

Memory Systems and Memory-Centric Computing Systems

Part 6: Principles and Conclusion

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3 February 2020

Champery Winter School

SAFARI

ETH zürich

Carnegie Mellon

Four Key Directions

- Fundamentally **Secure/Reliable/Safe** Architectures
- Fundamentally **Energy-Efficient** Architectures
 - **Memory-centric** (Data-centric) Architectures
- Fundamentally **Low-Latency** Architectures
- Architectures for **Genomics, Medicine, Health**

Guiding Principles

Some Solution Principles (So Far)

- Data-centric system design & intelligence spread around
 - Do not center everything around traditional computation units
- Better cooperation across layers of the system
 - Careful co-design of components and layers: system/arch/device
 - Better, richer, more expressive and flexible interfaces
- Better-than-worst-case design
 - Do not optimize for the worst case
 - Worst case should not determine the common case
- Heterogeneity in design (specialization, asymmetry)
 - Enables a more efficient design (No one size fits all)

Some Solution Principles (More Compact)

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

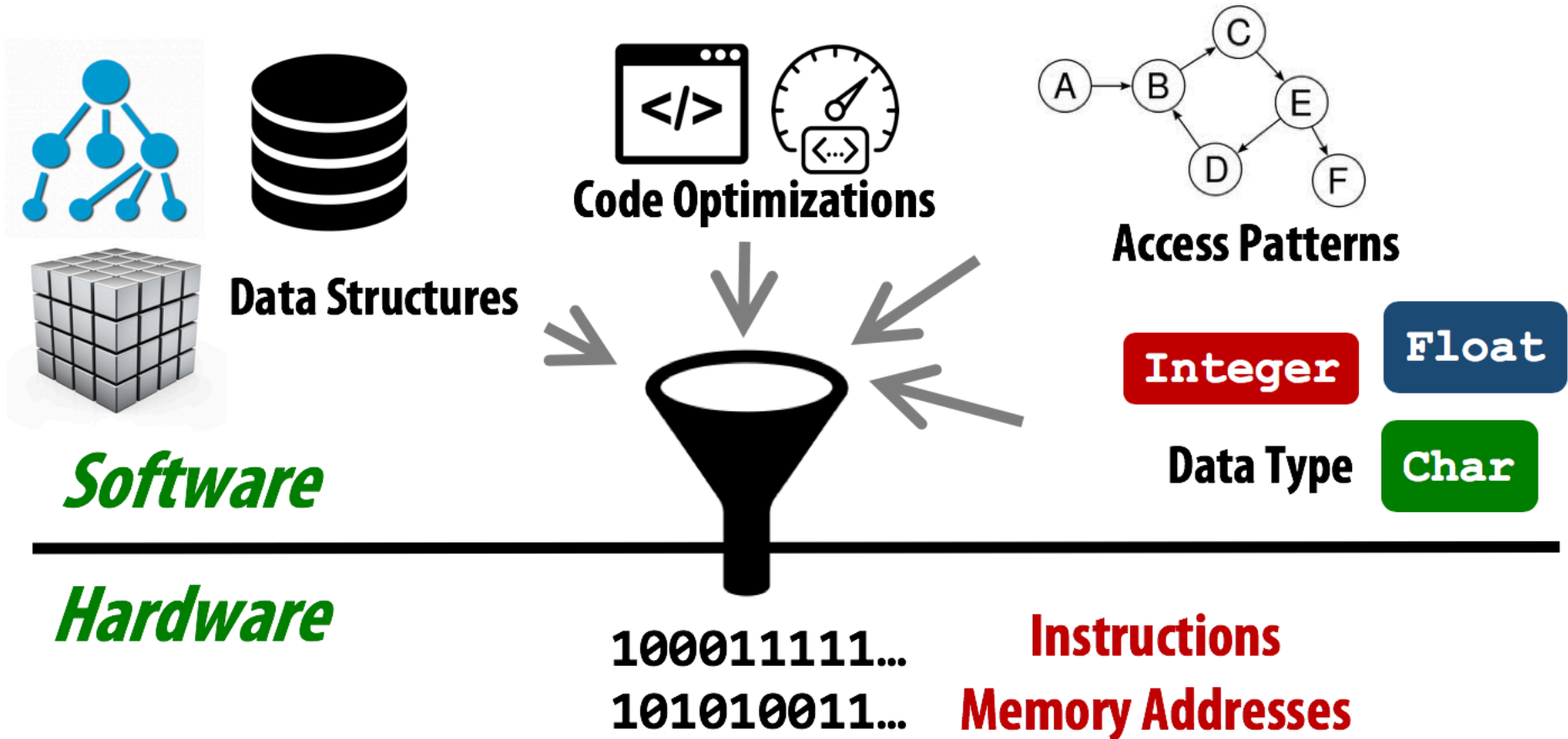
Open minds

Data-Aware Architectures

- A data-aware architecture understands what it can do with and to each piece of data
- It makes use of different properties of data to improve performance, efficiency and other metrics
 - ❑ Compressibility
 - ❑ Approximability
 - ❑ Locality
 - ❑ Sparsity
 - ❑ Criticality for Computation X
 - ❑ Access Semantics
 - ❑ ...

One Problem: Limited Interfaces

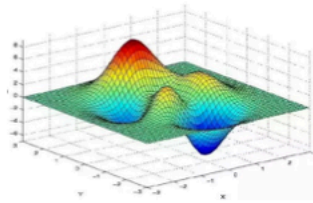
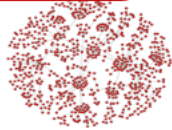
Higher-level information is not visible to HW



A Solution: More Expressive Interfaces

Performance

Software



Functionality



**ISA
Virtual Memory**

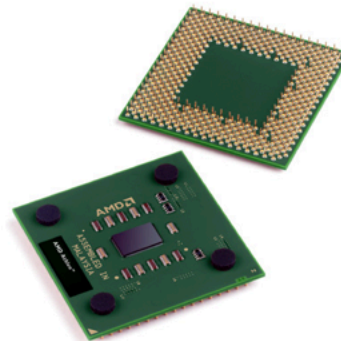
**Higher-level
Program
Semantics**

**Expressive
Memory
“XMem”**

Hardware



wiseGEEK



Expressive (Memory) Interfaces

- Nandita Vijaykumar, Abhilasha Jain, Diptesh Majumdar, Kevin Hsieh, Gennady Pekhimenko, Eiman Ebrahimi, Nastaran Hajinazar, Phillip B. Gibbons and Onur Mutlu, **"A Case for Richer Cross-layer Abstractions: Bridging the Semantic Gap with Expressive Memory"**
Proceedings of the 45th International Symposium on Computer Architecture (ISCA), Los Angeles, CA, USA, June 2018.
[[Slides \(pptx\) \(pdf\)](#)] [[Lightning Talk Slides \(pptx\) \(pdf\)](#)]
[[Lightning Talk Video](#)]

A Case for Richer Cross-layer Abstractions: Bridging the Semantic Gap with Expressive Memory

Nandita Vijaykumar^{†§} Abhilasha Jain[†] Diptesh Majumdar[†] Kevin Hsieh[†] Gennady Pekhimenko[‡]
Eiman Ebrahimi[⌘] Nastaran Hajinazar[†] Phillip B. Gibbons[†] Onur Mutlu^{§†}

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[⌘]NVIDIA

⁺Simon Fraser University

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Expressive (Memory) Interfaces for GPUs

- Nandita Vijaykumar, Eiman Ebrahimi, Kevin Hsieh, Phillip B. Gibbons and Onur Mutlu, **"The Locality Descriptor: A Holistic Cross-Layer Abstraction to Express Data Locality in GPUs"**
Proceedings of the 45th International Symposium on Computer Architecture (ISCA), Los Angeles, CA, USA, June 2018.
[[Slides \(pptx\) \(pdf\)](#)] [[Lightning Talk Slides \(pptx\) \(pdf\)](#)]
[[Lightning Talk Video](#)]

The Locality Descriptor:

A Holistic Cross-Layer Abstraction to Express Data Locality in GPUs

Nandita Vijaykumar^{†§} Eiman Ebrahimi[‡] Kevin Hsieh[†]

Phillip B. Gibbons[†] Onur Mutlu^{§†}

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Data-centric

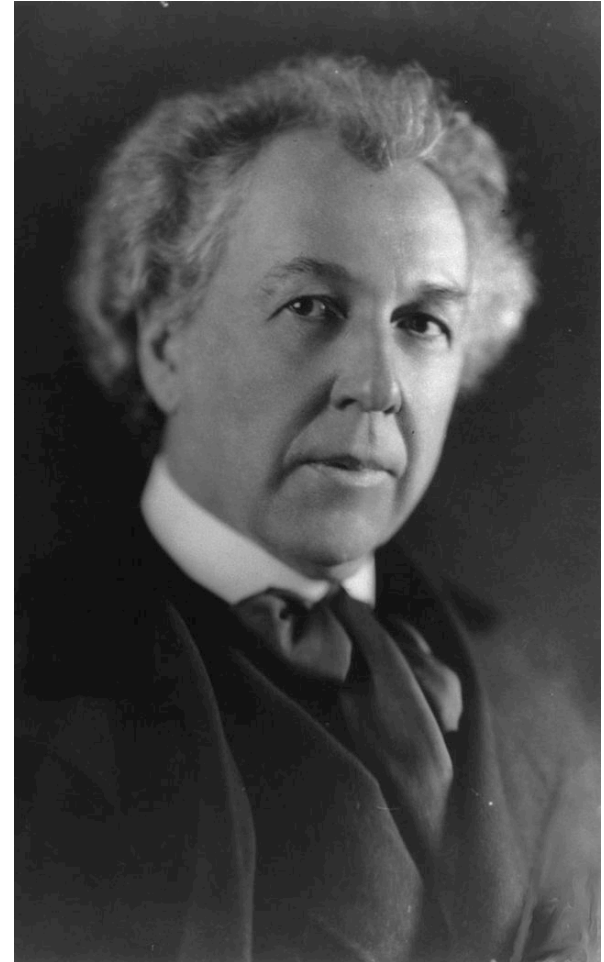
Data-driven

Data-aware

Concluding Remarks

A Quote from A Famous Architect

- “architecture [...] based upon **principle**, and not upon **precedent**”



Precedent-Based Design?

- “architecture [...] based upon **principle**, and not upon **precedent**”



Principled Design

- “architecture [...] based upon **principle**, and not upon **precedent**”





The Overarching Principle

Organic architecture

From Wikipedia, the free encyclopedia

Organic architecture is a [philosophy](#) of [architecture](#) which promotes harmony between human habitation and the natural world through design approaches so sympathetic and well integrated with its site, that buildings, furnishings, and surroundings become part of a unified, interrelated composition.

A well-known example of organic architecture is [Fallingwater](#), the residence Frank Lloyd Wright designed for the Kaufmann family in rural Pennsylvania. Wright had many choices to locate a home on this large site, but chose to place the home directly over the waterfall and creek creating a close, yet noisy dialog with the rushing water and the steep site. The horizontal striations of stone masonry with daring [cantilevers](#) of colored beige concrete blend with native rock outcroppings and the wooded environment.

Another Example: Precedent-Based Design



Principled Design



Another Principled Design



Source: By Martín Gómez Tagle - Lisbon, Portugal, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=13764903>

Source: <http://www.arcspace.com/exhibitions/unsorted/santiago-calatrava/>

Another Principled Design



Principle Applied to Another Structure



Source: By 準建築人手札網站 Forgemind ArchiMedia - Flickr: IMG_2489.JPG, CC BY 2.0

Source: <https://www.dezeen.com/2016/08/29/santiago-calatrava-oculus-world-trade-center-transportation-hub-new-york-photographs-hufton-crow/>
<https://commons.wikimedia.org/wiki/index.php?curid=91498396>, https://en.wikipedia.org/wiki/Santiago_Calatrava

The Overarching Principle

Zoomorphic architecture

From Wikipedia, the free encyclopedia

Zoomorphic architecture is the practice of using animal forms as the inspirational basis and blueprint for architectural design. "While animal forms have always played a role adding some of the deepest layers of meaning in architecture, it is now becoming evident that a new strand of **biomorphism** is emerging where the meaning derives not from any specific representation but from a more general allusion to biological processes."^[1]

Some well-known examples of Zoomorphic architecture can be found in the **TWA Flight Center** building in **New York City**, by **Eero Saarinen**, or the **Milwaukee Art Museum** by **Santiago Calatrava**, both inspired by the form of a bird's wings.^[3]

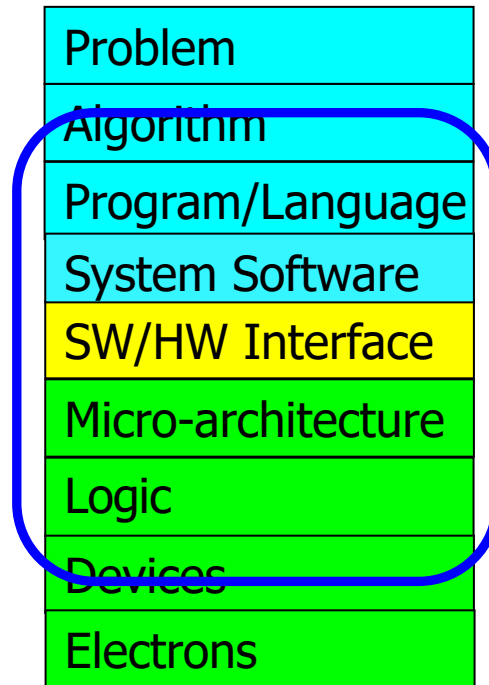
Overarching Principle for Computing?



Concluding Remarks

- It is time to design **principled system architectures** to solve the **memory** problem
- **Discover design principles for** fundamentally secure and reliable computer architectures
- **Design complete systems to be balanced and energy-efficient,** i.e., **low latency** and **data-centric (or memory-centric)**
- **Enable new and emerging memory architectures**
- **This can**
 - ❑ Lead to **orders-of-magnitude** improvements
 - ❑ **Enable new applications & computing platforms**
 - ❑ **Enable better understanding of nature**
 - ❑ ...

We Need to Think Across the Stack



We can get there step by step

If In Doubt, See Other Doubtful Technologies

- A very “doubtful” emerging technology
 - for at least two decades



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

Flash Memory Timeline

Flash Memory Timeline

1967

Dawon Kahng and Simon M. Sze invent the Non-Volatile Memory Floating Gate at Bell Labs; this is published as "A Floating Gate and Its Application to Memory Devices" (Bell System Technical Journal). Simon M. Sze went on to receive the 2014 FMS Lifetime Achievement Award

1970

Dov Frohman-Bentchkowsky invents the Erasable Programmable Read-Only Memory (EPROM) at Intel; this is published as "Memory Behavior in a Floating-Gate Avalanche-Injection MOS (FAMOS) Structure" in April 1971 (Applied Physics Letters), which cited the 1967 Kahng/Sze Bell Labs Floating Gate publication

1976

Hughes Microelectronics files Eli Haran patent for first practical floating gate EEPROM using thin SiO₂ and Fowler Nordheim tunneling for program and erase. Eli Haran went on to receive the 2012 FMS Lifetime Achievement Award

1977

Eli Haran of Hughes Microelectronics publishes "Conduction and Trapping of Electrons in Highly Stressed Thin Films of Thermal SiO₂" (Applied Physics Letters)

1978

Eli Haran of Hughes Microelectronics publishes "Dielectric Breakdown in Electrically Stressed Thin Films of Thermal SiO₂" (Journal of Applied Physics)

Hughes Microelectronics introduces first CMOS NOR-1T1R 256-bit chip (non-volatile SRAM) employing Fowler Nordheim floating gate EEPROM at IEEE ISSCC

1979

IEEE Solid State Circuits publishes paper titled "An Electrically Alterable Non-Volatile Memory Cell Using Floating Gate Structure" by Guleman, Rinawi, Chieu, Holvorson, and McEvoy of Texas Instruments

1980

Hughes Microelectronics introduces the 3108, first CMOS EEPROM, 8Kb chip employing Fowler Nordheim tunneling

Intel introduces the 2816, 16Kb HMOS EEPROM employing Fowler Nordheim tunneling

1981

British scientist and inventor Kane Kramer designs first digital audio player (IXI) based on magnetic bubble memory chips

1982

SEEO Technology introduces the 5213, first EEPROM with on-chip charge pump for in-system write and erase, an invention used in all flash memory devices

1983

Intel introduces 2817A 16Kb EEPROM

1984

First paper describing flash EEPROM presented by Fujio Masuoka of Toshiba at IEEE International Electron Devices Meeting (IEDM) in San Francisco. Fujio Masuoka went on to receive the 2013 FMS Lifetime Achievement Award

Intel begins flash process development

ATMEL (Advanced Technology for Memory and Logic) is founded by George Perlegos, who went on to receive the 2017 Lifetime Achievement Award



Flash Memory Summit

Flash Memory Timeline



PIM Review and Open Problems

Processing Data Where It Makes Sense: Enabling In-Memory Computation

Onur Mutlu^{a,b}, Saugata Ghose^b, Juan Gómez-Luna^a, Rachata Ausavarungnirun^{b,c}

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^c*King Mongkut's University of Technology North Bangkok*

Onur Mutlu, Saugata Ghose, Juan Gomez-Luna, and Rachata Ausavarungnirun,
**"Processing Data Where It Makes Sense: Enabling In-Memory
Computation"**

*Invited paper in Microprocessors and Microsystems (**MICPRO**), June 2019.
[arXiv version]*

PIM Review and Open Problems (II)

A Workload and Programming Ease Driven Perspective of Processing-in-Memory

Saugata Ghose[†] Amirali Boroumand[†] Jeremie S. Kim^{†§} Juan Gómez-Luna[§] Onur Mutlu^{§†}

[†]*Carnegie Mellon University*

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Saugata Ghose, Amirali Boroumand, Jeremie S. Kim, Juan Gomez-Luna, and Onur Mutlu,

"Processing-in-Memory: A Workload-Driven Perspective"

Invited Article in IBM Journal of Research & Development, Special Issue on Hardware for Artificial Intelligence, to appear in November 2019.

[Preliminary arXiv version]

A Final Detour

In-Memory Bulk Bitwise Operations

- We can support in-DRAM COPY, ZERO, AND, OR, NOT, MAJ
- At low cost
- Using analog computation capability of DRAM
 - Idea: activating multiple rows performs computation
- 30-60X performance and energy improvement
 - Seshadri+, "Ambit: In-Memory Accelerator for Bulk Bitwise Operations Using Commodity DRAM Technology," MICRO 2017.
- New memory technologies enable even more opportunities
 - Memristors, resistive RAM, phase change mem, STT-MRAM, ...
 - Can operate on data with minimal movement

More on Ambit

- Vivek Seshadri et al., “**Ambit: In-Memory Accelerator for Bulk Bitwise Operations Using Commodity DRAM Technology**,” MICRO 2017.

Ambit: In-Memory Accelerator for Bulk Bitwise Operations Using Commodity DRAM Technology

Vivek Seshadri^{1,5} Donghyuk Lee^{2,5} Thomas Mullins^{3,5} Hasan Hassan⁴ Amirali Boroumand⁵
Jeremie Kim^{4,5} Michael A. Kozuch³ Onur Mutlu^{4,5} Phillip B. Gibbons⁵ Todd C. Mowry⁵

¹Microsoft Research India ²NVIDIA Research ³Intel ⁴ETH Zürich ⁵Carnegie Mellon University

Ambit Sounds Good, No?

Review from ISCA 2016

Paper summary

The paper proposes to extend DRAM to include bulk, bit-wise logical operations directly between rows within the DRAM.

Strengths

- Very clever/novel idea.
 - Great potential speedup and efficiency gains.
-

Weaknesses

- Probably won't ever be built. Not practical to assume DRAM manufacturers will change DRAM in this way.

Another Review

Another Review from ISCA 2016

Strengths

The proposed mechanisms effectively exploit the operation of the DRAM to perform efficient bitwise operations across entire rows of the DRAM.

Weaknesses

This requires a modification to the DRAM that will only help this type of bitwise operation. It seems unlikely that something like that will be adopted.

Yet Another Review

Yet Another Review from ISCA 2016

Weaknesses

The core novelty of Buddy RAM is almost all circuits-related (by exploiting sense amps). I do not find architectural innovation even though the circuits technique benefits architecturally by mitigating memory bandwidth and relieving cache resources within a subarray. The only related part is the new ISA support for bitwise operations at DRAM side and its induced issue on cache coherence.

RowClone & Bitwise Ops in Real DRAM Chips

ComputeDRAM: In-Memory Compute Using Off-the-Shelf DRAMs

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Pinatubo: RowClone and Bitwise Ops in PCM

Pinatubo: A Processing-in-Memory Architecture for Bulk Bitwise Operations in Emerging Non-volatile Memories

Shuangchen Li^{1*}, Cong Xu², Qiaosha Zou^{1,5}, Jishen Zhao³, Yu Lu⁴, and Yuan Xie¹

University of California, Santa Barbara¹, Hewlett Packard Labs²

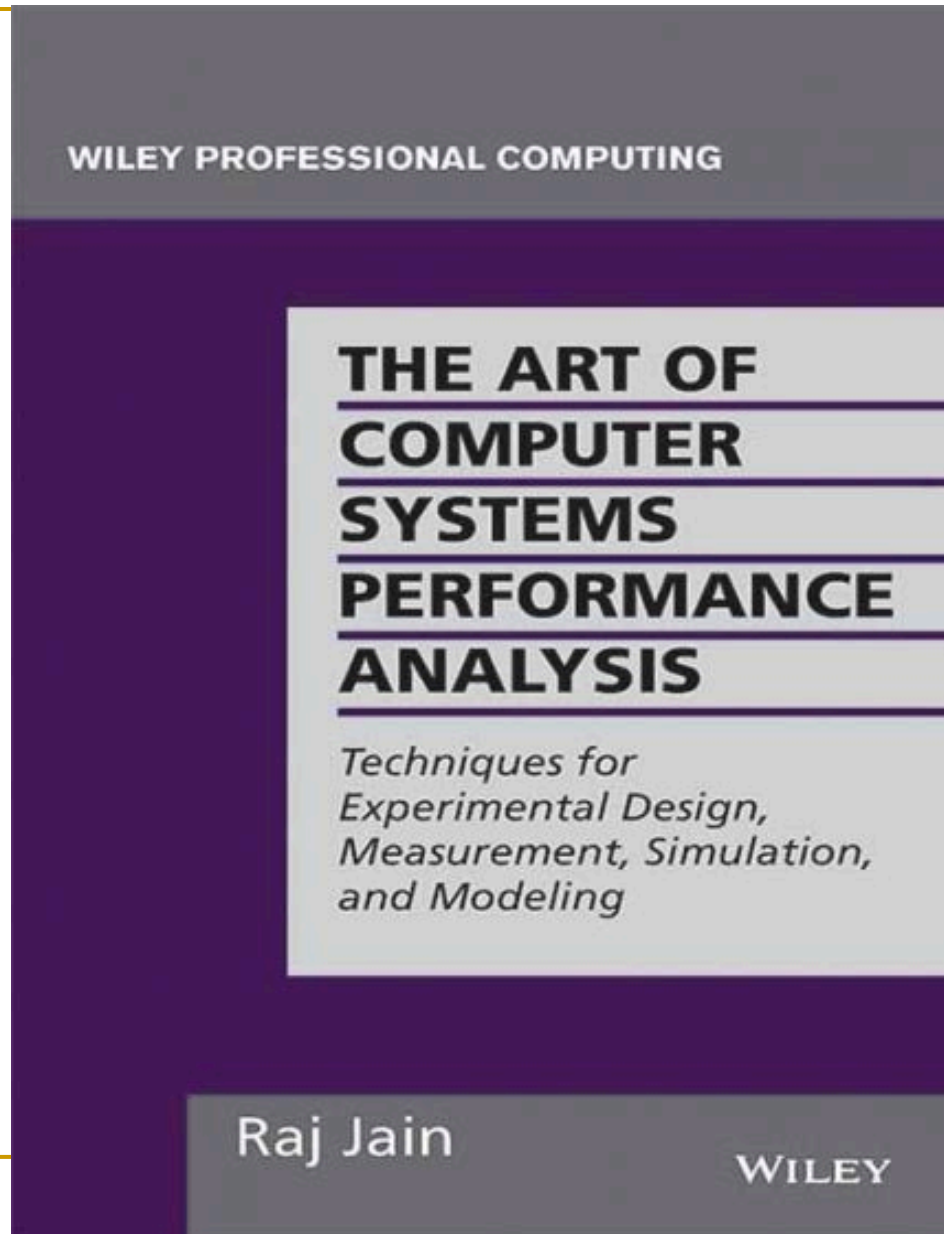
University of California, Santa Cruz³, Qualcomm Inc.⁴, Huawei Technologies Inc.⁵
{shuangchenli, yuanxie}@ece.ucsb.edu¹

We Have a Mindset Issue...

- There are many other similar examples from reviews...
 - For many other papers...
- And, we are not even talking about JEDEC yet...
- How do we fix the mindset problem?
- By doing more research, education, implementation in alternative processing paradigms

We need to work on enabling the better future...

Aside: A Recommended Book



Raj Jain, "[The Art of Computer Systems Performance Analysis](#)," Wiley, 1991.

10.8 DECISION MAKER'S GAMES

Even if the performance analysis is correctly done and presented, it may not be enough to persuade your audience—the decision makers—to follow your recommendations. The list shown in Box 10.2 is a compilation of reasons for rejection heard at various performance analysis presentations. You can use the list by presenting it immediately and pointing out that the reason for rejection is not new and that the analysis deserves more consideration. Also, the list is helpful in getting the competing proposals rejected!

There is no clear end of an analysis. Any analysis can be rejected simply on the grounds that the problem needs more analysis. This is the first reason listed in Box 10.2. The second most common reason for rejection of an analysis and for endless debate is the workload. Since workloads are always based on the past measurements, their applicability to the current or future environment can always be questioned. Actually workload is one of the four areas of discussion that lead a performance presentation into an endless debate. These “rat holes” and their relative sizes in terms of time consumed are shown in Figure 10.26. Presenting this cartoon at the beginning of a presentation helps to avoid these areas.

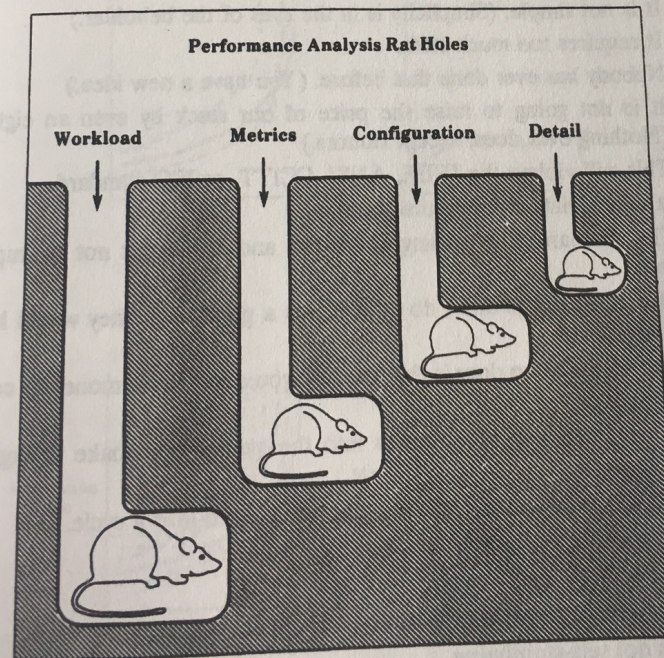


FIGURE 10.26 Four issues in performance presentations that commonly lead to endless discussion.

Raj Jain, "The Art of Computer Systems Performance Analysis," Wiley, 1991.

Box 10.2 Reasons for Not Accepting the Results of an Analysis

1. This needs more analysis.
2. You need a better understanding of the workload.
3. It improves performance only for long I/O's, packets, jobs, and files, and most of the I/O's, packets, jobs, and files are short.
4. It improves performance only for short I/O's, packets, jobs, and files, but who cares for the performance of short I/O's, packets, jobs, and files; its the long ones that impact the system.
5. It needs too much memory/CPU/bandwidth and memory/CPU/bandwidth isn't free.
6. It only saves us memory/CPU/bandwidth and memory/CPU/bandwidth is cheap.
7. There is no point in making the networks (similarly, CPUs/disks/...) faster; our CPUs/disks (any component other than the one being discussed) aren't fast enough to use them.
8. It improves the performance by a factor of x , but it doesn't really matter at the user level because everything else is so slow.
9. It is going to increase the complexity and cost.
10. Let us keep it simple stupid (and your idea is not stupid).
11. It is not simple. (Simplicity is in the eyes of the beholder.)
12. It requires too much state.
13. Nobody has ever done that before. (You have a new idea.)
14. It is not going to raise the price of our stock by even an eighth. (Nothing ever does, except rumors.)
15. This will violate the IEEE, ANSI, CCITT, or ISO standard.
16. It may violate some future standard.
17. The standard says nothing about this and so it must not be important.
18. Our competitors don't do it. If it was a good idea, they would have done it.
19. Our competition does it this way and you don't make money by copying others.
20. It will introduce randomness into the system and make debugging difficult.
21. It is too deterministic; it may lead the system into a cycle.
22. It's not interoperable.
23. This impacts hardware.
24. That's beyond today's technology.
25. It is not self-stabilizing.
26. Why change—it's working OK.

Raj Jain, "The Art of Computer Systems Performance Analysis," Wiley, 1991.

Suggestions to Reviewers


- Be fair; you do not know it all
- Be open-minded; you do not know it all
- Be accepting of diverse research methods: there is no single way of doing research
- Be constructive, not destructive
- Do not have double standards...

Do not block or delay scientific progress for non-reasons

Initial RowHammer Reviews

Disturbance Errors in DRAM: Demonstration, Characterization, and Prevention

Rejected (R2)

 863kB

Friday 31 May 2013 2:00:53pm PDT

b9bf06021da54cddf4cd0b3565558a181868b972

You are an **author** of this paper.

+ ABSTRACT

+ AUTHORS

	OveMer	Nov	WriQua	RevExp
Review #66A	1	4	4	4
Review #66B	5	4	5	3
Review #66C	2	3	5	4
Review #66D	1	2	3	4
Review #66E	4	4	4	3
Review #66F	2	4	4	3

Missing the Point **Reviews from Micro 2013**

PAPER WEAKNESSES

This is an excellent test methodology paper, but there is no micro-architectural or architectural content.

PAPER WEAKNESSES

- Whereas they show disturbance may happen in DRAM array, authors don't show it can be an issue in realistic DRAM usage scenario
- Lacks architectural/microarchitectural impact on the DRAM disturbance analysis

PAPER WEAKNESSES

The mechanism investigated by the authors is one of many well known disturb mechanisms. The paper does not discuss the root causes to sufficient depth and the importance of this mechanism compared to others. Overall the length of the sections restating known information is much too long in relation to new work.

Dismissing Science

Reviews from ISCA 2014

PAPER WEAKNESSES

1) The disturbance error (a.k.a coupling or cross-talk noise induced error) is a known problem to the DRAM circuit community.

2) What you demonstrated in this paper is so called DRAM row hammering issue - you can even find a Youtube video showing this! - <http://www.youtube.com/watch?v=i3-gQSnBcdo>

2) The architectural contribution of this study is too insignificant.

PAPER WEAKNESSES

- Row Hammering appears to be well-known, and solutions have already been proposed by industry to address the issue.

- The paper only provides a qualitative analysis of solutions to the problem. A more robust evaluation is really needed to know whether the proposed solution is necessary.

Final RowHammer Reviews

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

Accepted



639kB

21 Nov 2013 10:53:11pm CST |

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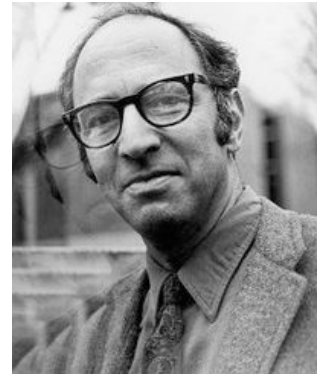
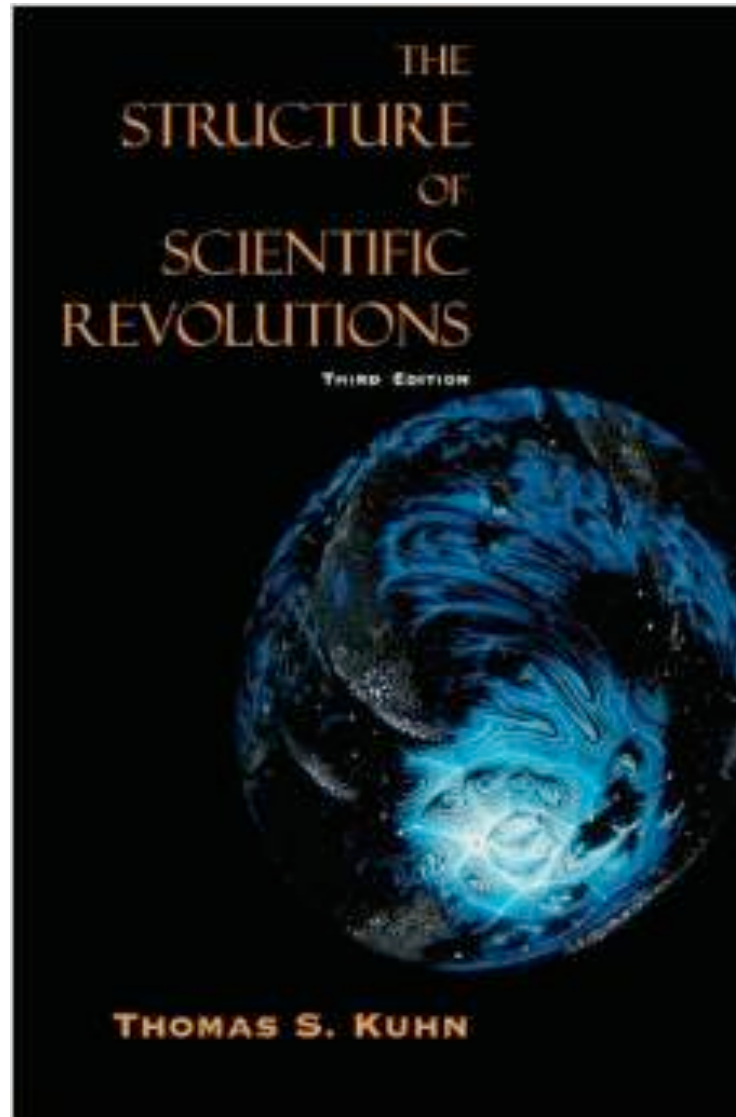
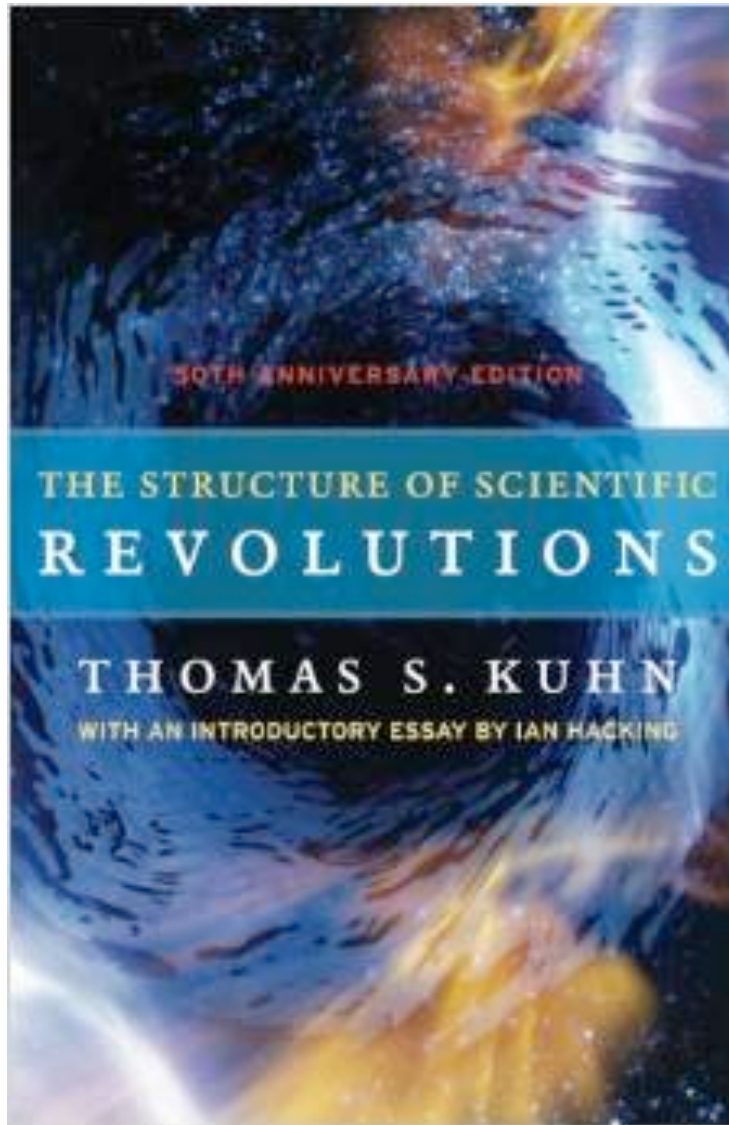
You are an **author** of this paper.

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Review #41A	8	4	5	3
Review #41B	7	4	4	3
Review #41C	6	4	4	3
Review #41D	2	2	5	4
Review #41E	3	2	3	3
Review #41F	7	4	4	3

We Need to Fix the Reviewer Accountability Problem

Eliminate
Double Standards

Another Recommended Book



Computer Architecture Today

- You can revolutionize the way computers are built, if you understand both the hardware and the software (and change each accordingly)
- You can invent new paradigms for computation, communication, and storage
- Recommended book: Thomas Kuhn, “[The Structure of Scientific Revolutions](#)” (1962)
 - ❑ Pre-paradigm science: no clear consensus in the field
 - ❑ Normal science: dominant theory used to explain/improve things (business as usual); exceptions considered anomalies
 - ❑ Revolutionary science: underlying assumptions re-examined



Suggestion to Researchers: Principle: Passion

Follow Your Passion
**(Do not get derailed
by naysayers)**

Suggestion to Researchers: Principle: Resilience

Be Resilient

Principle: Learning and Scholarship

Focus on
learning and scholarship

Principle: Learning and Scholarship

The quality of your work
defines your impact

More Thoughts and Suggestions

- Onur Mutlu,
"Some Reflections (on DRAM)"
*Award Speech for ACM SIGARCH Maurice Wilkes Award, at the **ISCA** Awards Ceremony, Phoenix, AZ, USA, 25 June 2019.*
[[Slides \(pptx\)](#) ([pdf](#))]
[[Video of Award Acceptance Speech \(Youtube; 10 minutes\)](#) ([Youku; 13 minutes](#))]
[[Video of Interview after Award Acceptance \(Youtube; 1 hour 6 minutes\)](#) ([Youku; 1 hour 6 minutes](#))]
[[News Article on "ACM SIGARCH Maurice Wilkes Award goes to Prof. Onur Mutlu"](#)]
- Onur Mutlu,
"How to Build an Impactful Research Group"
Design Automation Conference Early Career Workshop, Las Vegas, NV, USA, June 2019.
[[Slides \(pptx\)](#) ([pdf](#))]

Acknowledgments

■ My current and past students and postdocs

- ❑ Rachata Ausavarungnirun, Abhishek Bhowmick, Amirali Boroumand, Rui Cai, Yu Cai, Kevin Chang, Saugata Ghose, Kevin Hsieh, Tyler Huberty, Ben Jaiyen, Samira Khan, Jeremie Kim, Yoongu Kim, Yang Li, Jamie Liu, Lavanya Subramanian, Donghyuk Lee, Yixin Luo, Justin Meza, Gennady Pekhimenko, Vivek Seshadri, Lavanya Subramanian, Nandita Vijaykumar, HanBin Yoon, Jishen Zhao, ...

■ My collaborators

- ❑ Can Alkan, Chita Das, Phil Gibbons, Sriram Govindan, Norm Jouppi, Mahmut Kandemir, Mike Kozuch, Konrad Lai, Ken Mai, Todd Mowry, Yale Patt, Moinuddin Qureshi, Partha Ranganathan, Bikash Sharma, Kushagra Vaid, Chris Wilkerson, ...

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- NSF
- NIH
- GSRC
- SRC
- CyLab

Acknowledgments

SAFARI

SAFARI Research Group

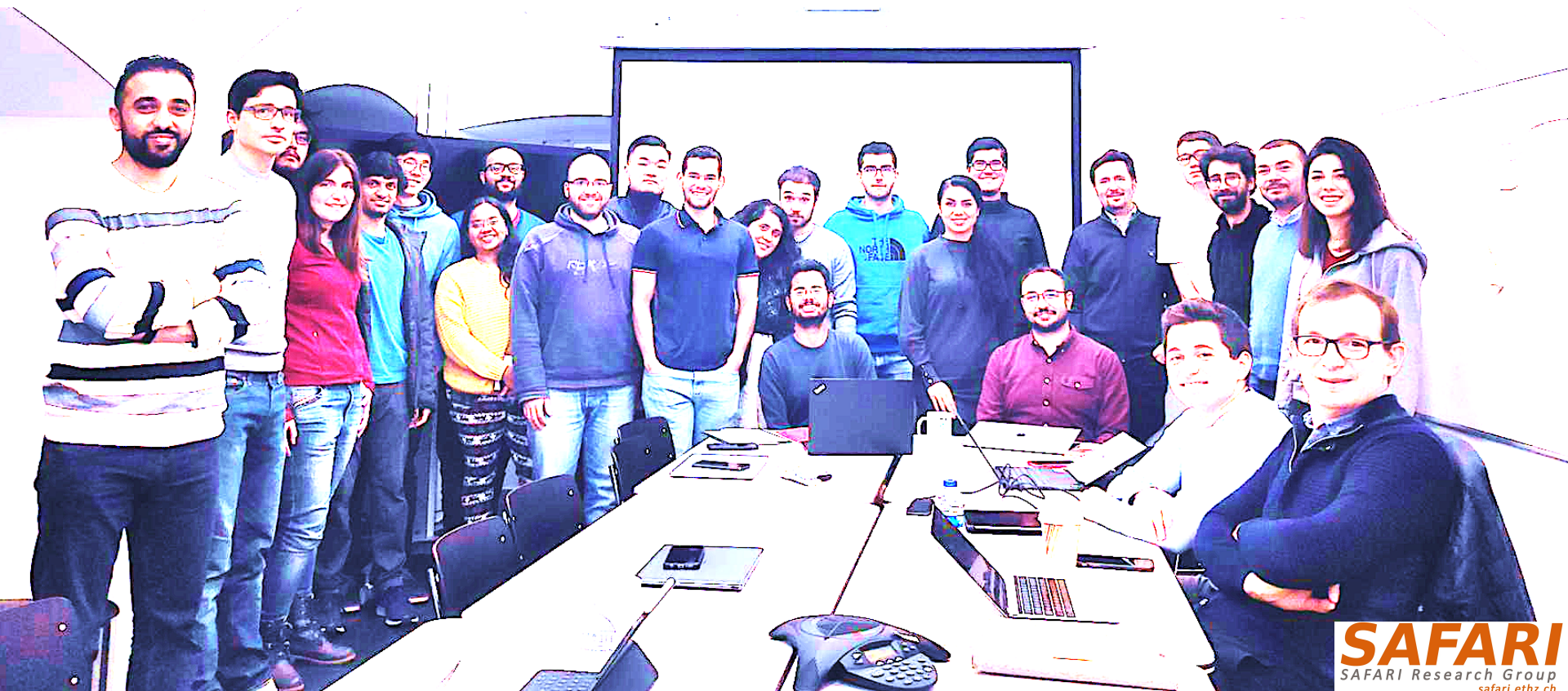
safari.ethz.ch

Think BIG, Aim HIGH!

<https://safari.ethz.ch>

SAFARI Research Group

31 ☺ = 1 Professor, 2 Lecturers & Senior Researchers, 3 Senior Researchers, 12 PhD Students, 3 Masters, 8 Interns, 2 Admins



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Think BIG, Aim HIGH!

SAFARI

<https://safari.ethz.ch>

Memory Systems and Memory-Centric Computing Systems

Part 6: Principles and Conclusion

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3 February 2020

Champery Winter School

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Carnegie Mellon

Slides Not Covered
But Could Be Useful

Readings, Videos, Reference Materials

Accelerated Memory Course (~6.5 hours)

■ ACACES 2018

- ❑ Memory Systems and Memory-Centric Computing Systems
- ❑ Taught by Onur Mutlu July 9-13, 2018
- ❑ ~6.5 hours of lectures

■ Website for the Course including Videos, Slides, Papers

- ❑ https://safari.ethz.ch/memory_systems/ACACES2018/
- ❑ <https://www.youtube.com/playlist?list=PL5Q2soXY2Zi-HXxomthrpDpMJm05P6J9x>

■ All Papers are at:

- ❑ <https://people.inf.ethz.ch/omutlu/projects.htm>
- ❑ Final lecture notes and readings (for all topics)

Longer Memory Course (~18 hours)

■ Tu Wien 2019

- ❑ Memory Systems and Memory-Centric Computing Systems
- ❑ Taught by Onur Mutlu June 12-19, 2019
- ❑ ~18 hours of lectures

■ Website for the Course including Videos, Slides, Papers

- ❑ https://safari.ethz.ch/memory_systems/TUWien2019
- ❑ https://www.youtube.com/playlist?list=PL5Q2soXY2Zi_gntM55VoMIKlw7YrXOhbl

■ All Papers are at:

- ❑ <https://people.inf.ethz.ch/omutlu/projects.htm>
- ❑ Final lecture notes and readings (for all topics)

Some Overview Talks

https://www.youtube.com/watch?v=kgiZISOcGFM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJI

■ Future Computing Architectures

- https://www.youtube.com/watch?v=kgiZISOcGFM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJI&index=1

■ Enabling In-Memory Computation

- https://www.youtube.com/watch?v=oHqsNbxgdzM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJI&index=7

■ Accelerating Genome Analysis

- https://www.youtube.com/watch?v=hPnSmfwu2-A&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJI&index=9

■ Rethinking Memory System Design

- https://www.youtube.com/watch?v=F7xZLNMIY1E&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJI&index=3

Reference Overview Paper I

Processing Data Where It Makes Sense: Enabling In-Memory Computation

Onur Mutlu^{a,b}, Saugata Ghose^b, Juan Gómez-Luna^a, Rachata Ausavarungnirun^{b,c}

^a*ETH Zürich*

^b*Carnegie Mellon University*

^c*King Mongkut's University of Technology North Bangkok*

Onur Mutlu, Saugata Ghose, Juan Gomez-Luna, and Rachata Ausavarungnirun,
**"Processing Data Where It Makes Sense: Enabling In-Memory
Computation"**

*Invited paper in Microprocessors and Microsystems (**MICPRO**), June 2019.
[arXiv version]*

Reference Overview Paper II

Enabling the Adoption of Processing-in-Memory: Challenges, Mechanisms, Future Research Directions

SAUGATA GHOSE, KEVIN HSIEH, AMIRALI BOROUMAND,
RACHATA AUSAVARUNGNIRUN

Carnegie Mellon University

ONUR MUTLU

ETH Zürich and Carnegie Mellon University

Saugata Ghose, Kevin Hsieh, Amirali Boroumand, Rachata Ausavarungnirun, Onur Mutlu,
**"Enabling the Adoption of Processing-in-Memory: Challenges, Mechanisms,
Future Research Directions"**

Invited Book Chapter, to appear in 2018.

[[Preliminary arxiv.org version](https://arxiv.org/pdf/1802.00320.pdf)]

Reference Overview Paper III

- Onur Mutlu and Lavanya Subramanian,
"Research Problems and Opportunities in Memory Systems"
Invited Article in Supercomputing Frontiers and Innovations (SUPERFRI), 2014/2015.

Research Problems and Opportunities in Memory Systems

Onur Mutlu¹, Lavanya Subramanian¹

Reference Overview Paper IV

- 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>

Reference Overview Paper V

- Onur Mutlu,
"Memory Scaling: A Systems Architecture Perspective"

*Technical talk at MemCon 2013 (**MEMCON**), Santa Clara, CA, August 2013. [[Slides \(pptx\)](#)] [[pdf](#)]
[[Video](#)] [[Coverage on StorageSearch](#)]*

Memory Scaling: A Systems Architecture Perspective

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



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

Reference Overview Paper VII

- 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](#)]

RowHammer: A Retrospective

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

Reference Overview Paper VIII

A Workload and Programming Ease Driven Perspective of Processing-in-Memory

Saugata Ghose[†] Amirali Boroumand[†] Jeremie S. Kim^{†§} Juan Gómez-Luna[§] Onur Mutlu^{§†}

[†]*Carnegie Mellon University*

[§]*ETH Zürich*

Saugata Ghose, Amirali Boroumand, Jeremie S. Kim, Juan Gomez-Luna, and Onur Mutlu,

"Processing-in-Memory: A Workload-Driven Perspective"

Invited Article in IBM Journal of Research & Development, Special Issue on Hardware for Artificial Intelligence, to appear in November 2019.

[Preliminary arXiv version]

Reference Overview Paper IX

- Vivek Seshadri and Onur Mutlu,
"In-DRAM Bulk Bitwise Execution Engine"
Invited Book Chapter in Advances in Computers, to appear
in 2020.
[[Preliminary arXiv version](#)]

In-DRAM Bulk Bitwise Execution Engine

Vivek Seshadri
Microsoft Research India
`visesha@microsoft.com`

Onur Mutlu
ETH Zürich
`onur.mutlu@inf.ethz.ch`

Related Videos and Course Materials (I)

- **Undergraduate Computer Architecture Course Lecture Videos (2015, 2014, 2013)**
- **Undergraduate Computer Architecture Course Materials (2015, 2014, 2013)**

- **Graduate Computer Architecture Course Lecture Videos (2018, 2017, 2015, 2013)**
- **Graduate Computer Architecture Course Materials (2018, 2017, 2015, 2013)**

- **Parallel Computer Architecture Course Materials (Lecture Videos)**

Related Videos and Course Materials (II)

- **Freshman Digital Circuits and Computer Architecture Course Lecture Videos (2018, 2017)**
- **Freshman Digital Circuits and Computer Architecture Course Materials (2018)**
- **Memory Systems Short Course Materials (Lecture Video on Main Memory and DRAM Basics)**

Some Open Source Tools (I)

- Rowhammer – Program to Induce RowHammer Errors
 - <https://github.com/CMU-SAFARI/rowhammer>
- Ramulator – Fast and Extensible DRAM Simulator
 - <https://github.com/CMU-SAFARI/ramulator>
- MemSim – Simple Memory Simulator
 - <https://github.com/CMU-SAFARI/memsim>
- NOCulator – Flexible Network-on-Chip Simulator
 - <https://github.com/CMU-SAFARI/NOCulator>
- SoftMC – FPGA-Based DRAM Testing Infrastructure
 - <https://github.com/CMU-SAFARI/SoftMC>
- Other open-source software from my group
 - <https://github.com/CMU-SAFARI/>
 - <http://www.ece.cmu.edu/~safari/tools.html>

Some Open Source Tools (II)

- MQSim – A Fast Modern SSD Simulator
 - <https://github.com/CMU-SAFARI/MQSim>
- Mosaic – GPU Simulator Supporting Concurrent Applications
 - <https://github.com/CMU-SAFARI/Mosaic>
- IMPICA – Processing in 3D-Stacked Memory Simulator
 - <https://github.com/CMU-SAFARI/IMPICA>
- SMLA – Detailed 3D-Stacked Memory Simulator
 - <https://github.com/CMU-SAFARI/SMLA>
- HWASim – Simulator for Heterogeneous CPU-HWA Systems
 - <https://github.com/CMU-SAFARI/HWASim>
- Other open-source software from my group
 - <https://github.com/CMU-SAFARI/>
 - <http://www.ece.cmu.edu/~safari/tools.html>

More Open Source Tools (III)

- A lot more open-source software from my group
 - ❑ <https://github.com/CMU-SAFARI/>
 - ❑ <http://www.ece.cmu.edu/~safari/tools.html>



SAFARI Research Group at ETH Zurich and Carnegie Mellon University

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

📍 ETH Zurich and Carnegi... 🔗 <http://www.ece.cmu.ed...> ✉ omutlu@gmail.com

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MQSim

MQSim is a fast and accurate simulator modeling the performance of modern multi-queue (MQ) SSDs as well as traditional SATA based SSDs. MQSim faithfully models new high-bandwidth protocol implementations, steady-state SSD conditions, and the full end-to-end latency of requests in modern SSDs. It is described in detail in the FAST 2018 paper by A...

🌟 14 🍴 14 🏢 MIT Updated 8 days ago



Top languages

● C++ ● C ● C# ● AGS Script
● Verilog

Most used topics

Manage

dram reliability

Referenced Papers

- All are available at

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

<http://scholar.google.com/citations?user=7XyGUGkAAAAJ&hl=en>

<https://people.inf.ethz.ch/omutlu/acaces2018.html>

Ramulator: A Fast and Extensible DRAM Simulator

[IEEE Comp Arch Letters'15]

Ramulator Motivation

- DRAM and Memory Controller landscape is changing
- Many new and upcoming standards
- Many new controller designs
- A fast and easy-to-extend simulator is very much needed

<i>Segment</i>	<i>DRAM Standards & Architectures</i>
Commodity	DDR3 (2007) [14]; DDR4 (2012) [18]
Low-Power	LPDDR3 (2012) [17]; LPDDR4 (2014) [20]
Graphics	GDDR5 (2009) [15]
Performance	eDRAM [28], [32]; RLDram3 (2011) [29]
3D-Stacked	WIO (2011) [16]; WIO2 (2014) [21]; MCDRAM (2015) [13]; HBM (2013) [19]; HMC1.0 (2013) [10]; HMC1.1 (2014) [11]
Academic	SBA/SSA (2010) [38]; Staged Reads (2012) [8]; RAIDR (2012) [27]; SALP (2012) [24]; TL-DRAM (2013) [26]; RowClone (2013) [37]; Half-DRAM (2014) [39]; Row-Buffer Decoupling (2014) [33]; SARP (2014) [6]; AL-DRAM (2015) [25]

Table 1. Landscape of DRAM-based memory

Ramulator

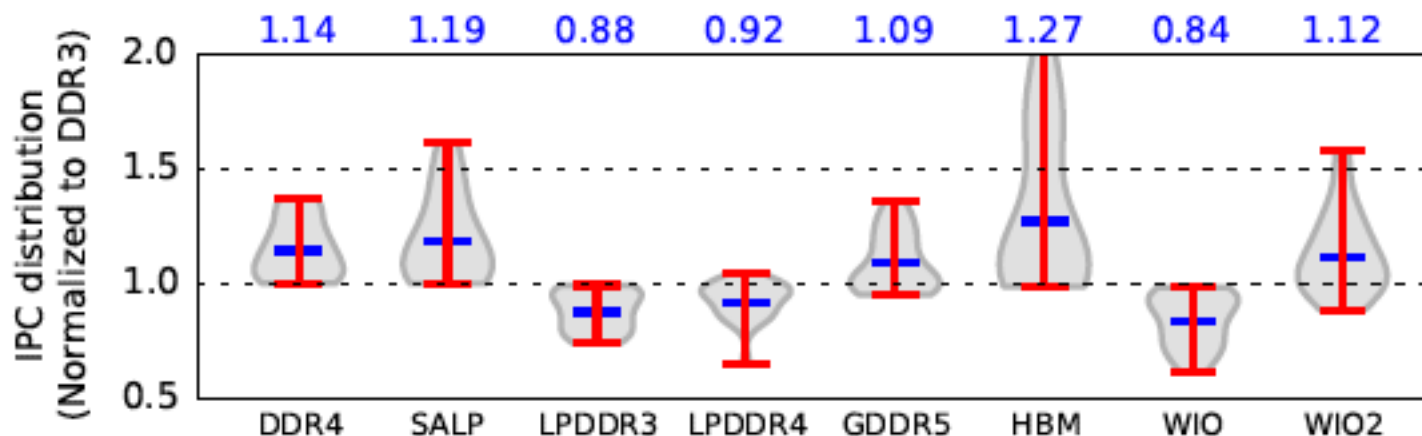
- Provides out-of-the box support for many DRAM standards:
 - DDR3/4, LPDDR3/4, GDDR5, WIO1/2, HBM, plus new proposals (SALP, AL-DRAM, TLDRAM, RowClone, and SARP)
- ~2.5X faster than fastest open-source simulator
- Modular and extensible to different standards

<i>Simulator</i> (clang -O3)	<i>Cycles (10⁶)</i>		<i>Runtime (sec.)</i>		<i>Req/sec (10³)</i>		<i>Memory</i> (MB)
	<i>Random</i>	<i>Stream</i>	<i>Random</i>	<i>Stream</i>	<i>Random</i>	<i>Stream</i>	
Ramulator	652	411	752	249	133	402	2.1
DRAMSim2	645	413	2,030	876	49	114	1.2
USIMM	661	409	1,880	750	53	133	4.5
DrSim	647	406	18,109	12,984	6	8	1.6
NVMain	666	413	6,881	5,023	15	20	4,230.0

Table 3. Comparison of five simulators using two traces

Case Study: Comparison of DRAM Standards

<i>Standard</i>	<i>Rate (MT/s)</i>	<i>Timing (CL-RCD-RP)</i>	<i>Data-Bus (Width×Chan.)</i>	<i>Rank-per-Chan</i>	<i>BW (GB/s)</i>
DDR3	1,600	11-11-11	64-bit × 1	1	11.9
DDR4	2,400	16-16-16	64-bit × 1	1	17.9
SALP [†]	1,600	11-11-11	64-bit × 1	1	11.9
LPDDR3	1,600	12-15-15	64-bit × 1	1	11.9
LPDDR4	2,400	22-22-22	32-bit × 2*	1	17.9
GDDR5 [12]	6,000	18-18-18	64-bit × 1	1	44.7
HBM	1,000	7-7-7	128-bit × 8*	1	119.2
WIO	266	7-7-7	128-bit × 4*	1	15.9
WIO2	1,066	9-10-10	128-bit × 8*	1	127.2



Across 22
workloads,
simple CPU
model

Figure 2. Performance comparison of DRAM standards

Ramulator Paper and Source Code

- Yoongu Kim, Weikun Yang, and Onur Mutlu,
"Ramulator: A Fast and Extensible DRAM Simulator"
IEEE Computer Architecture Letters (CAL), March 2015.
[[Source Code](#)]
- Source code is released under the liberal MIT License
 - <https://github.com/CMU-SAFARI/ramulator>

Ramulator: A Fast and Extensible DRAM Simulator

Yoongu Kim¹ Weikun Yang^{1,2} Onur Mutlu¹
¹Carnegie Mellon University ²Peking University

Optional Assignment

- Review the Ramulator paper
 - Email me your review (omutlu@gmail.com)
- Download and run Ramulator
 - Compare DDR3, DDR4, SALP, HBM for the libquantum benchmark (provided in Ramulator repository)
 - Email me your report (omutlu@gmail.com)
- This **will** help you get into **memory systems research**

Some More Suggested Readings

Some Key Readings on DRAM (I)

■ DRAM Organization and Operation

- ❑ Lee et al., “Tiered-Latency DRAM: A Low Latency and Low Cost DRAM Architecture,” HPCA 2013.
https://people.inf.ethz.ch/omutlu/pub/tldram_hpca13.pdf
- ❑ Kim et al., “A Case for Subarray-Level Parallelism (SALP) in DRAM,” ISCA 2012.
https://people.inf.ethz.ch/omutlu/pub/salp-dram_isca12.pdf
- ❑ Lee et al., “Simultaneous Multi-Layer Access: Improving 3D-Stacked Memory Bandwidth at Low Cost,” ACM TACO 2016.
https://people.inf.ethz.ch/omutlu/pub/smla_high-bandwidth-3d-stacked-memory_taco16.pdf

Some Key Readings on DRAM (II)

■ DRAM Refresh

- ❑ Liu et al., “RAIDR: Retention-Aware Intelligent DRAM Refresh,” ISCA 2012.
https://people.inf.ethz.ch/omutlu/pub/raidr-dram-refresh_isca12.pdf
- ❑ Chang et al., “Improving DRAM Performance by Parallelizing Refreshes with Accesses,” HPCA 2014.
https://people.inf.ethz.ch/omutlu/pub/dram-access-refresh-parallelization_hpca14.pdf
- ❑ Patel et al., “The Reach Profiler (REAPER): Enabling the Mitigation of DRAM Retention Failures via Profiling at Aggressive Conditions,” ISCA 2017.
https://people.inf.ethz.ch/omutlu/pub/reaper-dram-retention-profiling-lpddr4_isca17.pdf

Reading on Simulating Main Memory

- How to evaluate future main memory systems?
- An open-source simulator and its brief description
- Yoongu Kim, Weikun Yang, and Onur Mutlu,
"Ramulator: A Fast and Extensible DRAM Simulator"
IEEE Computer Architecture Letters (**CAL**), March 2015.
[[Source Code](#)]

Some Key Readings on Memory Control 1

- ❑ Mutlu+, "Parallelism-Aware Batch Scheduling: Enhancing both Performance and Fairness of Shared DRAM Systems," ISCA 2008.
https://people.inf.ethz.ch/omutlu/pub/parbs_isca08.pdf
- ❑ Kim et al., "Thread Cluster Memory Scheduling: Exploiting Differences in Memory Access Behavior," MICRO 2010.
https://people.inf.ethz.ch/omutlu/pub/tcm_micro10.pdf
- ❑ Subramanian et al., "BLISS: Balancing Performance, Fairness and Complexity in Memory Access Scheduling," TPDS 2016.
https://people.inf.ethz.ch/omutlu/pub/bliss-memory-scheduler_ieee-tpds16.pdf
- ❑ Usui et al., "DASH: Deadline-Aware High-Performance Memory Scheduler for Heterogeneous Systems with Hardware Accelerators," TACO 2016.
https://people.inf.ethz.ch/omutlu/pub/dash_deadline-aware-heterogeneous-memory-scheduler_taco16.pdf

Some Key Readings on Memory Control 2

- ❑ Ipek+, “Self Optimizing Memory Controllers: A Reinforcement Learning Approach,” ISCA 2008.
https://people.inf.ethz.ch/omutlu/pub/rlmc_isca08.pdf
- ❑ Ebrahimi et al., “Fairness via Source Throttling: A Configurable and High-Performance Fairness Substrate for Multi-Core Memory Systems,” ASPLOS 2010.
https://people.inf.ethz.ch/omutlu/pub/fst_asplos10.pdf
- ❑ Subramanian et al., “The Application Slowdown Model: Quantifying and Controlling the Impact of Inter-Application Interference at Shared Caches and Main Memory,” MICRO 2015.
https://people.inf.ethz.ch/omutlu/pub/application-slowdown-model_micro15.pdf
- ❑ Lee et al., “Decoupled Direct Memory Access: Isolating CPU and IO Traffic by Leveraging a Dual-Data-Port DRAM,” PACT 2015.
https://people.inf.ethz.ch/omutlu/pub/decoupled-dma_pact15.pdf

More Readings

- To come as we cover the future topics
- Search for “DRAM” or “Memory” in:
 - <https://people.inf.ethz.ch/omutlu/projects.htm>