cell-transistor degradation due to technology scaling. This comprehensive scheme leads to a reduced probability of failure, due to row hammer attacks, by 93.1% and an improvement in retention time by 17%.

Industry's RowHammer Solutions (II)



ISSCC 2023 / SESSION 28 / HIGH-DENSITY MEMORIES /

28.8 A 1.1V 16Gb DDR5 DRAM with Probabilistic-Aggressor Tracking, Refresh-Management Functionality, Per-Row Hammer Tracking, a Multi-Step Precharge, and Core-Bias Modulation for Security and Reliability Enhancement

Woongrae Kim, Chulmoon Jung, Seongnyuh Yoo, Duckhwa Hong, Jeongjin Hwang, Jungmin Yoon, Ohyoung Jung, Joonwoo Choi, Sanga Hyun, Mankeun Kang, Sangho Lee, Dohong Kim, Sanghyun Ku, Donhyun Choi, Nogeun Joo, Sangwoo Yoon, Junseok Noh, Byeongyong Go, Cheolhoe Kim, Sunil Hwang, Mihyun Hwang, Seol-Min Yi, Hyungmin Kim, Sanghyuk Heo, Yeonsu Jang, Kyoungchul Jang, Shinho Chu, Yoonna Oh, Kwidong Kim, Junghyun Kim, Soohwan Kim, Jeongtae Hwang, Sangil Park, Junphyo Lee, Inchul Jeong, Joohwan Cho, Jonghwan Kim

SK hynix Semiconductor, Icheon, Korea

RowHammer in 2023: Samsung

DSAC: Low-Cost Rowhammer Mitigation Using In-DRAM Stochastic and Approximate Counting Algorithm

Seungki Hong Dongha Kim Jaehyung Lee Reum Oh
Changsik Yoo Sangjoon Hwang Jooyoung Lee

DRAM Design Team, Memory Division, Samsung Electronics


<https://arxiv.org/pdf/2302.03591v1.pdf>

Panopticon: A Complete In-DRAM Rowhammer Mitigation

Tanj Bennett[§], Stefan Saroiu, Alec Wolman, and Lucian Cojocar
Microsoft, [§]Avant-Gray LLC

<https://stefan.t8k2.com/publications/dramsec/2021/panopticon.pdf>

Solutions in JEDEC (2024)



Global Standards for the Microelectronics Industry

STANDARDS & DOCUMENTS

COMMITTEES

NEWS

EVENTS & MEETINGS

JOIN

DDR5 SDRAM

JESD79-5C

Apr 2024

Release Number: Version 1.30

Version 1.30

This standard defines the DDR5 SDRAM specification, including features, functionalities, AC and DC characteristics, packages, and ball/signal assignments. The purpose of this Standard is to define the minimum set of requirements for JEDEC compliant 8 Gb through 32 Gb for x4, x8, and x16 DDR5 SDRAM devices. This standard was created based on the DDR4 standards (JESD79-4) and some aspects of the DDR, DDR2, DDR3, and LPDDR4 standards (JESD79, JESD79-2, JESD79-3, and JESD209-4).

Committee(s): [JC-42](#), [JC-42.3](#)

Evaluation of Industry's Recent Solutions

- **Appears at DRAMSec 2024**

Understanding the Security Benefits and Overheads of Emerging Industry Solutions to DRAM Read Disturbance

Oğuzhan Canpolat^{§†}

A. Giray Yağlıkçı[§]

Geraldo F. Oliveira[§]

Ataberk Olgun[§]

Oğuz Ergin[†]

Onur Mutlu[§]

[§]*ETH Zürich*

[†]*TOBB University of Economics and Technology*

<https://arxiv.org/pdf/2406.19094>

<https://github.com/CMU-SAFARI/ramulator2>

Are we now
RowHammer-free
in 2024 and Beyond?

Are We Now BitFlip Free?

- **Appeared at ISCA in June 2023**

What if there is another phenomenon that **does NOT require high row activation count?**

RowPress: Amplifying Read-Disturbance in Modern DRAM Chips

Haocong Luo Ataberk Olgun A. Giray Yağlıkçı Yahya Can Tuğrul Steve Rhyner
Meryem Banu Cavlak Joël Lindegger Mohammad Sadrosadati Onur Mutlu
ETH Zürich

<https://arxiv.org/pdf/2306.17061.pdf>

RowPress



- Haocong Luo, Ataberk Olgun, Giray Yaglikci, Yahya Can Tugrul, Steve Rhyner, M. Banu Cavlak, Joel Lindegger, Mohammad Sadrosadati, and Onur Mutlu, **"RowPress: Amplifying Read Disturbance in Modern DRAM Chips"**

Proceedings of the 50th International Symposium on Computer Architecture (ISCA), Orlando, FL, USA, June 2023.

[[Slides \(pptx\)](#) ([pdf](#))]

[[Lightning Talk Slides \(pptx\)](#) ([pdf](#))]

[[Lightning Talk Video](#) (3 minutes)]

[[RowPress Source Code and Datasets \(Officially Artifact Evaluated with All Badges\)](#)]

***Officially artifact evaluated as available, reusable and reproducible.
Best artifact award at ISCA 2023. IEEE Micro Top Pick in 2024.***

RowPress: Amplifying Read-Disturbance in Modern DRAM Chips

Haocong Luo Ataberk Olgun A. Giray Yağlıkçı Yahya Can Tuğrul Steve Rhyner
Meryem Banu Cavlak Joël Lindegger Mohammad Sadrosadati Onur Mutlu

ETH Zürich



RowPress

Amplifying Read Disturbance in Modern DRAM Chips

ISCA 2023 Session 2B: Monday 19 June, 2:15 PM EDT

Haocong Luo

Ataberk Olgun

A. Giray Yağlıkçı

Yahya Can Tuğrul

Steve Rhyner

Meryem Banu Cavlak

Joël Lindegger

Mohammad Sadrosadati

Onur Mutlu

SAFARI

ETH zürich

High-Level Summary

- We demonstrate and analyze **RowPress, a new read disturbance phenomenon** that causes bitflips in real DRAM chips
- We show that RowPress is **different from the RowHammer vulnerability**
- We demonstrate RowPress **using a user-level program** on a real Intel system with real DRAM chips
- We provide **effective solutions** to RowPress

What is RowPress?

Keeping a DRAM row **open for a long time** causes bitflips in adjacent rows

These bitflips do **NOT** require many row activations

Only one activation is enough in some cases!



Now, let's delve into some background and see how this is **different from RowHammer**

Are There Other Read-Disturb Issues in DRAM?

- RowHammer is the only studied read-disturb phenomenon
- Mitigations work by detecting **high row activation count**

What if there is another read-disturb phenomenon that **does NOT rely on high row activation count**?



https://www.reddit.com/r/CrappyDesign/comments/arw0q8/now_this_this_is_poor_fencing/

RowPress vs. RowHammer

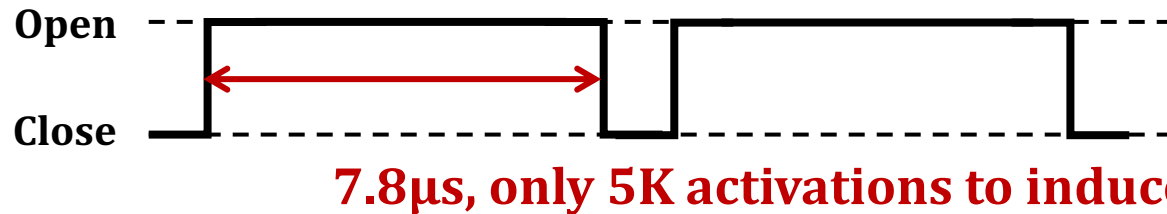
Instead of using a high activation count,

☞ increase the time that the aggressor row stays open

RowHammer
Aggressor Row



RowPress
Aggressor Row

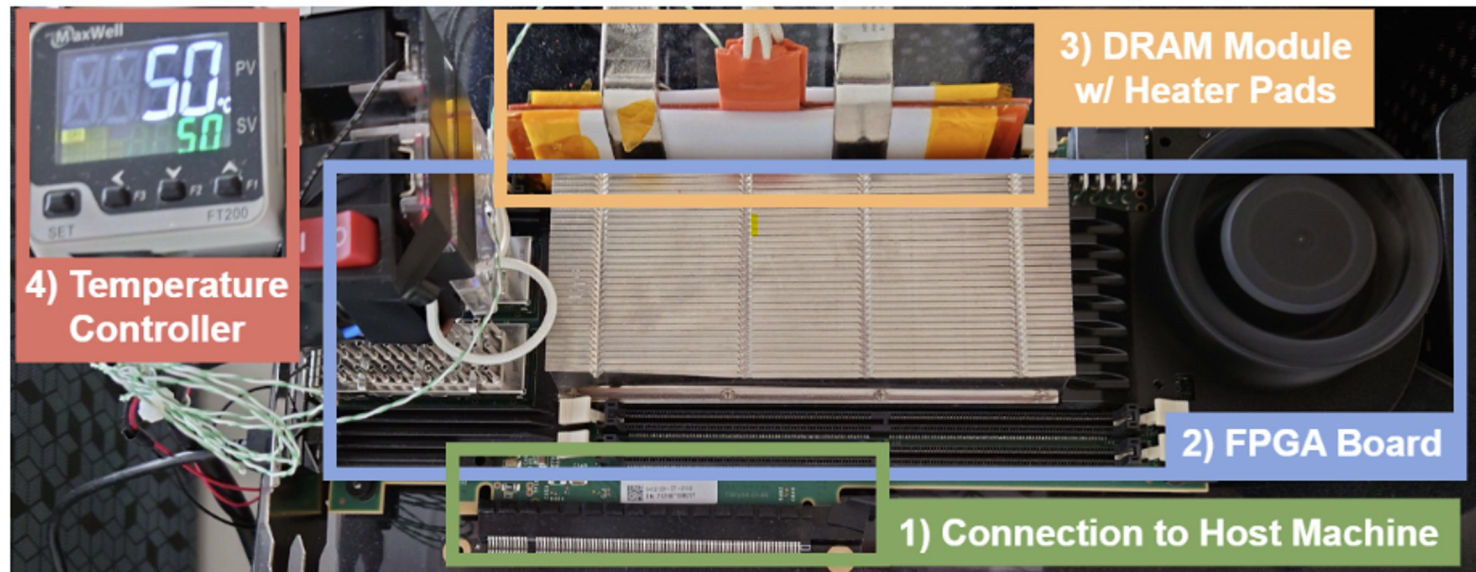


We observe bitflips even with **ONLY ONE activation** in extreme cases where the row stays open for 30ms

Real DRAM Chip Characterization (I)

FPGA-Based DDR4 Testing Infrastructure

- Based on [SoftMC \[Hassan+, HPCA'17\]](#) and [DRAM Bender \[Olgun+, TCAD'23\]](#)
- **Fine-grained control** over DRAM commands, timings, and temperature



Real DRAM Chip Characterization (II)

DRAM chips tested

- 164 DDR4 chips from all 3 major DRAM manufacturers
- Covers different die densities and revisions

Mfr.	#DIMMs	#Chips	Density	Die Rev.	Org.	Date
Mfr. S (Samsung)	2	8	8Gb	B	x8	20-53
	1	8	8Gb	C	x8	N/A
	3	8	8Gb	D	x8	21-10
	2	8	4Gb	F	x8	N/A
Mfr. H (SK Hynix)	1	8	4Gb	A	x8	19-46
	1	8	4Gb	X	x8	N/A
	2	8	16Gb	A	x8	20-51
	2	8	16Gb	C	x8	21-36
Mfr. M (Micron)	1	16	8Gb	B	x4	N/A
	2	4	16Gb	B	x16	21-26
	1	16	16Gb	E	x4	20-14
	2	4	16Gb	E	x16	20-46
	1	4	16Gb	F	x16	21-50

Major Takeaways from Real DRAM Chips

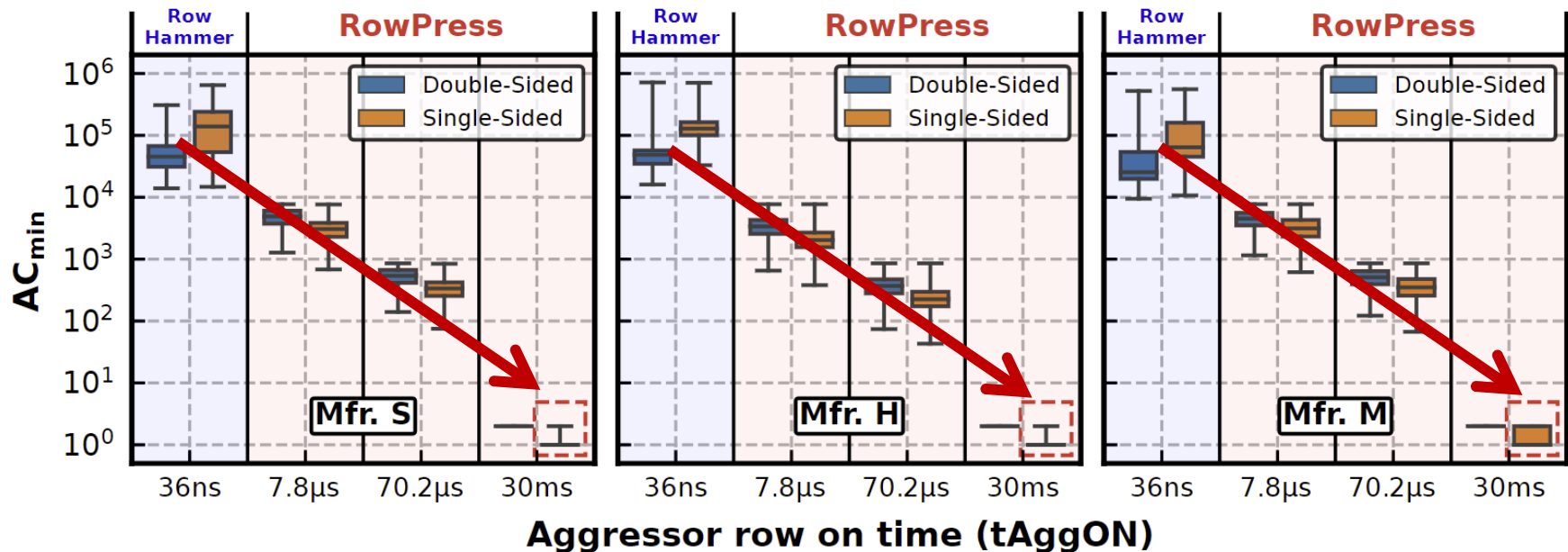
RowPress significantly **amplifies** DRAM's vulnerability to **read disturbance**

RowPress has a **different** underlying error **mechanism** from RowHammer

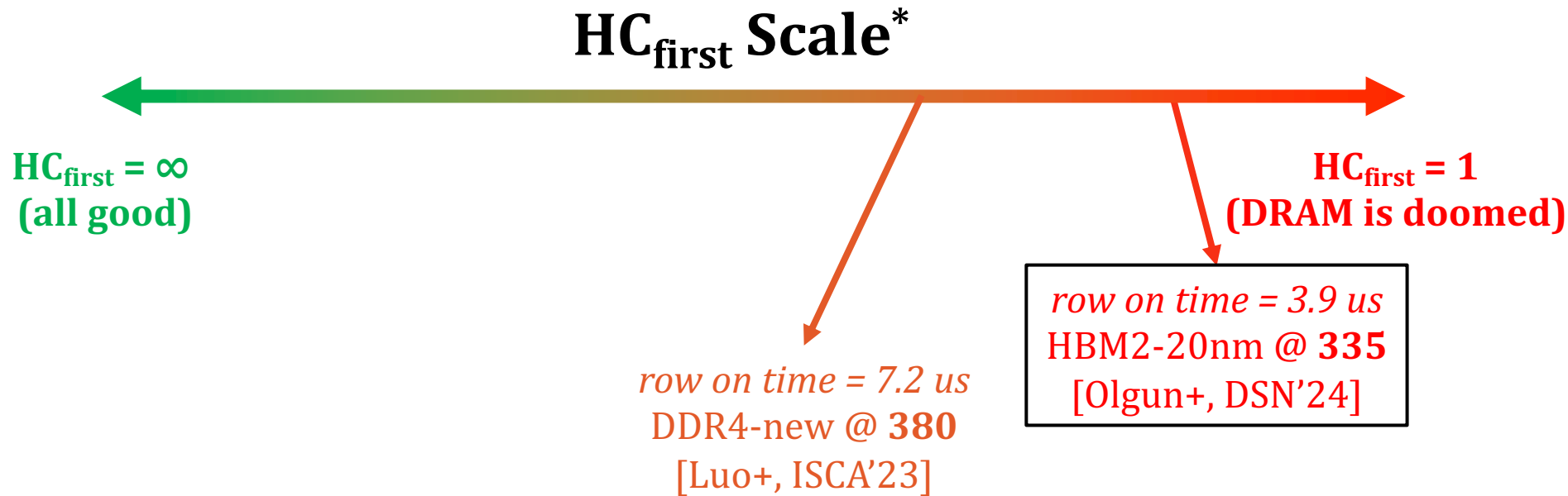
Key Characteristics of RowPress (I)

Amplifying Read Disturbance in DRAM

- Reduces the minimum number of row activations needed to induce a bitflip (AC_{min}) by **1-2 orders of magnitude**
- In extreme cases, activating a row **only once** induces bitflips



RowPress at $t_{\text{AggON}} = \text{Refresh Interval}$



*Not shown: Significant variance in HC_{first} across vendors and die variations

RowPress at $t_{\text{AggON}} = 9 * \text{Refresh Interval}$

$\text{HC}_{\text{first}} = \infty$
(all good)

$\text{HC}_{\text{first}} \text{ Scale}^*$

$\text{HC}_{\text{first}} = 1$
(DRAM is doomed)

row on time = 70.2 us
DDR4-new @ **51**
[Luo+, ISCA'23]

row on time = 35.1 us
HBM2-20nm @ **123**
[Olgun+, DSN'24]

*Not shown: Significant variance in HC_{first} across vendors and die variations

Key Characteristics of RowPress (II)

Amplifying Read Disturbance in DRAM

- Reduces the minimum number of row activations needed to induce a bitflip (AC_{min}) by **1-2 orders of magnitude**
- In extreme cases, activating a row **only once** induces bitflips
- Gets worse as **temperature increases**

Different From RowHammer

- Affects a **different set of cells** compared to RowHammer and retention failures
- **Behaves differently** as access pattern and temperature changes compared to RowHammer

Real-System Demonstration (I)



Intel Core i5-10400
(Comet Lake)



Samsung DDR4 Module
M378A2K43CB1-CTD
(Date Code: 20-10)

w/ TRR RowHammer Mitigation

Key Idea: A proof-of-concept RowPress program keeps a DRAM row open for a longer period by **keeping on accessing different cache blocks in the row**

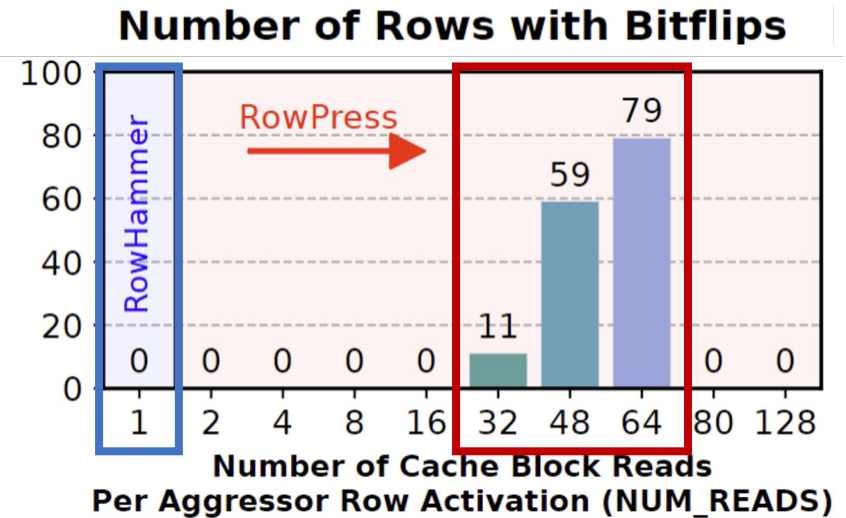
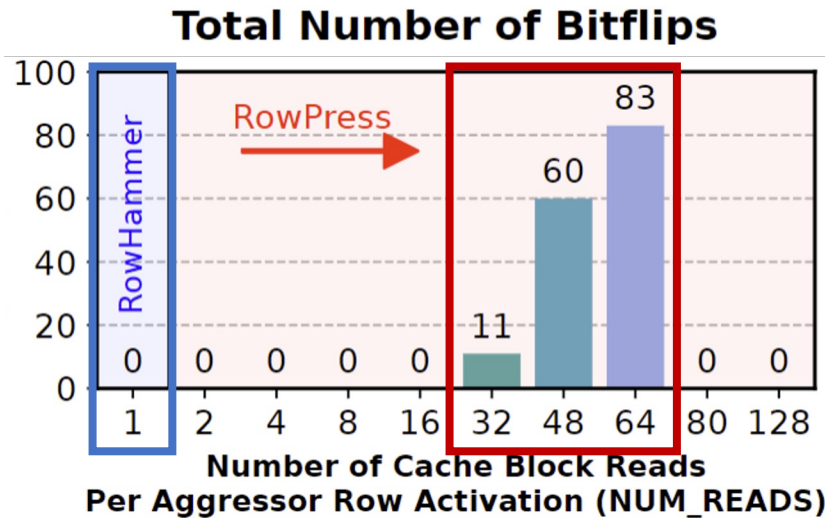
```
// Sync with Refresh and Loop Below
```

```
for (k = 0; k < NUM_AGGR_ACTS; k++)  
    for (j = 0; j < NUM_READS; j++) *AGGRESSOR1[j];  
    for (j = 0; j < NUM_READS; j++) *AGGRESSOR2[j];  
    for (j = 0; j < NUM_READS; j++)  
        clflushopt(AGGRESSOR1[j]);  
        clflushopt(AGGRESSOR2[j]);  
    mfence();  
    activate_dummy_rows();
```

**Number of Cache Blocks Accessed
Per Aggressor Row ACT
(NUM_READS=1 is Rowhammer)**

Real-System Demonstration (II)

On 1500 victim rows



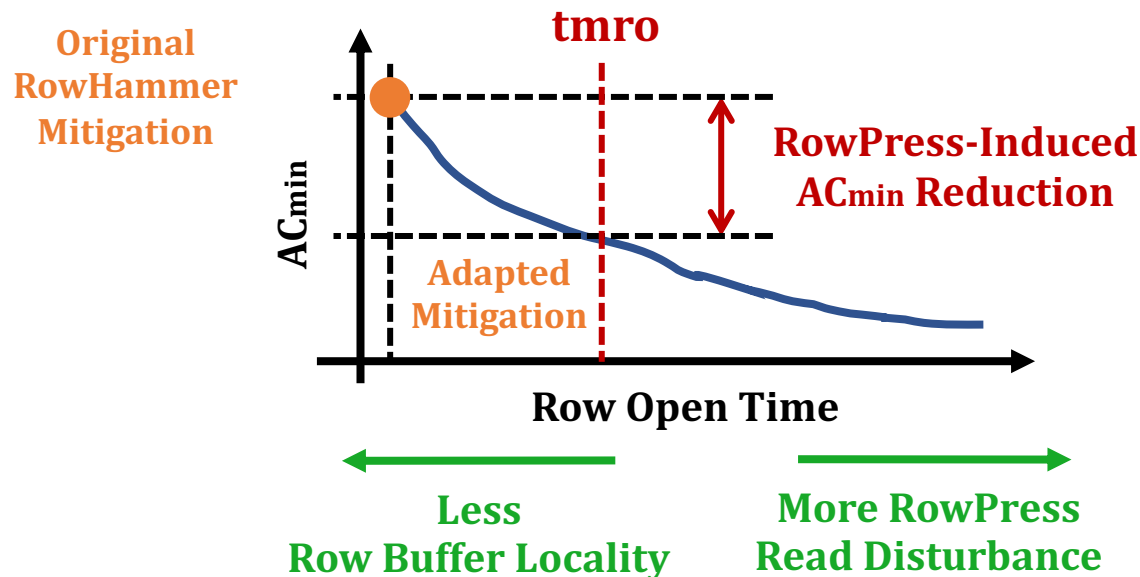
Leveraging RowPress, our user-level program induces bitflips when RowHammer cannot

Mitigating RowPress (I)

We propose a methodology to adapt existing RowHammer mitigations to **also mitigate RowPress**

Key Idea:

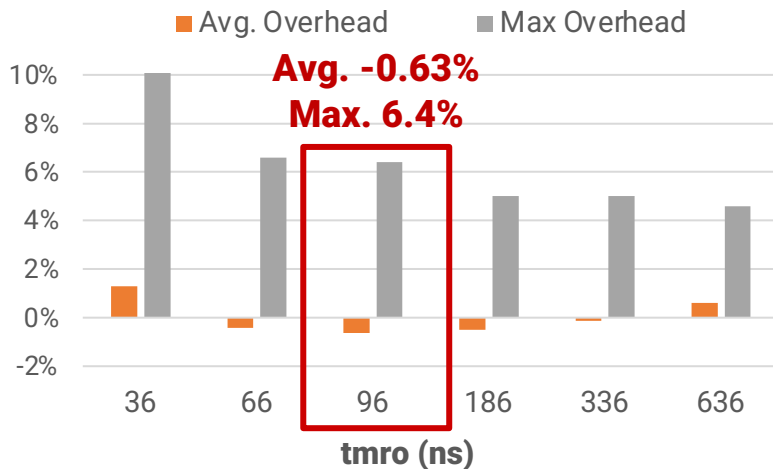
1. Limit the maximum row open time (**tmro**)
2. Configure the RowHammer mitigation to account for the **RowPress-induced reduction in ACmin**



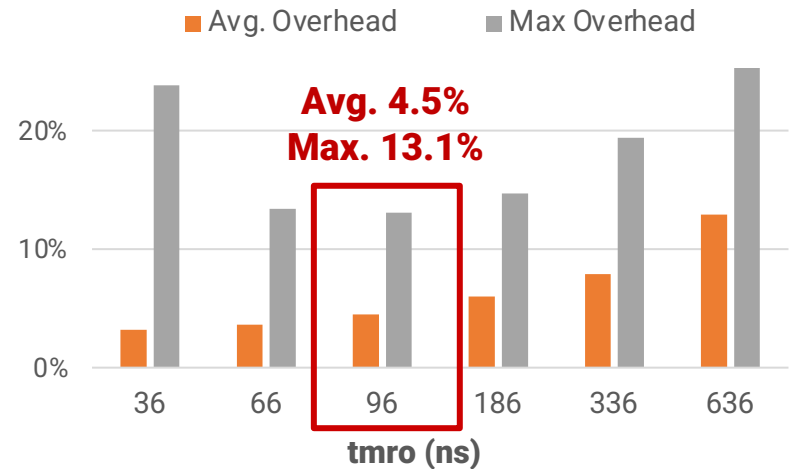
Mitigating RowPress (II)

Key evaluation results

Additional Performance Overhead of Graphene-RP



Additional Performance Overhead of PARA-RP



**Our solutions mitigate RowPress
at low additional performance overhead**

More Results & Source Code

Many more results & analyses in the paper

- 6 major takeaways
- 19 major empirical observations
- 3 more potential mitigations



Fully open source and artifact evaluated

- <https://github.com/CMU-SAFARI/RowPress>





- Haocong Luo, Ataberk Olgun, Giray Yaglikci, Yahya Can Tugrul, Steve Rhyner, M. Banu Cavlak, Joel Lindegger, Mohammad Sadrosadati, and Onur Mutlu, **"RowPress: Amplifying Read Disturbance in Modern DRAM Chips"**

Proceedings of the 50th International Symposium on Computer Architecture (ISCA), Orlando, FL, USA, June 2023.

[[Slides \(pptx\)](#) ([pdf](#))]

[[Lightning Talk Slides \(pptx\)](#) ([pdf](#))]

[[Lightning Talk Video](#) (3 minutes)]

[[RowPress Source Code and Datasets \(Officially Artifact Evaluated with All Badges\)](#)]

***Officially artifact evaluated as available, reusable and reproducible.
Best artifact award at ISCA 2023. IEEE Micro Top Pick in 2024.***

RowPress: Amplifying Read-Disturbance in Modern DRAM Chips

Haocong Luo Ataberk Olgun A. Giray Yağlıkçı Yahya Can Tuğrul Steve Rhyner
Meryem Banu Cavlak Joël Lindegger Mohammad Sadrosadati Onur Mutlu

ETH Zürich

More to Come...

Two Major Directions

- **Understanding Bitflips (Hardware errors in general)**
 - Many effects on bitflips still need to be rigorously examined
 - Aging of DRAM Chips
 - Environmental Conditions (e.g., Process, Voltage, Temperature)
 - Memory Access Patterns
 - Memory Controller & System Design Decisions
 - ...

- **Solving Bitflips (Hardware errors in general)**
 - Flexible and efficient solutions are necessary
 - In-field patchable / reconfigurable / programmable solutions
 - Co-architecting across the system stack/components is important
 - To avoid performance and denial-of-service problems

A RowHammer Survey: Recent Update

- Onur Mutlu, Ataberk Olgun, and A. Giray Yaglikci,
"Fundamentally Understanding and Solving RowHammer"
Invited Special Session Paper at the 28th Asia and South Pacific Design Automation Conference (ASP-DAC), Tokyo, Japan, January 2023.
[arXiv version]
[Slides (pptx) (pdf)]
[Talk Video (26 minutes)]

Fundamentally Understanding and Solving RowHammer

Onur Mutlu
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ETH Zürich
Zürich, Switzerland

<https://arxiv.org/pdf/2211.07613.pdf>

Combining RowHammer and RowPress

- **Appears at DSN Disrupt 2024**

An Experimental Characterization of Combined RowHammer and RowPress Read Disturbance in Modern DRAM Chips

Haocong Luo İsmail Emir Yüksel Ataberk Olgun A. Giray Yağlıkçı
Mohammad Sadrosadati Onur Mutlu
ETH Zürich

A Case for Transparent Reliability in DRAM Systems

Minesh Patel[†] Taha Shahroodi^{‡†} Aditya Manglik[†] A. Giray Yağlıkçı[†]
Ataberk Olgun[†] Haocong Luo[†] Onur Mutlu[†]

[†]*ETH Zürich* [‡]*TU Delft*

<https://arxiv.org/pdf/2204.10378.pdf>

Better Partitioning of DRAM & Controller

A Case for Self-Managing DRAM Chips: Improving Performance, Efficiency, Reliability, and Security via Autonomous in-DRAM Maintenance Operations

Hasan Hassan

Ataberk Olgun

A. Giray Yağlıkçı

Haocong Luo

Onur Mutlu

ETH Zürich

<https://arxiv.org/pdf/2207.13358.pdf>

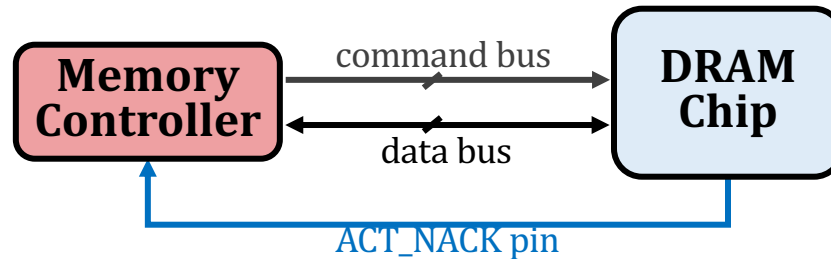
Self-Managing DRAM: Overview

Self-Managing DRAM (SMD)

enables autonomous in-DRAM maintenance operations

Key Idea:

Prevent the memory controller from accessing DRAM regions that are *under maintenance* by **rejecting** row activation (**ACT**) commands



Leveraging the ability to *reject an ACT*, a **maintenance operation** can be implemented **completely within a DRAM chip**

SMD-Based Maintenance Mechanisms

DRAM Refresh

Fixed Rate (SMD-FR)

uniformly refreshes **all** DRAM rows with a **fixed** refresh period

Variable Rate (SMD-VR)

skips refreshing rows that can **retain their data for longer** than the default refresh period

RowHammer Protection

Probabilistic (SMD-PRP)

Performs **neighbor** row refresh with a **small probability** on every row activation

Deterministic (SMD-DRP)

keeps track of most **frequently activated** rows and performs **neighbor** row refresh when activation count threshold is exceeded

Memory Scrubbing

Periodic Scrubbing (SMD-MS)

periodically **scans** the **entire** DRAM for errors and corrects them

Self-Managing DRAM: Summary

The three major DRAM maintenance operations:

- ❖ Refresh
- ❖ RowHammer Protection
- ❖ Memory Scrubbing

Implementing new **maintenance mechanisms** often requires **difficult-to-realize changes**

Our Goal

- ① Ease the process of enabling new DRAM maintenance operations
- ② Enable more efficient in-DRAM maintenance operations

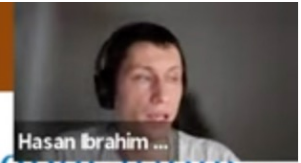
Self-Managing DRAM (SMD)

Enables implementing new **in-DRAM** maintenance mechanisms with **no further changes** in the *DRAM interface* and *memory controller*

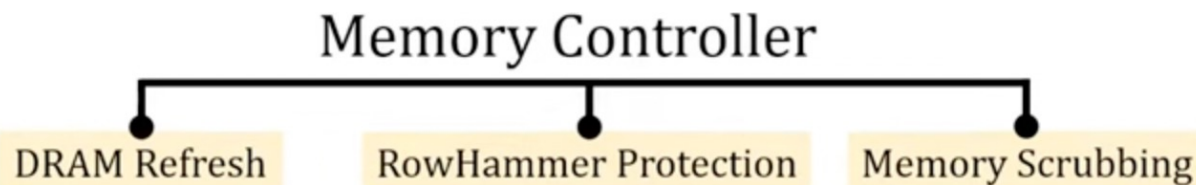
SMD-based *refresh*, *RowHammer protection*, and *scrubbing* achieve **9.2% speedup** and **6.2% lower DRAM energy** vs. conventional DRAM

Talk on Self-Managing DRAM

Problem: The Rigid DRAM Interface



The **Memory Controller** manages DRAM maintenance operations



Changes to maintenance operations are often reflected to the memory controller design, DRAM interface, and other system components



Implementing new maintenance operations
(or modifying the existing ones) is difficult-to-realize



SAFARI Live Seminars 2022

SAFARI Live Seminar - Improving DRAM Performance, Reliability, and Security by Understanding DRAM

1,039 views • Streamed live on Sep 15, 2022

37 DISLIKE SHARE DOWNLOAD CLIP SAVE ...



Onur Mutlu Lectures
27.6K subscribers

ANALYTICS

EDIT VIDEO

ABACuS: Another Intelligent Memory Controller

- Ataberk Olgun, Yahya Can Tugrul, Nisa Bostanci, Ismail Emir Yuksel, Haocong Luo, Steve Rhyner, Abdullah Giray Yaglikci, Geraldo F. Oliveira, and Onur Mutlu,

"ABACuS: All-Bank Activation Counters for Scalable and Low Overhead RowHammer Mitigation"

*To appear in Proceedings of the 33rd USENIX Security Symposium (**USENIX Security**), Philadelphia, PA, USA, August 2024.*

[arXiv version]

[ABACuS Source Code]

ABACuS: All-Bank Activation Counters for Scalable and Low Overhead RowHammer Mitigation

Ataberk Olgun Yahya Can Tugrul Nisa Bostanci Ismail Emir Yuksel
Haocong Luo Steve Rhyner Abdullah Giray Yaglikci Geraldo F. Oliveira Onur Mutlu

ETH Zurich

CoMeT: Another Intelligent Memory Controller

- **Appears at HPCA 2024**

CoMeT: Count-Min-Sketch-based Row Tracking to Mitigate RowHammer at Low Cost

F. Nisa Bostancı İsmail Emir Yüksel Ataberk Olgun Konstantinos Kanellopoulos
Yahya Can Tuğrul A. Giray Yağlıkçı Mohammad Sadrosadati Onur Mutlu
ETH Zürich

<https://arxiv.org/pdf/2402.18769>

<https://github.com/CMU-SAFARI/CoMeT>

SVaRD: Another Intelligent Memory Controller

- **Appears at HPCA 2024**

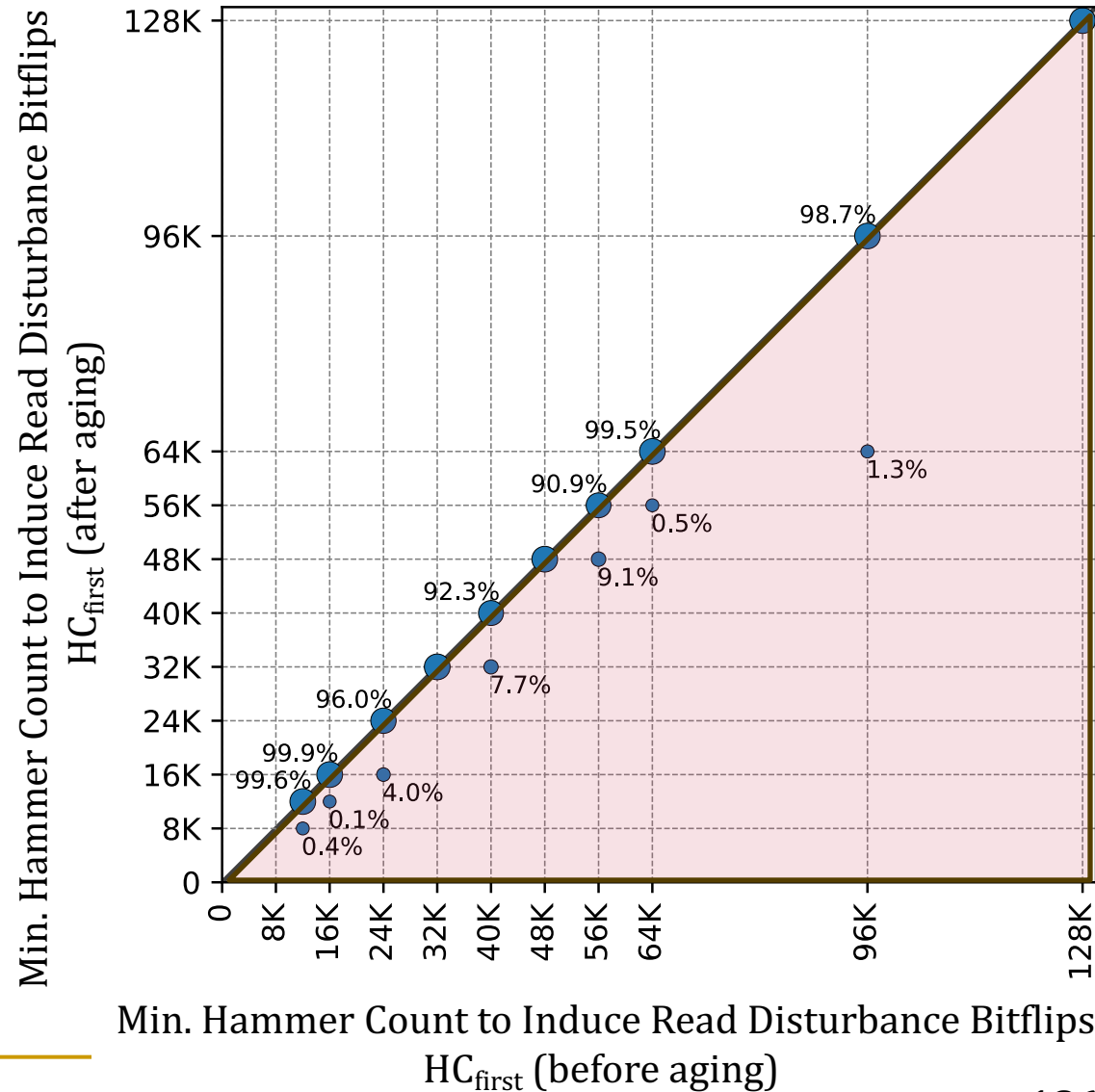
Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Abdullah Giray Yağlıkçı Yahya Can Tuğrul Geraldo F. Oliveira
İsmail Emir Yüksel Ataberk Olgun Haocong Luo Onur Mutlu
ETH Zürich

<https://arxiv.org/pdf/2402.18652>

Effect of Aging on RowHammer BitFlips

Aging can lead to RowHammer bitflips at **smaller** hammer counts



RowHammer Defenses Can Cause Denial of Service

Leveraging Adversarial Detection to Enable Scalable and Low Overhead RowHammer Mitigations

Oğuzhan Canpolat^{§†} A. Giray Yağlıkçı[§] Ataberk Olgun[§] İsmail Emir Yüksel[§] Yahya Can Tuğrul^{§†}
Konstantinos Kanellopoulos[§] Oğuz Ergin[†] Onur Mutlu[§]
[§]*ETH Zürich* [†]*TOBB University of Economics and Technology* ^{*}*SAFARI Research Group*

<https://arxiv.org/pdf/2404.13477>

BreakHammer

- **Key Observation:** Mitigating DRAM read disturbance causes delays in memory accesses
- **Our Exploit:** Denial of memory service is possible via triggering mitigation mechanisms
- **Key Idea:** Throttling memory accesses of threads that trigger mitigation mechanisms repeatedly
- **BreakHammer:**
 - Detects the threads that repeatedly trigger the mitigation mechanisms
 - Limits their on-the-fly memory request counts and MSHRs
 - Near-zero area overhead and no additional memory access latency
- **Evaluation:**
 - Improves **system performance** by **48.7%** on average (**105.5%** max)
 - Reduces the **maximum slowdown** by **14.6%** on average

Industry's Recent Solutions Are Vulnerable

- **Appears at DRAMSec 2024**

Understanding the Security Benefits and Overheads of Emerging Industry Solutions to DRAM Read Disturbance

Oğuzhan Canpolat^{§†}

A. Giray Yağlıkçı[§]

Geraldo F. Oliveira[§]

Ataberk Olgun[§]

Oğuz Ergin[†]

Onur Mutlu[§]

[§]*ETH Zürich*

[†]*TOBB University of Economics and Technology*

<https://arxiv.org/pdf/2406.19094>

<https://github.com/CMU-SAFARI/ramulator2>

Some RowHammer Works in 2024 (I)



Session 5B: Rowhammer

Location: Sidlaw

Session Chair: TBD

10:00 AM – 10:20 AM

Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Abdullah Giray Yaglikci, Geraldo Francisco de Oliveira Junior,
Yahya Can Tugrul, Ismail Yuksel, Ataberk Olgun, Haocong Luo,
Onur Mutlu

10:20 AM – 10:40 AM

START: Scalable Tracking for Any Rowhammer Threshold

Anish Saxena, Moinuddin Qureshi

10:40 AM – 11:00 AM

CoMeT: Count-Min Sketch-based Row Tracking to Mitigate RowHammer with Low Cost

Nisa Bostanci, Ismail Emir Yuksel, Ataberk Olgun, Konstantinos
Kanellopoulos, Yahya Can Tuğrul, Giray Yaglikci, Mohammad
Sadrosadati, Onur Mutlu



ABACuS: All-Bank Activation Counters for Scalable and Low Overhead RowHammer Mitigation
Ataberk Olgun, Yahya Can Tugrul, Nisa Bostanci, Ismail Emir Yuksel, Haocong Luo, Steve Rhyner, A
Zurich

Go Go Gadget Hammer: Flipping Nested Pointers for Arbitrary Data Leakage
Youssef Tobah, *University of Michigan*; Andrew Kwong, *UNC Chapel Hill*; Ingab Kang
Michigan

SledgeHammer: Amplifying Rowhammer via Bank-level Parallelism
Ingab Kang, *University of Michigan*; Walter Wang and Jason Kim, *Georgia Tech*; Step
Tech; Andrew Kwong, *UNC Chapel Hill*; Yuval Yarom, *Ruhr University Bochum*

ZenHammer: Rowhammer Attacks on AMD Zen-based Platforms
Patrick Jattke, Max Wipfli, Flavien Solt, Michele Marazzi, Matej Bölskei,



**PrIDE: Achieving Secure Rowhammer
Mitigation with Low-Cost In-DRAM
Trackers**

Track 2

[Show details ▶](#)

Side Channel II:
RowHammer



Rubix: Reducing the Overhead of Secure Rowhammer Mitigations via Randomized Line-to-Row Mapping

TAROT: A CXL SmartNIC-Based Defense Against Multi-bit Errors by Row-Hammer Attacks

**Read Disturbance in High Bandwidth Memory: A
by Ataberk Olgun, Majd Osseiran, Giray Yaglikci,
Salami, Juan Gómez Luna, Onur Mutlu**

**An Experimental Analysis of Combined RowHammer and RowPress
Chips by Haocong Luo, İsmail Emir Yüksel, Ataberk Olgun, Giray Yaglikci,
Mutlu**



Some RowHammer Works in 2024 (II)

Fourth Workshop on DRAM Security (DRAMSec) June 29, 2024, co-located with ISCA 2024

RISC-H: Rowhammer Attacks on RISC-V

Michele Marazzi, Kaveh Razavi

Paper

GbHammer: Malicious Inter-process Page Sharing by Hammering Global Bits in Page Table Entries

Keigo Yoshioka, Soramichi Akiyama

Paper

Understanding the Security Benefits and Overheads of Emerging Industry Solutions to DRAM Read Disturbance

Oğuzhan Canpolat, Giray Yaglikci, Geraldo Francisco de Oliveira Junior, Ataberk Olgun, Oguz Ergin, Onur Mutlu

SoothSayer: Bypassing DSAC Mitigation by Predicting Counter Replacement

Salman Qazi, Daniel Moghimi

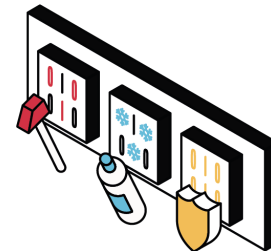
Paper

Six Years of Rowhammer: Breakthroughs and Future Directions

Stefan Saroiu

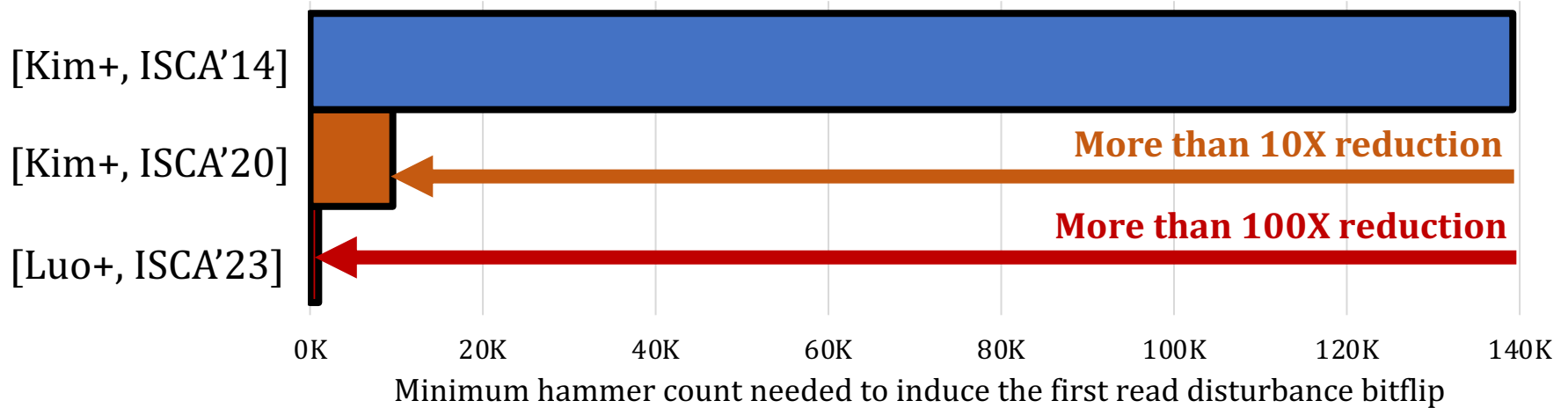
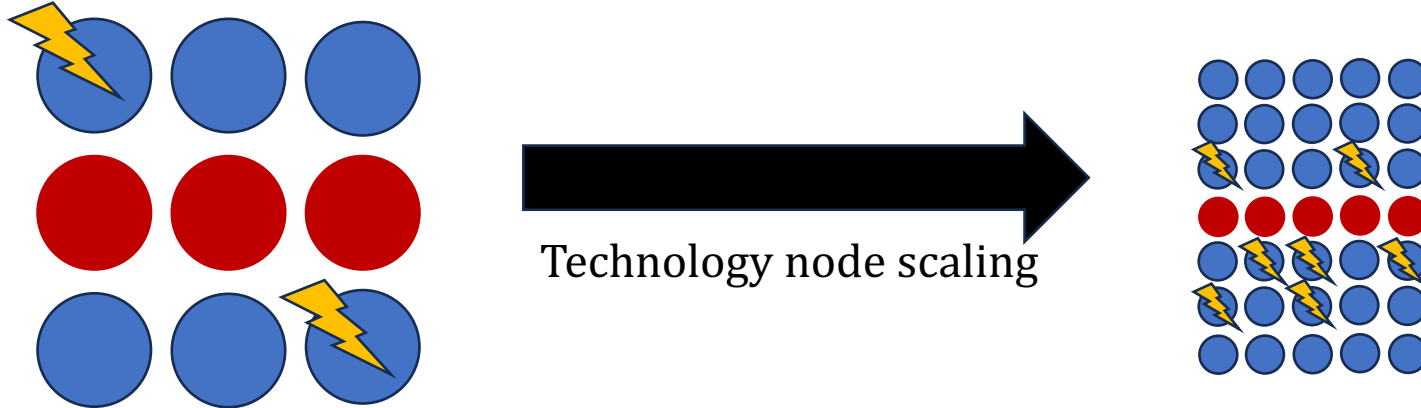
Microsoft Research

This talk will present the work done over the past six years as part of Project STEMA at Microsoft. STEMA stands for Secure, Trusted, and Enhanced Memory for Azure. We will discuss our journey in understanding Rowhammer, developing a testing methodology for cloud providers, and finding effective solutions for the DRAM industry to address Rowhammer once and for all. We will also highlight significant related work that has helped keep the DRAM industry honest. We will explain why Rowhammer remains a significant attack vector, particularly in the context of nation-state attacks, and how this has driven us to develop a suite of pragmatic solutions. Finally, we will argue that Rowhammer is far from being a solved problem and outline several important research challenges that remain in this space.



Future Memory Robustness Challenges

Technology Scaling Worsens Vulnerability



DRAM cells become **increasingly more vulnerable (to read disturbance)**

Future of Main Memory Robustness

- DRAM is becoming less reliable → more vulnerable
- Due to difficulties in DRAM scaling, other problems may also appear (or they may be going unnoticed)
- Some errors may already be slipping into the field
 - Read disturb errors (Rowhammer)
 - Retention errors
 - Read errors, write errors
 - ...
- These errors can also pose security vulnerabilities

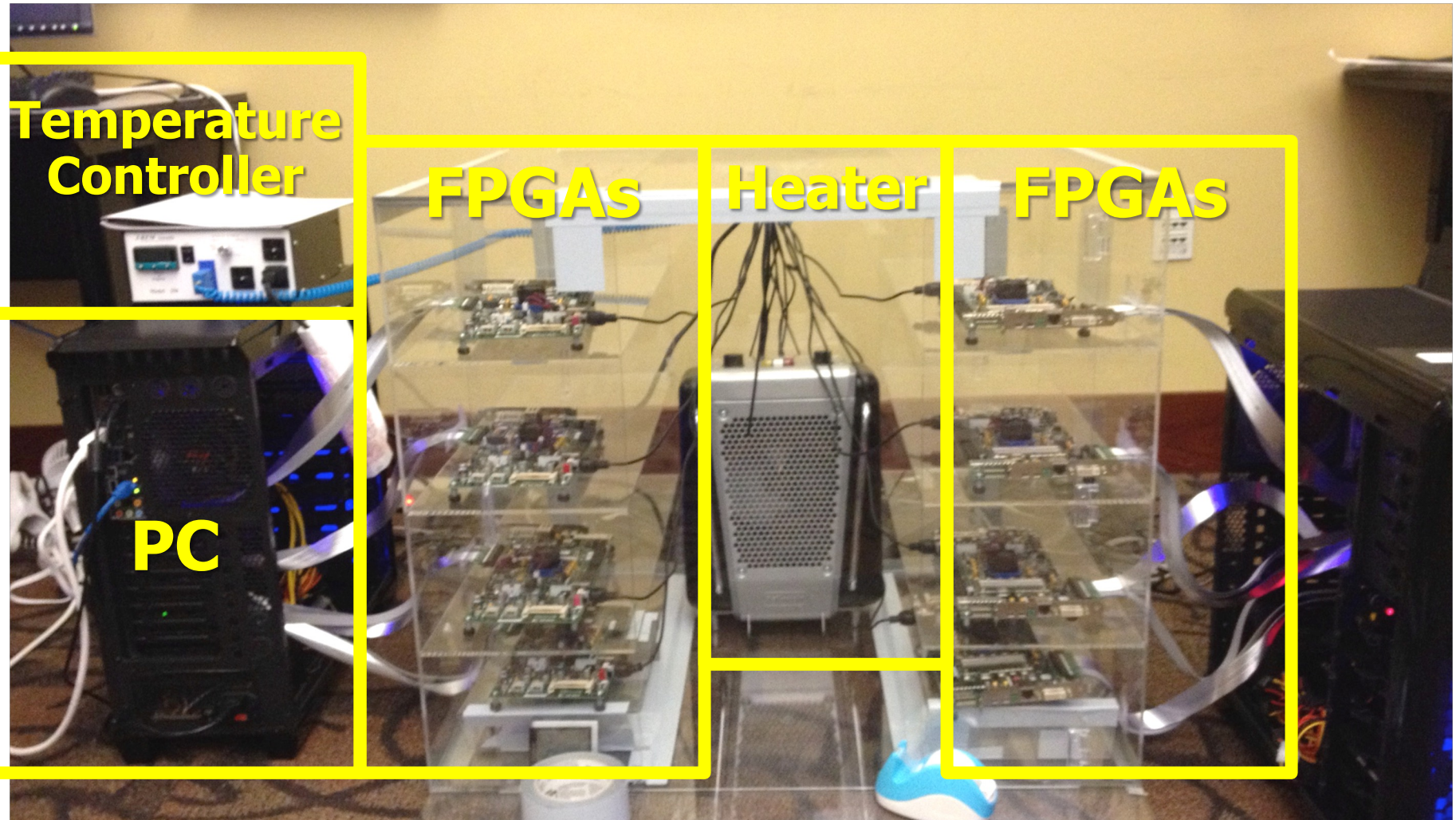
Future of Main Memory Robustness

- DRAM
- Flash memory
- Emerging Technologies
 - Phase Change Memory
 - STT-MRAM
 - RRAM, memristors
 - ...

Architecting Robust Memory Systems

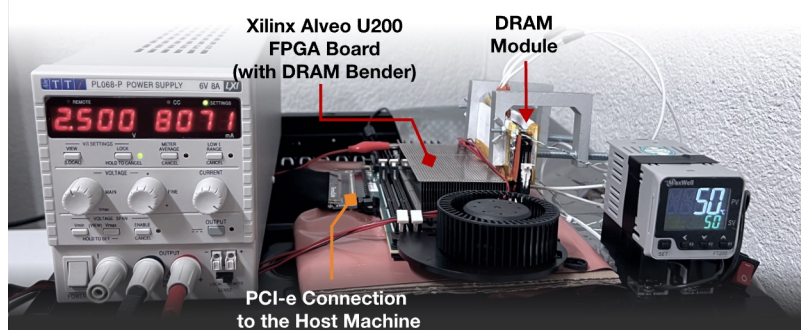
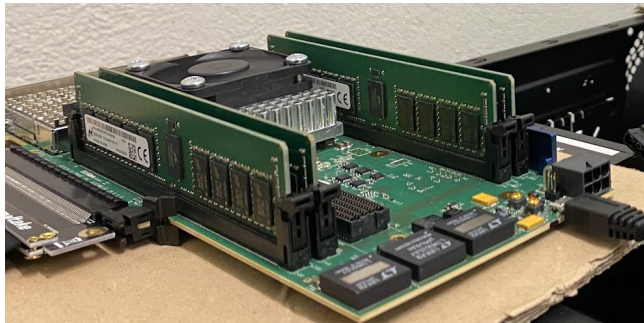
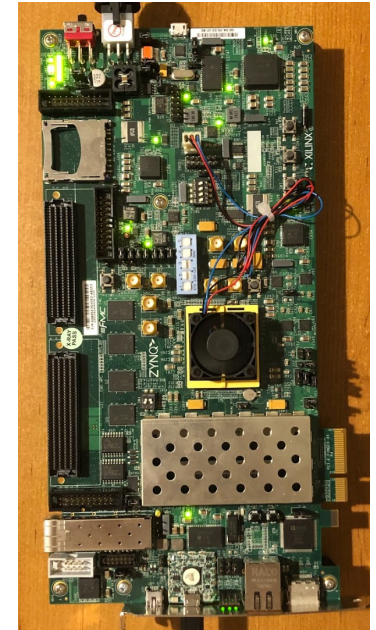
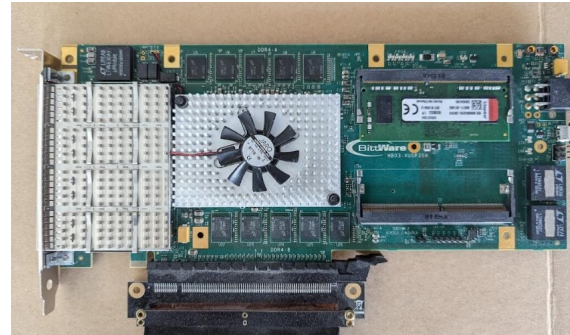
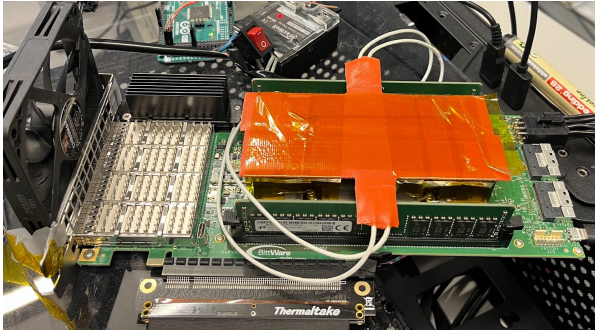
- **Understand:** Methods for vulnerability modeling & discovery
 - Modeling and prediction based on real (device) data and analysis
- **Architect:** Principled architectures with security as key concern
 - Good partitioning of duties across the stack
 - Cannot give up performance and efficiency
 - Patch-ability in the field
- **Design & Test:** Principled design, automation, (online) testing
 - Design for security/safety/reliability
 - High coverage and good interaction with system reliability methods

Understand and Model with Experiments (DRAM)



Understand and Model with Experiments (DRAM)

Five out of the box FPGA-based prototypes



Understand and Model with Experiments (Flash)



[DATE 2012, ICCD 2012, DATE 2013, ITJ 2013, ICCD 2013, SIGMETRICS 2014, HPCA 2015, DSN 2015, MSST 2015, JSAC 2016, HPCA 2017, DFRWS 2017, PIEEE 2017, HPCA 2018, SIGMETRICS 2018]

Cai+, "Error Characterization, Mitigation, and Recovery in Flash Memory Based Solid State Drives," Proc. IEEE 2017.

Collapse of the “Galloping Gertie” (1940)



Another Example (1994)



Yet Another Example (2007)



Source: Morry Gash/AP,
<https://www.npr.org/2017/08/01/540669701/10-years-after-bridge-collapse-america-is-still-crumbing?t=1535427165809>

A More Recent Example (2018)



A Most Recent Example (2022)



A Most Recent Example (2022)



A Most Recent Example (2022)



A Most Recent Example (2022)



Intelligent Memory Controllers

Can Avoid Such Failures

Main Memory Needs
Intelligent Controllers
for Security, Safety,
Reliability, Scaling

Fundamentally Robust (Reliable, Secure, Safe) Computing Architectures

Final Thoughts on RowHammer

Aside: Byzantine Failures

- This class of failures is known as **Byzantine failures**
- Characterized by
 - **Undetected erroneous computation**
 - Opposite of “fail fast (with an error or no result)”
- “erroneous” can be “malicious” (intent is the only distinction)
- Very difficult to detect and confine Byzantine failures
- **Do all you can to avoid them**
- Lamport et al., “The Byzantine Generals Problem,” ACM TOPLAS 1982.

Aside: Byzantine Generals Problem

The Byzantine Generals Problem

LESLIE LAMPORT, ROBERT SHOSTAK, and MARSHALL PEASE
SRI International

Reliable computer systems must handle malfunctioning components that give conflicting information to different parts of the system. This situation can be expressed abstractly in terms of a group of generals of the Byzantine army camped with their troops around an enemy city. Communicating only by messenger, the generals must agree upon a common battle plan. However, one or more of them may be traitors who will try to confuse the others. The problem is to find an algorithm to ensure that the loyal generals will reach agreement. It is shown that, using only oral messages, this problem is solvable if and only if more than two-thirds of the generals are loyal; so a single traitor can confound two loyal generals. With unforgeable written messages, the problem is solvable for any number of generals and possible traitors. Applications of the solutions to reliable computer systems are then discussed.

Categories and Subject Descriptors: C.2.4. [**Computer-Communication Networks**]: Distributed Systems—*network operating systems*; D.4.4 [**Operating Systems**]: Communications Management—*network communication*; D.4.5 [**Operating Systems**]: Reliability—*fault tolerance*

General Terms: Algorithms, Reliability

Additional Key Words and Phrases: Interactive consistency

ACM TOPLAS 1982

Before RowHammer (I)

Using Memory Errors to Attack a Virtual Machine

Sudhakar Govindavajhala * Andrew W. Appel
Princeton University
{sudhakar,appel}@cs.princeton.edu

We present an experimental study showing that soft memory errors can lead to serious security vulnerabilities in Java and .NET virtual machines, or in any system that relies on type-checking of untrusted programs as a protection mechanism. Our attack works by sending to the JVM a Java program that is designed so that almost any memory error in its address space will allow it to take control of the JVM. All conventional Java and .NET virtual machines are vulnerable to this attack. The technique of the attack is broadly applicable against other language-based security schemes such as proof-carrying code.

We measured the attack on two commercial Java Virtual Machines: Sun's and IBM's. We show that a single-bit error in the Java program's data space can be exploited to execute arbitrary code with a probability of about 70%, and multiple-bit errors with a lower probability.

Our attack is particularly relevant against smart cards or tamper-resistant computers, where the user has physical access (to the outside of the computer) and can use various means to induce faults; we have successfully used heat. Fortunately, there are some straightforward defenses against this attack.

7 Physical fault injection

If the attacker has physical access to the outside of the machine, as in the case of a smart card or other tamper-resistant computer, the attacker can induce memory errors. We considered attacks on boxes in form factors ranging from a credit card to a palmtop to a desktop PC.

We considered several ways in which the attacker could induce errors.⁴

IEEE S&P 2003

Before RowHammer (II)

Using Memory Errors to Attack a Virtual Machine

Sudhakar Govindavajhala *

Andrew W. Appel

Princeton University

{sudhakar,appel}@cs.princeton.edu

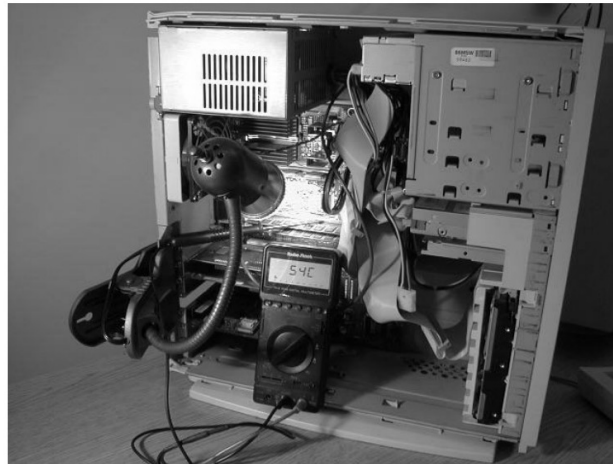


Figure 3. Experimental setup to induce memory errors, showing a PC built from surplus components, clip-on gooseneck lamp, 50-watt spotlight bulb, and digital thermometer. Not shown is the variable AC power supply for the lamp.

IEEE S&P 2003

After RowHammer

A simple, exploitable memory error
can be induced by software

WIRED

Forget Software—Now Hackers Are Exploiting Physics

BUSINESS	CULTURE	DESIGN	GEAR	SCIENCE
----------	---------	--------	------	---------

ANDY GREENBERG SECURITY 08.31.16 7:00 AM

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18276



TWEET

FORGET SOFTWARE—NOW HACKERS ARE EXPLOITING PHYSICS

After RowHammer

A simple, exploitable memory error
can be induced by software



BIZ & IT TECH SCIENCE POLICY CARS GAMING & CULTURE ST

SON OF ROWHAMMER —

There's a new way to flip bits in DRAM, and it works against the latest defenses

New technique produces lots of bitflips and could one day help form an attack.

DAN GOODIN - 10/19/2023, 5:30 AM



RowHammer: Retrospective

- New mindset that has enabled a renewed interest in HW security attack research:
 - ❑ Real (memory) chips are vulnerable, in a simple and widespread manner
→ this causes real security problems
 - ❑ Hardware reliability → security connection is now mainstream discourse
- Many new RowHammer & bitflip attacks...
 - ❑ Tens of papers in top security, architecture, systems venues
 - ❑ **More to come** as RowHammer is getting worse (DDR4 & beyond)
- Many new RowHammer solutions...
 - ❑ Apple security release; Memtest86 updated
 - ❑ Many solution proposals in top venues (latest in HPCA/Usenix Sec 2024)
 - ❑ Principled system-DRAM co-design (in original RowHammer paper)
 - ❑ **More to come...**

Perhaps Most Importantly...

- RowHammer enabled a shift of mindset in mainstream security researchers
 - General-purpose hardware is fallible, in a widespread manner
 - Its problems are exploitable
- This mindset has enabled many systems security researchers to examine hardware in more depth
 - And understand HW's inner workings and vulnerabilities
- It is no coincidence that two of the groups that discovered Meltdown and Spectre heavily worked on RowHammer attacks before
 - **More to come...**

Conclusion

Summary: RowHammer

- Memory reliability is reducing
- Reliability issues open up security and safety vulnerabilities
 - Very hard to defend against
- **Rowhammer is a prime example**
 - First example of how a simple hardware failure mechanism can create a widespread system security vulnerability
 - Implications on system security & safety are tremendous & exciting
- Bad news: RowHammer is getting worse
- **Good news: We have a lot more to do**
 - We are now fully aware hardware is easily fallible
 - We are developing both attacks and defenses
 - We are developing principled models, methodologies, solutions

Data Corruption in Logic

Data Corruption is in Logic, Too

- Intermittent defects can cause silent data corruption
- They may be hard to detect or replicate
- They may be exploitable

Silent Data Corruption in Logic (2021)

Silent Data Corruptions at Scale

Harish Dattatraya
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Cores that don't count

Peter H. Hochschild
Paul Turner
Jeffrey C. Mogul
Google
Sunnyvale, CA, US

Rama Govindaraju
Parthasarathy
Ranganathan
Google
Sunnyvale, CA, US

David E. Culler
Amin Vahdat
Google
Sunnyvale, CA, US

Silent Data Corruption In-the-Field (2021)

We have a *new* problem: cores that disobey instructions

CPU cores that

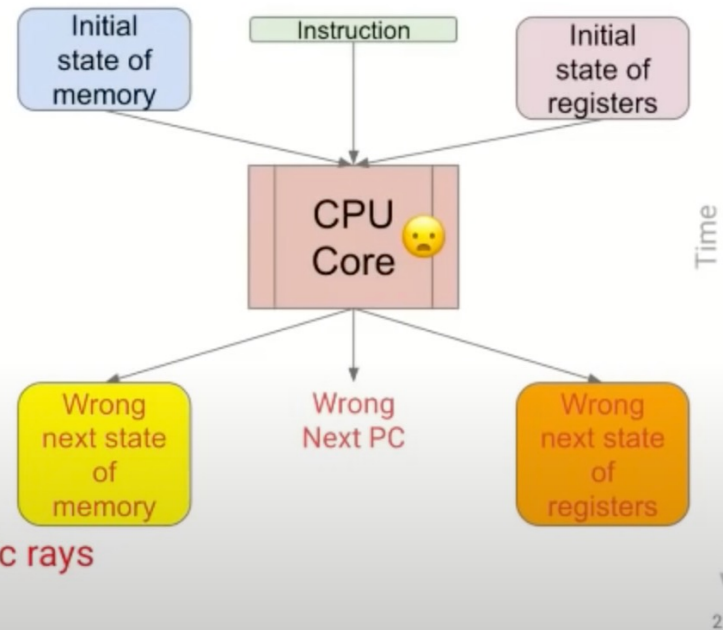
- repeatedly
- but not always
- mis-calculate
- certain computations
- without giving any obvious signal

"Mercurial cores" committing

"Corrupt Execution Errors"

Due to local silicon defects, not eg cosmic rays

Google



0:19 / 9:14

• We have a new problem: cores that disobey instructions >

HotOS 2021: Cores That Don't Count (Fun Hardware)

<https://www.youtube.com/watch?v=QMF3rqhjYuM>

Silent Data Corruption in Logic (2023)

Understanding Silent Data Corruptions in a Large Production CPU Population

Shaobu Wang
Tsinghua University

Guangyan Zhang*
Tsinghua University

Junyu Wei
Tsinghua University

Yang Wang
The Ohio State University

Jiesheng Wu
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Understanding and Mitigating Hardware Failures in Deep Learning Training Accelerator Systems

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Takeaways

- Both memory and logic errors will become worse with technology scaling
- Hardware errors will create worse robustness problems
- **We cannot afford to ignore data corruption**

Acknowledgments

Acknowledgments

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- <https://safari.ethz.ch/safari-newsletter-december-2021/>

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SAFARI Newsletter June 2023 Edition

- <https://safari.ethz.ch/safari-newsletter-june-2023/>

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- <https://safari.ethz.ch/safari-newsletter-july-2024/>



SAFARI Introduction & Research

Computer architecture, HW/SW, systems, bioinformatics, security, memory



Seminar in Computer Architecture - Lecture 5: Potpourri of Research Topics (Spring 2023)



Onur Mutlu Lectures
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<https://www.youtube.com/watch?v=mV2OuB2djEs>

Funding Acknowledgments

- Alibaba, AMD, ASML, Google, Facebook, Hi-Silicon, HP Labs, Huawei, IBM, Intel, Microsoft, Nvidia, Oracle, Qualcomm, Rambus, Samsung, Seagate, VMware, Xilinx
- NSF
- NIH
- GSRC
- SRC
- CyLab
- EFCL
- SNSF
- ACCESS

Thank you!

Referenced Papers, Talks, Artifacts

- All are available at

<https://people.inf.ethz.ch/omutlu/projects.htm>

<https://www.youtube.com/onurmutlulectures>

<https://github.com/CMU-SAFARI/>

Open Source Tools: SAFARI GitHub



SAFARI Research Group at ETH Zurich and Carnegie Mellon University

Site for source code and tools distribution from SAFARI Research Group at ETH Zurich and Carnegie Mellon University.

👤 440 followers 📍 ETH Zurich and Carnegie Mellon U... 🔗 <https://safari.ethz.ch/> ✉ omutlu@gmail.com

🏠 Overview 📁 Repositories 98 📁 Projects 📦 Packages 👤 People 13

📁 ramulator Public

A Fast and Extensible DRAM Simulator, with built-in support for modeling many different DRAM technologies including DDRx, LPDDRx, GDDRx, WIOx, HBMx, and various academic proposals. Described in the...

● C++ ☆ 519 🍴 206

📁 prim-benchmarks Public

PrIM (Processing-In-Memory benchmarks) is the first benchmark suite for a real-world processing-in-memory (PIM) architecture. PrIM is developed to evaluate, analyze, and characterize the first publ...

● C ☆ 125 🍴 45

📁 MQSim Public

MQSim is a fast and accurate simulator modeling the performance of modern multi-queue (MQ) SSDs as well as traditional SATA based SSDs. MQSim faithfully models new high-bandwidth protocol implement...

● C++ ☆ 265 🍴 144

📁 rowhammer Public

Source code for testing the Row Hammer error mechanism in DRAM devices. Described in the ISCA 2014 paper by Kim et al. at http://users.ece.cmu.edu/~omutlu/pub/dram-row-hammer_isca14.pdf.

● C ☆ 210 🍴 43

📁 SoftMC Public

SoftMC is an experimental FPGA-based memory controller design that can be used to develop tests for DDR3 SODIMMs using a C++ based API. The design, the interface, and its capabilities and limitatio...

● Verilog ☆ 120 🍴 27

📁 Pythia Public

A customizable hardware prefetching framework using online reinforcement learning as described in the MICRO 2021 paper by Bera et al. (<https://arxiv.org/pdf/2109.12021.pdf>).

● C++ ☆ 107 🍴 34

<https://github.com/CMU-SAFARI/>

Ramulator 2.0

- Haocong Luo, Yahya Can Tugrul, F. Nisa Bostanci, Ataberk Olgun, A. Giray Yaglikci, and Onur Mutlu,
"Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator"
*Preprint on **arxiv**, August 2023.*
[[arXiv version](#)]
[[Ramulator 2.0 Source Code](#)]

Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator

Haocong Luo, Yahya Can Tuğrul, F. Nisa Bostancı, Ataberk Olgun, A. Giray Yağlıkçı, and Onur Mutlu

<https://arxiv.org/pdf/2308.11030.pdf>

DRAM Bender

- Ataberk Olgun, Hasan Hassan, A Giray Yağlıkçı, Yahya Can Tuğrul, Lois Orosa, Haocong Luo, Minesh Patel, Oğuz Ergin, and Onur Mutlu,
"DRAM Bender: An Extensible and Versatile FPGA-based Infrastructure to Easily Test State-of-the-art DRAM Chips"
IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (TCAD), 2023.
[[Extended arXiv version](#)]
[[DRAM Bender Source Code](#)]
[[DRAM Bender Tutorial Video](#) (43 minutes)]

DRAM Bender: An Extensible and Versatile FPGA-based Infrastructure to Easily Test State-of-the-art DRAM Chips

Ataberk Olgun[§] Hasan Hassan[§] A. Giray Yağlıkçı[§] Yahya Can Tuğrul^{§†}
Lois Orosa^{§⊙} Haocong Luo[§] Minesh Patel[§] Oğuz Ergin[†] Onur Mutlu[§]
 [§]*ETH Zürich* [†]*TOBB ETÜ* [⊙]*Galician Supercomputing Center*

RowHammer & DRAM Exploration (Fall 2022)

Fall 2022 Edition:

- ❑ https://safari.ethz.ch/projects_and_seminars/fall2022/doku.php?id=softmc

Spring 2022 Edition:

- ❑ https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=softmc

Youtube Livestream (Spring 2022):

- ❑ https://www.youtube.com/watch?v=r5QxuoJWttg&list=PL5Q2soXY2Zi_1trfCckr6PTN8WR72icUO

Bachelor's course

- ❑ Elective at ETH Zurich
- ❑ Introduction to DRAM organization & operation
- ❑ Tutorial on using FPGA-based infrastructure
- ❑ Verilog & C++
- ❑ Potential research exploration

<https://www.youtube.com/onurmutlulectures>

Lecture Video Playlist on YouTube

Lecture Playlist



2022 Meetings/Schedule (Tentative)

Week	Date	Livestream	Meeting	Learning Materials	Assignments
W0	23.02 Wed.		P&S SoftMC Tutorial	SoftMC Tutorial Slides (PDF) (PPT)	
W1	08.03 Tue.		M1: Logistics & Intro to DRAM and SoftMC (PDF) (PPT)	Required Materials Recommended Materials	HW0
W2	15.03 Tue.		M2: Revisiting RowHammer (PDF) (PPT)	(Paper PDF)	
W3	22.03 Tue.		M3: Uncovering in-DRAM TRR & TRRespass (PDF) (PPT)		
W4	29.03 Tue.		M4: Deeper Look Into RowHammer's Sensitivities (PDF) (PPT)		
W5	05.04 Tue.		M5: QUAC-TRNG (PDF) (PPT)		
W6	12.04 Tue.		M6: PiDRAM (PDF) (PPT)		

Exploration of Emerging Memory Systems (Fall 2022)

Fall 2022 Edition:

- ❑ https://safari.ethz.ch/projects_and_seminars/fall2022/doku.php?id=ramulator

Spring 2022 Edition:

- ❑ https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=ramulator

Youtube Livestream (Spring 2022):

- ❑ https://www.youtube.com/watch?v=aM-lIXRQd3s&list=PL5Q2soXY2Zi_TlmlGw_Z8hBo2925ZAqV

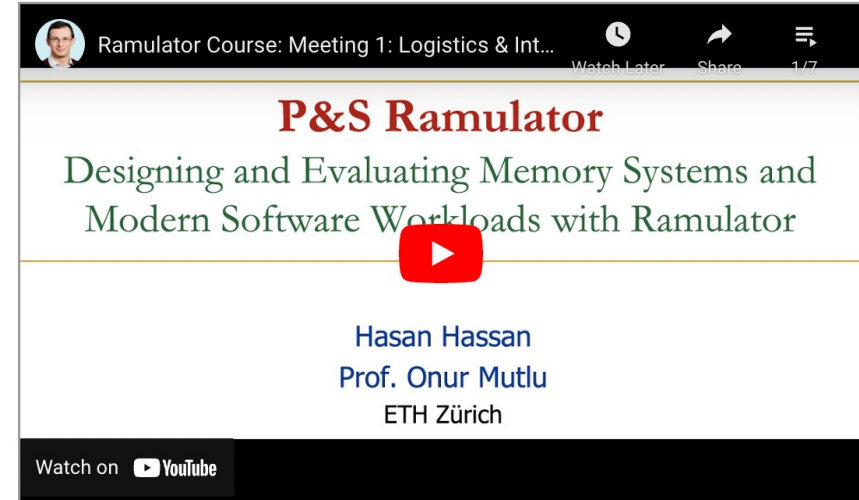
Bachelor's course

- ❑ Elective at ETH Zurich
- ❑ Introduction to memory system simulation
- ❑ Tutorial on using Ramulator
- ❑ C++
- ❑ Potential research exploration

<https://www.youtube.com/onurmutlulectures>

Lecture Video Playlist on YouTube

Lecture Playlist



2022 Meetings/Schedule (Tentative)

Week	Date	Livestream	Meeting	Learning Materials	Assignments
W1	09.03 Wed.	YouTube Video	M1: Logistics & Intro to Simulating Memory Systems Using Ramulator PDF (PDF) PPT (PPT)		HW0
W2	16.03 Fri.	YouTube Video	M2: Tutorial on Using Ramulator PDF (PDF) PPT (PPT)		
W3	25.02 Fri.	YouTube Video	M3: BlockHammer PDF (PDF) PPT (PPT)		
W4	01.04 Fri.	YouTube Video	M4: CLR-DRAM PDF (PDF) PPT (PPT)		
W5	08.04 Fri.	YouTube Video	M5: SIMDRAM PDF (PDF) PPT (PPT)		
W6	29.04 Fri.	YouTube Video	M6: DAMOV PDF (PDF) PPT (PPT)		
W7	06.05 Fri.	YouTube Video	M7: Synchron PDF (PDF) PPT (PPT)		



Memory Systems and Memory-Centric Computing

Lecture 4.2: Memory Robustness

Onur Mutlu

omutlu@gmail.com

<https://people.inf.ethz.ch/omutlu>

18 July 2024

HiPEAC ACACES Summer School 2024

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More RowHammer in 2020-2024

RowHammer in 2020 (I)

MICRO 2020

Submit Work ▾

Program ▾

Attend

Session 1A: Security & Privacy I

5:00 PM CEST – 5:15 PM CEST

Graphene: Strong yet Lightweight Row Hammer Protection

Yeonhong Park, Woosuk Kwon, Eojin Lee, Tae Jun Ham, Jung Ho Ahn, Jae W. Lee (Seoul National University)

5:15 PM CEST – 5:30 PM CEST

Persist Level Parallelism: Streamlining Integrity Tree Updates for Secure Persistent Memory

Alexander Freij, Shougang Yuan, Huiyang Zhou (NC State University); Yan Solihin (University of Central Florida)

5:30 PM CEST – 5:45 PM CEST

PThammer: Cross-User-Kernel-Boundary Rowhammer through Implicit Accesses

Zhi Zhang (University of New South Wales and Data61, CSIRO, Australia); Yueqiang Cheng (Baidu Security); Dongxi Liu, Surya Nepal (Data61, CSIRO, Australia); Zhi Wang (Florida State University); Yuval Yarom (University of Adelaide and Data61, CSIRO, Australia)

RowHammer in 2020 (II)

S & P

Home

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Workshops ▼

Session #5: Rowhammer

Room 2

Session chair: Michael Franz (UC Irvine)

RAMBleed: Reading Bits in Memory Without Accessing Them

Andrew Kwong (University of Michigan), Daniel Genkin (University of Michigan), Daniel Gruss (Data61)

Are We Susceptible to Rowhammer? An End-to-End Methodology for Cloud Providers

Lucian Cojocar (Microsoft Research), Jeremie Kim (ETH Zurich, CMU), Minesh Patel (ETH Zurich, Microsoft Research), Onur Mutlu (ETH Zurich, CMU)

Leveraging EM Side-Channel Information to Detect Rowhammer Attacks

Zhenkai Zhang (Texas Tech University), Zihao Zhan (Vanderbilt University), Daniel Balasubramanian (Vanderbilt University), Peter Volgyesi (Vanderbilt University), Xenofon Koutsoukos (Vanderbilt University)

TRRespass: Exploiting the Many Sides of Target Row Refresh

Pietro Frigo (Vrije Universiteit Amsterdam, The Netherlands), Emanuele Vannacci (Vrije Universiteit Amsterdam), Onur Mutlu (Qualcomm Technologies, Inc.), Onur Mutlu (ETH Zürich), Cristiano Giuffrida (Vrije Universiteit Amsterdam, The Netherlands), Kaveh Razavi (Vrije Universiteit Amsterdam, The Netherlands)

RowHammer in 2020 (III)

29TH USENIX
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ABOUT

DeepHammer: Depleting the Intelligence of Deep Neural Networks through Targeted Chain of Bit Flips

Fan Yao, *University of Central Florida*; Adnan Siraj Rakin and Deliang Fan, *Arizona State University*

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RowHammer in 2020 (IV)

■ CHES 2020

JackHammer: Efficient Rowhammer on Heterogeneous FPGA-CPU Platforms

Zane Weissman¹, Thore Tiemann², Daniel Moghimi¹, Evan Custodio³,
Thomas Eisenbarth² and Berk Sunar¹

¹ Worcester Polytechnic Institute, MA, USA

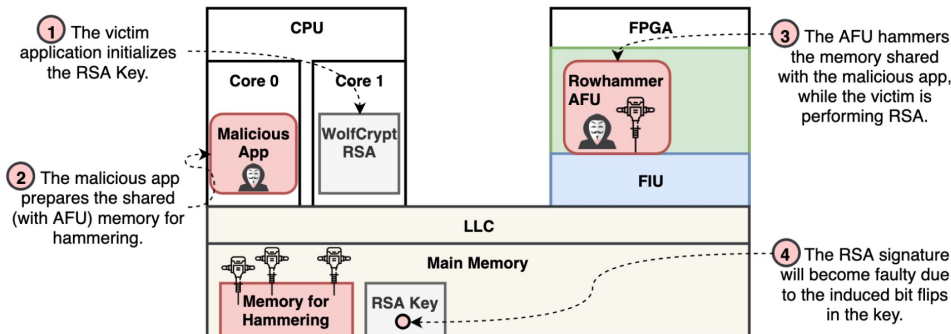
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³ Intel Corporation, Hudson, MA, USA

evan.custodio@intel.com



An **FPGA-based** RowHammer attack recovering **private keys** twice as fast compared to **CPU-based** attacks

RowHammer in 2021 (I)

HotOS XVIII

The 18th Workshop on Hot Topics in Operating Systems

31-May 1 June–3 June 2021, Cyberspace, People's Couches, and Zoom

Stop! Hammer Time: Rethinking Our Approach to Rowhammer Mitigations

RowHammer in 2021 (II)

30TH USENIX
SECURITY SYMPOSIUM

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SMASH: Synchronized Many-sided Rowhammer Attacks from JavaScript

RowHammer in 2021 (III)



Session 10A: Security & Privacy III

Session Chair: Hoda Naghibijouybari (Binghamton)

9:00 PM CEST – 9:15 PM CEST

A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses

Lois Orosa, Abdullah Giray Yaglikci, Haocong Luo (ETH Zurich); Ataberk Olgun (TOBB University of Economics and Technology); Jisung Park, Hasan Hassan, Minesh Patel, Jeremie S. Kim, Onur Mutlu (ETH Zurich)

 [Paper](#)

9:15 PM CEST – 9:30 PM CEST

Uncovering In-DRAM RowHammer Protection Mechanisms: A New Methodology, Custom RowHammer Patterns, and Implications

Hasan Hassan (ETH Zurich); Yahya Can Tugrul (TOBB University of Economics and Technology); Jeremie S. Kim (ETH Zurich); Victor van der Veen (Qualcomm); Kaveh Razavi, Onur Mutlu (ETH Zurich)

 [Paper](#)

RowHammer in 2022 (I)

MAY 22-26, 2022 AT THE HYATT REGENCY, SAN FRANCISCO, CA

43rd IEEE Symposium on Security and Privacy

BLACKSMITH: Scalable Rowhammering in the Frequency Domain

**SpecHammer: Combining Spectre and Rowhammer
for New Speculative Attacks**

**PROTRR: Principled yet Optimal In-DRAM
Target Row Refresh**

**DeepSteal: Advanced Model Extractions Leveraging Efficient
Weight Stealing in Memories**

RowHammer in 2022 (II)



Randomized Row-Swap: Mitigating Row Hammer by Breaking Spatial Correlation between Aggressor and Victim Rows

RowHammer in 2022 (III)

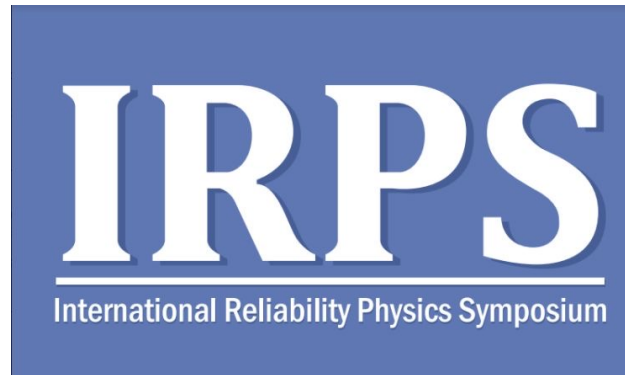
HPCA 2022

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

SafeGuard: Reducing the Security Risk from Row-Hammer via Low-Cost Integrity Protection

Mithril: Cooperative Row Hammer Protection on Commodity DRAM Leveraging Managed Refresh

RowHammer in 2022 (IV)



IRPS 2022

The Price of Secrecy: How Hiding Internal DRAM Topologies Hurts Rowhammer Defenses

Stefan Saroiu, Alec Wolman, Lucian Cojocar
Microsoft

RowHammer in 2022 (V)



Half-Double: Hammering From the Next Row Over

Andreas Kogler¹ Jonas Juffinger^{1,2} Salman Qazi³ Yoongu Kim³ Moritz Lipp^{4*}
Nicolas Boichat³ Eric Shiu⁵ Mattias Nissler³ Daniel Gruss¹

¹*Graz University of Technology* ²*Lamarr Security Research* ³*Google*
⁴*Amazon Web Services* ⁵*Rivos*

RowHammer in 2022 (VI)



HAMMERSCOPE: Observing DRAM Power Consumption Using Rowhammer

**When Frodo Flips:
End-to-End Key Recovery on FrodoKEM via Rowhammer**

RowHammer in 2022 (VII)



AQUA: Scalable Rowhammer Mitigation by Quarantining Aggressor Rows at Runtime

Anish Saxena, Gururaj Saileshwar (Georgia Institute of Technology); Prashant J. Nair (University of British Columbia); Moinuddin Qureshi (Georgia Institute of Technology)

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

Abdullah Giray Yaglikci (ETH Zürich); Ataberk Olgun (TOBB University of Economics and Technology); Lois Orosa, Minesh Patel, Haocong Luo, Hasan Hassan (ETH Zürich); Oguz Ergin (TOBB University of Economics and Technology); Onur Mutlu (ETH Zürich)

RowHammer in 2022 (VII)

- A. Giray Yaglikci, Ataberk Olgun, Minesh Patel, Haocong Luo, Hasan Hassan, Lois Orosa, Oguz Ergin, and Onur Mutlu,
"HiRA: Hidden Row Activation for Reducing Refresh Latency of Off-the-Shelf DRAM Chips"
Proceedings of the 55th International Symposium on Microarchitecture (MICRO),
Chicago, IL, USA, October 2022.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Longer Lecture Slides \(pptx\)](#)] [[pdf](#)]
[[Lecture Video](#) (36 minutes)]
[[arXiv version](#)]

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

A. Giray Yağlıkçı¹ Ataberk Olgun^{1,2} Minesh Patel¹ Haocong Luo¹ Hasan Hassan¹
Lois Orosa^{1,3} Oğuz Ergin² Onur Mutlu¹

¹ETH Zürich

²TOBB University of Economics and Technology

³Galicia Supercomputing Center (CESGA)

<https://arxiv.org/pdf/2209.10198.pdf>

RowHammer in 2022 (VIII)

A Case for Transparent Reliability in DRAM Systems

Minesh Patel[†] Taha Shahroodi^{‡‡} Aditya Manglik[†] A. Giray Yağlıkçı[†]
Ataberk Olgun[†] Haocong Luo[†] Onur Mutlu[†]

[†]*ETH Zürich* [‡]*TU Delft*

<https://arxiv.org/pdf/2204.10378.pdf>

RowHammer in 2022 (IX)

A Case for Self-Managing DRAM Chips: Improving Performance, Efficiency, Reliability, and Security via Autonomous in-DRAM Maintenance Operations

Hasan Hassan

Ataberk Olgun

A. Giray Yağlıkçı

Haocong Luo

Onur Mutlu

ETH Zürich

<https://arxiv.org/pdf/2207.13358.pdf>

RowHammer in 2023 (I)

MAY 22-26, 2023 AT THE HYATT REGENCY, SAN FRANCISCO, CA

44th IEEE Symposium on Security and Privacy

Session 6C: Rowhammer and spectre

Bayview AB

11:00 AM – 12:15 PM

Session Chair: Eyal Ronen

REGA: Scalable Rowhammer Mitigation with Refresh-Generating Activations

Michele Marazzi (ETH Zurich), Flavien Solt (ETH Zurich), Patrick Jattke (ETH Zurich), Kubo Takashi (Zentel Japan), Kaveh Razavi (ETH Zurich)

CSI:Rowhammer - Cryptographic Security and Integrity against Rowhammer

Jonas Juffinger (Lamarr Security Research, Graz University of Technology, Austria), Lukas Lamster (Graz University of Technology, Austria), Andreas Kogler (Graz University of Technology, Austria), Maria Eichlseder (Graz University of Technology, Austria), Moritz Lipp (Amazon Web Services, Austria), Daniel Gruss (Graz University of Technology, Austria)

Jolt: Recovering TLS Signing Keys via Rowhammer Faults

Koksal Mus (Worcester Polytechnic Institute), Yarkin Doröz (Worcester Polytechnic Institute), M. Caner Tol (Worcester Polytechnic Institute), Kristi Rahman (Worcester Polytechnic Institute), Berk Sunar (Worcester Polytechnic Institute)

RowHammer in 2023 (II)

HPCA 2023

The 29th IEEE International Symposium on High-Performance Computer Architecture (HPCA-29)

**Scalable and Secure Row-Swap:
Efficient and Safe Row Hammer
Mitigation in Memory Systems**

*Jeonghyun Woo (University of
British Columbia),
Gururaj Saileshwar (Georgia
Institute of Technology),
Prashant J. Nair (University of
British Columbia)*

**SHADOW: Preventing Row
Hammer in DRAM with Intra-
Subarray Row Shuffling**

*Minbok Wi (Seoul National
University),
Jaehyun Park (Seoul National
University),
Seoyoung Ko (Seoul National
University), Michael Jaemin Kim
(Seoul National University),
Nam Sung Kim (UIUC),
Eojin Lee (Inha University),
Jung Ho Ahn (Seoul National
University)*

RowHammer in 2023 (III): SK Hynix

ISSCC 2023 / SESSION 28 / HIGH-DENSITY MEMORIES /

28.8 A 1.1V 16Gb DDR5 DRAM with Probabilistic-Aggressor Tracking, Refresh-Management Functionality, Per-Row Hammer Tracking, a Multi-Step Precharge, and Core-Bias Modulation for Security and Reliability Enhancement

Woongrae Kim, Chulmoon Jung, Seongnyuh Yoo, Duckhwa Hong, Jeongjin Hwang, Jungmin Yoon, Ohyong Jung, Joonwoo Choi, Sanga Hyun, Mankeun Kang, Sangho Lee, Dohong Kim, Sanghyun Ku, Donhyun Choi, Nogeun Joo, Sangwoo Yoon, Junseok Noh, Byeongyong Go, Cheolhoe Kim, Sunil Hwang, Mihyun Hwang, Seol-Min Yi, Hyungmin Kim, Sanghyuk Heo, Yeonsu Jang, Kyoungchul Jang, Shinho Chu, Yoonna Oh, Kwidong Kim, Junghyun Kim, Soohwan Kim, Jeongtae Hwang, Sangil Park, Junphyo Lee, Inchul Jeong, Joohwan Cho, Jonghwan Kim

SK hynix Semiconductor, Icheon, Korea

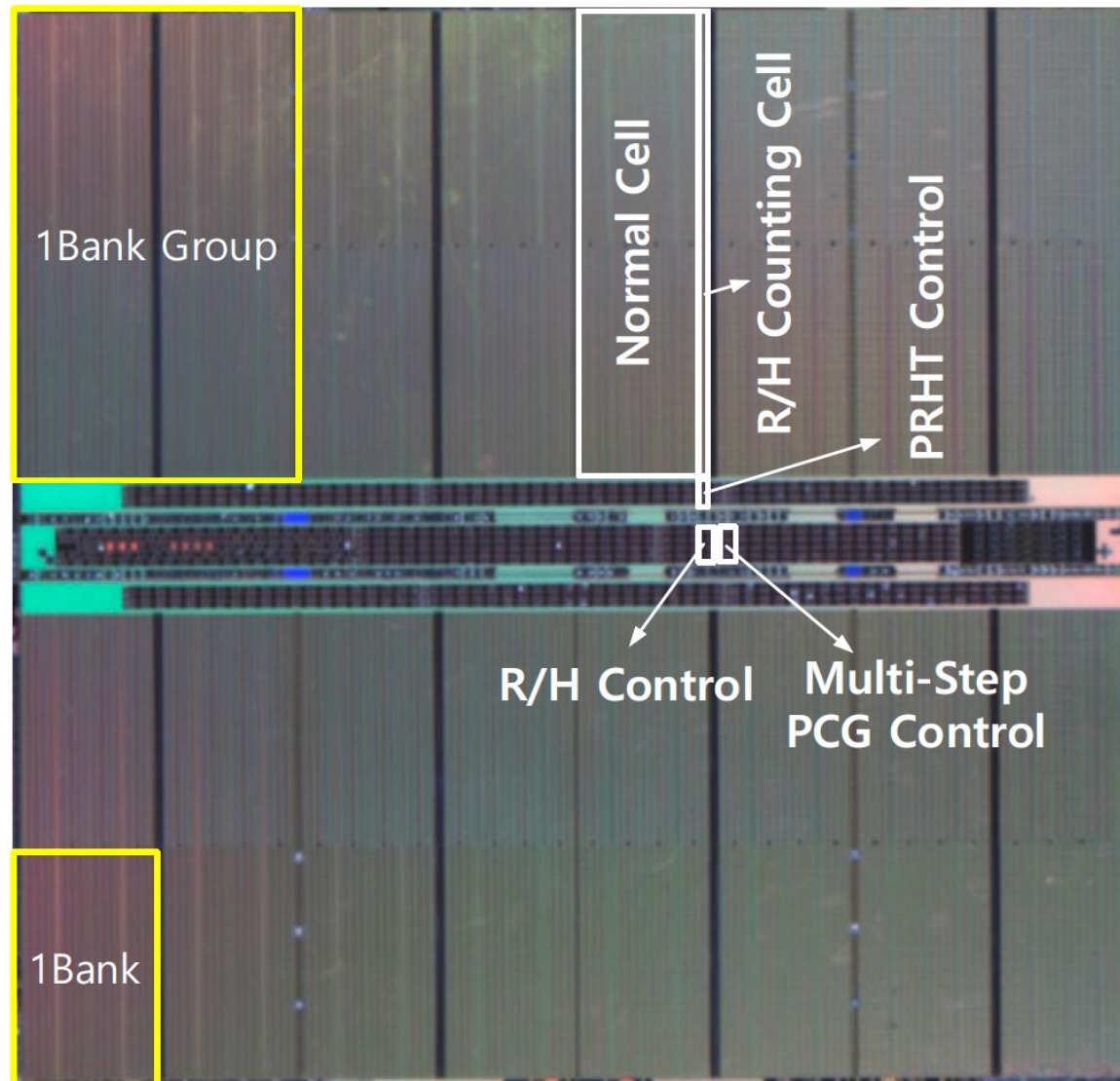


Industry's RowHammer Solutions (I)

SK hynix Semiconductor, Icheon, Korea

DRAM products have been recently adopted in a wide range of high-performance computing applications: such as in cloud computing, in big data systems, and IoT devices. This demand creates larger memory capacity requirements, thereby requiring aggressive DRAM technology node scaling to reduce the cost per bit [1,2]. However, DRAM manufacturers are facing technology scaling challenges due to row hammer and refresh retention time beyond 1a-nm [2]. Row hammer is a failure mechanism, where repeatedly activating a DRAM row disturbs data in adjacent rows. Scaling down severely threatens reliability since a reduction of DRAM cell size leads to a reduction in the intrinsic row hammer tolerance [2,3]. To improve row hammer tolerance, there is a need to probabilistically activate adjacent rows with carefully sampled active addresses and to improve intrinsic row hammer tolerance [2]. In this paper, row-hammer-protection and refresh-management schemes are presented to guarantee DRAM security and reliability despite the aggressive scaling from 1a-nm to sub 10-nm nodes. The probabilistic-aggressor-tracking scheme with a refresh-management function (RFM) and per-row hammer tracking (PRHT) improve DRAM resilience. A multi-step precharge reinforces intrinsic row-hammer tolerance and a core-bias modulation improves retention time: even in the face of cell-transistor degradation due to technology scaling. This comprehensive scheme leads to a reduced probability of failure, due to row hammer attacks, by 93.1% and an improvement in retention time by 17%.

Industry's RowHammer Solutions (II)



ISSCC 2023 / SESSION 28 / HIGH-DENSITY MEMORIES

28.8 A 1.1V 16Gb DDR5 DRAM with Probabilistic-Aggressor Tracking, Refresh-Management Functionality, Per-Row Hammer Tracking, a Multi-Step Precharge, and Core-Bias Modulation for Security and Reliability Enhancement

Woongrae Kim, Chulmoon Jung, Seongnyuh Yoo, Duckhwa Hong, Jeongjin Hwang, Jungmin Yoon, Ohyoung Jung, Joonwoo Choi, Sanga Hyun, Mankeun Kang, Sangho Lee, Dohong Kim, Sanghyun Ku, Donhyun Choi, Nogeun Joo, Sangwoo Yoon, Junseok Noh, Byeongyong Go, Cheolhoe Kim, Sunil Hwang, Mihyun Hwang, Seol-Min Yi, Hyungmin Kim, Sanghyuk Heo, Yeonsu Jang, Kyoungchul Jang, Shinho Chu, Yoonna Oh, Kwidong Kim, Junghyun Kim, Soohwan Kim, Jeongtae Hwang, Sangil Park, Junphyo Lee, Inchul Jeong, Joohwan Cho, Jonghwan Kim

SK hynix Semiconductor, Icheon, Korea

RowHammer in 2023 (IV): Samsung

DSAC: Low-Cost Rowhammer Mitigation Using In-DRAM Stochastic and Approximate Counting Algorithm

Seungki Hong Dongha Kim Jaehyung Lee Reum Oh
Changsik Yoo Sangjoon Hwang Jooyoung Lee

DRAM Design Team, Memory Division, Samsung Electronics

<https://arxiv.org/pdf/2302.03591v1.pdf>

RowHammer in 2023 (V)



[28 June, 14:30-16:00] RT-3: Memory 1 (Session Chair: TBD)

Compiler-Implemented Differential Checksums: Effective Detection and Correction of Transient and Permanent Memory Errors (REG)

C. Borchert; H. Schirmeier; O. Spinczyk

PT-Guard: Integrity-Protected Page Tables to Defend Against Breakthrough Rowhammer Attacks (REG)

A. Saxena; G. Saileshwar; J. Juffinger; A. Kogler; D. Gruss; M. Qureshi

Don't Knock! Rowhammer at the Backdoor of DNN Models (REG)

M. Tol; S. Islam; A. Adiletta; B. Sunar; Z. Zhang

[29 June, 16:00-17:30] DS23-4: Hardware Resilience and Human Factors (Session Chair: TBD)

An Experimental Analysis of RowHammer in HBM2 DRAM Chips

Ataberk Olgun, Majd Osseiran, Abdullah Giray Yaglikci, Yahya Can Tugrul, Juan Gomez Luna, Haocong Luo, Behzad Salami, Steve Rhyner and Onur Mutlu

RowHammer in 2023 (VI)

■ SOSP 2023

SOSP 2023

The 29th ACM Symposium on Operating Systems Principles
October 23-26, 2023

Siloz: Leveraging DRAM Isolation Domains to Prevent Inter-VM Rowhammer

Kevin Loughlin
University of Michigan

Jonah Rosenblum
University of Michigan

Stefan Saroiu
Microsoft

Alec Wolman
Microsoft

Dimitrios Skarlatos
Carnegie Mellon University

Baris Kasikci
University of Washington and Google

RowHammer in 2023 (VII)

■ IEEE Computer Architecture Letters, 2023

NoHammer: Preventing Row Hammer with Last-Level Cache Management

Seunghak Lee, Ki-Dong Kang, Gyeongseo Park, Nam Sung Kim, and Daehoon Kim

Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator

Haocong Luo, Yahya Can Tuğrul, F. Nisa Bostancı, Ataberk Olgun, A. Giray Yağlıkçı, and Onur Mutlu

■ IEEE Embedded Systems Letters, 2023

Flipping Bits Like a Pro: Precise Rowhammering on Embedded Devices

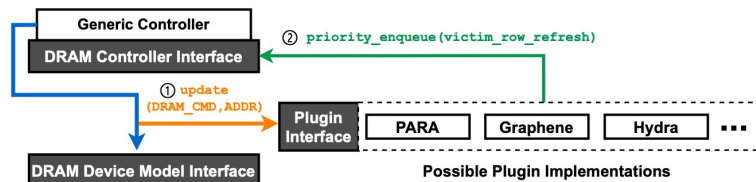
Anandpreet Kaur, Pravin Srivastav, Bibhas Ghoshal
Systems Lab, Indian Institute of Information Technology Allahabad (IIITA)

Ramulator 2.0

"Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator"

IEEE Computer Architecture Letters, August 2023. (*Preprint on **arxiv***)

[[arXiv version](#)] [[Ramulator 2.0 Source Code](#)]



CMU-SAFARI / ramulator2 Public

Notifications Fork 15 Star 68

Code Issues 7 Pull requests Actions Projects Security Insights

main 1 branch 0 tags Go to file Code About

Haocong Luo Fix bug in LDST trace frontend (Issue #10) 58f2819 3 weeks ago 22 commits

perf_comparison	Add missing files.	3 weeks ago
resources/gem5_wrap...	Add missing files.	3 weeks ago
rh_study	Init	2 months ago
src	Fix bug in LDST trace frontend (Issue #10)	3 weeks ago
verilog_verification	Init	2 months ago

Ramulator 2.0 is a modern, modular, extensible, and fast cycle-accurate DRAM simulator. It provides support for agile implementation and evaluation of new memory system designs (e.g., new DRAM standards, emerging RowHammer mitigation techniques). Described in our paper https://people.inf.ethz.ch/omutlu/pub/Ramulator2_arxiv23.pdf

Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator

Haocong Luo, Yahya Can Tuğrul, F. Nisa Bostancı, Ataberk Olgun, A. Giray Yağlıkçı, and Onur Mutlu

RowHammer in 2023 (VIII)

■ MEMSYS 2023

RAMPART: RowHammer Mitigation and Repair for Server Memory Systems

Steven C. Woo
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■ MICRO 2023

How to Kill the Second Bird with One ECC: The Pursuit of Row Hammer Resilient DRAM

Michael Jaemin Kim, Minbok Wi, Jaehyun Park, Seoyoung Ko, Jae Young Choi, Hwayoung Nam (Seoul National University); Nam Sung Kim (University of Illinois Urbana Champaign); Jung Ho Ahn (Seoul National University); Eojin Lee (Inha University)

Related Courses

DDCA (Spring 2022)

Spring 2022 Edition:

- <https://safari.ethz.ch/digitaltechnik/spring2022/doku.php?id=schedule>

Spring 2021 Edition:

- <https://safari.ethz.ch/digitaltechnik/spring2021/doku.php?id=schedule>

Youtube Livestream (Spring 2022):

- <https://www.youtube.com/watch?v=cpXdE3HwvK0&list=PL5Q2soXY2Zi97Ya5DEUpMpO2bbAoaG7c6>

Youtube Livestream (Spring 2021):

- https://www.youtube.com/watch?v=LbC0EZY8yw4&list=PL5Q2soXY2Zi_uej3aY39YB5pfW4SJ7LIN

Bachelor's course

- 2nd semester at ETH Zurich
- Rigorous introduction into "How Computers Work"
- Digital Design/Logic
- Computer Architecture
- 10 FPGA Lab Assignments

<https://www.youtube.com/onurmutlulectures>



Trace: - schedule

Home

Announcements

Materials

- Lectures/Schedule
- Lecture Buzzwords
- Readings
- Optional HWs
- Labs
- Extra Assignments
- Exams
- Technical Docs

Resources

- Computer Architecture (CMU) SS15: Lecture Videos
- Computer Architecture (CMU) SS15: Course Website
- Digitaltechnik SS18: Lecture Videos
- Digitaltechnik SS18: Course Website
- Digitaltechnik SS19: Lecture Videos
- Digitaltechnik SS19: Course Website
- Digitaltechnik SS20: Lecture Videos
- Digitaltechnik SS20: Course Website
- Moodle

Lecture Video Playlist on YouTube

Livestream Lecture Playlist

Onur Mutlu: Digital Design and Computer Architecture Today

- Computing landscape is very different from 10-20 years ago
- Applications and technology both demand novel architectures

Watch on YouTube

Recorded Lecture Playlist

Digital Design & Computer Architecture: Lect...

How Computers Work


(from the ground up)

Watch on YouTube

Spring 2021 Lectures/Schedule

Week	Date	Livestream	Lecture	Readings	Lab	HW
W1	25.02 Thu.	YouTube Live	L1: Introduction and Basics G2a (PDF) G2a (PPT)	Required Suggested Mentioned		
	26.02 Fri.	YouTube Live	L2a: Tradeoffs, Metrics, Mindset G2a (PDF) G2a (PPT)	Required		
			L2b: Mysteries in Computer Architecture G2a (PDF) G2a (PPT)	Required Mentioned		
W2	04.03 Thu.	YouTube Live	L3a: Mysteries in Computer Architecture II G2a (PDF) G2a (PPT)	Required Suggested Mentioned		

Comp Arch (Fall 2022)



Computer Architecture - Fall 2022

Recent Changes Media Manager Sitemap

Trace: start schedule

Home

Announcements

Materials

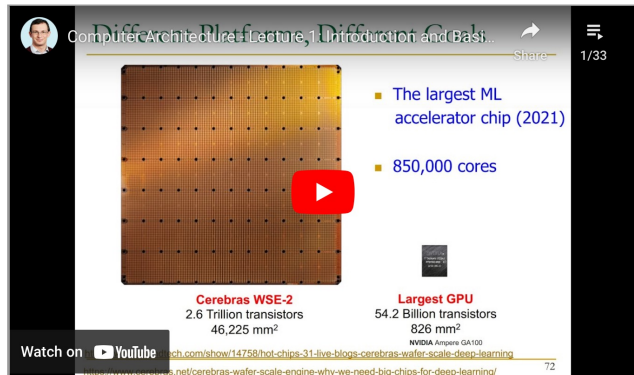
- Lectures/Schedule
- Lecture Buzzwords
- Readings
- HWs
- Labs
- Exams
- Related Courses
- Tutorials

Resources

- Computer Architecture FS21: Course Webpage
- Computer Architecture FS21: Lecture Videos
- Digitaltechnik SS21: Course Webpage
- Digitaltechnik SS21: Lecture Videos
- Moodle
- HotCRP
- Verilog Practice Website (HDLBits)

Lecture Video Playlist on YouTube

Livestream Lecture Playlist




The largest ML accelerator chip (2021)

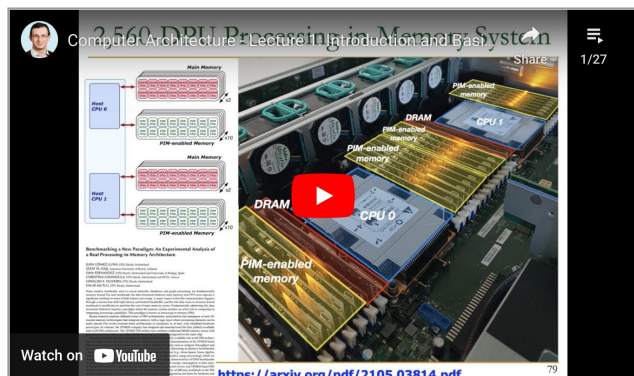
850,000 cores


Cerebras WSE-2
2.6 Trillion transistors
46,225 mm²

Largest GPU
54.2 Billion transistors
826 mm²
NVIDIA Ampere GA100












Watch on  [ch.com/show/14756/hot-chips-31-live-blogs-cerebras-wafer-scale-deep-learning](https://www.youtube.com/watch?v=4yfkM_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF)

Lecture Playlist from Fall 2021



Watch on  <https://arxiv.org/pdf/2105.03814.pdf>

Fall 2022 Lectures & Schedule

Week	Date	Livestream	Lecture	Readings	Lab	HW
W1	29.09 Thu.	 Live	L1: Introduction and Basics  (PDF)  (PPT)	Required Mentioned	Lab 1 Out	HW 0 Out
	30.09 Fri.	 Live	L2a: Memory Systems: Challenges and Opportunities  (PDF)  (PPT) L2b: Course Info & Logistics  (PDF)  (PPT)	Described Suggested		
W2	06.10 Thu.	 Live	L3: Processing using Memory  (PDF)  (PPT)	Described Suggested		HW 1 Out

- **Fall 2022 Edition:**
 - ❑ <https://safari.ethz.ch/architecture/fall2022/doku.php?id=schedule>
- **Fall 2021 Edition:**
 - ❑ <https://safari.ethz.ch/architecture/fall2021/doku.php?id=schedule>
- **Youtube Livestream (2022):**
 - ❑ https://www.youtube.com/watch?v=4yfkM_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF
- **Youtube Livestream (2021):**
 - ❑ https://www.youtube.com/watch?v=4yfkM_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF
- Master's level course
 - ❑ Taken by Bachelor's/Masters/PhD students
 - ❑ Cutting-edge research topics + fundamentals in Computer Architecture
 - ❑ 5 Simulator-based Lab Assignments
 - ❑ Potential research exploration
 - ❑ Many research readings

<https://www.youtube.com/onurmutlulectures>

RowHammer & DRAM Exploration (Fall 2022)

Fall 2022 Edition:

- ❑ https://safari.ethz.ch/projects_and_seminars/fall2022/doku.php?id=softmc

Spring 2022 Edition:

- ❑ https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=softmc

Youtube Livestream (Spring 2022):

- ❑ https://www.youtube.com/watch?v=r5QxuoJWttg&list=PL5Q2soXY2Zi_1trfCckr6PTN8WR72icUO

Bachelor's course

- ❑ Elective at ETH Zurich
- ❑ Introduction to DRAM organization & operation
- ❑ Tutorial on using FPGA-based infrastructure
- ❑ Verilog & C++
- ❑ Potential research exploration

<https://www.youtube.com/onurmutlulectures>

Lecture Video Playlist on YouTube

Lecture Playlist



2022 Meetings/Schedule (Tentative)

Week	Date	Livestream	Meeting	Learning Materials	Assignments
W0	23.02 Wed.		P&S SoftMC Tutorial	SoftMC Tutorial Slides (PDF) (PPT)	
W1	08.03 Tue.		M1: Logistics & Intro to DRAM and SoftMC (PDF) (PPT)	Required Materials Recommended Materials	HW0
W2	15.03 Tue.		M2: Revisiting RowHammer (PDF) (PPT)	(Paper PDF)	
W3	22.03 Tue.		M3: Uncovering in-DRAM TRR & TRRespass (PDF) (PPT)		
W4	29.03 Tue.		M4: Deeper Look Into RowHammer's Sensitivities (PDF) (PPT)		
W5	05.04 Tue.		M5: QUAC-TRNG (PDF) (PPT)		
W6	12.04 Tue.		M6: PiDRAM (PDF) (PPT)		

Exploration of Emerging Memory Systems (Fall 2022)

Fall 2022 Edition:

- https://safari.ethz.ch/projects_and_seminars/fall2022/doku.php?id=ramulator

Spring 2022 Edition:

- https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=ramulator

Youtube Livestream (Spring 2022):

- https://www.youtube.com/watch?v=aM-lIXRQd3s&list=PL5Q2soXY2Zi_TlmlGw_Z8hBo2925ZApgV

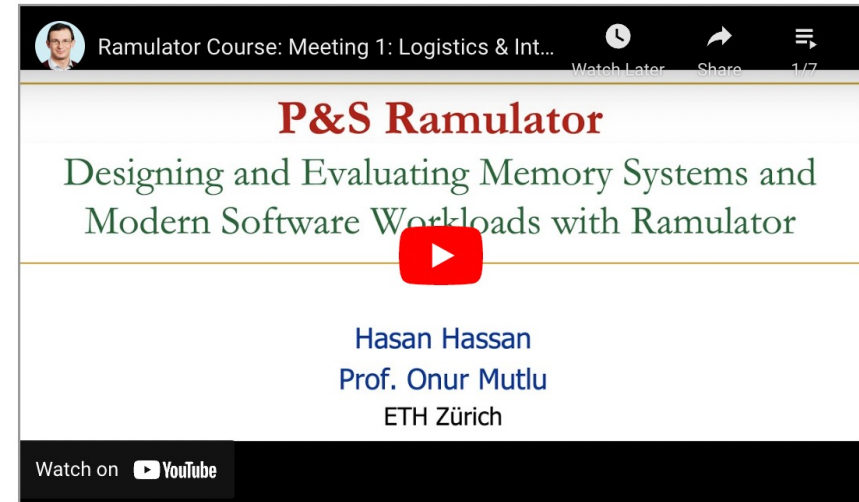
Bachelor's course

- Elective at ETH Zurich
- Introduction to memory system simulation
- Tutorial on using Ramulator
- C++
- Potential research exploration

<https://www.youtube.com/onurmutlulectures>

Lecture Video Playlist on YouTube

Lecture Playlist



2022 Meetings/Schedule (Tentative)

Week	Date	Livestream	Meeting	Learning Materials	Assignments
W1	09.03 Wed.	YouTube Video	M1: Logistics & Intro to Simulating Memory Systems Using Ramulator PDF (PDF) PPT (PPT)		HW0
W2	16.03 Fri.	YouTube Video	M2: Tutorial on Using Ramulator PDF (PDF) PPT (PPT)		
W3	25.02 Fri.	YouTube Video	M3: BlockHammer PDF (PDF) PPT (PPT)		
W4	01.04 Fri.	YouTube Video	M4: CLR-DRAM PDF (PDF) PPT (PPT)		
W5	08.04 Fri.	YouTube Video	M5: SIMDRAM PDF (PDF) PPT (PPT)		
W6	29.04 Fri.	YouTube Video	M6: DAMOV PDF (PDF) PPT (PPT)		
W7	06.05 Fri.	YouTube Video	M7: Synchron PDF (PDF) PPT (PPT)		