



# Understanding & Solving RowHammer

Onur Mutlu

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10 August 2023

Flash Memory Summit

**SAFARI**

**ETH** zürich

**Carnegie Mellon**

# How Reliable/Secure/Safe is This Bridge?

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# Collapse of the “Galloping Gertie”

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# How Secure Are These People?

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**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
  - >80% of the tested DRAM chips are 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

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CULTURE

DESIGN

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SCIENCE

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bird

TWEET

ANDY GREENBERG

SECURITY

08.31.16

7:00 AM

FORGET SOFTWARE—NOW  
HACKERS ARE EXPLOITING  
PHYSICS

# An “Early” Position Paper [IMW’13]

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- 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

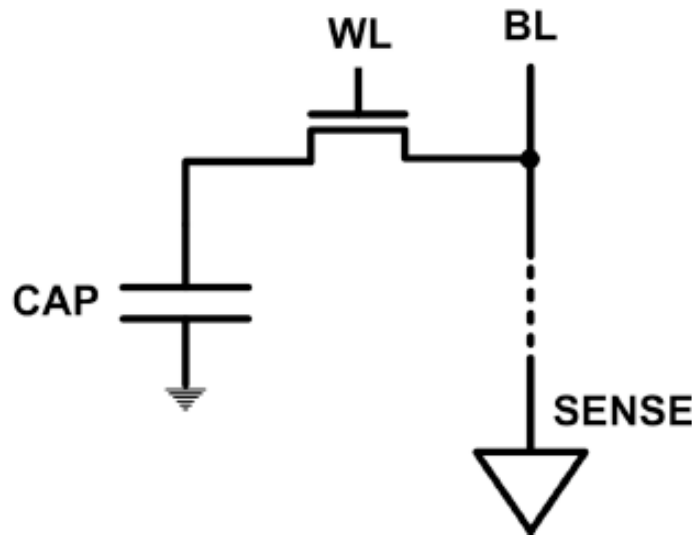
## Memory Scaling: A Systems Architecture Perspective

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

# The DRAM Scaling Problem

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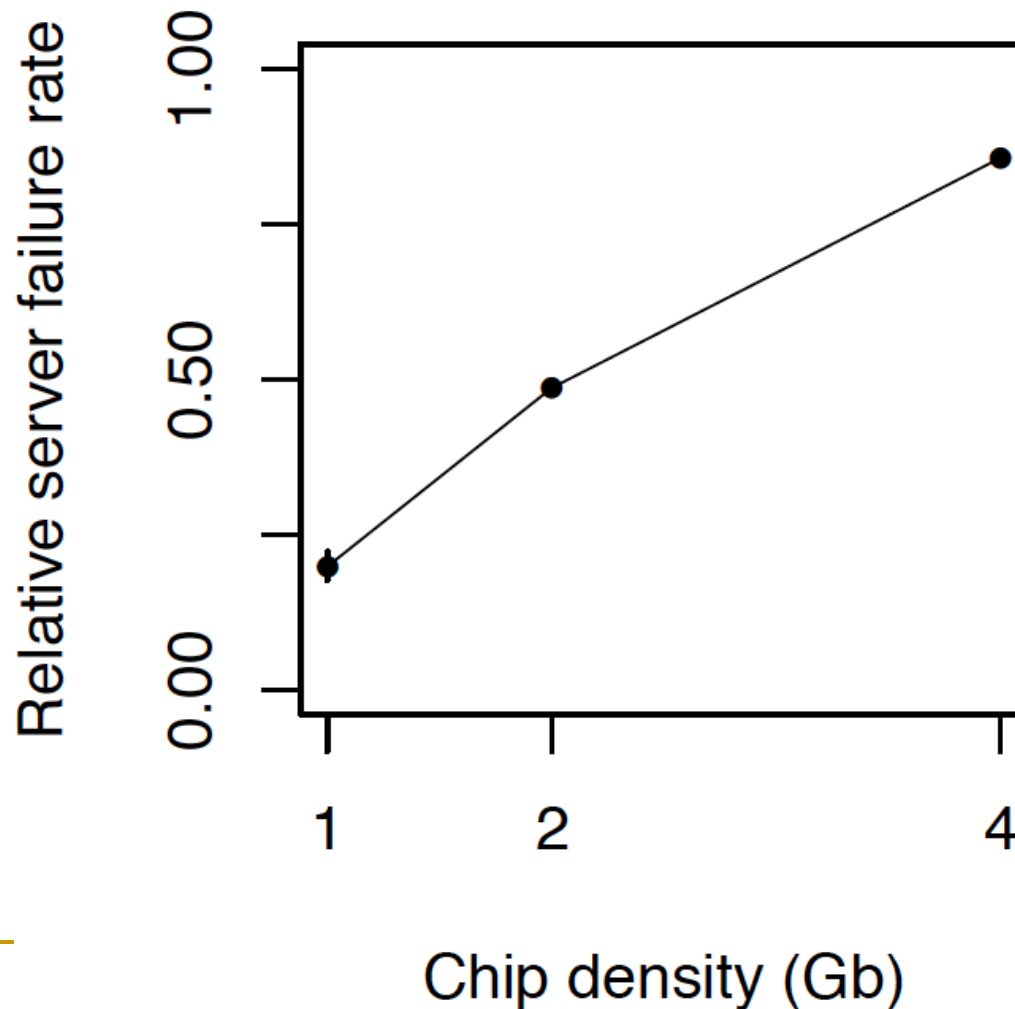
- DRAM stores charge in a capacitor (charge-based memory)
  - Capacitor must be large enough for reliable sensing
  - Access transistor should be large enough for low leakage and high retention time
  - Scaling beyond 40-35nm (2013) is challenging [ITRS, 2009]



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

# 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

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- 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



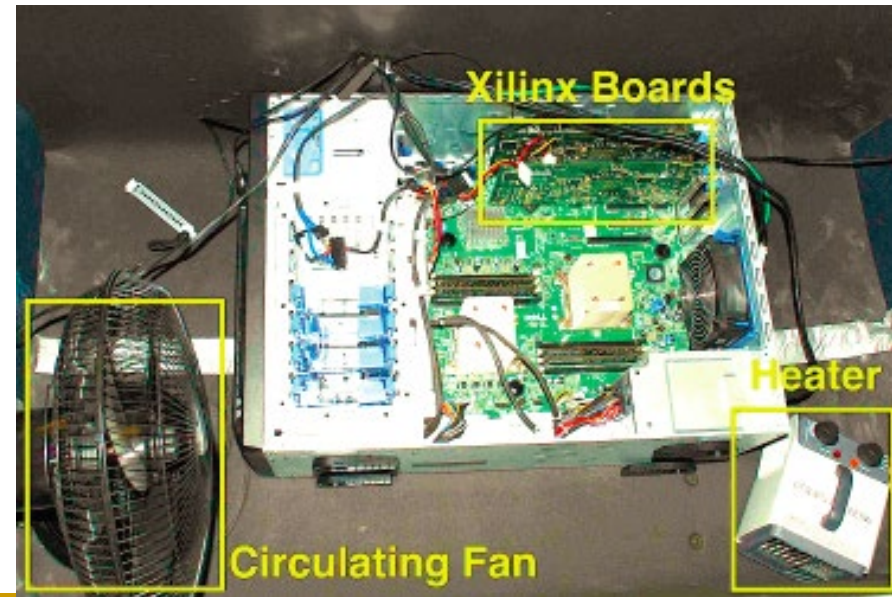
Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors (Kim et al., ISCA 2014)

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)

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)



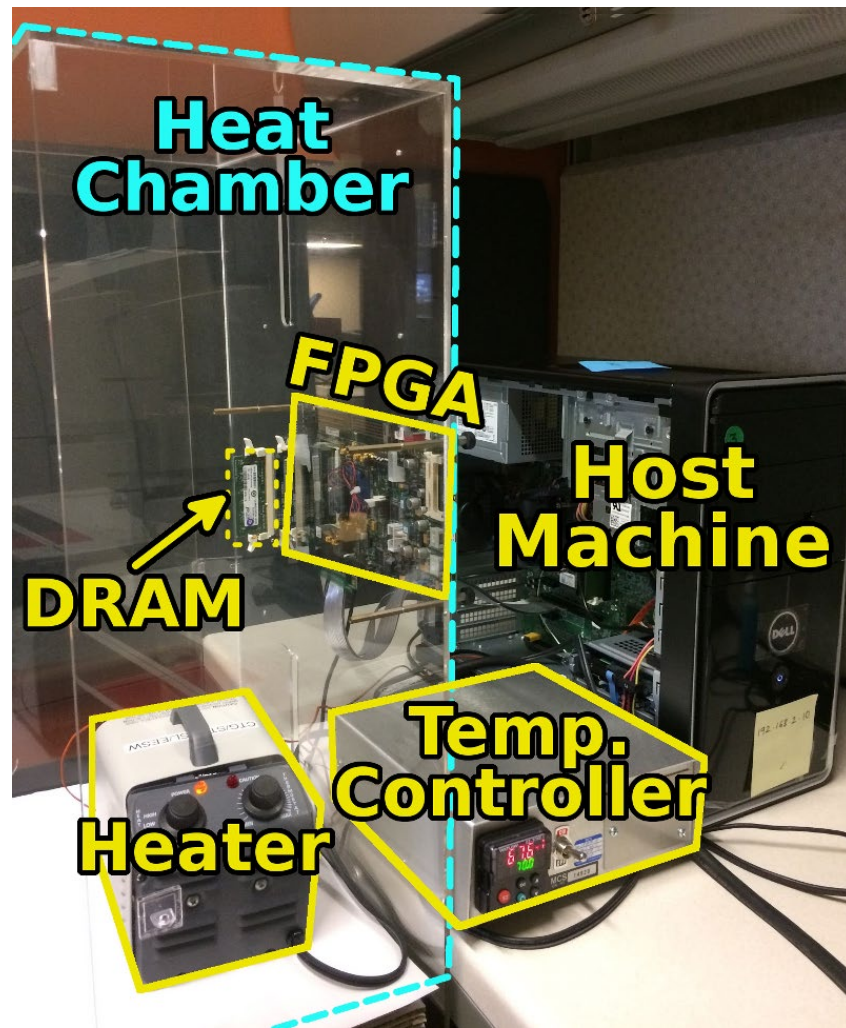




# SoftMC: Open Source DRAM Infrastructure

- 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](https://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<sup>1,2,3</sup> Nandita Vijaykumar<sup>3</sup> Samira Khan<sup>4,3</sup> Saugata Ghose<sup>3</sup> Kevin Chang<sup>3</sup>  
Gennady Pekhimenko<sup>5,3</sup> Donghyuk Lee<sup>6,3</sup> Oguz Ergin<sup>2</sup> Onur Mutlu<sup>1,3</sup>

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

# DRAM Bender

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- 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

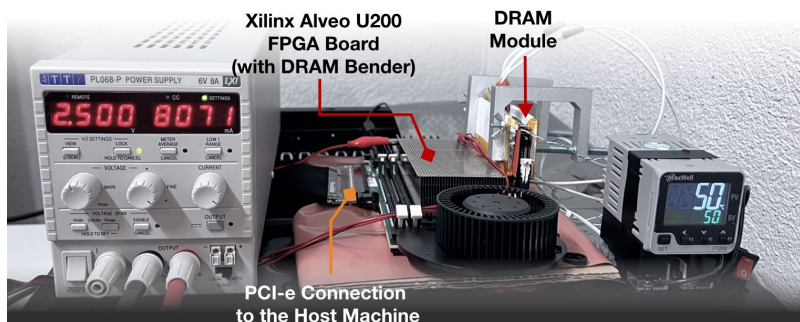
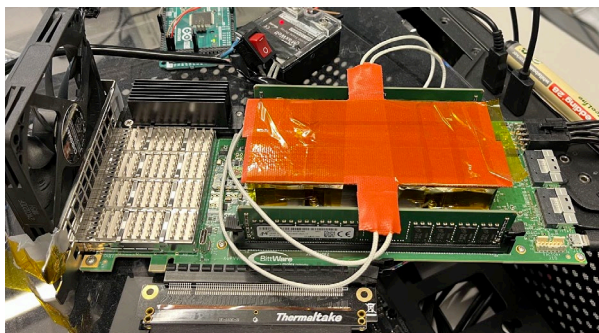
Ataberk Olgun<sup>§</sup>      Hasan Hassan<sup>§</sup>      A. Giray Yağlıkçı<sup>§</sup>      Yahya Can Tuğrul<sup>§†</sup>  
Lois Orosa<sup>§⊙</sup>      Haocong Luo<sup>§</sup>      Minesh Patel<sup>§</sup>      Oğuz Ergin<sup>†</sup>      Onur Mutlu<sup>§</sup>  
          <sup>§</sup>*ETH Zürich*      <sup>†</sup>*TOBB ETÜ*      <sup>⊙</sup>*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
<b>DRAM Bender (this work)</b>	<b>DDR3/DDR4</b>	<b>Five Prototypes</b>

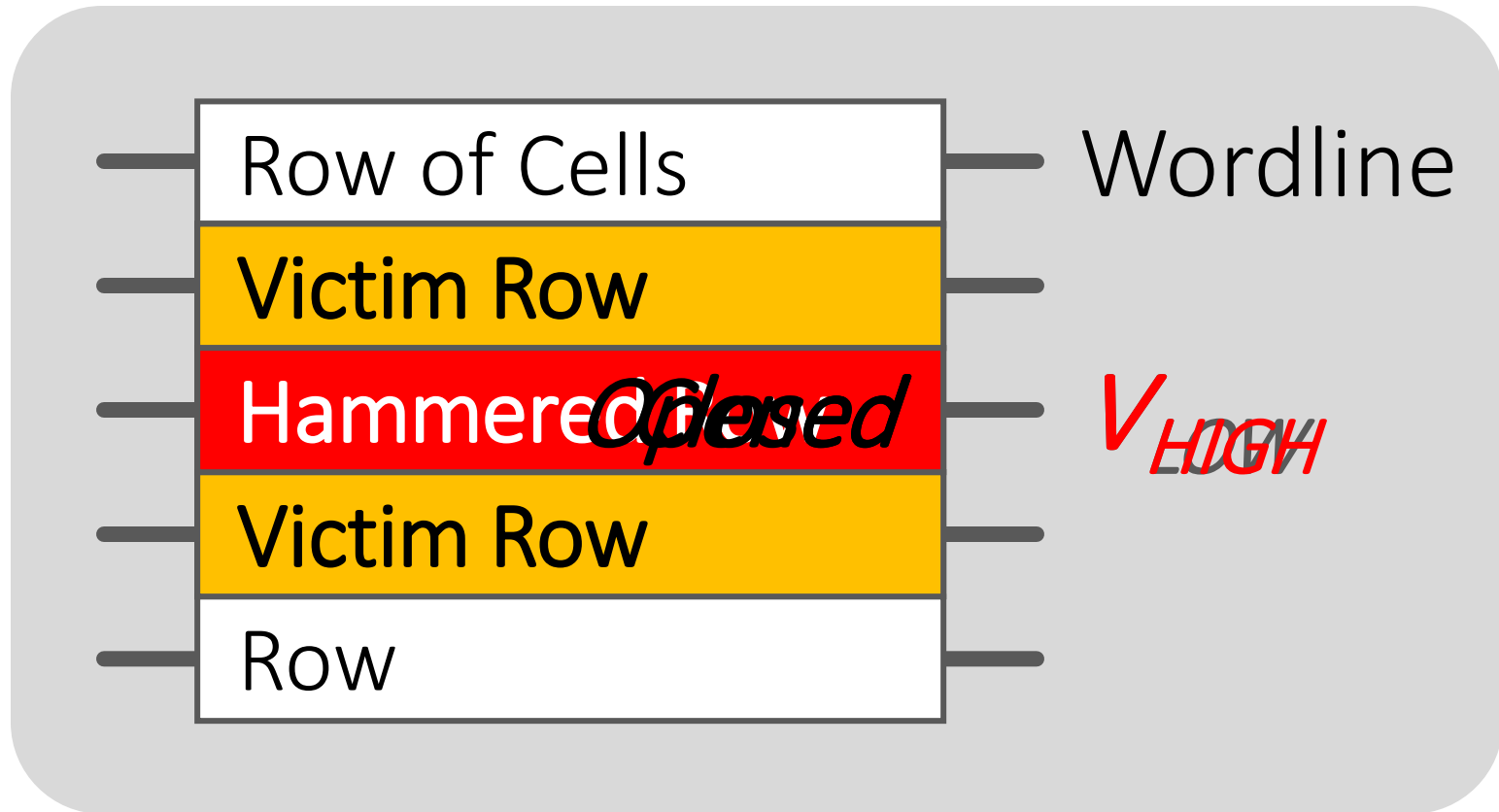
Five out of the box FPGA-based prototypes





# A Curious Phenomenon

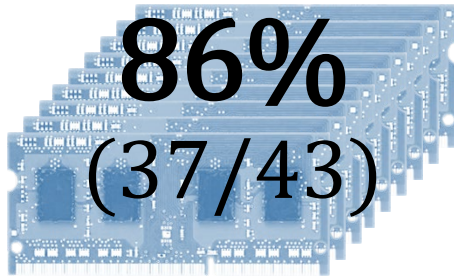
# Modern DRAM is Prone to Disturbance Errors



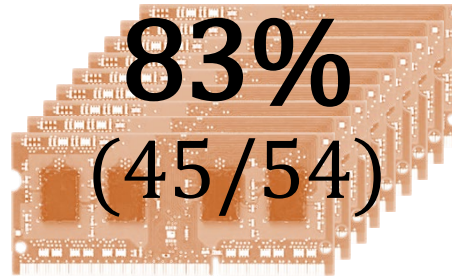
Repeatedly reading a row enough times (before memory gets refreshed) induces **disturbance errors** in **adjacent rows** in **most real DRAM chips you can buy today**

# Most DRAM Modules Are Vulnerable

A company



B company



C company

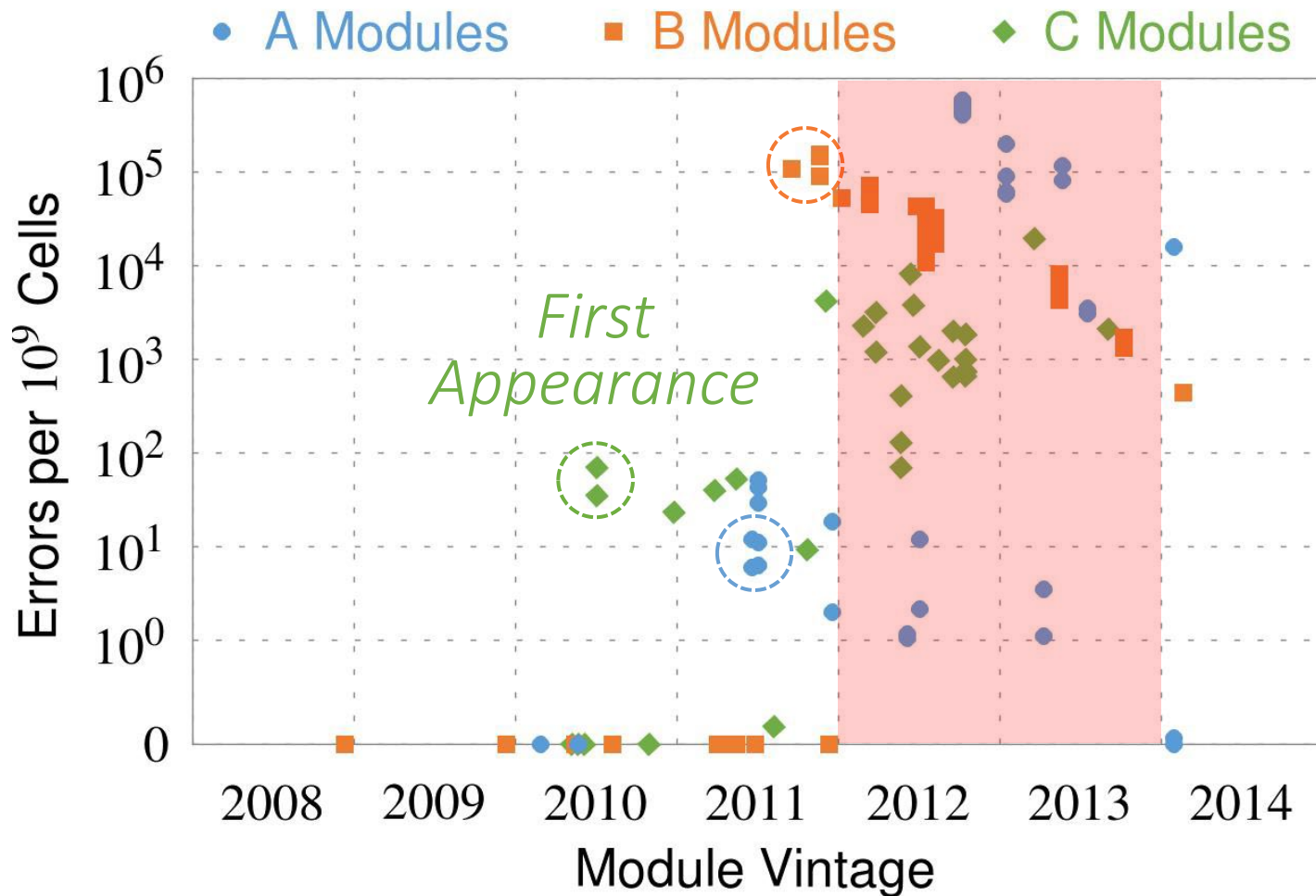


Up to  
 $1.0 \times 10^7$   
errors

Up to  
 $2.7 \times 10^6$   
errors

Up to  
 $3.3 \times 10^5$   
errors

# Recent DRAM Is More Vulnerable



*All modules from 2012-2013 are vulnerable*

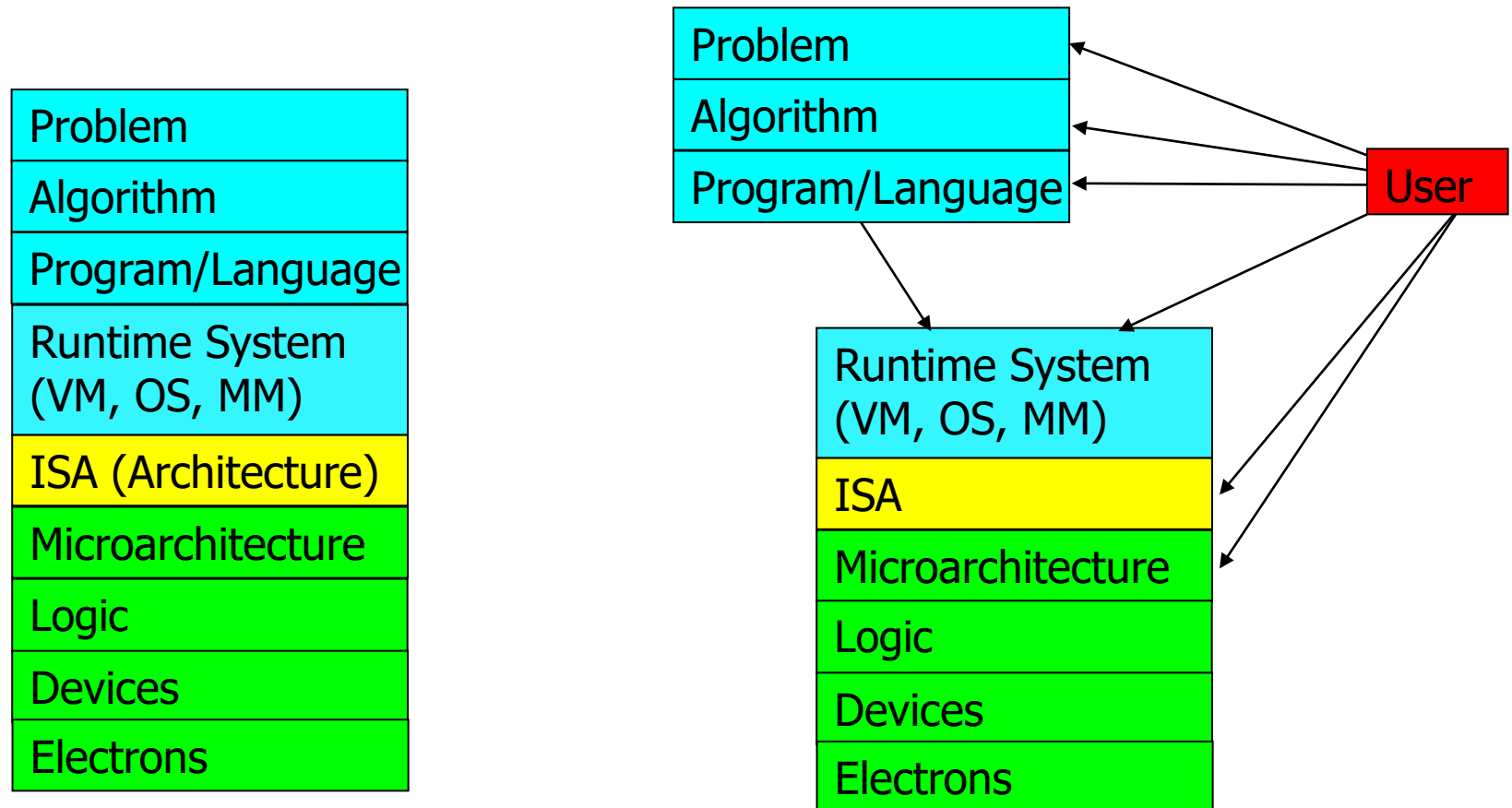
# Why Is This Happening?

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- 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

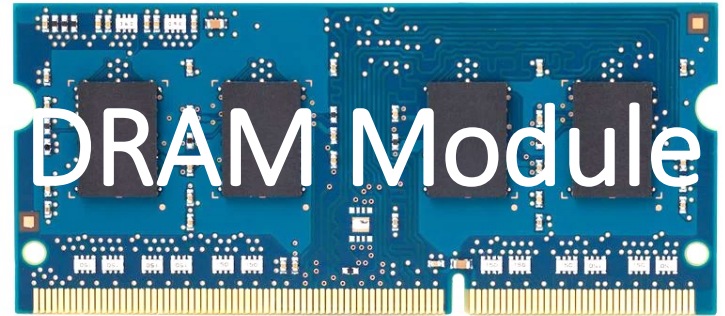
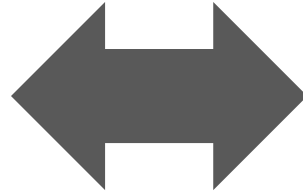
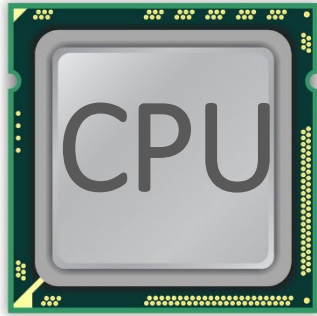
# Higher-Level Implications

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

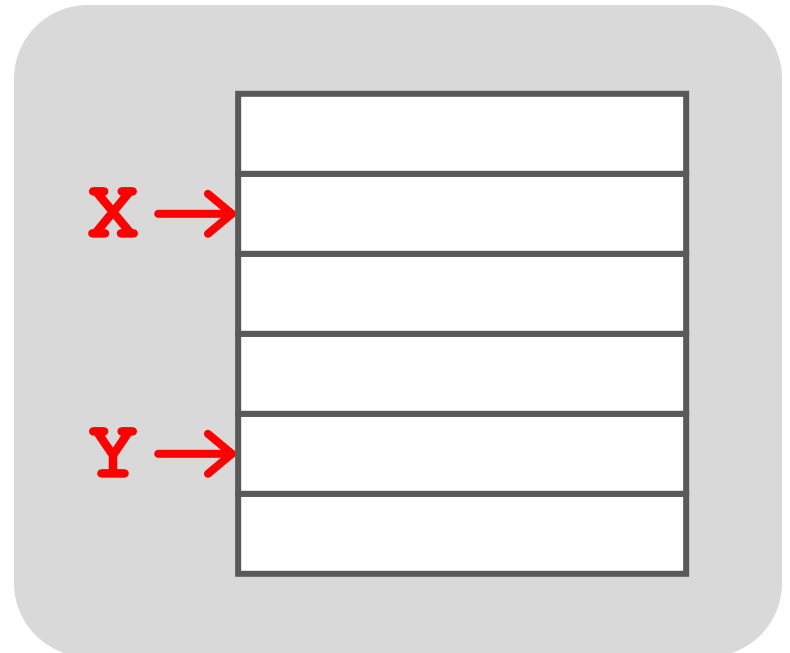




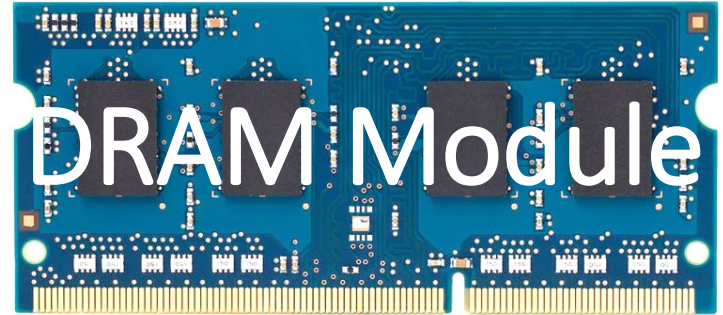
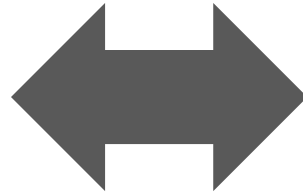
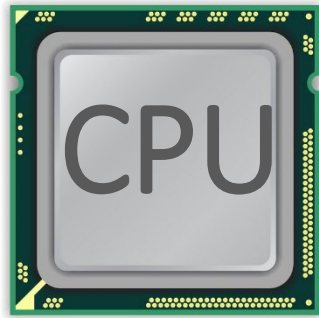
# A Simple Program Can Induce Many Errors



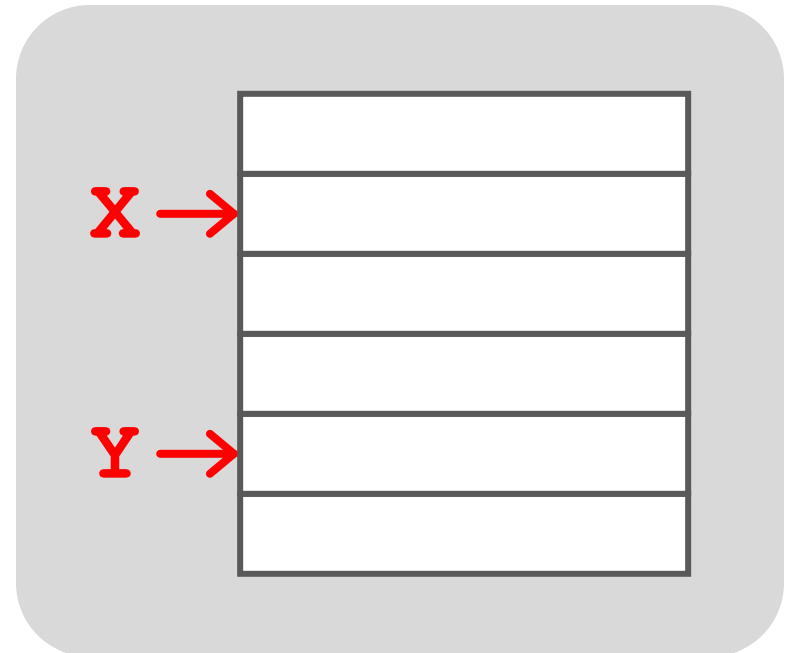
```
loop:  
  mov  (X), %eax  
  mov  (Y), %ebx  
  clflush (X)  
  clflush (Y)  
  mfence  
  jmp  loop
```



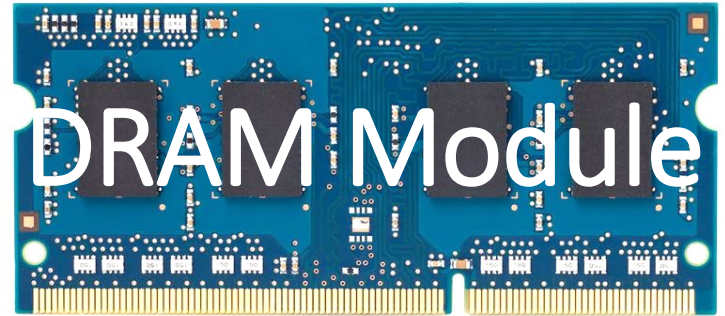
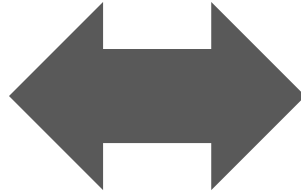
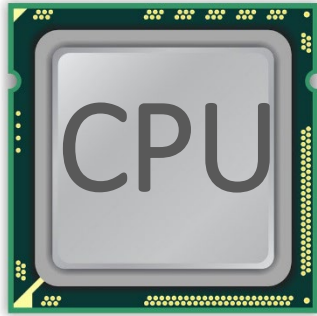
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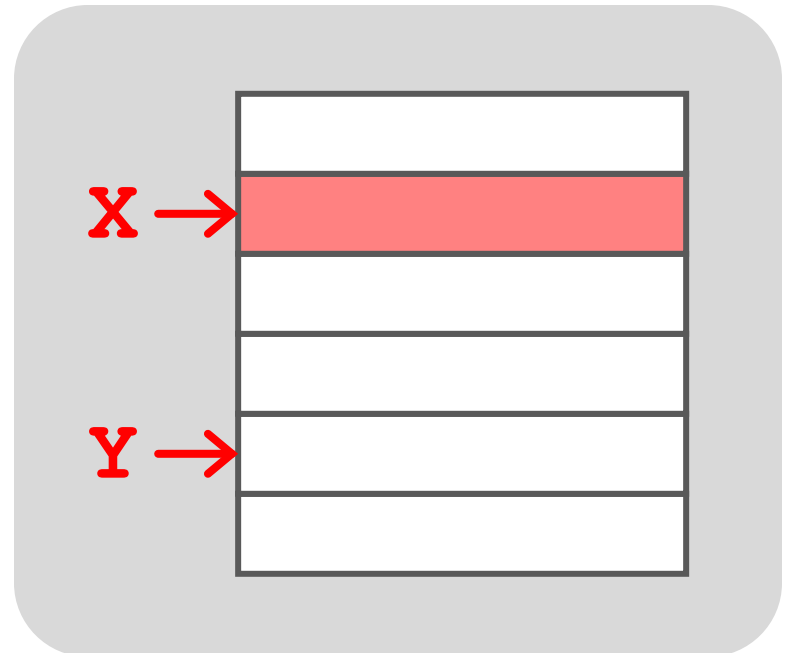
1. Avoid *cache hits*
  - Flush **X** from cache
2. Avoid *row hits* to **X**
  - Read **Y** in another row



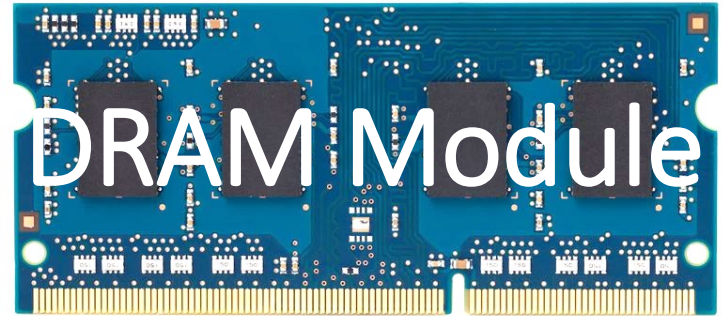
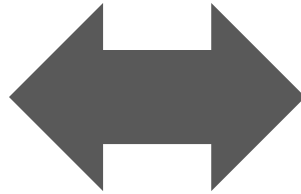
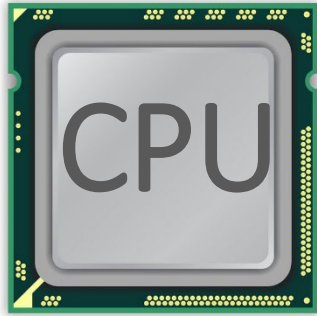
# A Simple Program Can Induce Many Errors



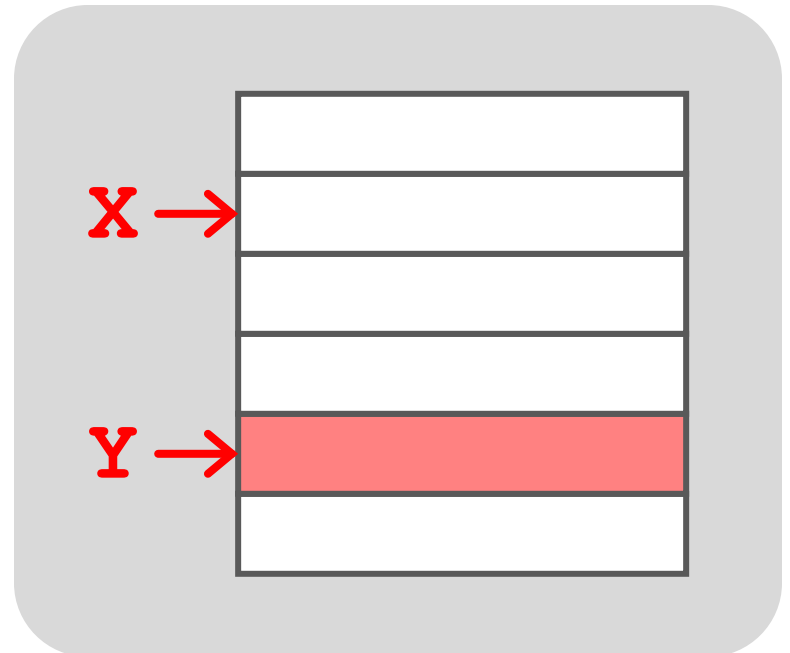
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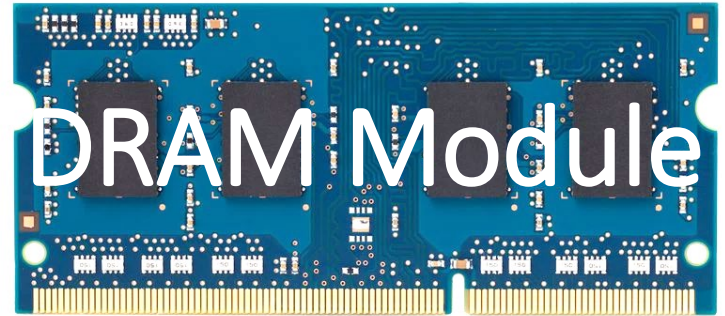
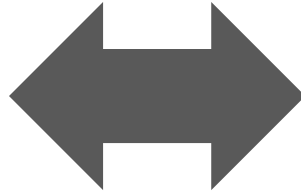
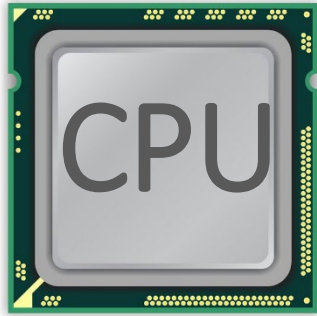
# A Simple Program Can Induce Many Errors



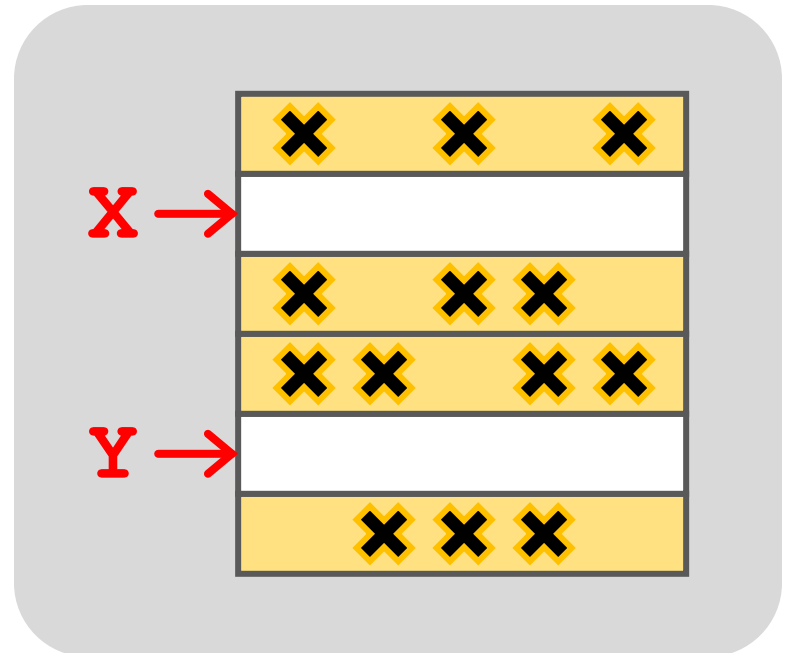
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  mfence  
  jmp  loop
```



# 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 reliability & security issue**



# One Can Take Over an Otherwise-Secure System

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## 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

# RowHammer Security Attack Example

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- “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

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# 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 34

# 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

Pietro Frigo  
Vrije Universiteit  
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Kaveh Razavi  
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Amsterdam  
kaveh@cs.vu.nl



# 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)

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## ■ 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

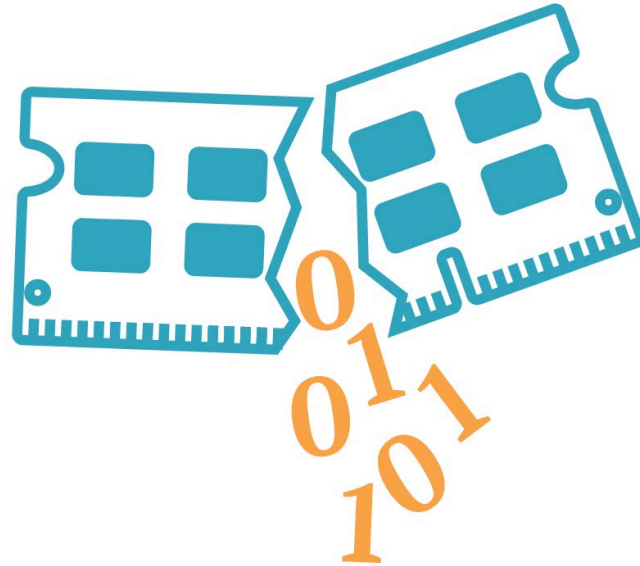
Lukas Raab  
Graz University of Technology

Lukas Lamster  
Graz University of Technology

# More Security Implications (VI)

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- IEEE S&P 2020



RAMBleed

## RAMBleed: Reading Bits in Memory Without Accessing Them

Andrew Kwong  
*University of Michigan*  
[ankwong@umich.edu](mailto:ankwong@umich.edu)

Daniel Genkin  
*University of Michigan*  
[genkin@umich.edu](mailto:genkin@umich.edu)

Daniel Gruss  
*Graz University of Technology*  
[daniel.gruss@iaik.tugraz.at](mailto:daniel.gruss@iaik.tugraz.at)

Yuval Yarom  
*University of Adelaide and Data61*  
[yval@cs.adelaide.edu.au](mailto:yval@cs.adelaide.edu.au)

# More Security Implications (VII)

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## ■ USENIX Security 2019

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

Sanghyun Hong, Pietro Frigo<sup>†</sup>, Yiğitcan Kaya, Cristiano Giuffrida<sup>†</sup>, Tudor Dumitraş

*University of Maryland, College Park*

*<sup>†</sup>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

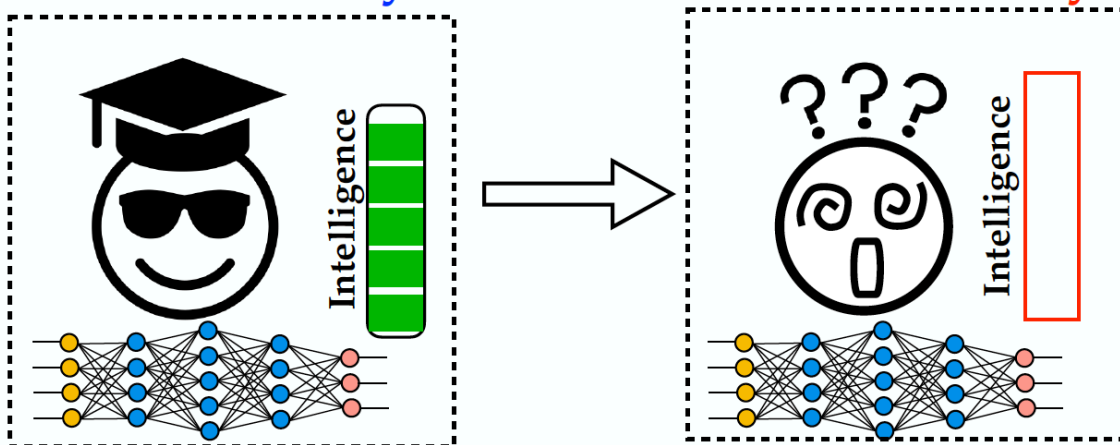
Adnan Siraj Rakin  
Arizona State University  
asrakin@asu.edu

Deliang Fan  
Arizona State University  
dfan@asu.edu

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?

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# A RowHammer Survey Across the Stack

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- 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<sup>§‡</sup>      Jeremie S. Kim<sup>‡§</sup>  
§ETH Zürich      ‡Carnegie Mellon University



# A RowHammer Survey: Recent Update

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- 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

A. Giray Yağlıkçı  
giray.yaglikci@safari.ethz.ch  
ETH Zürich  
Zürich, Switzerland

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

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# Understanding RowHammer

# First RowHammer 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"**

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*One of the 7 papers of 2012-2017 selected as Top Picks in Hardware and Embedded Security for IEEE TCAD (link).*

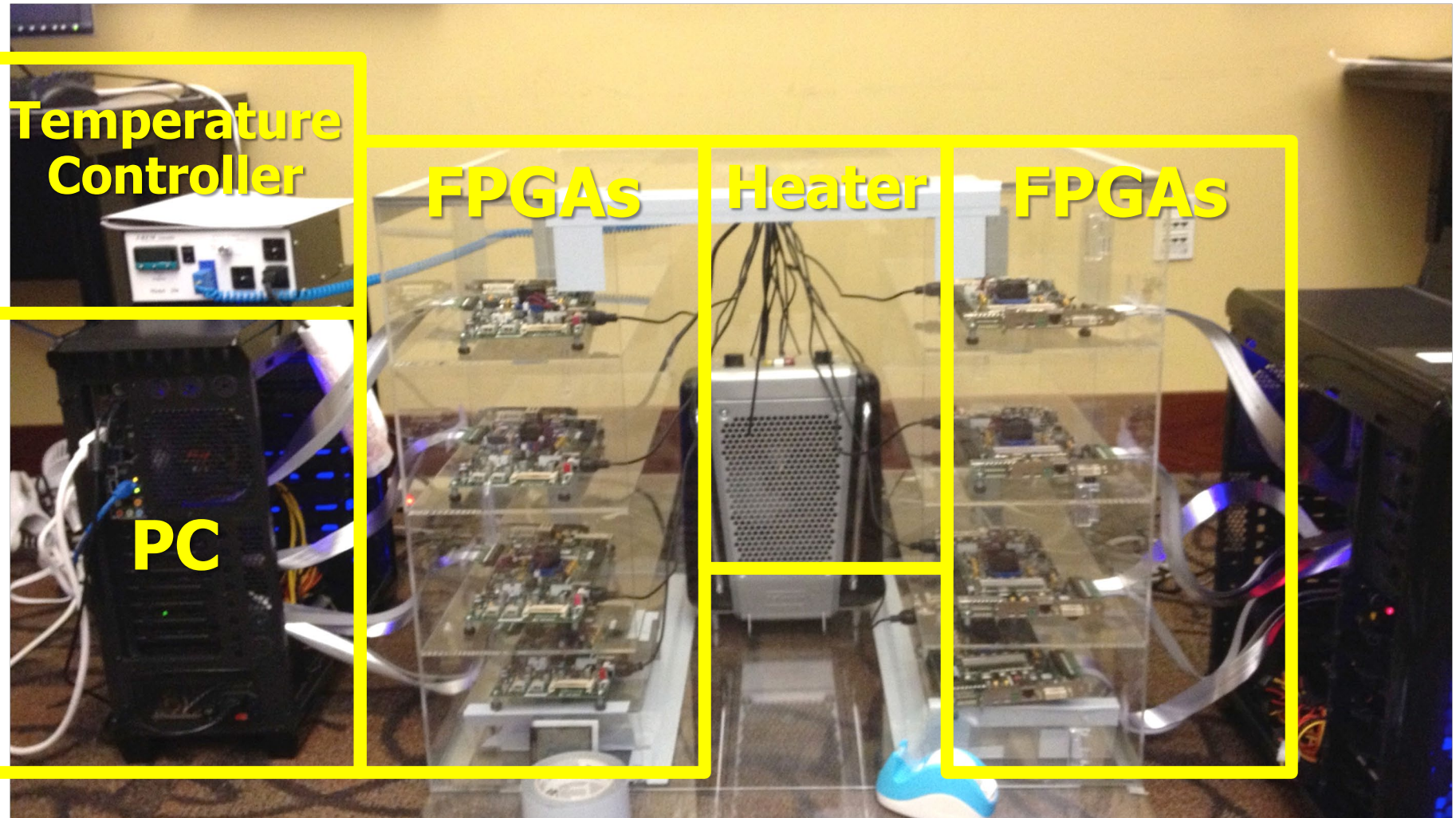
*Selected to the ISCA-50 25-Year Retrospective Issue covering 1996-2020 in 2023 (Retrospective (pdf) Full Issue).*

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

Yoongu Kim<sup>1</sup> Ross Daly\* Jeremie Kim<sup>1</sup> Chris Fallin\* Ji Hye Lee<sup>1</sup>  
Donghyuk Lee<sup>1</sup> Chris Wilkerson<sup>2</sup> Konrad Lai Onur Mutlu<sup>1</sup>

<sup>1</sup>Carnegie Mellon University      <sup>2</sup>Intel Labs

# RowHammer Infrastructure (2012-2014)



# Tested DRAM Modules from 2008-2014 (129 total)

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

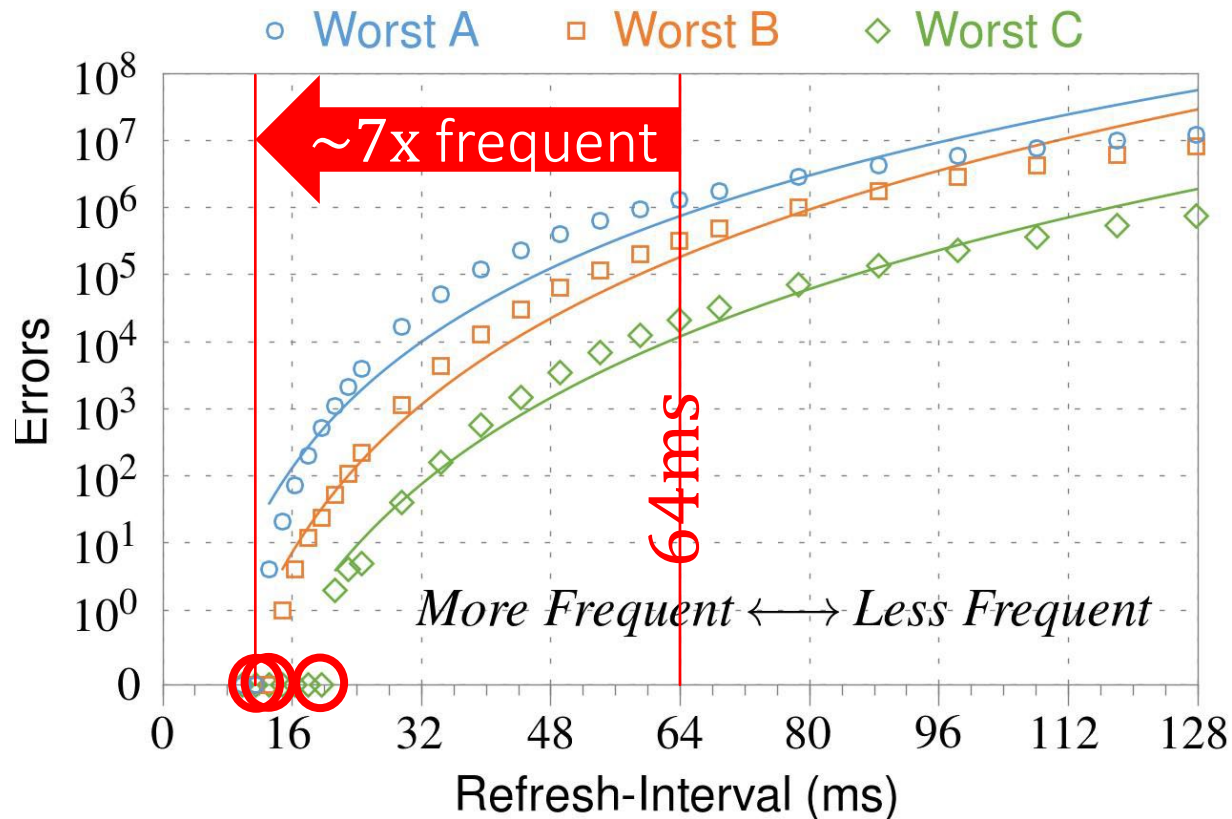
Table 3. Sample population of 129 DDR3 DRAM modules, categorized by manufacturer and sorted by manufacture date

# 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



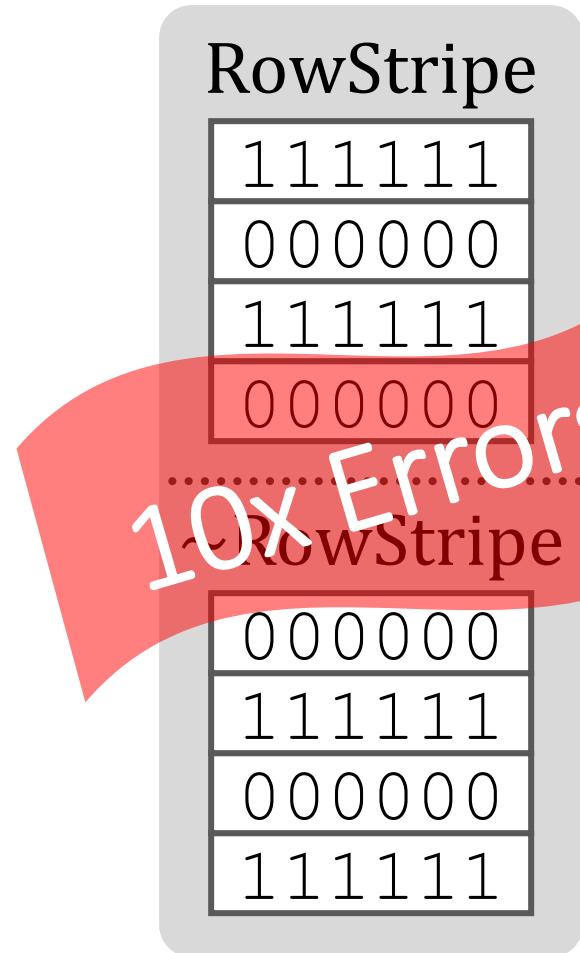
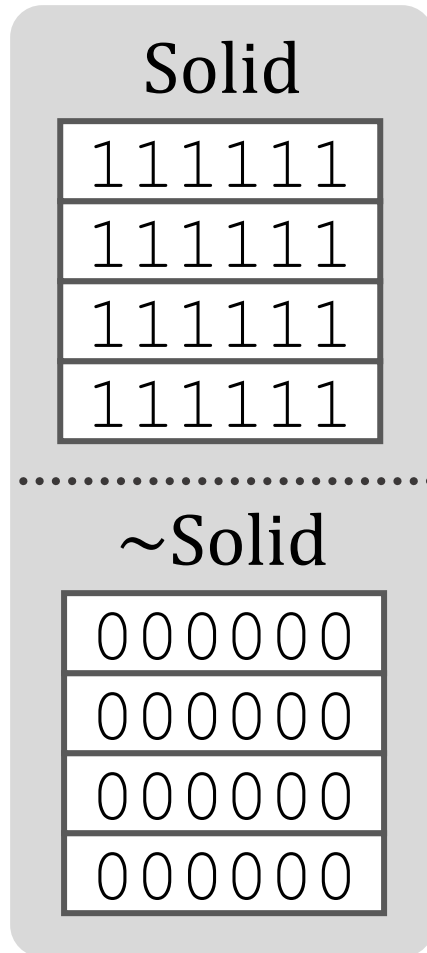
## 2 Refresh Interval



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

*More frequent refreshes → 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"**  
*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](#)).*

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

Yoongu Kim<sup>1</sup>   Ross Daly\*   Jeremie Kim<sup>1</sup>   Chris Fallin\*   Ji Hye Lee<sup>1</sup>  
Donghyuk Lee<sup>1</sup>   Chris Wilkerson<sup>2</sup>   Konrad Lai   Onur Mutlu<sup>1</sup>

<sup>1</sup>Carnegie Mellon University   <sup>2</sup>Intel Labs

# 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"**  
*Proceedings of the 47th International Symposium on Computer Architecture (ISCA)*, Valencia, Spain, June 2020.  
[[Slides \(pptx\)](#)] [[pdf](#)]  
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]  
[[Talk Video](#) (20 minutes)]  
[[Lightning Talk Video](#) (3 minutes)]

## Revisiting RowHammer: An Experimental Analysis of Modern DRAM Devices and Mitigation Techniques

Jeremie S. Kim<sup>§†</sup>      Minesh Patel<sup>§</sup>      A. Giray Yağlıkçı<sup>§</sup>  
Hasan Hassan<sup>§</sup>      Roknoddin Azizi<sup>§</sup>      Lois Orosa<sup>§</sup>      Onur Mutlu<sup>§†</sup>  
<sup>§</sup>*ETH Zürich*      <sup>†</sup>*Carnegie Mellon University*



# RowHammer Has Many Dimensions (2021)

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- 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](#)]  
[[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\*  
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ETH Zürich, TOBB ETÜ

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Hasan Hassan  
ETH Zürich

Minesh Patel  
ETH Zürich

Jeremie S. Kim  
ETH Zürich

Onur Mutlu  
ETH Zürich

# RowHammer vs. Wordline Voltage (2022)

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- 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 Yağlıkçı<sup>1</sup> Haocong Luo<sup>1</sup> Geraldo F. de Oliveira<sup>1</sup> Ataberk Olgun<sup>1</sup> Minesh Patel<sup>1</sup>  
Jisung Park<sup>1</sup> Hasan Hassan<sup>1</sup> Jeremie S. Kim<sup>1</sup> Lois Orosa<sup>1,2</sup> Onur Mutlu<sup>1</sup>  
<sup>1</sup>*ETH Zürich* <sup>2</sup>*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 Olgun<sup>1</sup> Majd Osseiran<sup>1,2</sup> A. Giray Yağlıkçı<sup>1</sup> Yahya Can Tuğrul<sup>1</sup>  
Haocong Luo<sup>1</sup> Steve Rhyner<sup>1</sup> Behzad Salami<sup>1</sup> Juan Gomez Luna<sup>1</sup> Onur Mutlu<sup>1</sup>  
<sup>1</sup>SAFARI Research Group, ETH Zürich      <sup>2</sup>American University of Beirut

# RowHammer Solutions

# Two Types of RowHammer Solutions

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## ■ Immediate

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

## ■ Longer-term

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

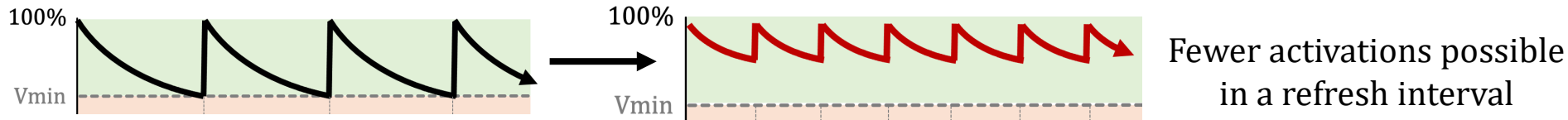
## ■ Our ISCA 2014 paper proposes both types of solutions

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

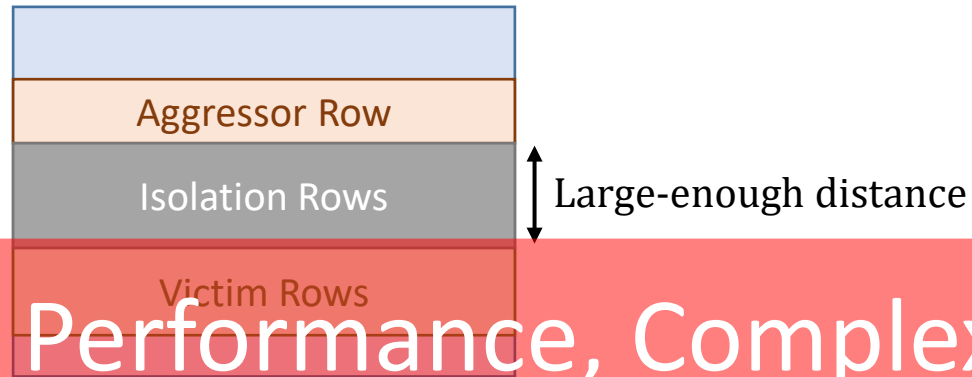


# RowHammer Solution Approaches

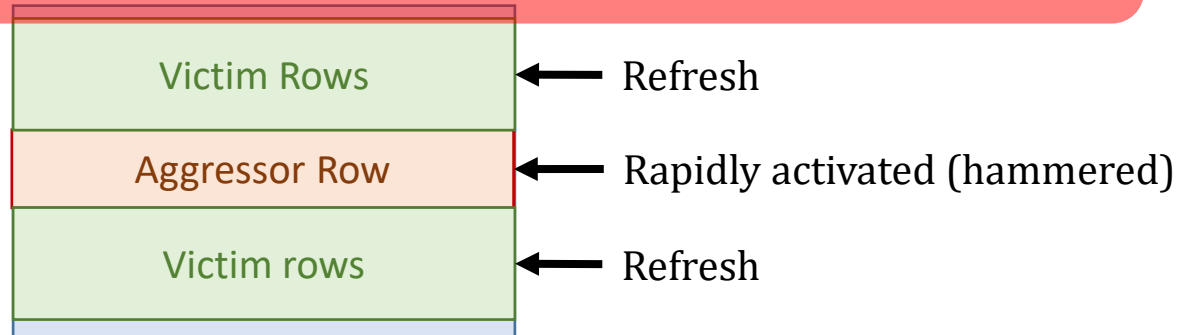
- More robust DRAM chips **and/or** error-correcting codes
- Increased refresh rate



- Physical isolation

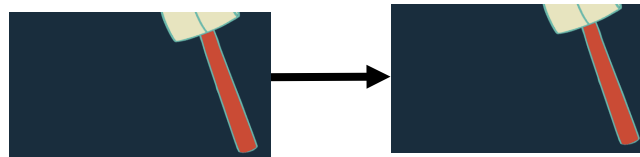


- Reactive refresh



- Proactive throttling

SAFARI



Fewer activations allowed for aggressive applications

# Apple's Security Patch for RowHammer

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- <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, we activate (i.e., refresh) one of its neighbors with a low probability:  $p = 0.005$
- Reliability Guarantee
  - When  $p=0.005$ , errors in one year:  $9.4 \times 10^{-14}$
  - By adjusting the value of  $p$ , we can vary the strength of protection against errors

# Advantages of PARA

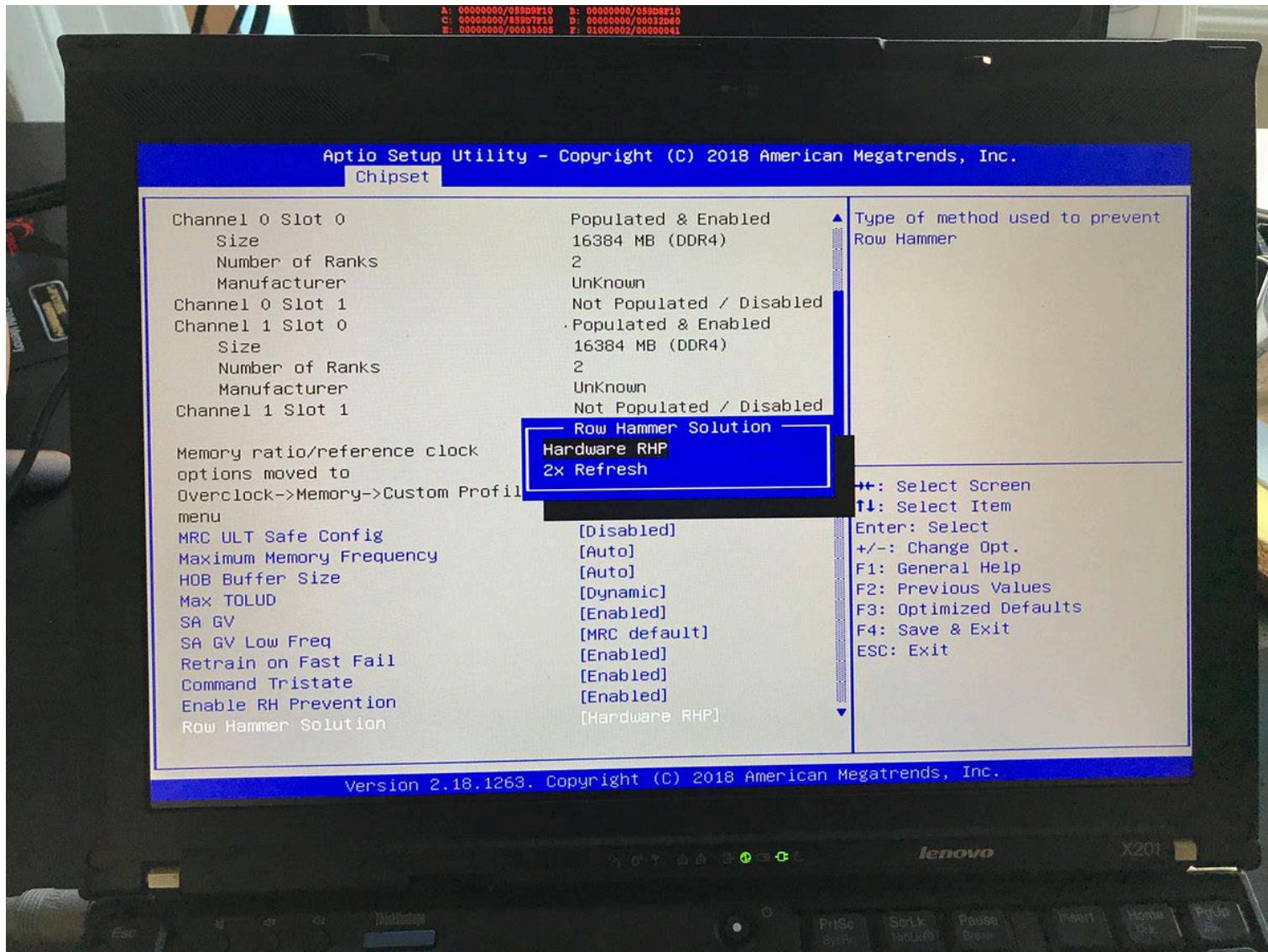
- *PARA refreshes rows infrequently*
  - Low power
  - Low performance-overhead
    - Average slowdown: **0.20%** (for 29 benchmarks)
    - Maximum slowdown: **0.75%**
- *PARA is stateless*
  - Low cost
  - Low complexity
- *PARA is an effective and low-overhead solution to prevent disturbance errors*

# Requirements for PARA

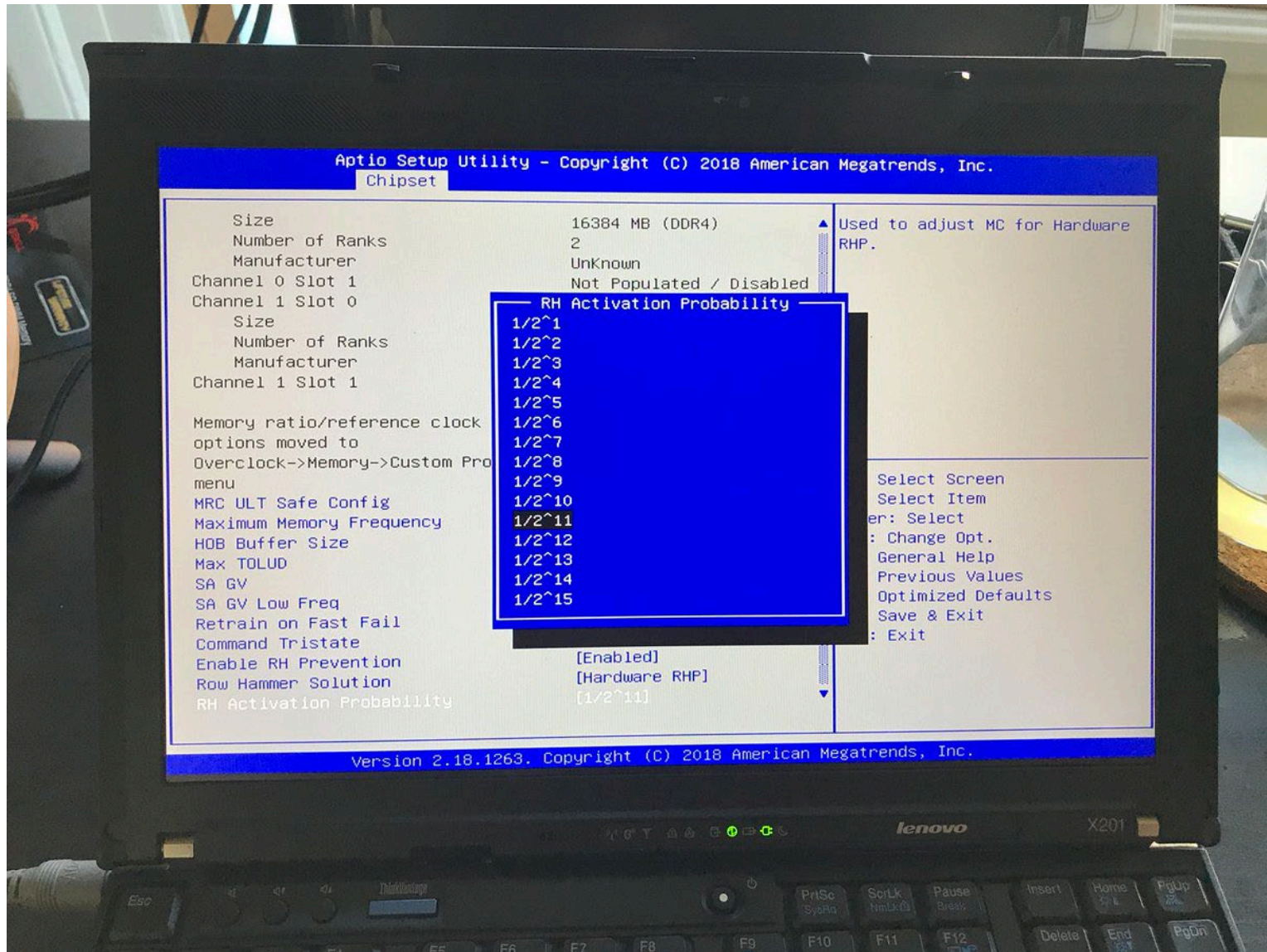
- If implemented in **DRAM chip** (done today)
  - Enough slack in timing and refresh parameters
  - Plenty of slack today:
    - Lee et al., “**Adaptive-Latency DRAM: Optimizing DRAM Timing for the Common Case**,” HPCA 2015.
    - Chang et al., “**Understanding Latency Variation in Modern DRAM Chips**,” 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,

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

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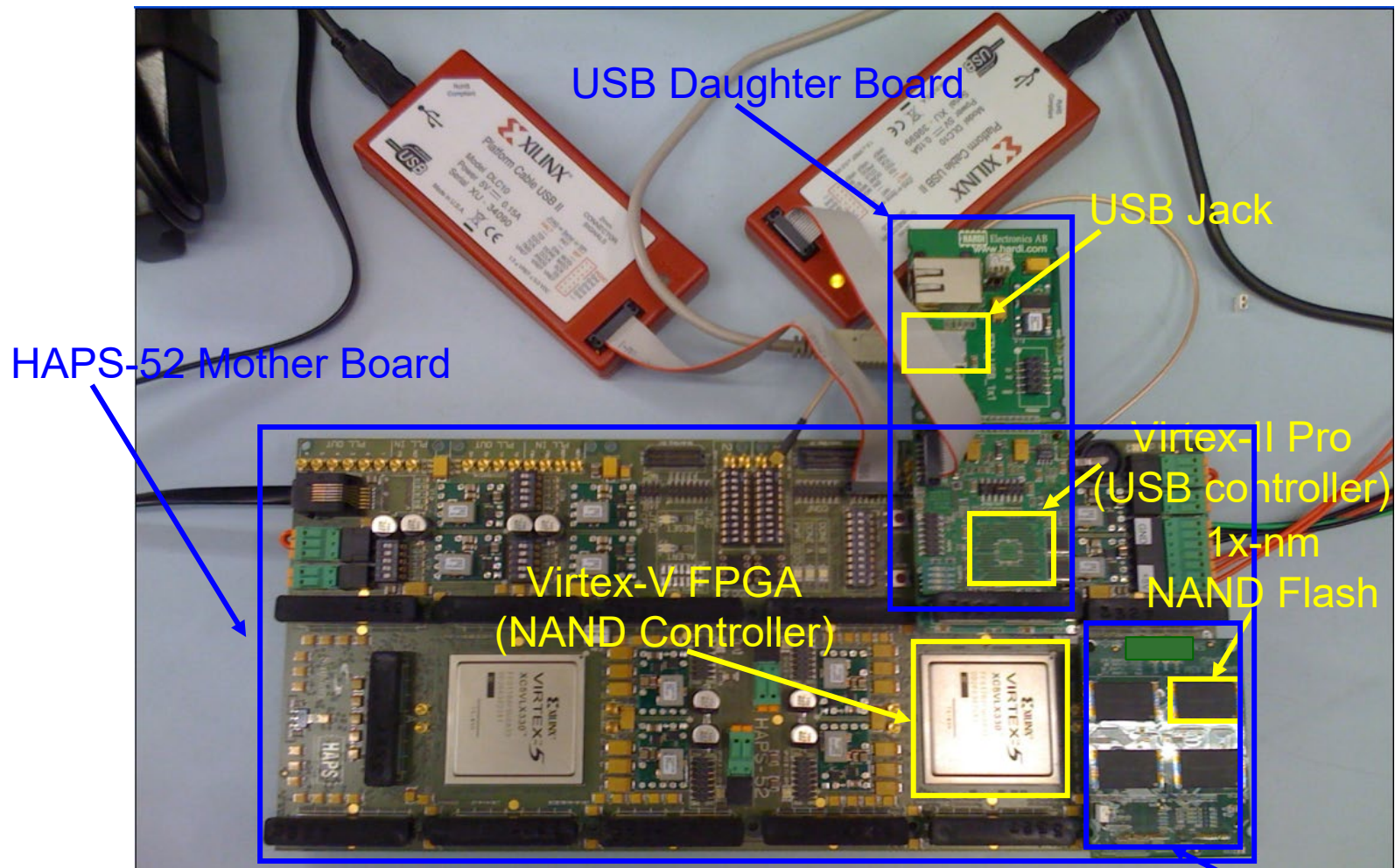
## **Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors**

Yoongu Kim<sup>1</sup>   Ross Daly\*   Jeremie Kim<sup>1</sup>   Chris Fallin\*   Ji Hye Lee<sup>1</sup>  
Donghyuk Lee<sup>1</sup>   Chris Wilkerson<sup>2</sup>   Konrad Lai   Onur Mutlu<sup>1</sup>

<sup>1</sup>Carnegie Mellon University   <sup>2</sup>Intel Labs

**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

<https://arxiv.org/pdf/1706.08642>

# 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 RowHammer 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 2020-2023

# Revisiting RowHammer

# RowHammer is Getting Much Worse

---

- 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"**  
*Proceedings of the 47th International Symposium on Computer Architecture (ISCA)*, Valencia, Spain, June 2020.  
[[Slides \(pptx\)](#)] [[pdf](#)]  
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]  
[[Talk Video](#) (20 minutes)]  
[[Lightning Talk Video](#) (3 minutes)]

## Revisiting RowHammer: An Experimental Analysis of Modern DRAM Devices and Mitigation Techniques

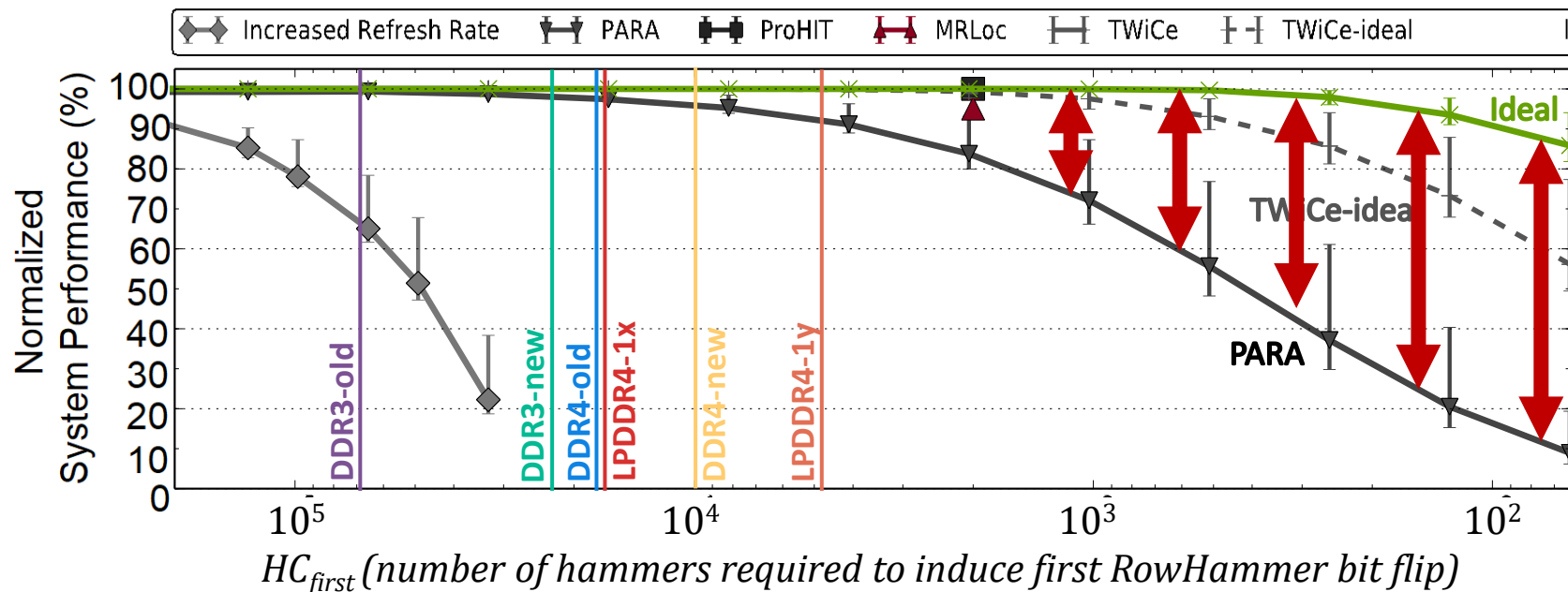
Jeremie S. Kim<sup>§†</sup>      Minesh Patel<sup>§</sup>      A. Giray Yağlıkçı<sup>§</sup>  
Hasan Hassan<sup>§</sup>      Roknoddin Azizi<sup>§</sup>      Lois Orosa<sup>§</sup>      Onur Mutlu<sup>§†</sup>  
<sup>§</sup>*ETH Zürich*      <sup>†</sup>*Carnegie Mellon University*



# 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**

# 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  $HC_{first}$

# 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  
ETH Zürich

Ataberk Olgun  
ETH Zürich, TOBB ETÜ

Jisung Park  
ETH Zürich

Hasan Hassan  
ETH Zürich

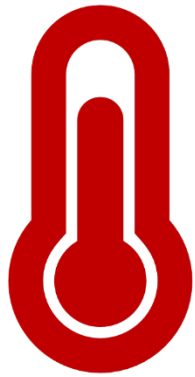
Minesh Patel  
ETH Zürich

Jeremie S. Kim  
ETH Zürich

Onur Mutlu  
ETH Zürich

# Our Goal

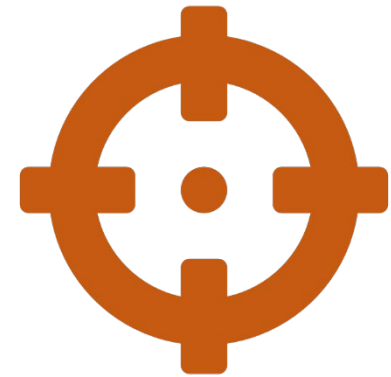
Provide insights into **three fundamental properties**



Temperature



Aggressor Row  
Active Time



Victim DRAM Cell's  
Physical Location

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

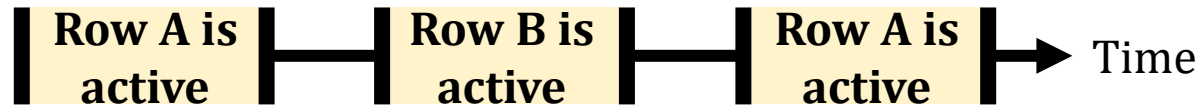


# Summary of The Study & Key Results

- **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:

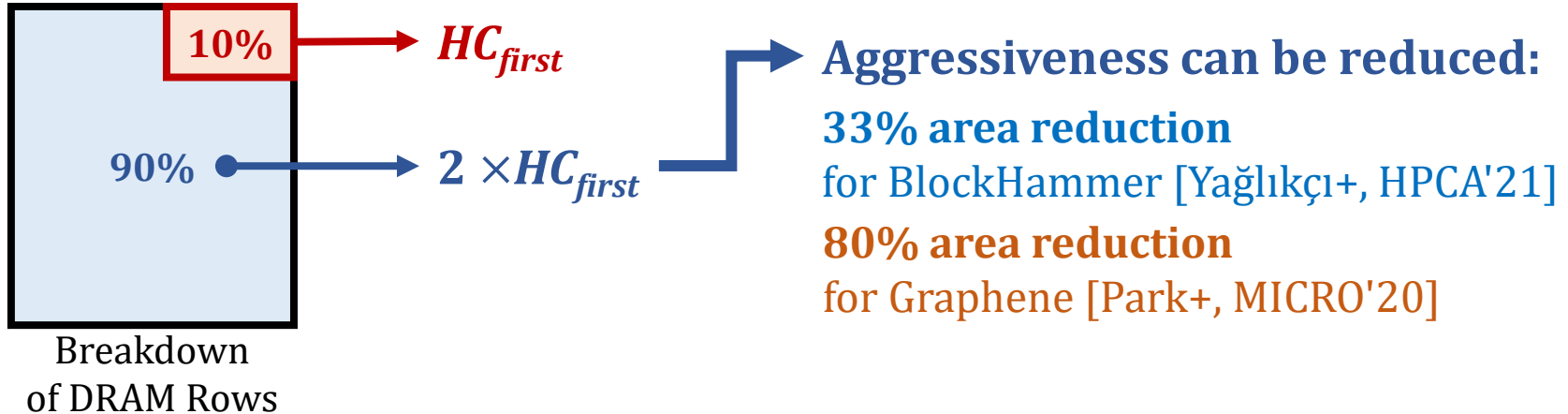


**Reduces** the minimum activation count to induce a bit flip **by 36%**

**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 Yaglici

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.  
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[[arXiv version](#)]  
[[Talk Video](#) (34 minutes, including Q&A)]  
[[Lightning Talk Video](#) (2 minutes)]

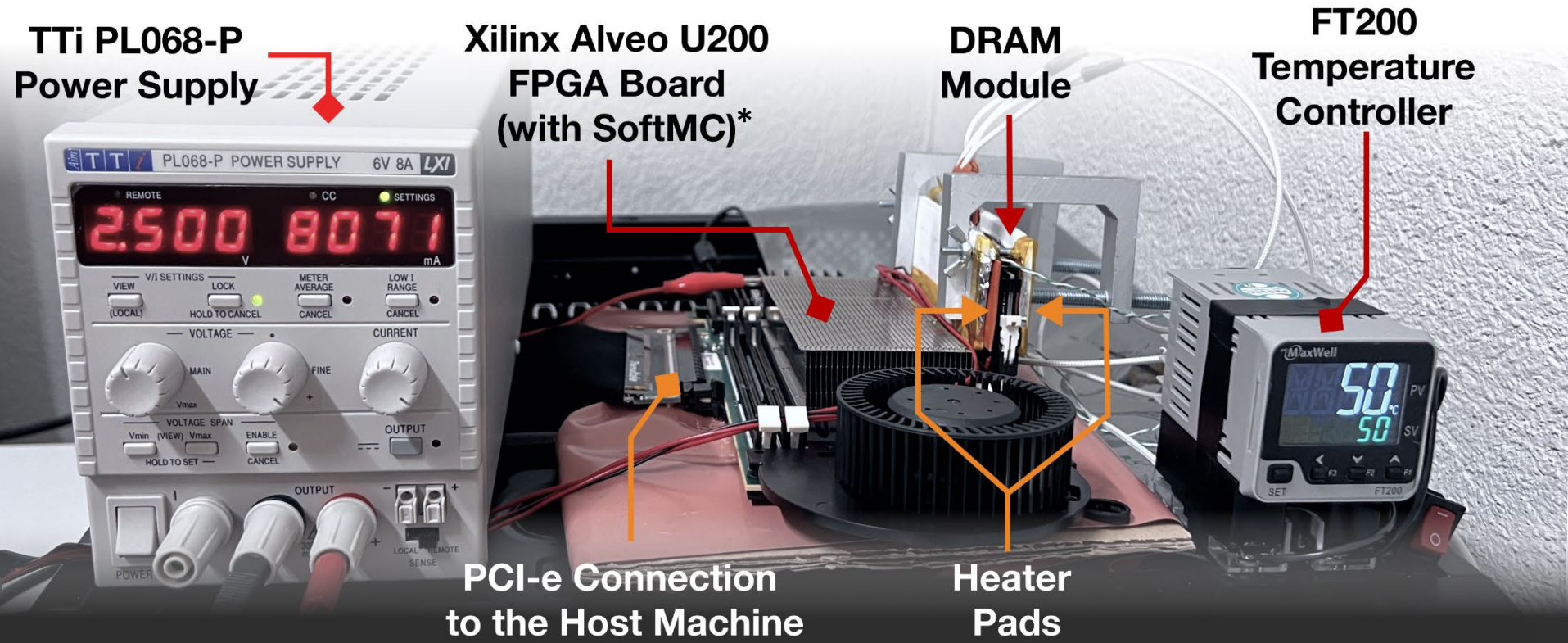
## Understanding RowHammer Under Reduced Wordline Voltage: An Experimental Study Using Real DRAM Devices

A. Giray Yağlıkçı<sup>1</sup> Haocong Luo<sup>1</sup> Geraldo F. de Oliveira<sup>1</sup> Ataberk Olgun<sup>1</sup> Minesh Patel<sup>1</sup>  
Jisung Park<sup>1</sup> Hasan Hassan<sup>1</sup> Jeremie S. Kim<sup>1</sup> Lois Orosa<sup>1,2</sup> Onur Mutlu<sup>1</sup>  
<sup>1</sup>*ETH Zürich* <sup>2</sup>*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

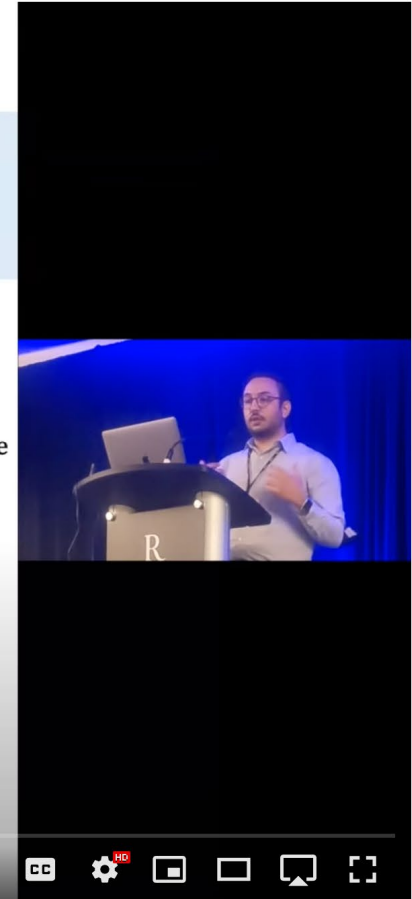
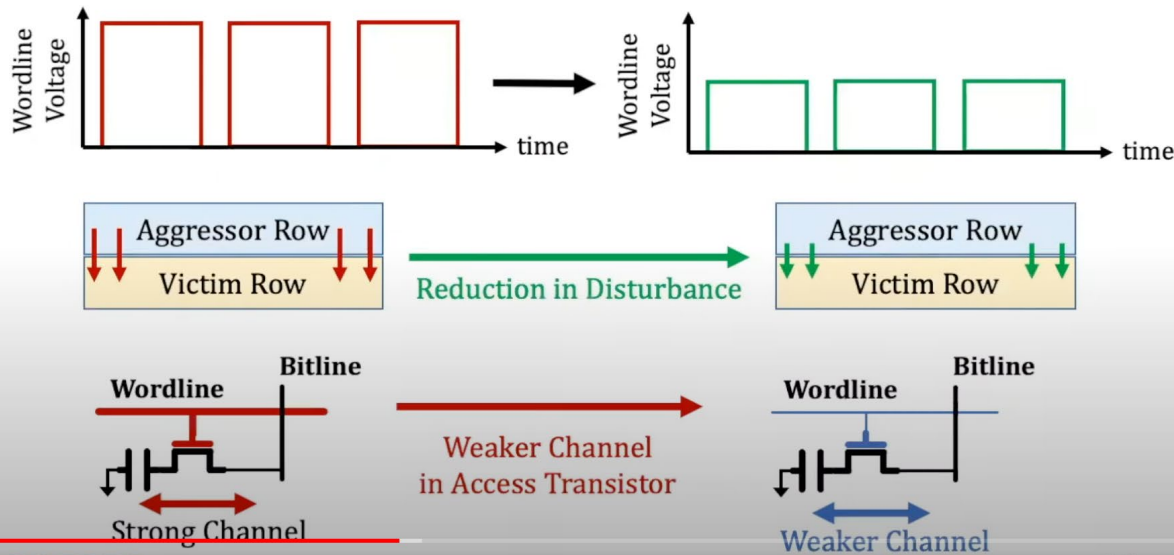
- **80%** of the tested DRAM chips **reliably operate using nominal refresh rate**
- Remaining **20%** **reliably operate** by
  - Using **single error correcting codes**
  - **Doubling the refresh rate** for **a small fraction (16.4%) of DRAM rows**

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 Olgun<sup>1</sup> Majd Osseiran<sup>1,2</sup> A. Giray Yağlıkçı<sup>1</sup> Yahya Can Tuğrul<sup>1</sup>  
Haocong Luo<sup>1</sup> Steve Rhyner<sup>1</sup> Behzad Salami<sup>1</sup> Juan Gomez Luna<sup>1</sup> Onur Mutlu<sup>1</sup>  
<sup>1</sup>SAFARI Research Group, ETH Zürich      <sup>2</sup>American University of Beirut

# New RowHammer Solutions

# Industry-Adopted Solutions Do Not Work

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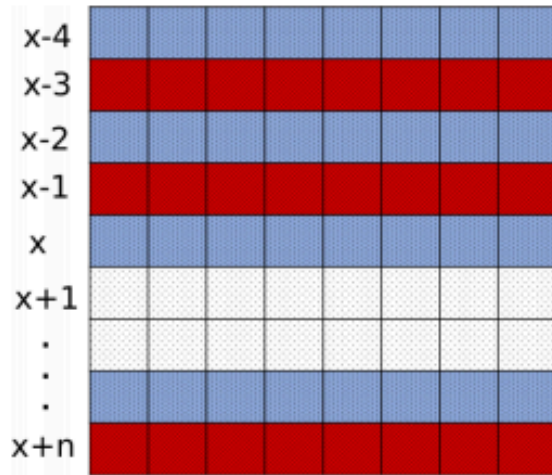
- Pietro Frigo, Emanuele Vannacci, Hasan Hassan, Victor van der Veen, Onur Mutlu, Cristiano Giuffrida, Herbert Bos, and Kaveh Razavi,  
**"TRRespass: Exploiting the Many Sides of Target Row Refresh"**  
*Proceedings of the 41st IEEE Symposium on Security and Privacy (S&P), San Francisco, CA, USA, May 2020.*  
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[Lecture Video] (59 minutes)  
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*Best paper award.*  
*Pwnie Award 2020 for Most Innovative Research.* Pwnie Awards 2020

## TRRespass: Exploiting the Many Sides of Target Row Refresh

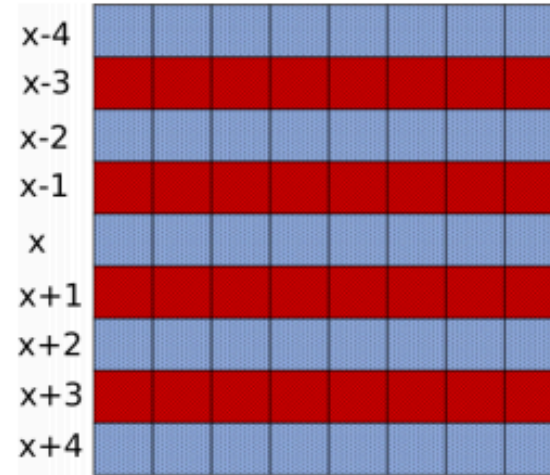
Pietro Frigo<sup>\*†</sup>   Emanuele Vannacci<sup>\*†</sup>   Hasan Hassan<sup>§</sup>   Victor van der Veen<sup>¶</sup>  
Onur Mutlu<sup>§</sup>   Cristiano Giuffrida<sup>\*</sup>   Herbert Bos<sup>\*</sup>   Kaveh Razavi<sup>\*</sup>



# 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 (■).

RowHammer is still  
an open problem

Security by obscurity  
is likely not a good solution

# 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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[[Talk Video](#) (25 minutes)]  
[[Lightning Talk Video](#) (100 seconds)]  
[[arXiv version](#)]

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

Hasan Hassan<sup>†</sup>

Yahya Can Tuğrul<sup>†‡</sup>

Jeremie S. Kim<sup>†</sup>

Victor van der Veen<sup>σ</sup>

Kaveh Razavi<sup>†</sup>

Onur Mutlu<sup>†</sup>

<sup>†</sup>ETH Zürich

<sup>‡</sup>TOBB University of Economics & Technology

<sup>σ</sup>Qualcomm Technologies Inc.

# 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 <sup>†</sup>	Max. Bit Flips per Row per Hammer <sup>†</sup>
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

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

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## 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 Kogler<sup>1</sup>   Jonas Juffinger<sup>1,2</sup>   Salman Qazi<sup>3</sup>   Yoongu Kim<sup>3</sup>   Moritz Lipp<sup>4\*</sup>  
Nicolas Boichat<sup>3</sup>   Eric Shiu<sup>5</sup>   Mattias Nissler<sup>3</sup>   Daniel Gruss<sup>1</sup>

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

# 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.

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[[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 Yağlıkçı<sup>1</sup> Minesh Patel<sup>1</sup> Jeremie S. Kim<sup>1</sup> Roknoddin Azizi<sup>1</sup> Ataberk Olgun<sup>1</sup> Lois Orosa<sup>1</sup>  
Hasan Hassan<sup>1</sup> Jisung Park<sup>1</sup> Konstantinos Kanellopoulos<sup>1</sup> Taha Shahroodi<sup>1</sup> Saugata Ghose<sup>2</sup> Onur Mutlu<sup>1</sup>

<sup>1</sup>ETH Zürich

<sup>2</sup>University of Illinois at Urbana-Champaign

# Two Key Challenges

1

## **Scalability**

with worsening RowHammer vulnerability

2

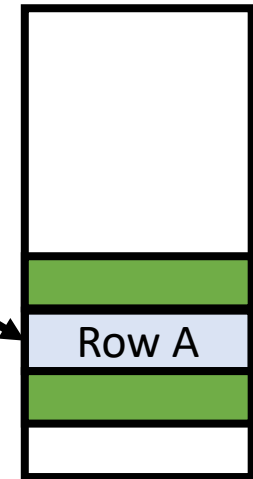
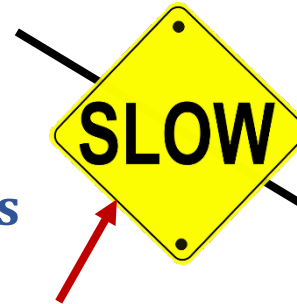
## **Compatibility**

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



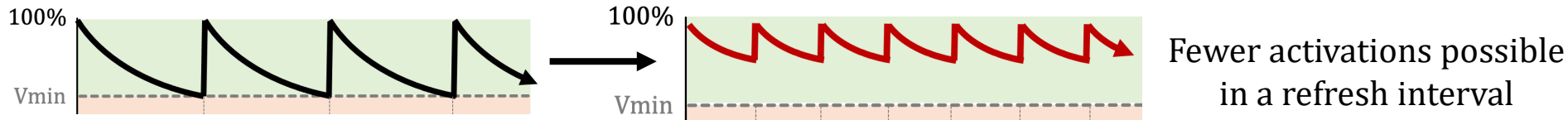
Physical  
Row Layout

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

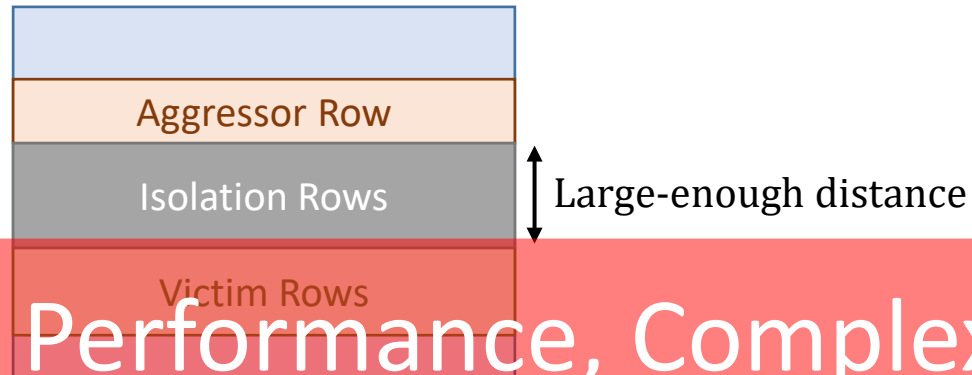
**Main Memory Needs**  
**Intelligent Controllers**  
**for Security, Safety,**  
**Reliability, Scaling**

# RowHammer Solution Approaches

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

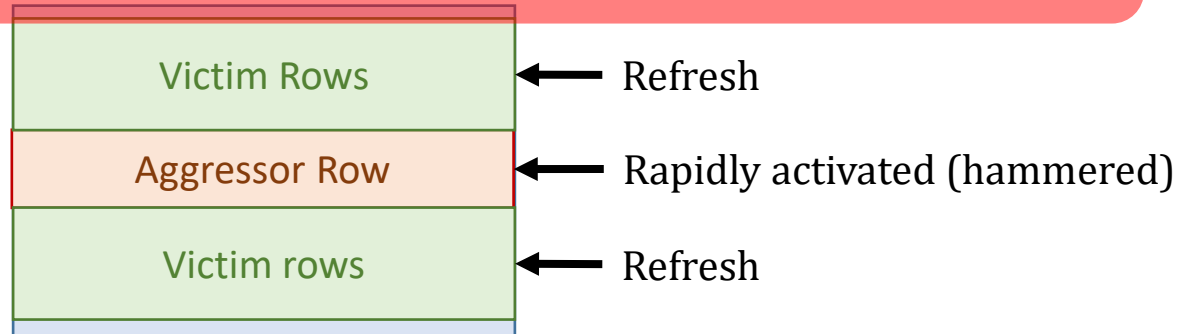


- Physical isolation



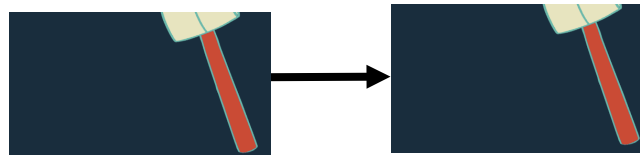
Cost, Power, Performance, Complexity

- 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



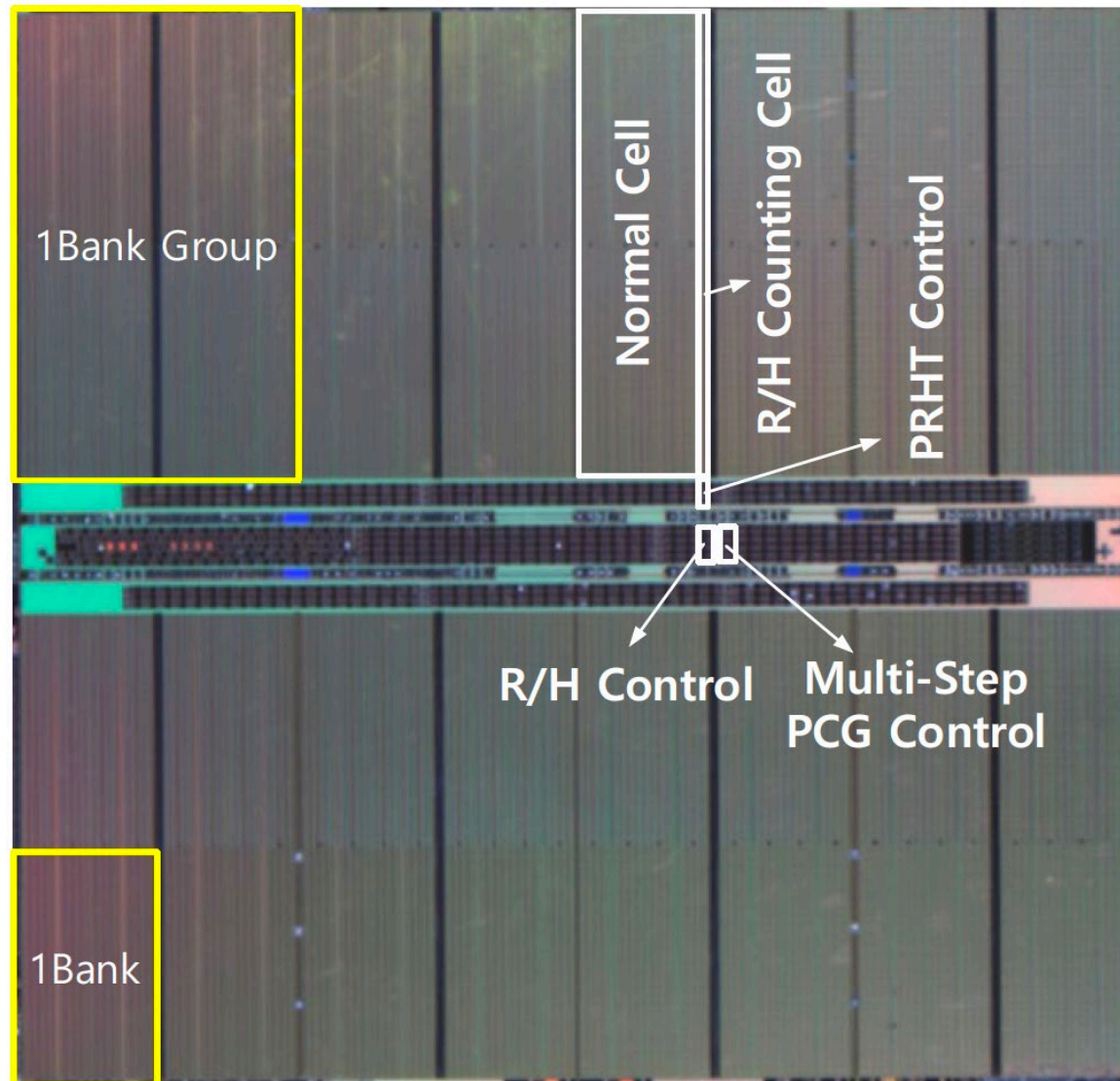
# Industry's RowHammer Solutions (I)

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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, Dhyong 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

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## 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>

Are we now  
RowHammer-free  
in 2023 and Beyond?

# Are We Now RowHammer Free in 2023?

---

- **Appeared at ISCA in June 2023**

## **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://people.inf.ethz.ch/omutlu/pub/RowPress\\_isca23.pdf](https://people.inf.ethz.ch/omutlu/pub/RowPress_isca23.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.*

## 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

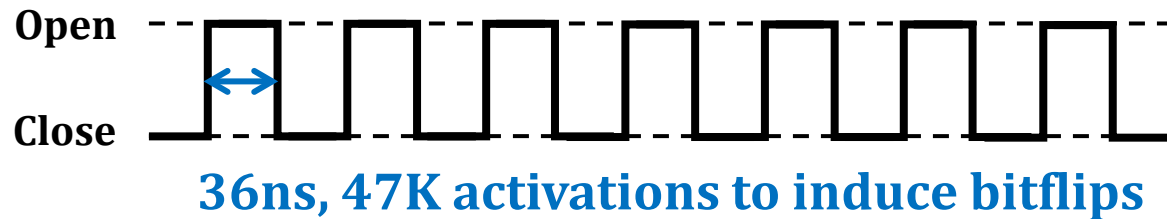
- We demonstrate and analyze **RowPress, a new read disturbance phenomenon** that causes bitflips in real DRAM chips
- We show that RowPress is **different from the RowHammer vulnerability**
- We demonstrate RowPress **using a user-level program** on a real Intel system with real DRAM chips
- We provide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

# RowPress vs. RowHammer

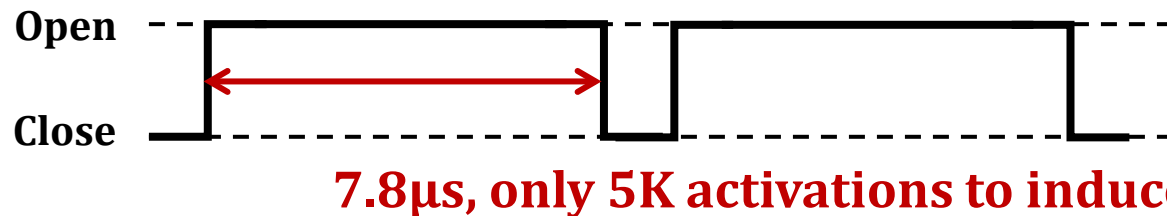
Instead of using a high activation count,

👉 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

# Major Takeaways from Real DRAM Chips

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

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



# Real-System Demonstration (I)



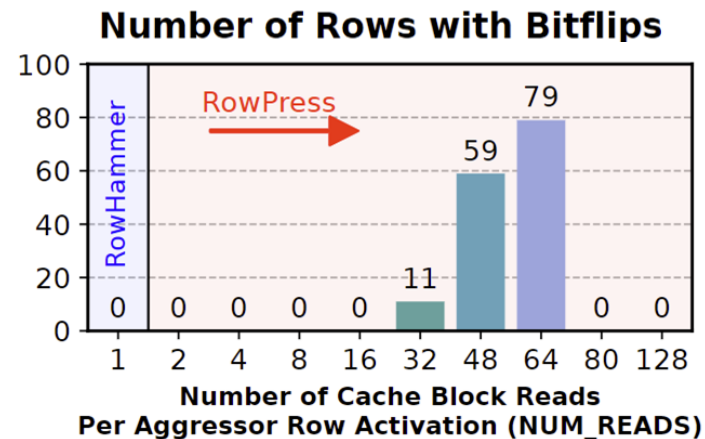
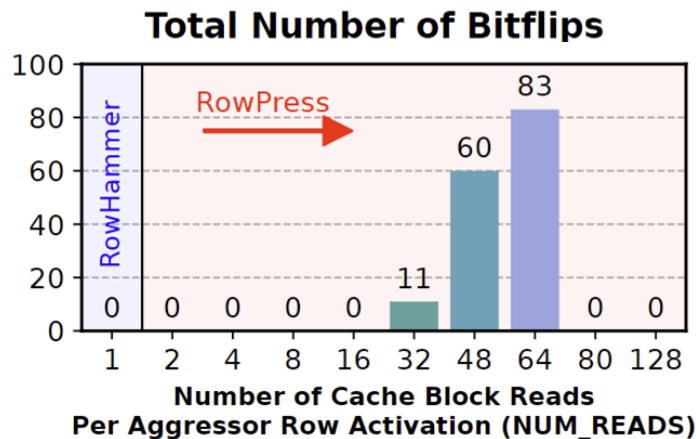
**Intel Core i5-10400**  
**(Comet Lake)**



**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**

# Real-System Demonstration (II)



**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**

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

# 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.*

## 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 RowHammer Directions

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- **Understanding RowHammer (DRAM 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 RowHammer**
  - Flexible and efficient RowHammer solutions are necessary
    - In-field patchable / reconfigurable / programmable solutions
  - Co-architecting System and Memory 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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Zürich, Switzerland

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A. Giray Yağlıkçı  
giray.yaglikci@safari.ethz.ch  
ETH Zürich  
Zürich, Switzerland

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

---

## A Case for Transparent Reliability in DRAM Systems

Minesh Patel<sup>†</sup> Taha Shahroodi<sup>‡‡</sup> Aditya Manglik<sup>†</sup> A. Giray Yağlıkçı<sup>†</sup>  
Ataberk Olgun<sup>†</sup> Haocong Luo<sup>†</sup> Onur Mutlu<sup>†</sup>

<sup>†</sup>*ETH Zürich* <sup>‡</sup>*TU Delft*

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

# Better Coordination 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>

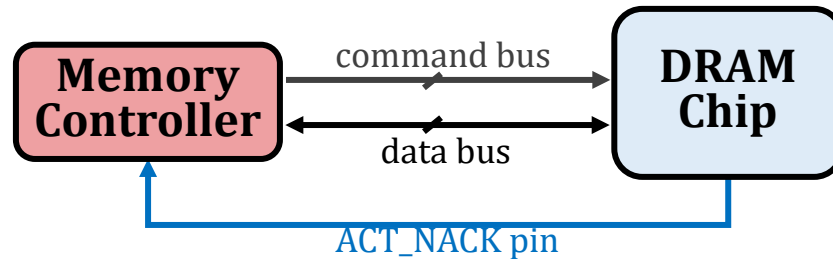
# Self-Managing DRAM: Overview

## 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*

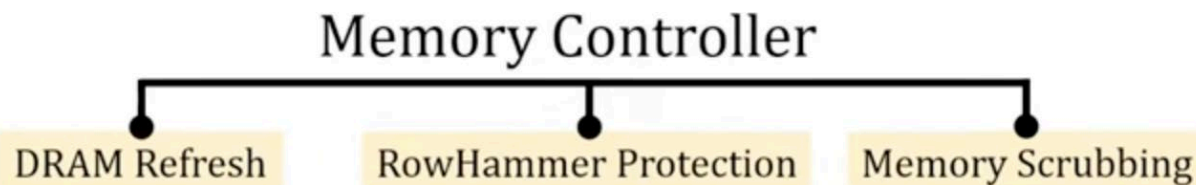
SMD-based *refresh*, *RowHammer protection*, and *scrubbing* achieve **9.2% speedup** and **6.2% lower DRAM energy** vs. conventional DRAM



# 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



1:57:08 / 3:37:58

SoftMC (HPCA'17) > U-TRR (MICRO'21) > SMD (Ongoing) > CROW (ISCA'19)



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

# Future Memory Reliability/Security Challenges

# Collapse of the “Galloping Gertie” (1940)

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# Another Example (1994)





# Yet Another Example (2007)

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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**



# Comp Arch (Fall 2022)



Computer Architecture - Fall 2022

Recent Changes Media Manager Sitemap

Trace: start schedule

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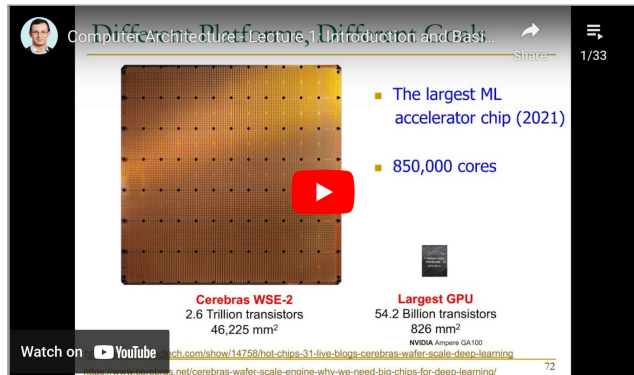
- Lectures/Schedule
- Lecture Buzzwords
- Readings
- HWs
- Labs
- Exams
- Related Courses
- Tutorials

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)

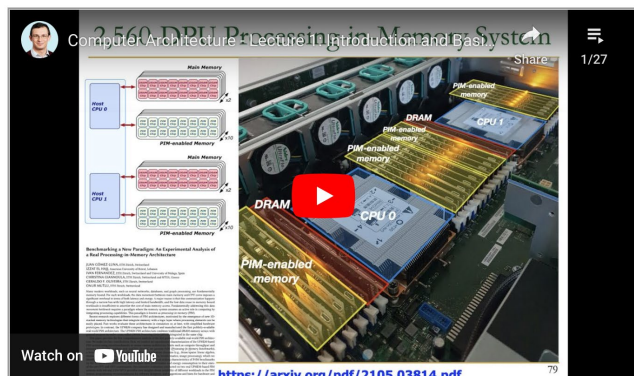
## Lecture Video Playlist on YouTube

Livestream Lecture Playlist



Watch on YouTube [https://www.youtube.com/watch?v=4yfkM\\_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF](https://www.youtube.com/watch?v=4yfkM_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF)

Lecture Playlist from Fall 2021



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

## Fall 2022 Lectures & Schedule

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

# 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](https://www.youtube.com/watch?v=LbC0EZY8yw4&list=PL5Q2soXY2Zi_uej3aY39YB5pfW4SJ7LIN)

## Bachelor's course

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

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



Digital Design and Computer Architecture -  
Spring 2021

Trace: [schedule](#)

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- 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

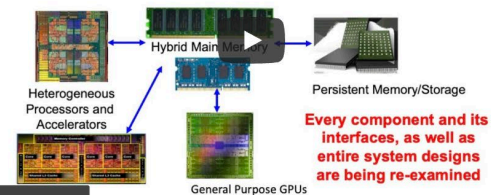
Livestream Lecture Playlist





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






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.	 Live	<b>L1: Introduction and Basics</b> <a href="#">Q2A (PDF)</a> <a href="#">Q2B (PPT)</a>	Required Suggested Mentioned		
			<b>L2a: Tradeoffs, Metrics, Mindset</b> <a href="#">Q2A (PDF)</a> <a href="#">Q2B (PPT)</a>	Required		
	26.02 Fri.	 Live	<b>L2b: Mysteries in Computer Architecture</b> <a href="#">Q2A (PDF)</a> <a href="#">Q2B (PPT)</a>	Required Mentioned		
W2	04.03 Thu.	 Live	<b>L3a: Mysteries in Computer Architecture II</b> <a href="#">Q2A (PDF)</a> <a href="#">Q2B (PPT)</a>	Required Suggested Mentioned		

# RowHammer & DRAM Exploration (Fall 2022)

## Fall 2022 Edition:

- [https://safari.ethz.ch/projects\\_and\\_seminars/fall2022/doku.php?id=softmc](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](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](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.		<b>P&amp;S SoftMC Tutorial</b>	SoftMC Tutorial Slides (PDF)  (PPT)	
W1	08.03 Tue.		<b>M1: Logistics &amp; Intro to DRAM and SoftMC</b> (PDF)  (PPT)	Required Materials Recommended Materials	HW0
W2	15.03 Tue.		<b>M2: Revisiting RowHammer</b> (PDF)  (PPT)	(Paper PDF)	
W3	22.03 Tue.		<b>M3: Uncovering in-DRAM TRR &amp; TRRespass</b> (PDF)  (PPT)		
W4	29.03 Tue.		<b>M4: Deeper Look Into RowHammer's Sensitivities</b> (PDF)  (PPT)		
W5	05.04 Tue.		<b>M5: QUAC-TRNG</b> (PDF)  (PPT)		
W6	12.04 Tue.		<b>M6: PiDRAM</b> (PDF)  (PPT)		

# Exploration of Emerging Memory Systems (Fall 2022)

## Fall 2022 Edition:

- ❑ [https://safari.ethz.ch/projects\\_and\\_seminars/fall2022/doku.php?id=ramulator](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](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](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.	Video	M1: Logistics & Intro to Simulating Memory Systems Using Ramulator (PDF)  (PPT)		HW0
W2	16.03 Fri.	Video	M2: Tutorial on Using Ramulator (PDF)  (PPT)		
W3	25.02 Fri.	Video	M3: BlockHammer (PDF)  (PPT)		
W4	01.04 Fri.	Video	M4: CLR-DRAM (PDF)  (PPT)		
W5	08.04 Fri.	Video	M5: SIMDRAM (PDF)  (PPT)		
W6	29.04 Fri.	Video	M6: DAMOV (PDF)  (PPT)		
W7	06.05 Fri.	Video	M7: Synchron (PDF)  (PPT)		



# Understanding & Solving RowHammer

Onur Mutlu

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10 August 2023

Flash Memory Summit

**SAFARI**

**ETH** zürich

**Carnegie Mellon**



TRRespass

# Industry-Adopted Solutions Do Not Work

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- 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.  
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[[Talk Video](#)] (17 minutes)  
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*Best paper award.*  
*Pwnie Award 2020 for Most Innovative Research.* [Pwnie Awards 2020](#)

## TRRespass: Exploiting the Many Sides of Target Row Refresh

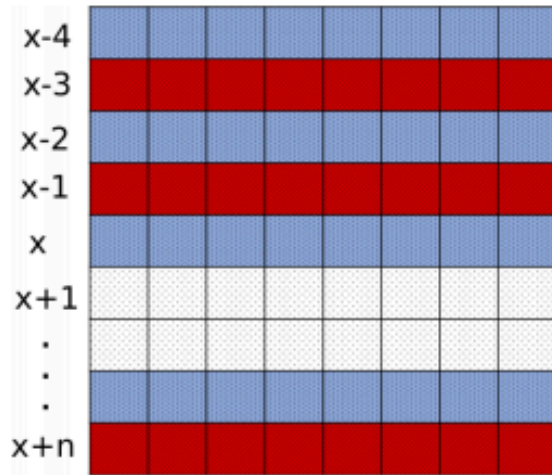
Pietro Frigo<sup>\*†</sup>   Emanuele Vannacci<sup>\*†</sup>   Hasan Hassan<sup>§</sup>   Victor van der Veen<sup>¶</sup>  
Onur Mutlu<sup>§</sup>   Cristiano Giuffrida<sup>\*</sup>   Herbert Bos<sup>\*</sup>   Kaveh Razavi<sup>\*</sup>

# TRRespass

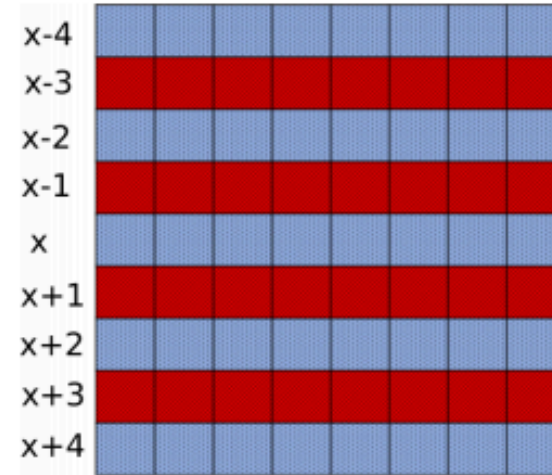
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- First work to show that TRR-protected DRAM chips are vulnerable to RowHammer in the field
  - Mitigations advertised as secure are not secure
- Introduces the Many-sided RowHammer attack
  - Idea: Hammer many rows to bypass TRR mitigations (e.g., 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 (■).

# 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 <sup>†</sup>	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 <sup>†</sup>	3000	8	1	16	×8	UL	—	—	—	—	—	—
$\mathcal{B}_{4,5}$	19-08 <sup>†</sup>	2666	8	2	16	×8	UL	—	—	—	—	—	—
$\mathcal{B}_{6,7}$	19-08 <sup>†</sup>	2400	4	1	16	×8	UL	—	—	—	—	—	—
$\mathcal{B}_8^{\diamond}$	19-08 <sup>†</sup>	2400	8	1	16	×8	UL	—	—	—	—	—	—
$\mathcal{B}_9^{\diamond}$	19-08 <sup>†</sup>	2400	8	1	16	×8	UL	2	3-sided	12	—	12	✓
$\mathcal{B}_{10,11}$	16-13 <sup>†</sup>	2132	8	2	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_{0,1}$	18-46	2666	16	2	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_{2,3}$	19-08 <sup>†</sup>	2800	4	1	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_{4,5}$	19-08 <sup>†</sup>	3000	8	1	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_{6,7}$	19-08 <sup>†</sup>	3000	16	2	16	×8	UL	—	—	—	—	—	—
$\mathcal{C}_8$	19-08 <sup>†</sup>	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 <sup>†</sup>	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	—

<sup>†</sup> The module does not report manufacturing date. Therefore, we report purchase date as an approximation.

<sup>‡</sup> Analyzed using the FPGA-based SoftMC.

<sup>◊</sup> 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 <sup>†</sup>	✓
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 <sup>†</sup>	✓
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	—

<sup>†</sup> 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>	$\tau$ (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	—	—

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

# TRRespass Key Results

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- 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

# Uncovering TRR Almost Completely



# Industry-Adopted Solutions Are Very Poor

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- 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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[[Talk Video](#) (25 minutes)]  
[[Lightning Talk Video](#) (100 seconds)]  
[[arXiv version](#)]

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

Hasan Hassan<sup>†</sup>

Yahya Can Tuğrul<sup>†‡</sup>

Jeremie S. Kim<sup>†</sup>

Victor van der Veen<sup>σ</sup>

Kaveh Razavi<sup>†</sup>

Onur Mutlu<sup>†</sup>

<sup>†</sup>ETH Zürich

<sup>‡</sup>TOBB University of Economics & Technology

<sup>σ</sup>Qualcomm Technologies Inc.

# 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 <sup>†</sup>	Max. Bit Flips per Row per Hammer <sup>†</sup>
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

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

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## Google Security Blog

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

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### 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

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- **Appears at USENIX Security 2022**

## **Half-Double: Hammering From the Next Row Over**

Andreas Kogler<sup>1</sup>   Jonas Juffinger<sup>1,2</sup>   Salman Qazi<sup>3</sup>   Yoongu Kim<sup>3</sup>   Moritz Lipp<sup>4\*</sup>  
Nicolas Boichat<sup>3</sup>   Eric Shiu<sup>5</sup>   Mattias Nissler<sup>3</sup>   Daniel Gruss<sup>1</sup>

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



More RowHammer in 2020-2023

# RowHammer in 2020 (I)

MICRO 2020

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## 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

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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 (ETH Zürich), Cristiano Giuffrida (Vrije Universiteit Amsterdam, The Netherlands), Kaveh Razavi (Vrije Universiteit Amsterdam, The Netherlands)

# RowHammer in 2020 (III)

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29<sup>TH</sup> USENIX  
SECURITY SYMPOSIUM

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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 2021 (I)

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**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)

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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)

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

# RowHammer in 2022 (III)

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## **HPCA 2022**

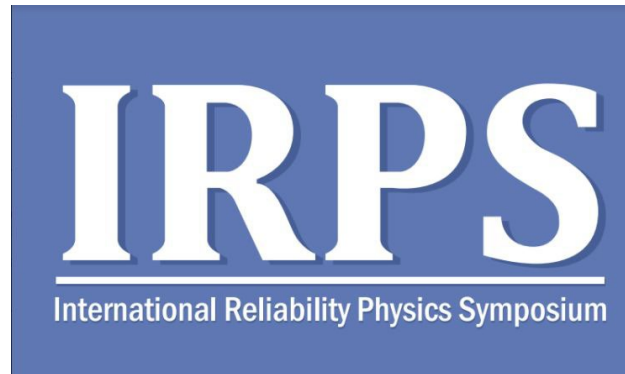
The 28th IEEE International Symposium on High-Performance Computer Architecture (HPCA-28), Seoul, South Korea

### **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)

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## 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)

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## **Half-Double: Hammering From the Next Row Over**

Andreas Kogler<sup>1</sup>   Jonas Juffinger<sup>1,2</sup>   Salman Qazi<sup>3</sup>   Yoongu Kim<sup>3</sup>   Moritz Lipp<sup>4\*</sup>  
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<sup>4</sup>*Amazon Web Services*   <sup>5</sup>*Rivos*



# RowHammer in 2022 (VI)

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**HAMMERSCOPE: Observing DRAM Power Consumption Using Rowhammer**

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

# RowHammer in 2022 (VII)

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## **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)

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- A. Giray Yağlıkçı, 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](#)]  
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[[arXiv version](#)]

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

A. Giray Yağlıkçı<sup>1</sup>    Ataberk Olgun<sup>1,2</sup>    Minesh Patel<sup>1</sup>    Haocong Luo<sup>1</sup>    Hasan Hassan<sup>1</sup>  
Lois Orosa<sup>1,3</sup>    Oğuz Ergin<sup>2</sup>    Onur Mutlu<sup>1</sup>

<sup>1</sup>*ETH Zürich*

<sup>2</sup>*TOBB University of Economics and Technology*

<sup>3</sup>*Galicia Supercomputing Center (CESGA)*

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

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# RowHammer in 2022 (VIII)

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## A Case for Transparent Reliability in DRAM Systems

Minesh Patel<sup>†</sup> Taha Shahroodi<sup>‡‡</sup> Aditya Manglik<sup>†</sup> A. Giray Yağlıkçı<sup>†</sup>  
Ataberk Olgun<sup>†</sup> Haocong Luo<sup>†</sup> Onur Mutlu<sup>†</sup>

<sup>†</sup>*ETH Zürich* <sup>‡</sup>*TU Delft*

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

# RowHammer in 2022 (IX)

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## **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)

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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)

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## 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 (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*

# Future Memory Reliability/Security Challenges

# Future of Main Memory Security

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- 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 Security

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

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



Intelligent  
Memory Controllers  
Can Avoid Many Failures  
& Enable Better Scaling

# Architecting Future Memory for Security

---

- **Understand:** Methods for vulnerability modeling & discovery
  - ❑ Modeling and prediction based on real (device) data and analysis
  - ❑ Understanding vulnerabilities
  - ❑ Developing reliable metrics
- **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
  - ❑ High coverage and good interaction with system reliability methods

# An Early Proposal for Intelligent Controllers [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/>

# Industry Is Writing Papers About It, Too

## DRAM Process Scaling Challenges

### ❖ Refresh

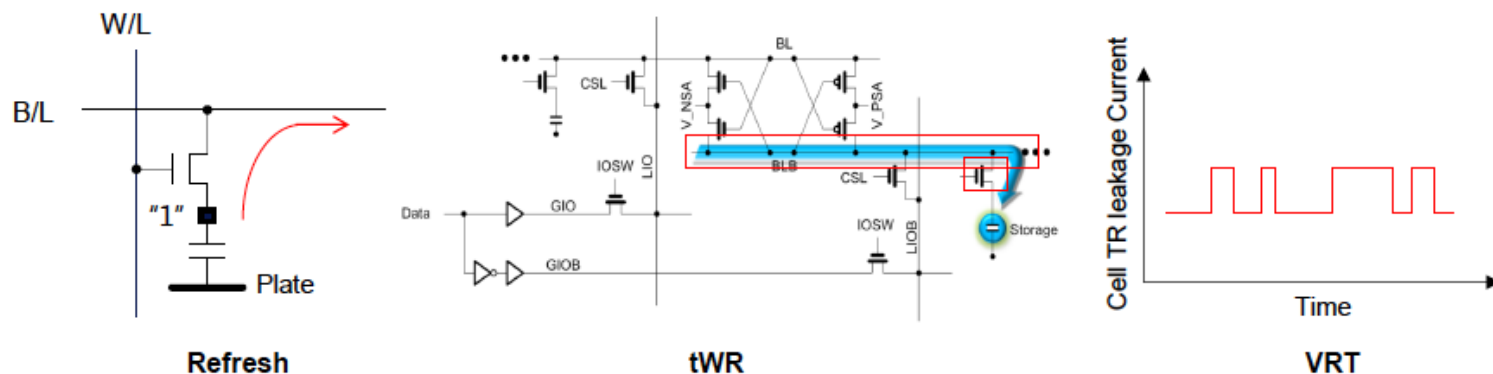
- Difficult to build high-aspect ratio cell capacitors decreasing cell capacitance
- Leakage current of cell access transistors increasing

### ❖ tWR

- Contact resistance between the cell capacitor and access transistor increasing
- On-current of the cell access transistor decreasing
- Bit-line resistance increasing

### ❖ VRT

- Occurring more frequently with cell capacitance decreasing



# Industry Is Writing Papers About It, Too

## DRAM Process Scaling Challenges

### ❖ Refresh

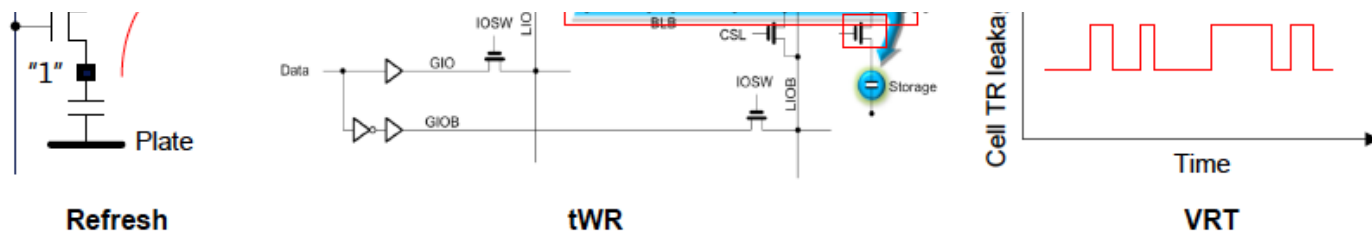
- Difficult to build high-aspect ratio cell capacitors decreasing cell capacitance

THE MEMORY FORUM 2014

## Co-Architecting Controllers and DRAM to Enhance DRAM Process Scaling

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

*Samsung Electronics, Hwasung, Korea / \*Samsung Electronics, San Jose / \*\*Intel*



# Final Thoughts on RowHammer



# Aside: Byzantine Failures

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- 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

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## 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)

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## 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.<sup>4</sup>

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

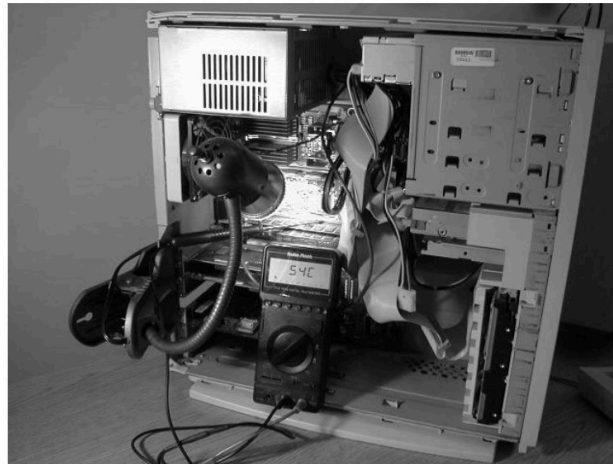


Figure 3. Experimental setup to induce memory errors, showing a PC built from surplus components, clip-on gooseneck lamp, 50-watt spotlight bulb, and digital thermometer. Not shown is the variable AC power supply for the lamp.

IEEE S&P 2003

# After RowHammer

---

A simple 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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TWEET

# FORGET SOFTWARE—NOW HACKERS ARE EXPLOITING PHYSICS

# 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 attacks...
  - ❑ Tens of papers in top security & architecture 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/S&P 2023)
  - ❑ Principled system-DRAM co-design (in original RowHammer paper)
  - ❑ **More to come...**



# Perhaps Most Importantly...

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- 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 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
  - Its implications on system security research 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 solutions
  - We are developing principled models, methodologies, solutions

# A RowHammer Survey Across the Stack

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- 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<sup>§‡</sup>      Jeremie S. Kim<sup>‡§</sup>  
<sup>§</sup>ETH Zürich      <sup>‡</sup>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

Onur Mutlu  
onur.mutlu@safari.ethz.ch  
ETH Zürich  
Zürich, Switzerland

Ataberk Olgun  
ataberk.olgün@safari.ethz.ch  
ETH Zürich  
Zürich, Switzerland

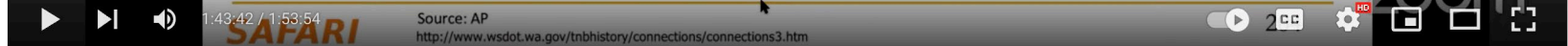
A. Giray Yağlıkcı  
giray.yaglikci@safari.ethz.ch  
ETH Zürich  
Zürich, Switzerland

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

---

# Latest RowHammer Lecture

## Collapse of the “Gallopig Gertie” (1940)



Seminar in Computer Architecture - Lecture 4: RowHammer (Spring 2023)



Onur Mutlu Lectures  
33.2K subscribers

Analytics

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408 views Streamed 2 months ago Livestream - Seminar in Computer Architecture - ETH Zürich (Spring 2023)  
Seminar in Computer Architecture, ETH Zürich, Spring 2023 ([https://safari.ethz.ch/architecture\\_s...](https://safari.ethz.ch/architecture_s...))



# The Story of RowHammer Tutorial ...

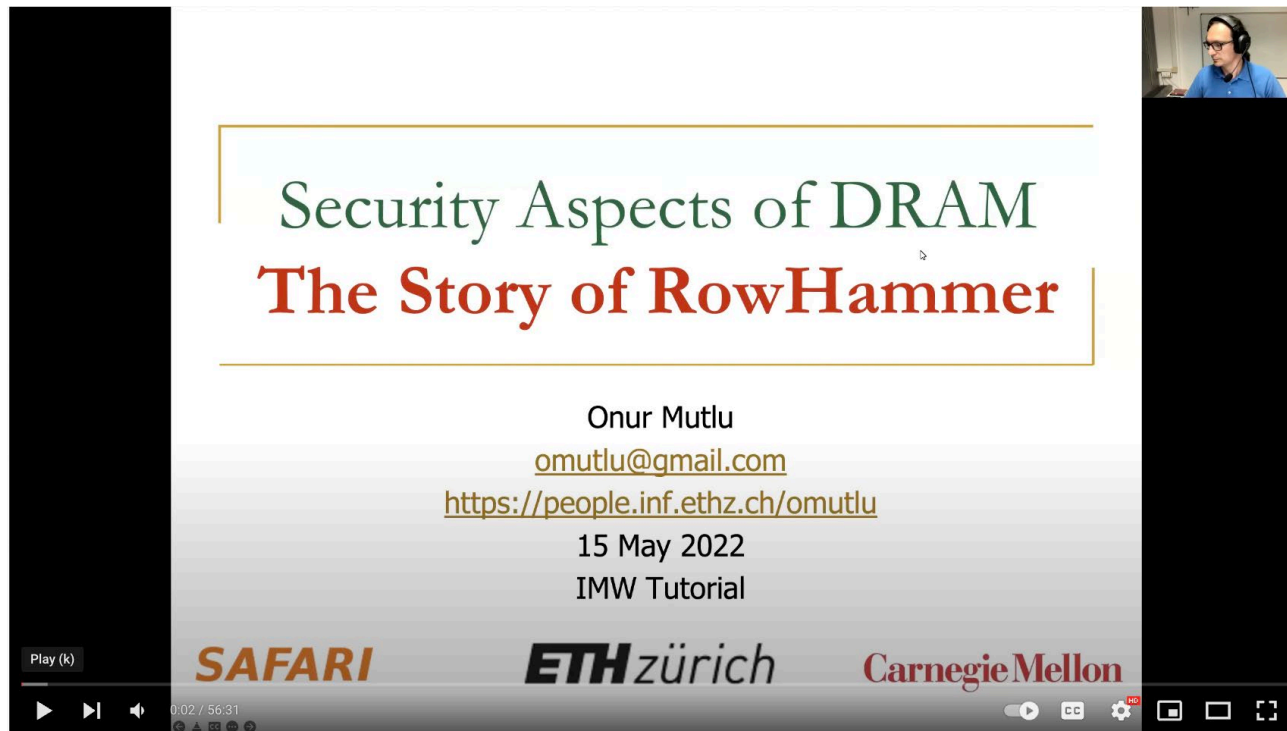
Onur Mutlu,

**"Security Aspects of DRAM: The Story of RowHammer"**

*Invited Tutorial at 14th IEEE Electron Devices Society International Memory Workshop (IMW), Dresden, Germany, May 2022.*

[Slides (pptx)(pdf)]

[Tutorial Video (57 minutes)]



Recent Premieres

The Story of RowHammer – Invited Tutorial at IMW 2022 (Intl. Memory Workshop) - Onur Mutlu

598 views • Premiered Jul 27, 2022

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Onur Mutlu Lectures  
27.6K subscribers

<https://www.youtube.com/watch?v=37hWglkQRG0>

ANALYTICS

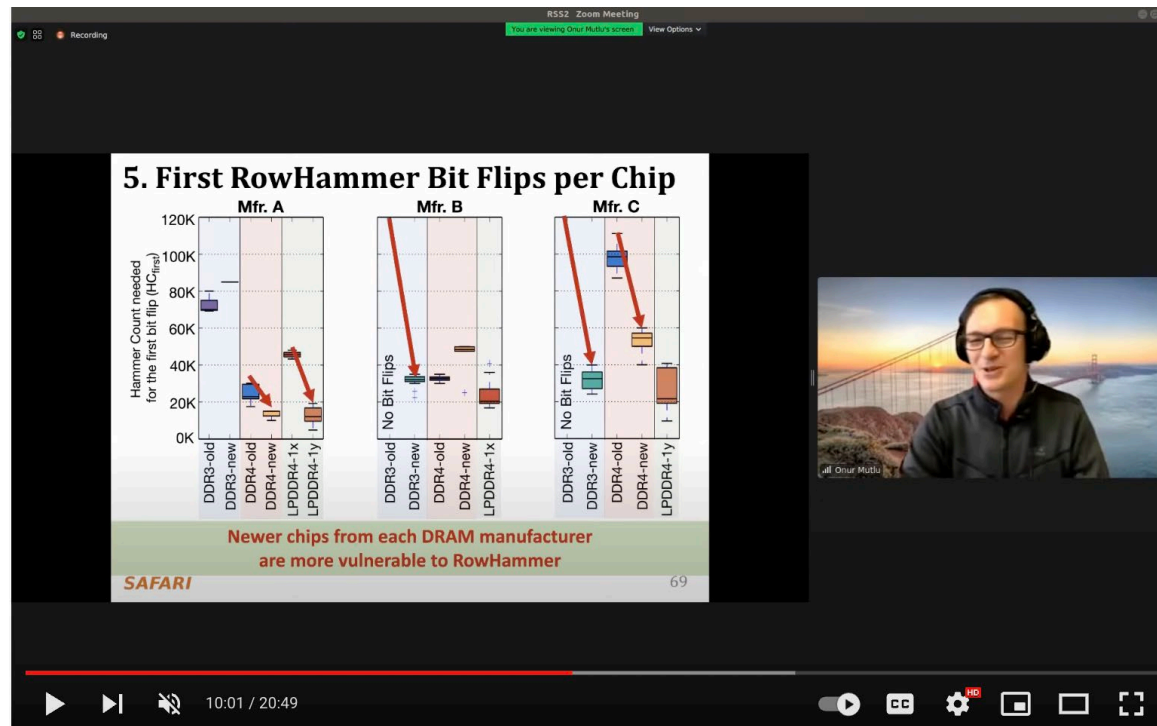
EDIT VIDEO

# The Story of RowHammer in 20 Minutes

- Onur Mutlu,  
["The Story of RowHammer"](#)

*Invited Talk at the [Workshop on Robust and Safe Software 2.0 \(RSS2\)](#), held with [the 27th International Conference on Architectural Support for Programming Languages and Operating Systems \(ASPLOS\)](#), Virtual, 28 February 2022.*

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



The Story of RowHammer - Invited Talk in Robust & Safe Software Workshop (ASPLOS 2022) - Onur Mutlu

402 views • Premiered Apr 27, 2022

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Onur Mutlu Lectures  
24.5K subscribers

<https://www.youtube.com/watch?v=ctKTRyi96Bk>

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Rowhammer

# Funding Acknowledgments

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- Alibaba, AMD, [ASML](#), [Google](#), [Facebook](#), [Hi-Silicon](#), HP Labs, [Huawei](#), IBM, [Intel](#), [Microsoft](#), Nvidia, Oracle, Qualcomm, Rambus, Samsung, Seagate, [VMware](#), [Xilinx](#)
- [Microsoft Swiss JRC](#)
- NSF
- NIH
- GSRC
- [SRC](#)
- CyLab
- [EFCL](#)

Thank you!

# Acknowledgments

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Think BIG, Aim HIGH!

<https://safari.ethz.ch>

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# SAFARI Research Group

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

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



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safari.ethz.ch

## Think BIG, Aim HIGH!

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<https://safari.ethz.ch>



# SAFARI Research Group: December 2021

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

**SAFARI**  
SAFARI Research Group

*Think Big, Aim High*

**ETH** zürich



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December 2021



# SAFARI Newsletter June 2023 Edition

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

**SAFARI**  
SAFARI Research Group

Think Big, Aim High

**ETH** zürich



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June 2023



# Detailed Lectures on RowHammer

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- Computer Architecture, Fall 2021, Lecture 5

- RowHammer (ETH Zürich, Fall 2021)
- <https://www.youtube.com/watch?v=7wVKnPj3NVw&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF&index=5>

- Computer Architecture, Fall 2021, Lecture 6

- RowHammer and Secure & Reliable Memory (ETH Zürich, Fall 2021)
- <https://www.youtube.com/watch?v=HNd4skQrt6I&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF&index=6>

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

# First RowHammer 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).*

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

Yoongu Kim<sup>1</sup>   Ross Daly\*   Jeremie Kim<sup>1</sup>   Chris Fallin\*   Ji Hye Lee<sup>1</sup>  
Donghyuk Lee<sup>1</sup>   Chris Wilkerson<sup>2</sup>   Konrad Lai   Onur Mutlu<sup>1</sup>

<sup>1</sup>Carnegie Mellon University   <sup>2</sup>Intel Labs

# Retrospective on RowHammer & Future

---

- Onur Mutlu,  
**"The RowHammer Problem and Other Issues We May Face as Memory Becomes Denser"**

*Invited Paper in Proceedings of the Design, Automation, and Test in Europe Conference (DATE), Lausanne, Switzerland, March 2017.*

*[Slides (pptx) (pdf)]*

## The RowHammer Problem and Other Issues We May Face as Memory Becomes Denser

Onur Mutlu  
ETH Zürich  
onur.mutlu@inf.ethz.ch  
<https://people.inf.ethz.ch/omutlu>

# A More Recent RowHammer Retrospective

---

- 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](#)]  
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[arXiv version]  
[Slides (pptx) (pdf)]  
[Talk Video (26 minutes)]

## Fundamentally Understanding and Solving RowHammer

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