

Memory-Centric Computing

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HipChips Workshop Keynote (with ISCA 2022)

SAFARI

ETH zürich

Carnegie Mellon

Computing

is Bottlenecked by Data

Data is Key for AI, ML, Genomics, ...

- Important workloads are all data intensive
- They require rapid and efficient processing of large amounts of data
- Data is increasing
 - We can generate more than we can process

Data is Key for Future Workloads



In-memory Databases

[Mao+, EuroSys'12;
Clapp+ (Intel), IISWC'15]



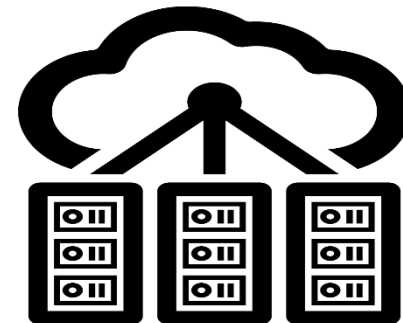
In-Memory Data Analytics

[Clapp+ (Intel), IISWC'15;
Awan+, BDCloud'15]



Graph/Tree Processing

[Xu+, IISWC'12; Umuroglu+, FPL'15]



Datacenter Workloads

[Kanev+ (Google), ISCA'15]

Data Overwhelms Modern Machines



In-memory Databases



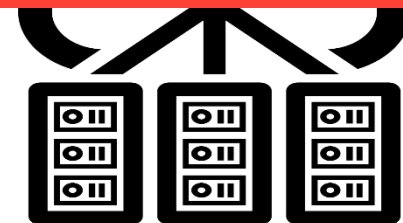
Graph/Tree Processing

Data → performance & energy bottleneck



In-Memory Data Analytics

[Clapp+ (Intel), IISWC'15;
Awan+, BDCloud'15]



Datacenter Workloads

[Kanev+ (Google), ISCA'15]

Data is Key for Future Workloads



Chrome

Google's web browser



TensorFlow Mobile

Google's machine learning
framework



Video Playback

Google's **video codec**



Video Capture

Google's **video codec**

Data Overwhelms Modern Machines



Chrome



TensorFlow Mobile

Data → performance & energy bottleneck

VP9



Video Playback

Google's **video codec**

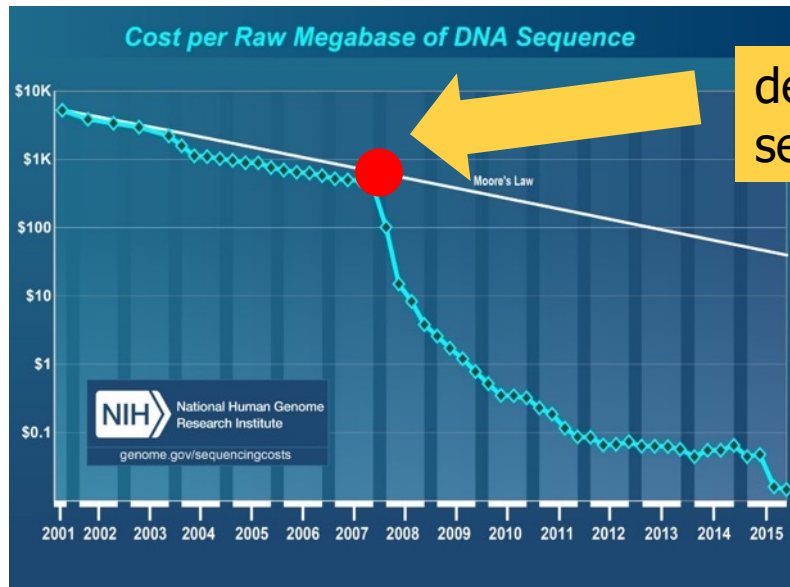
VP9



Video Capture

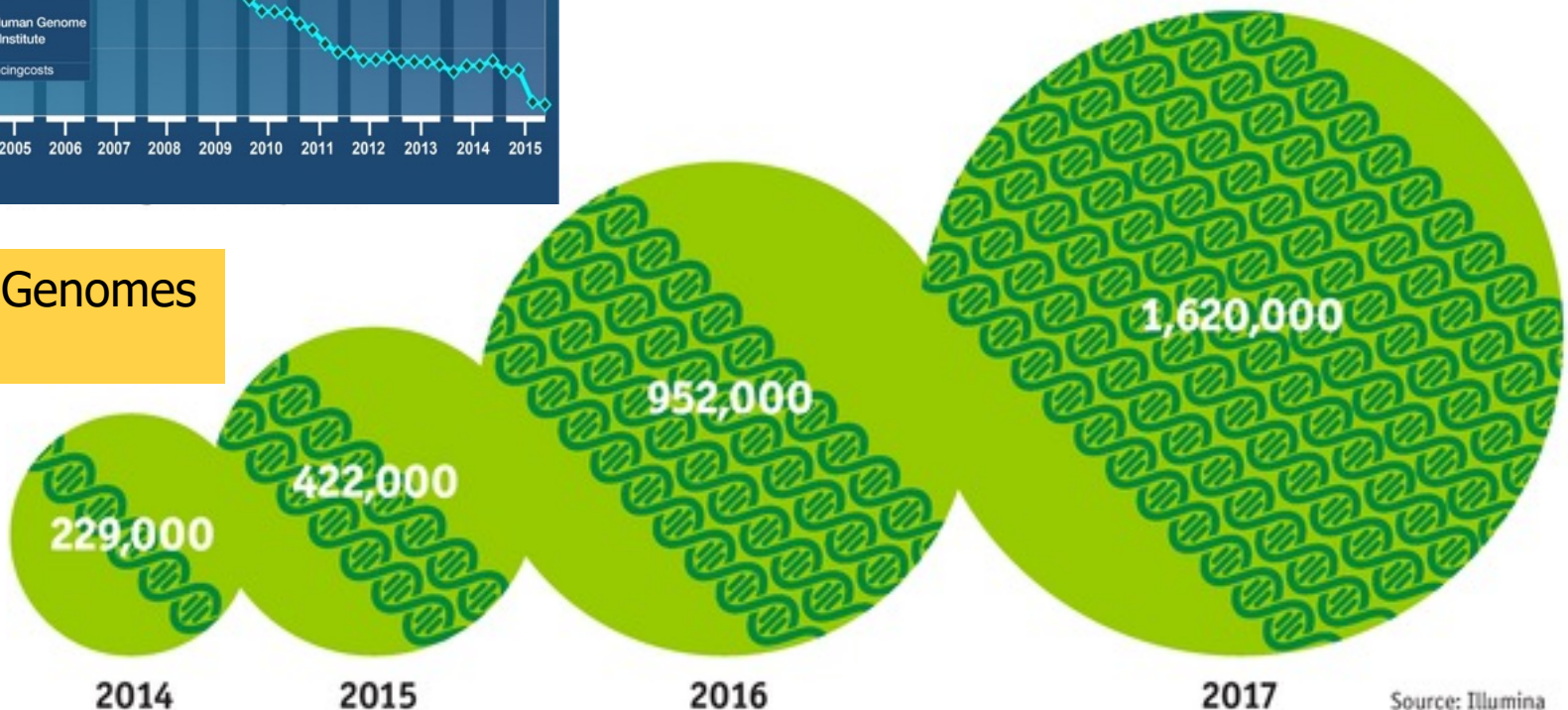
Google's **video codec**

Data is Key for Future Workloads

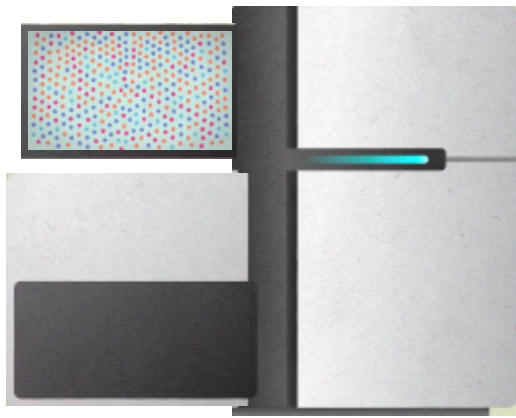


development of high-throughput sequencing (HTS) technologies

Number of Genomes Sequenced

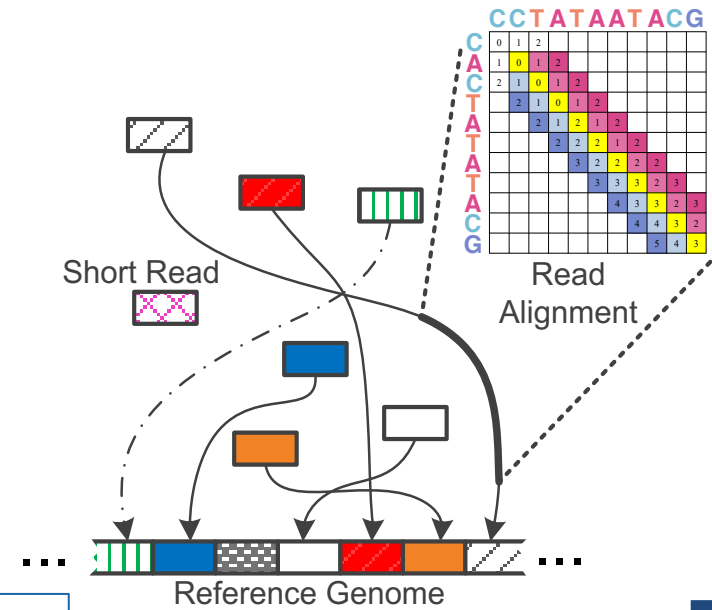


The Economist



Billions of Short Reads

ATATATACGTACTAGTACGT
 TTTAGTACGTACGT
 ATACGTACTAGTACGT
 CGCCCCTACGTA
 ACGTACTAGTACGT
 TTAGTACGTACGT
 TACGTACTAAAGTACGT
 TACGTACTAGTACGT
 TTTAAACGTA
 CGTACTAGTACGT
 GGGAGTACGTACGT



1 Sequencing

Genome Analysis

2 Read Mapping

Data → performance & energy bottleneck

read4: CGCTTCCAT
 read5: CCATGACGC
 read6: TTCCATGAC



3 Variant Calling

4 Scientific Discovery

New Genome Sequencing Technologies

Nanopore sequencing technology and tools for genome assembly: computational analysis of the current state, bottlenecks and future directions

Damla Senol Cali ✉, Jeremie S Kim, Saugata Ghose, Can Alkan, Onur Mutlu

Briefings in Bioinformatics, bby017, <https://doi.org/10.1093/bib/bby017>

Published: 02 April 2018 **Article history** ▼



Oxford Nanopore MinION

Senol Cali+, “**Nanopore Sequencing Technology and Tools for Genome Assembly: Computational Analysis of the Current State, Bottlenecks and Future Directions**,” *Briefings in Bioinformatics*, 2018.

[[Open arxiv.org version](#)]

New Genome Sequencing Technologies

Nanopore sequencing technology and tools for genome assembly: computational analysis of the current state, bottlenecks and future directions

Damla Senol Cali ✉, Jeremie S Kim, Saugata Ghose, Can Alkan, Onur Mutlu

Briefings in Bioinformatics, bby017, <https://doi.org/10.1093/bib/bby017>

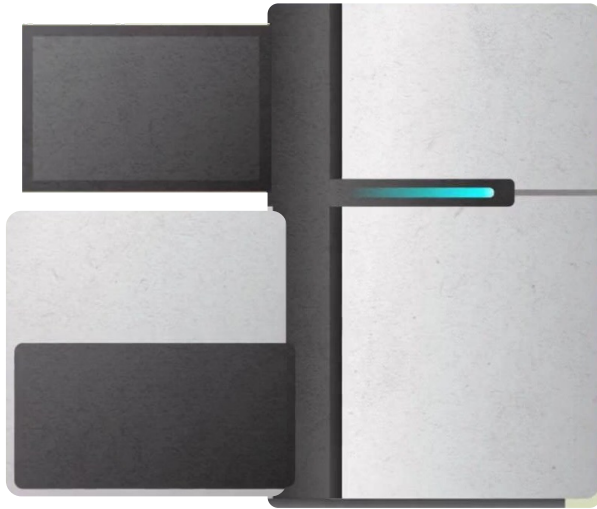
Published: 02 April 2018 **Article history** ▼



Oxford Nanopore MinION

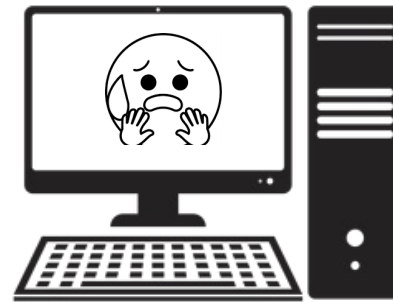
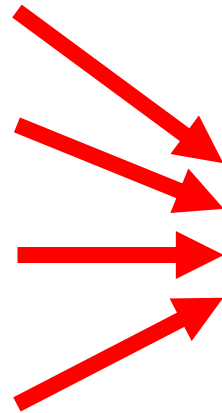
Data → performance & energy bottleneck

One Problem with (Genome) Analysis Today



Special-Purpose Machine
for **Sequencing**

FAST



General-Purpose Machine
for **Analysis**

SLOW

Slow and inefficient processing capability

SAFARI This picture is similar for many “data generators & analyzers” today

Accelerating Genome Analysis [IEEE MICRO 2020]

- Mohammed Alser, Zülal Bingöl, Damla Senol Cali, Jeremie Kim, Saugata Ghose, Can Alkan, and Onur Mutlu,
["Accelerating Genome Analysis: A Primer on an Ongoing Journey"](#)
[IEEE Micro \(IEEE MICRO\)](#), Vol. 40, No. 5, pages 65-75, September/October 2020.
[\[Slides \(pptx\)\(pdf\)\]](#)
[\[Talk Video \(1 hour 2 minutes\)\]](#)

Accelerating Genome Analysis: A Primer on an Ongoing Journey

Mohammed Alser

ETH Zürich

Zülal Bingöl

Bilkent University

Damla Senol Cali

Carnegie Mellon University

Jeremie Kim

ETH Zurich and Carnegie Mellon University

Saugata Ghose

University of Illinois at Urbana-Champaign and
Carnegie Mellon University

Can Alkan

Bilkent University

Onur Mutlu

ETH Zurich, Carnegie Mellon University, and
Bilkent University

FPGA-based Near-Memory Analytics

- Gagandeep Singh, Mohammed Alser, Damla Senol Cali, Dionysios Diamantopoulos, Juan Gómez-Luna, Henk Corporaal, and Onur Mutlu, ["FPGA-based Near-Memory Acceleration of Modern Data-Intensive Applications"](#) *IEEE Micro* (**IEEE MICRO**), 2021.

FPGA-based Near-Memory Acceleration of Modern Data-Intensive Applications

Gagandeep Singh[◇] Mohammed Alser[◇] Damla Senol Cali[✕]

Dionysios Diamantopoulos[▽] Juan Gómez-Luna[◇]

Henk Corporaal[★] Onur Mutlu^{◇✕}

[◇]*ETH Zürich* [✕]*Carnegie Mellon University*

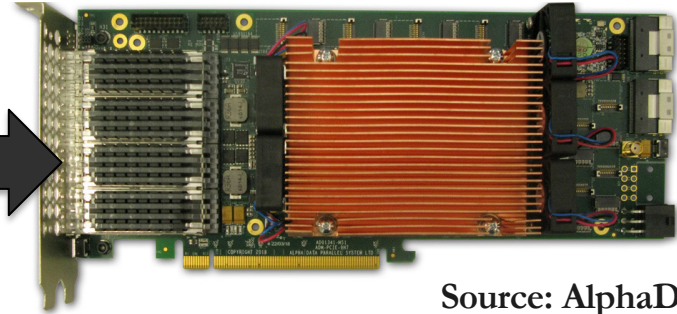
[★]*Eindhoven University of Technology* [▽]*IBM Research Europe*

Near-Memory Acceleration using FPGAs



Source: IBM

IBM POWER9 CPU



Source: AlphaData

HBM-based FPGA board

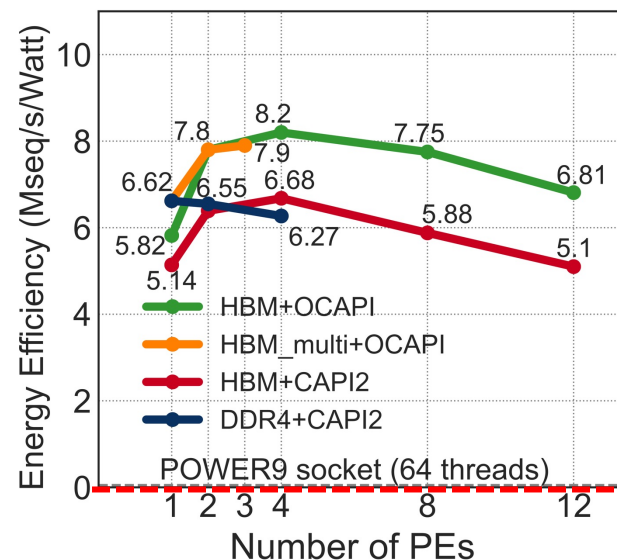
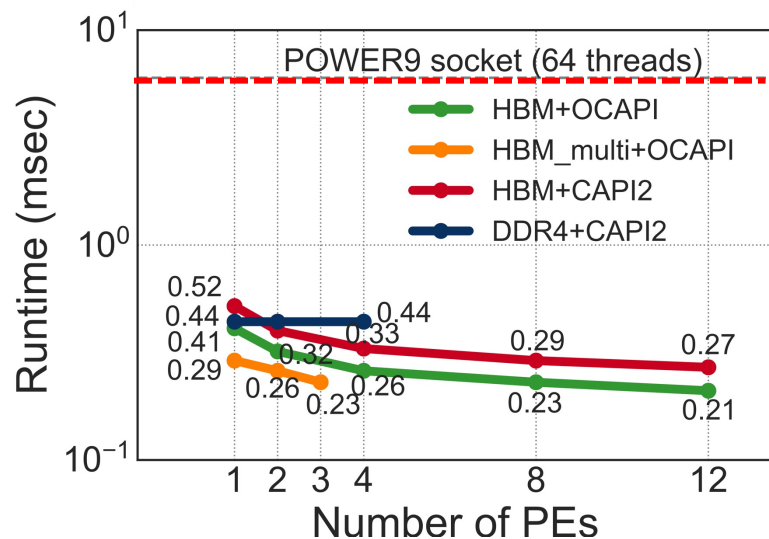
Near-HBM FPGA-based accelerator

Two communication technologies: CAPI2 and OCAPI

Two memory technologies: DDR4 and HBM

Two workloads: Weather Modeling and Genome Analysis

Performance & Energy Greatly Improve



5-27× performance vs. a 16-core (64-thread) IBM POWER9 CPU

12-133× energy efficiency vs. a 16-core (64-thread) IBM POWER9 CPU

HBM alleviates memory bandwidth contention vs. DDR4

GenASM Framework [MICRO 2020]

- Damla Senol Cali, Gurpreet S. Kalsi, Zulal Bingol, Can Firtina, Lavanya Subramanian, Jeremie S. Kim, Rachata Ausavarungnirun, Mohammed Alser, Juan Gomez-Luna, Amirali Boroumand, Anant Nori, Allison Scibisz, Sreenivas Subramoney, Can Alkan, Saugata Ghose, and Onur Mutlu, **"GenASM: A High-Performance, Low-Power Approximate String Matching Acceleration Framework for Genome Sequence Analysis"**
Proceedings of the 53rd International Symposium on Microarchitecture (MICRO), Virtual, October 2020.
[[Lighting Talk Video](#) (1.5 minutes)]
[[Lightning Talk Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (18 minutes)]
[[Slides \(pptx\)](#) ([pdf](#))]

GenASM: A High-Performance, Low-Power Approximate String Matching Acceleration Framework for Genome Sequence Analysis

Damla Senol Cali^{†⋈} Gurpreet S. Kalsi[⋈] Zülal Bingöl[▽] Can Firtina[◇] Lavanya Subramanian[‡] Jeremie S. Kim^{◇†}
Rachata Ausavarungnirun[○] Mohammed Alser[◇] Juan Gomez-Luna[◇] Amirali Boroumand[†] Anant Nori[⋈]
Allison Scibisz[†] Sreenivas Subramoney[⋈] Can Alkan[▽] Saugata Ghose^{*†} Onur Mutlu^{◇†▽}
[†]Carnegie Mellon University [⋈]Processor Architecture Research Lab, Intel Labs [▽]Bilkent University [◇]ETH Zürich
[‡]Facebook [○]King Mongkut's University of Technology North Bangkok ^{*}University of Illinois at Urbana-Champaign

In-Storage Genome Filtering [ASPLOS 2022]

- Nika Mansouri Ghiasi, Jisung Park, Harun Mustafa, Jeremie Kim, Ataberk Olgun, Arvid Gollwitzer, Damla Senol Cali, Can Firtina, Haiyu Mao, Nour Almadhoun Alserr, Rachata Ausavarungnirun, Nandita Vijaykumar, Mohammed Alser, and Onur Mutlu,

"GenStore: A High-Performance and Energy-Efficient In-Storage Computing System for Genome Sequence Analysis"

Proceedings of the 27th International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS), Virtual, February-March 2022.

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

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

[[Lightning Talk Video](#) (90 seconds)]

[[Talk Video](#) (17 minutes)]

GenStore: A High-Performance In-Storage Processing System for Genome Sequence Analysis

Nika Mansouri Ghiasi¹ Jisung Park¹ Harun Mustafa¹ Jeremie Kim¹ Ataberk Olgun¹
Arvid Gollwitzer¹ Damla Senol Cali² Can Firtina¹ Haiyu Mao¹ Nour Almadhoun Alserr¹
Rachata Ausavarungnirun³ Nandita Vijaykumar⁴ Mohammed Alser¹ Onur Mutlu¹

¹ETH Zürich ²Bionano Genomics ³KMUTNB ⁴University of Toronto

Accelerating Sequence-to-Graph Mapping

- Damla Senol Cali, Konstantinos Kanellopoulos, Joel Lindegger, Zulal Bingol, Gurpreet S. Kalsi, Ziyi Zuo, Can Firtina, Meryem Banu Cavlak, Jeremie Kim, Nika Mansouri Ghiasi, Gagandeep Singh, Juan Gomez-Luna, Nour Almadhoun Alserr, Mohammed Alser, Sreenivas Subramoney, Can Alkan, Saugata Ghose, and Onur Mutlu,
"SeGraM: A Universal Hardware Accelerator for Genomic Sequence-to-Graph and Sequence-to-Sequence Mapping"
Proceedings of the 49th International Symposium on Computer Architecture (ISCA), New York, June 2022.
[[arXiv version](#)]

SeGraM: A Universal Hardware Accelerator for Genomic Sequence-to-Graph and Sequence-to-Sequence Mapping

Damla Senol Cali¹ Konstantinos Kanellopoulos² Joël Lindegger² Zülal Bingöl³
Gurpreet S. Kalsi⁴ Ziyi Zuo⁵ Can Firtina² Meryem Banu Cavlak² Jeremie Kim²
Nika Mansouri Ghiasi² Gagandeep Singh² Juan Gómez-Luna² Nour Almadhoun Alserr²
Mohammed Alser² Sreenivas Subramoney⁴ Can Alkan³ Saugata Ghose⁶ Onur Mutlu²

¹Bionano Genomics ²ETH Zürich ³Bilkent University ⁴Intel Labs

⁵Carnegie Mellon University ⁶University of Illinois Urbana-Champaign

Future of Genome Sequencing & Analysis

Mohammed Alser, Zülal Bingöl, Damla Senol Cali, Jeremie Kim, Saugata Ghose, Can Alkan, Onur Mutlu
[“Accelerating Genome Analysis: A Primer on an Ongoing Journey”](#) IEEE Micro, August 2020.



MinION from ONT

Accelerating Genome Analysis: A Primer on an Ongoing Journey

Sept.-Oct. 2020, pp. 65-75, vol. 40

DOI Bookmark: [10.1109/MM.2020.3013728](https://doi.org/10.1109/MM.2020.3013728)

FPGA-Based Near-Memory Acceleration of Modern Data-Intensive Applications

July-Aug. 2021, pp. 39-48, vol. 41

DOI Bookmark: [10.1109/MM.2021.3088396](https://doi.org/10.1109/MM.2021.3088396)



SmidgION from ONT

More on Fast & Efficient Genome Analysis ...

- Onur Mutlu,
"Accelerating Genome Analysis: A Primer on an Ongoing Journey"
Invited Lecture at Technion, Virtual, 26 January 2021.
[Slides (pptx) (pdf)]
[Talk Video (1 hour 37 minutes, including Q&A)]
[Related Invited Paper (at IEEE Micro, 2020)]



Onur Mutlu - Invited Lecture @Technion: Accelerating Genome Analysis: A Primer on an Ongoing Journey

740 views • Premiered Feb 6, 2021

35 0 SHARE SAVE ...

SAFARI



Onur Mutlu Lectures
15.9K subscribers

<https://www.youtube.com/watch?v=r7sn41IH-4A>

ANALYTICS

EDIT VIDEO

Detailed Lectures on Genome Analysis

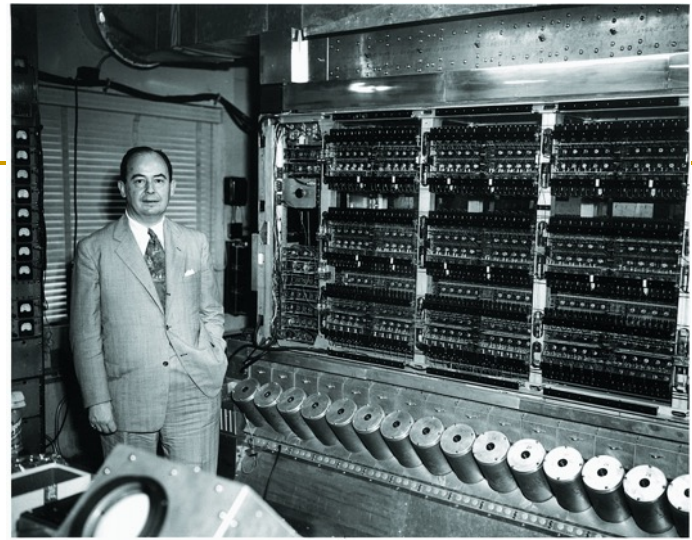
- **Computer Architecture, Fall 2020, Lecture 3a**
 - **Introduction to Genome Sequence Analysis** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=CrRb32v7SJc&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=5>
- **Computer Architecture, Fall 2020, Lecture 8**
 - **Intelligent Genome Analysis** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=ygmQpdDTL7o&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=14>
- **Computer Architecture, Fall 2020, Lecture 9a**
 - **GenASM: Approx. String Matching Accelerator** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=XoLpzmN-Pas&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=15>
- **Accelerating Genomics Project Course, Fall 2020, Lecture 1**
 - **Accelerating Genomics** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=rgjl8ZyLsAg&list=PL5Q2soXY2Zi9E2bBVAgCqLgwiDRQDTyId>

Data Overwhelms Modern Machines ...

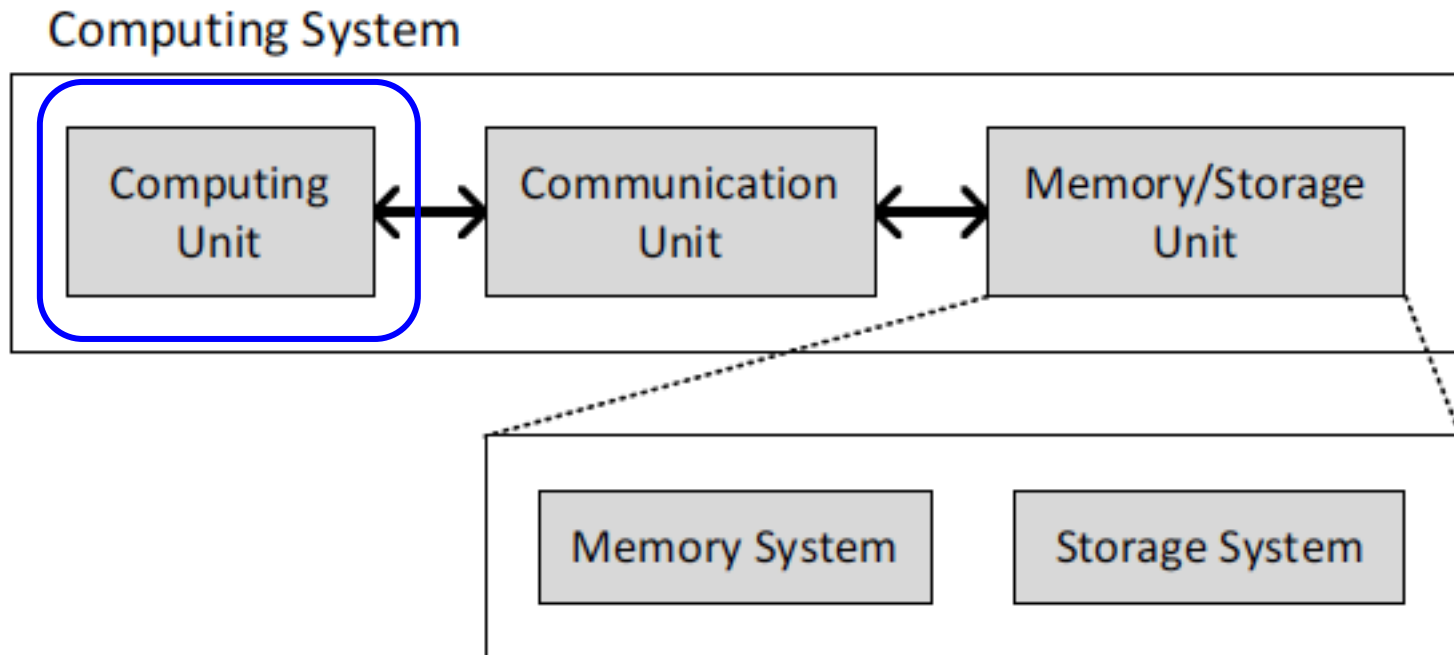
- Storage/memory capability
- Communication capability
- Computation capability
- Greatly impacts robustness, energy, performance, cost

A Computing System

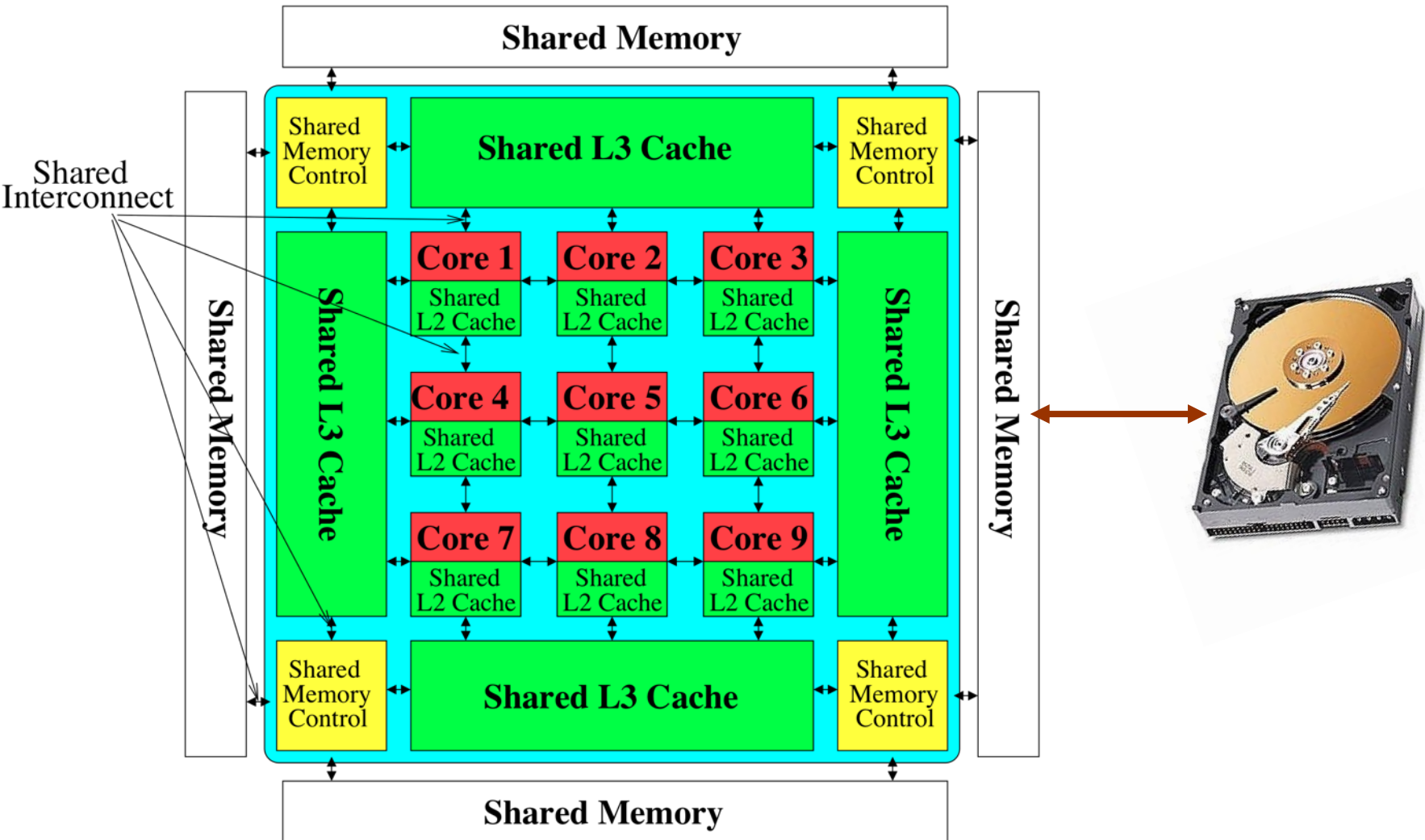
- Three key components
- Computation
- Communication
- Storage/memory



Burks, Goldstein, von Neumann, "Preliminary discussion of the logical design of an electronic computing instrument," 1946.



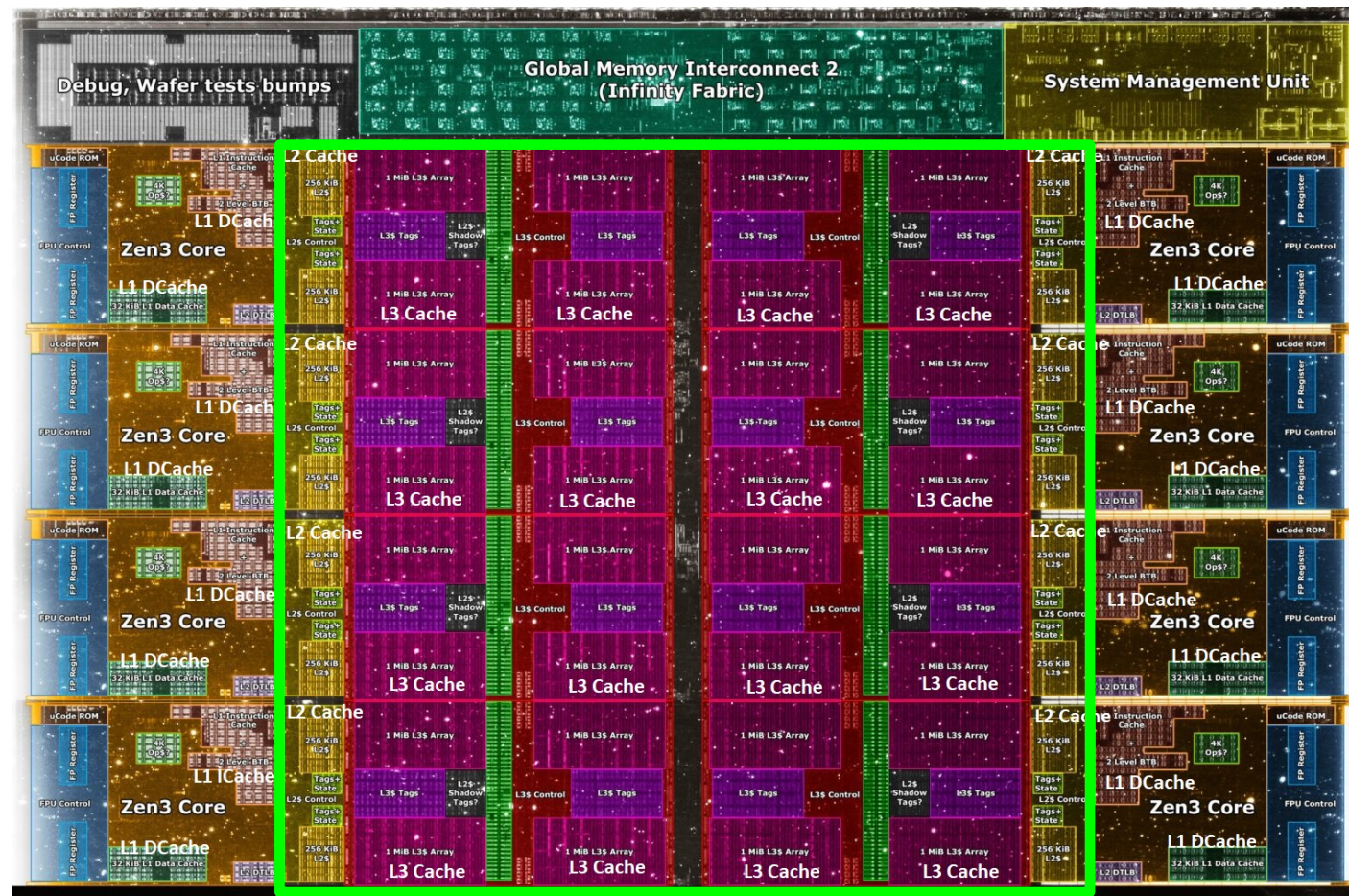
Perils of Processor-Centric Design



Most of the system is dedicated to storing and moving data

Yet, system is still bottlenecked by memory

Deeper and Larger Cache Hierarchies



Core Count:
8 cores/16 threads

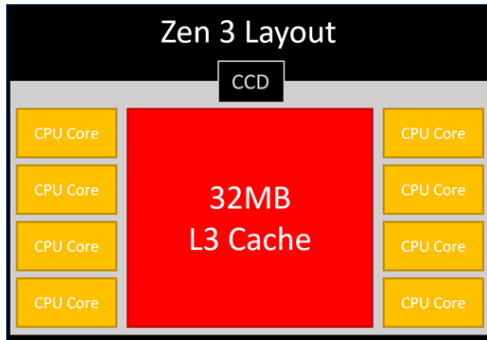
L1 Caches:
32 KB per core

L2 Caches:
512 KB per core

L3 Cache:
32 MB shared

AMD Ryzen 5000, 2020

AMD's 3D Last Level Cache (2021)

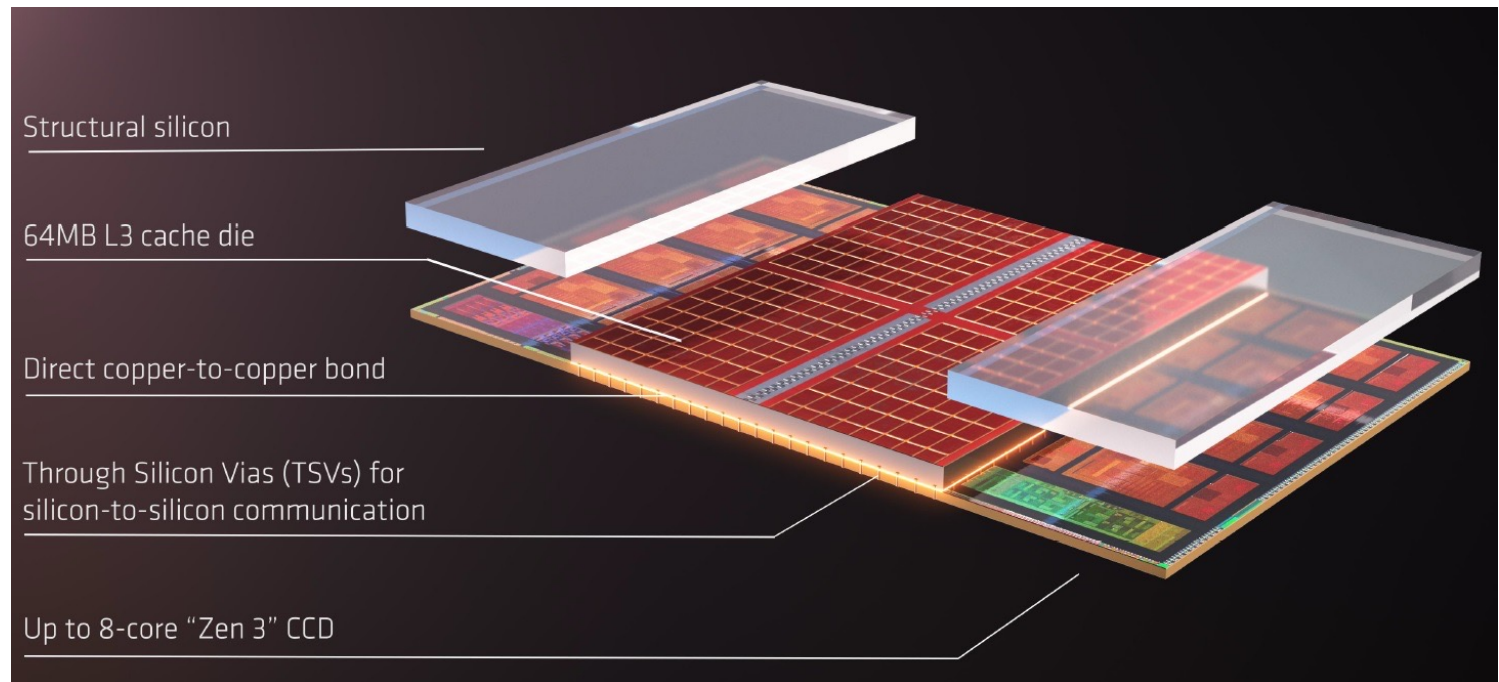


<https://community.microcenter.com/discussion/5134/comparing-zen-3-to-zen-2>

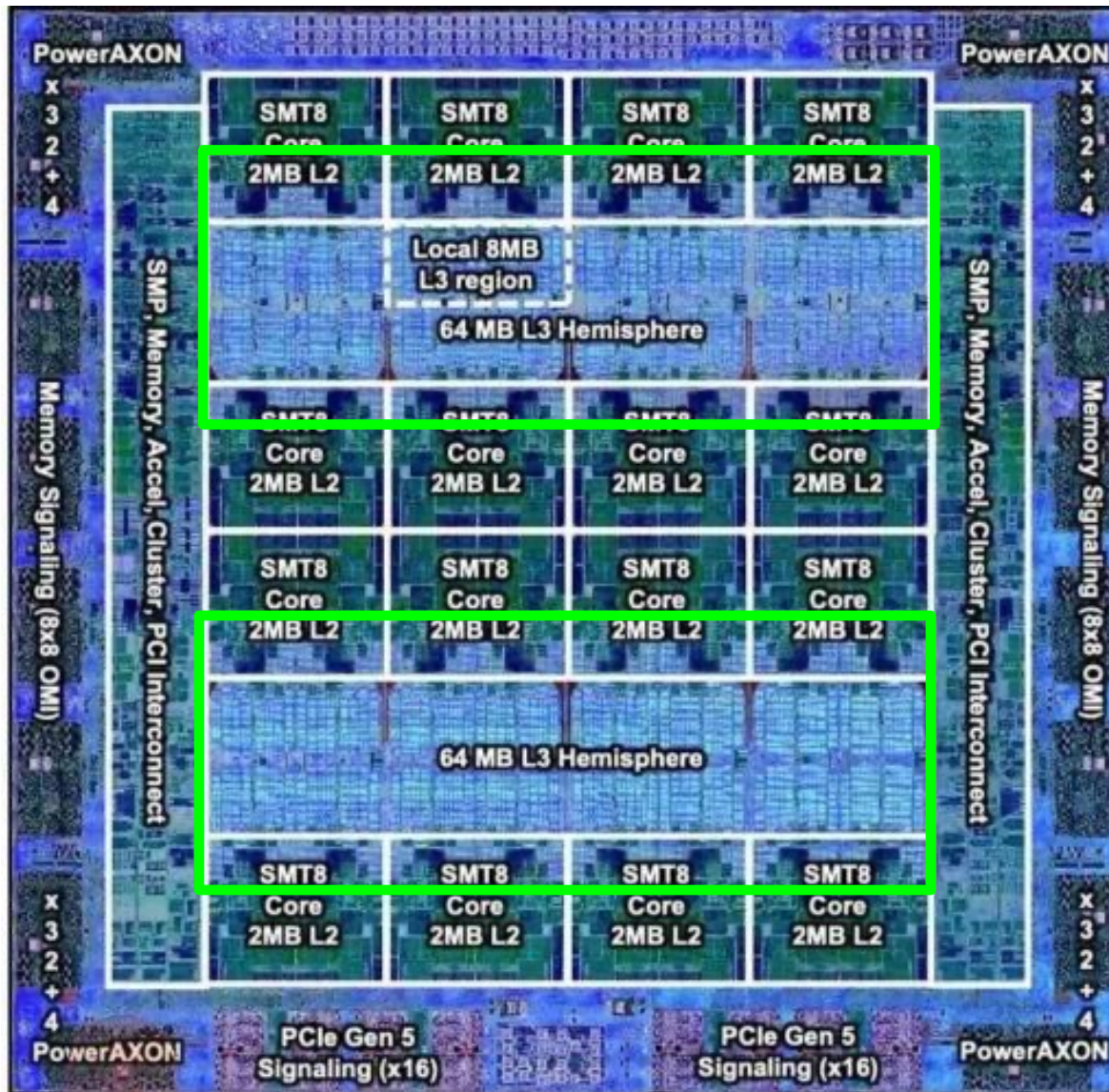
AMD increases the L3 size of their 8-core Zen 3 processors from 32 MB to 96 MB

Additional 64 MB L3 cache die
stacked on top of the processor die

- Connected using Through Silicon Vias (TSVs)
- Total of 96 MB L3 cache



Deeper and Larger Cache Hierarchies



IBM POWER10,
2020

Cores:
15-16 cores,
8 threads/core

L2 Caches:
2 MB per core

L3 Cache:
120 MB shared

Data Overwhelms Modern Machines



Chrome



TensorFlow Mobile

Data → performance & energy bottleneck

VP9



Video Playback

Google's **video codec**

VP9



Video Capture

Google's **video codec**

Data Movement Overwhelms Modern Machines

- Amirali Boroumand, Saugata Ghose, Youngsok Kim, Rachata Ausavarungnirun, Eric Shiu, Rahul Thakur, Daehyun Kim, Aki Kuusela, Allan Knies, Parthasarathy Ranganathan, and Onur Mutlu, ["Google Workloads for Consumer Devices: Mitigating Data Movement Bottlenecks"](#) *Proceedings of the 23rd International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, Williamsburg, VA, USA, March 2018.

**62.7% of the total system energy
is spent on data movement**

Google Workloads for Consumer Devices: Mitigating Data Movement Bottlenecks

Amirali Boroumand¹

Saugata Ghose¹

Youngsok Kim²

Rachata Ausavarungnirun¹

Eric Shiu³

Rahul Thakur³

Daehyun Kim^{4,3}

Aki Kuusela³

Allan Knies³

Parthasarathy Ranganathan³

Onur Mutlu^{5,1}

An Intelligent Architecture Handles Data Well

How to Handle Data Well

- Ensure data does not overwhelm the components
 - via intelligent algorithms
 - via intelligent architectures
 - via whole system designs: algorithm-architecture-devices
- Take advantage of vast amounts of data and metadata
 - to improve architectural & system-level decisions
- Understand and exploit properties of (different) data
 - to improve algorithms & architectures in various metrics

Corollaries: Architectures Today ...

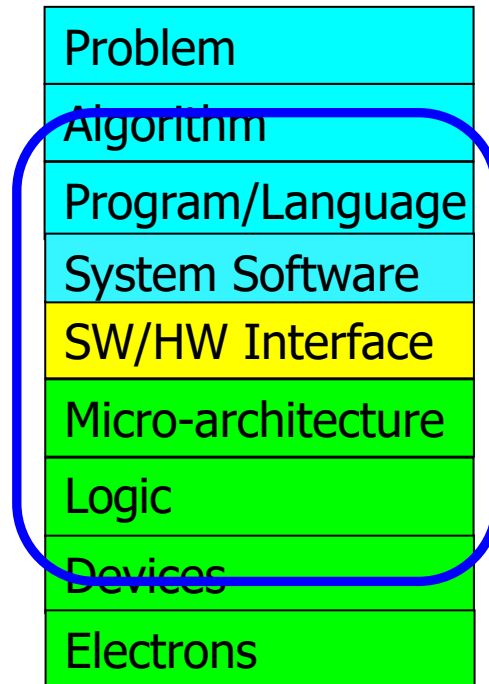
- Architectures are **terrible at dealing with data**
 - ❑ Designed to mainly store and move data vs. to compute
 - ❑ They are **processor-centric** as opposed to **data-centric**
- Architectures are **terrible at taking advantage of vast amounts of data** (and metadata) available to them
 - ❑ Designed to make simple decisions, ignoring lots of data
 - ❑ They make **human-driven decisions** vs. **data-driven**
- Architectures are **terrible at knowing and exploiting different properties of application data**
 - ❑ Designed to treat all data as the same
 - ❑ They make **component-aware decisions** vs. **data-aware**

Data-centric

Data-driven

Data-aware

We Need to Revisit the Entire Stack

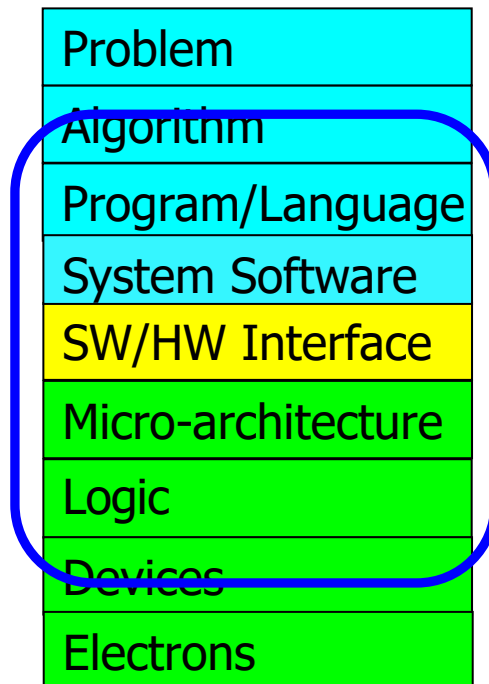


We can get there step by step

Axiom

To achieve the highest **energy efficiency** and **performance**:

we must take an expanded view
of computer architecture



Co-design across the hierarchy:
Algorithms to devices

Specialize as much as possible
within the design goals

Data-centric

Data-driven

Data-aware

A Blueprint for Fundamentally Better Architectures

- Onur Mutlu,
"Intelligent Architectures for Intelligent Computing Systems"
*Invited Paper in Proceedings of the Design, Automation, and Test in Europe Conference (**DATE**), Virtual, February 2021.*
[Slides (pptx) (pdf)]
[IEDM Tutorial Slides (pptx) (pdf)]
[Short DATE Talk Video (11 minutes)]
[Longer IEDM Tutorial Video (1 hr 51 minutes)]

Intelligent Architectures for Intelligent Computing Systems

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Data-Centric (Memory-Centric) Architectures

Data-Centric Architectures: Properties

- **Process data where it resides** (where it makes sense)
 - Processing in and near memory structures
- **Low-latency and low-energy data access**
 - Low latency memory
 - Low energy memory
- **Low-cost data storage and processing**
 - High capacity memory at low cost: hybrid memory, compression
- **Intelligent data management**
 - Intelligent controllers handling robustness, security, cost, perf.

Processing Data Where It Makes Sense

Processing in/near Memory: An Old Idea

- Kautz, "Cellular Logic-in-Memory Arrays", IEEE TC 1969.

IEEE TRANSACTIONS ON COMPUTERS, VOL. C-18, NO. 8, AUGUST 1969

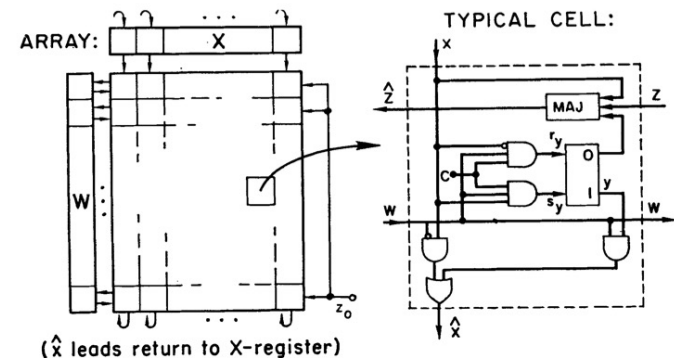
Cellular Logic-in-Memory Arrays

WILLIAM H. KAUTZ, MEMBER, IEEE

Abstract—As a direct consequence of large-scale integration, many advantages in the design, fabrication, testing, and use of digital circuitry can be achieved if the circuits can be arranged in a two-dimensional iterative, or cellular, array of identical elementary networks, or cells. When a small amount of storage is included in each cell, the same array may be regarded either as a logically enhanced memory array, or as a logic array whose elementary gates and connections can be "programmed" to realize a desired logical behavior.

In this paper the specific engineering features of such cellular logic-in-memory (CLIM) arrays are discussed, and one such special-purpose array, a cellular sorting array, is described in detail to illustrate how these features may be achieved in a particular design. It is shown how the cellular sorting array can be employed as a single-address, multiword memory that keeps in order all words stored within it. It can also be used as a content-addressed memory, a pushdown memory, a buffer memory, and (with a lower logical efficiency) a programmable array for the realization of arbitrary switching functions. A second version of a sorting array, operating on a different sorting principle, is also described.

Index Terms—Cellular logic, large-scale integration, logic arrays logic in memory, push-down memory, sorting, switching functions.



CELL EQUATIONS: $\hat{x} = \bar{w}x + wy$
 $s_y = wcx, r_y = w\bar{c}$
 $\hat{z} = M(x, \bar{y}, z) = x\bar{y} + z(x + \bar{y})$

Fig. 1. Cellular sorting array I.

Processing in/near Memory: An Old Idea

- Stone, "A Logic-in-Memory Computer," IEEE TC 1970.

A Logic-in-Memory Computer

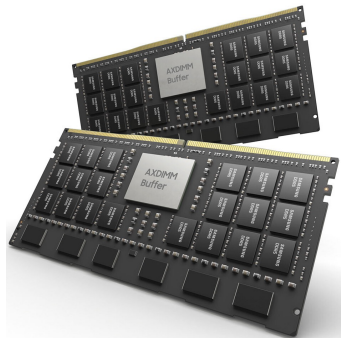
HAROLD S. STONE

Abstract—If, as presently projected, the cost of microelectronic arrays in the future will tend to reflect the number of pins on the array rather than the number of gates, the logic-in-memory array is an extremely attractive computer component. Such an array is essentially a microelectronic memory with some combinational logic associated with each storage element.

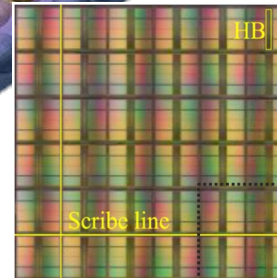
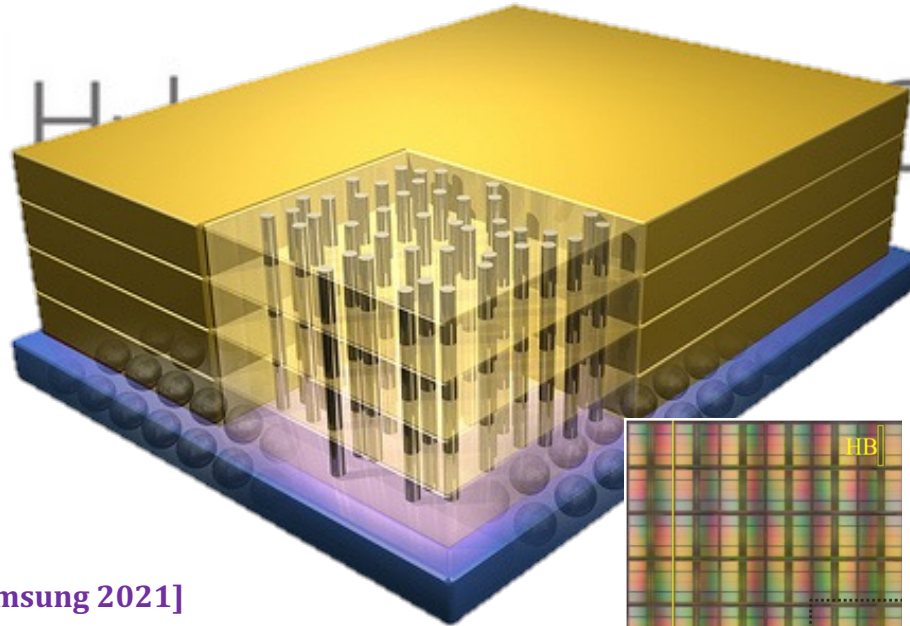
Why In-Memory Computation Today?

- Push from Technology
 - DRAM Scaling at jeopardy
 - Controllers close to DRAM
 - Industry open to new memory architectures

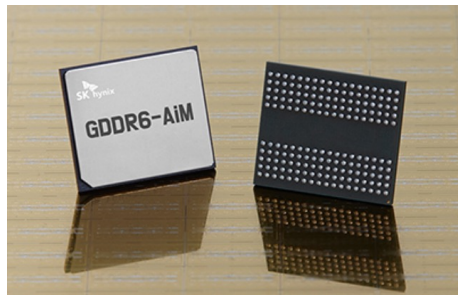
Why In-Memory Computation Today?



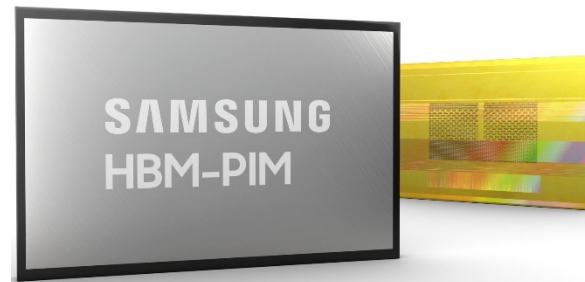
[Samsung 2021]



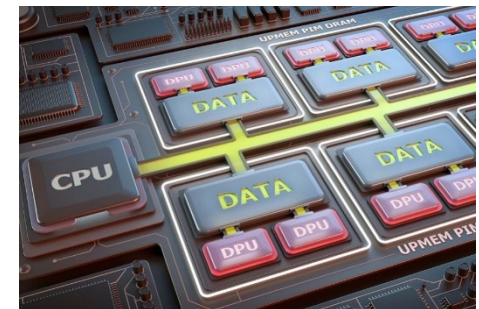
[Alibaba 2022]



[SK Hynix 2022]



[Samsung 2021]



[UPMEM 2019]

Memory Scaling Issues **Were** Real

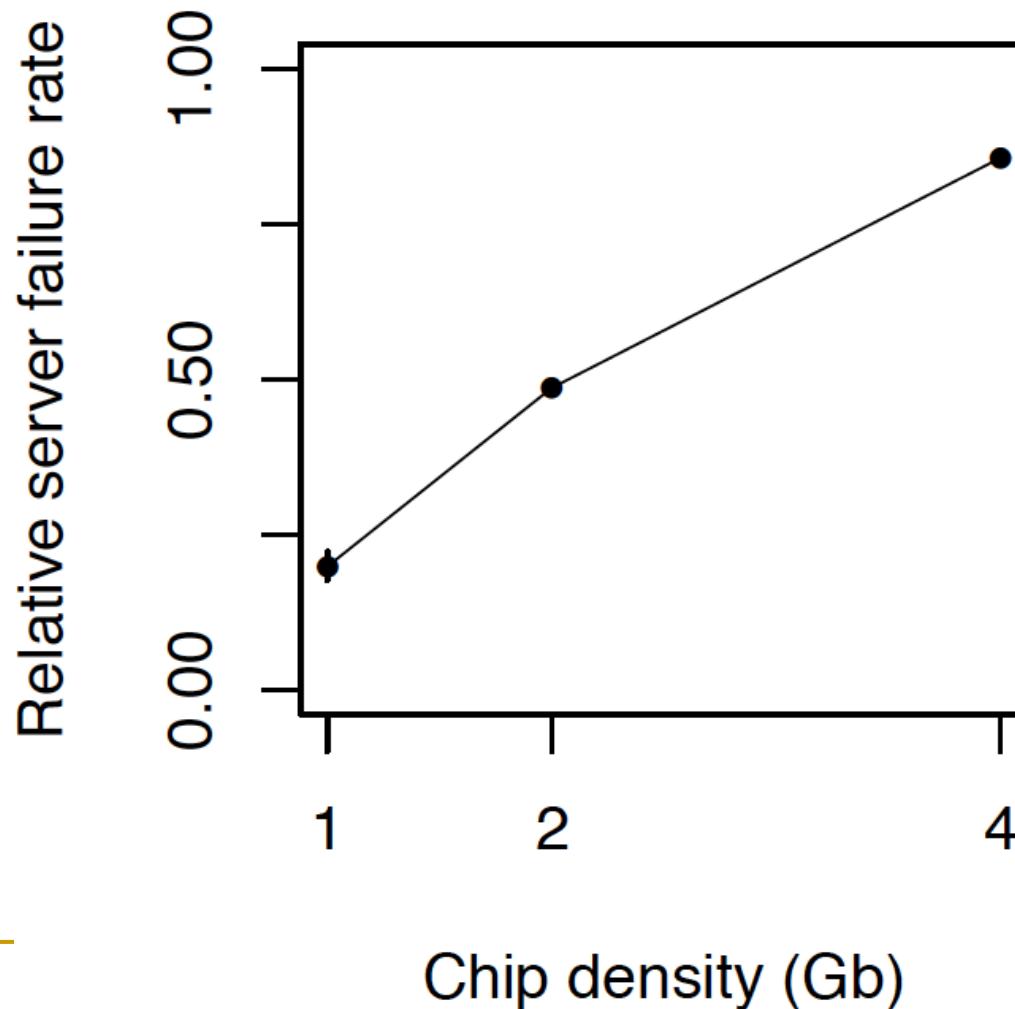
- Onur Mutlu,
"Memory Scaling: A Systems Architecture Perspective"
Proceedings of the 5th International Memory Workshop (IMW), Monterey, CA, May 2013. Slides
(pptx) (pdf)
EETimes Reprint

Memory Scaling: A Systems Architecture Perspective

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

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*

A Curious Phenomenon [Kim et al., ISCA 2014]

One can
predictably induce errors
in most DRAM memory chips

Kim+, "[Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors](#)," ISCA 2014.



Rowhammer

The RowHammer Vulnerability

A simple hardware failure mechanism
can create a widespread
system security vulnerability

WIRED

Forget Software—Now Hackers Are Exploiting Physics

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

ANDY GREENBERG SECURITY 08.31.16 7:00 AM

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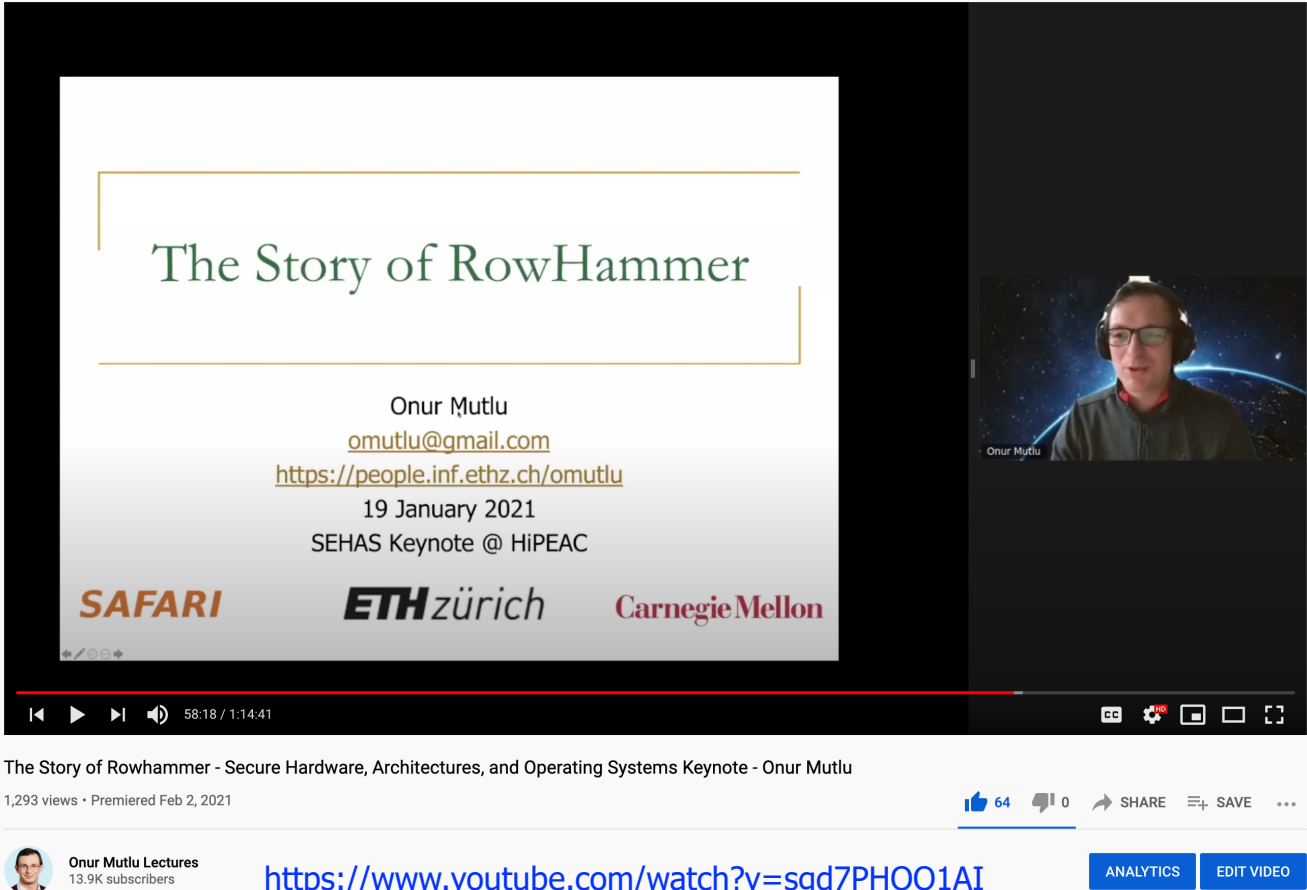


TWEET

FORGET SOFTWARE—NOW HACKERS ARE EXPLOITING PHYSICS

The Story of RowHammer Lecture ...

- Onur Mutlu,
["The Story of RowHammer"](#)
Keynote Talk at *Secure Hardware, Architectures, and Operating Systems Workshop (SeHAS)*, held with *HiPEAC 2021 Conference*, Virtual, 19 January 2021.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (1 hr 15 minutes, with Q&A)]



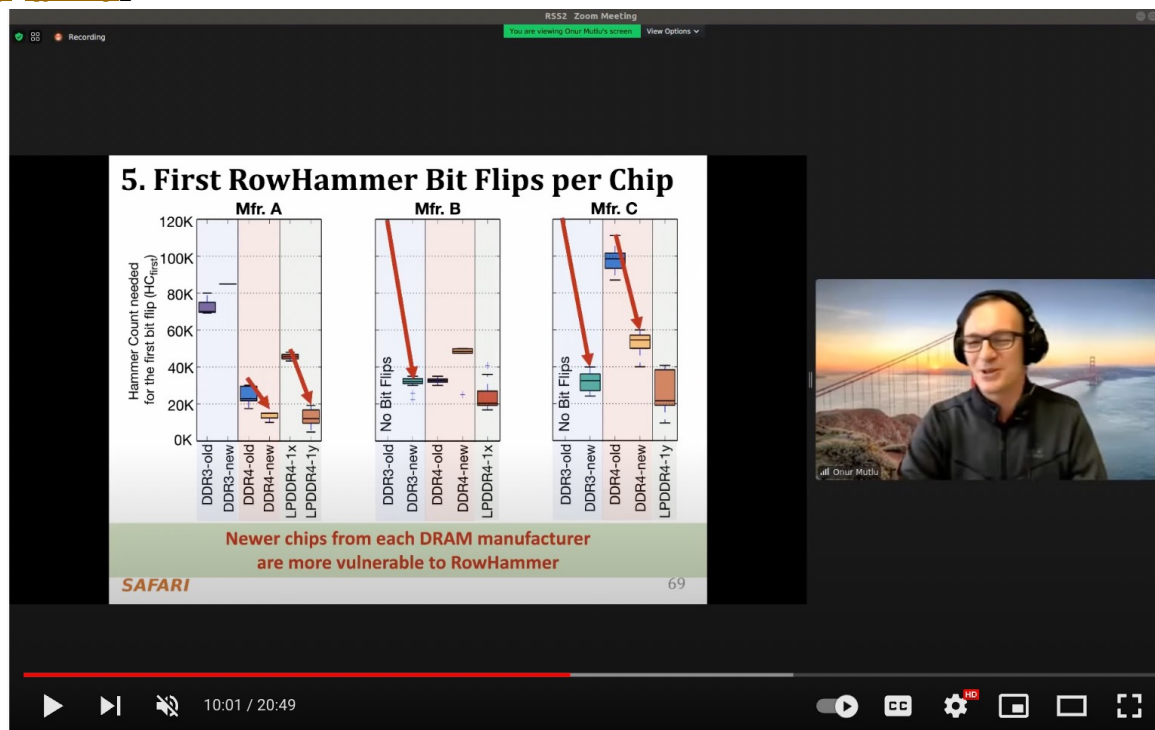
The video player displays a presentation slide titled "The Story of RowHammer" by Onur Mutlu. The slide includes contact information: omutlu@gmail.com, <https://people.inf.ethz.ch/omutlu>, and the date 19 January 2021. It also mentions "SEHAS Keynote @ HiPEAC" and features logos for SAFARI, ETH zürich, and Carnegie Mellon. The video player interface shows a progress bar at 58:18 / 1:14:41 and a video feed of Onur Mutlu on the right. Below the player, the video title "The Story of Rowhammer - Secure Hardware, Architectures, and Operating Systems Keynote - Onur Mutlu" is displayed, along with 1,293 views, a premiere date of Feb 2, 2021, and engagement metrics (64 likes, 0 comments). The channel name "Onur Mutlu Lectures" with 13.9K subscribers is shown, along with the URL <https://www.youtube.com/watch?v=sqd7PHQQ1AI> and buttons for "ANALYTICS" and "EDIT VIDEO".

10 Years 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>

SUBSCRIBED



Memory Scaling Issues **Are** Real

- 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](#)).

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

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

¹Carnegie Mellon University ²Intel Labs

Memory Scaling Issues **Are** Real

- 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>

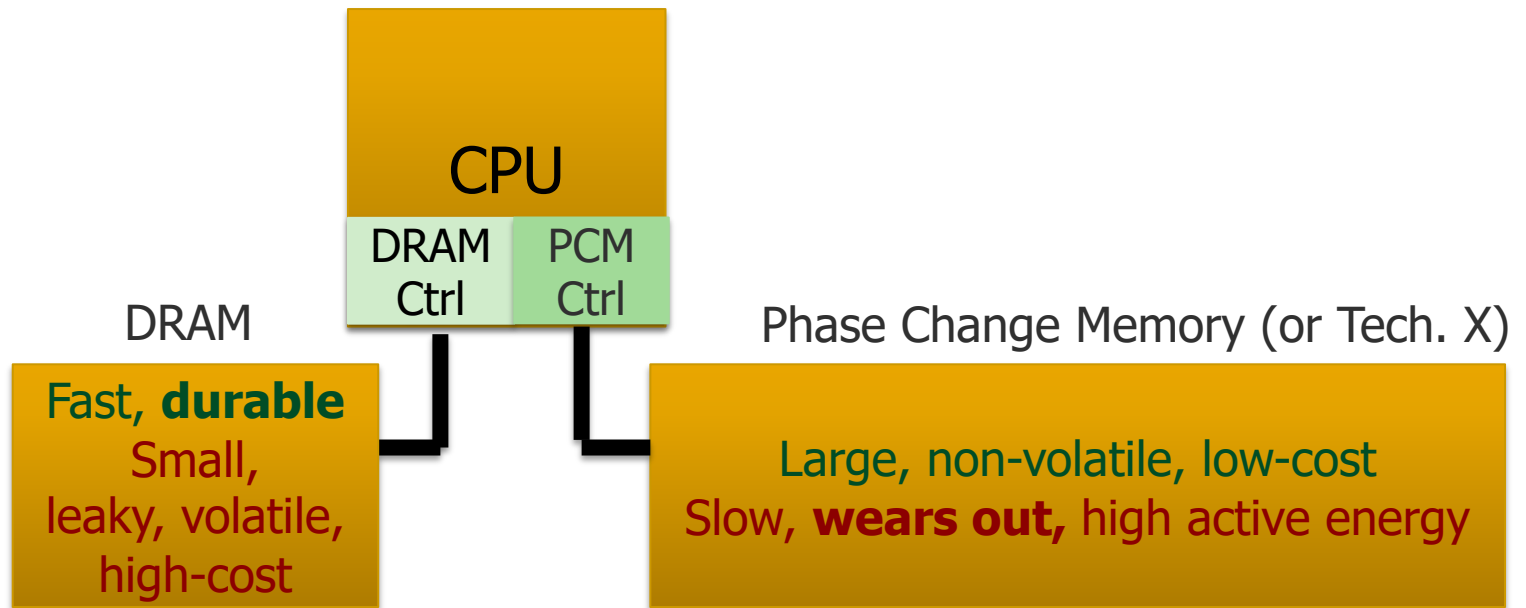
Memory Scaling Issues **Are** Real

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

RowHammer: A Retrospective

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

Hybrid Memory Enables Better Scaling



Hardware/software manage data allocation & movement
to achieve the best of multiple technologies

Meza+, "[Enabling Efficient and Scalable Hybrid Memories](#)," IEEE Comp. Arch. Letters, 2012.

Yoon+, "[Row Buffer Locality Aware Caching Policies for Hybrid Memories](#)," ICCD 2012 Best Paper Award.

Main Memory Needs Intelligent Controllers

An Example Intelligent Controller

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

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

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

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

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

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

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

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

A. Giray Yağlıkçı¹ Minesh Patel¹ Jeremie S. Kim¹ Roknoddin Azizi¹ Ataberk Olgun¹ Lois Orosa¹
Hasan Hassan¹ Jisung Park¹ Konstantinos Kanellopoulos¹ Taha Shahroodi¹ Saugata Ghose² Onur Mutlu¹

¹ETH Zürich

²University of Illinois at Urbana–Champaign

Industry Is Writing Papers About It, Too

DRAM Process Scaling Challenges

❖ Refresh

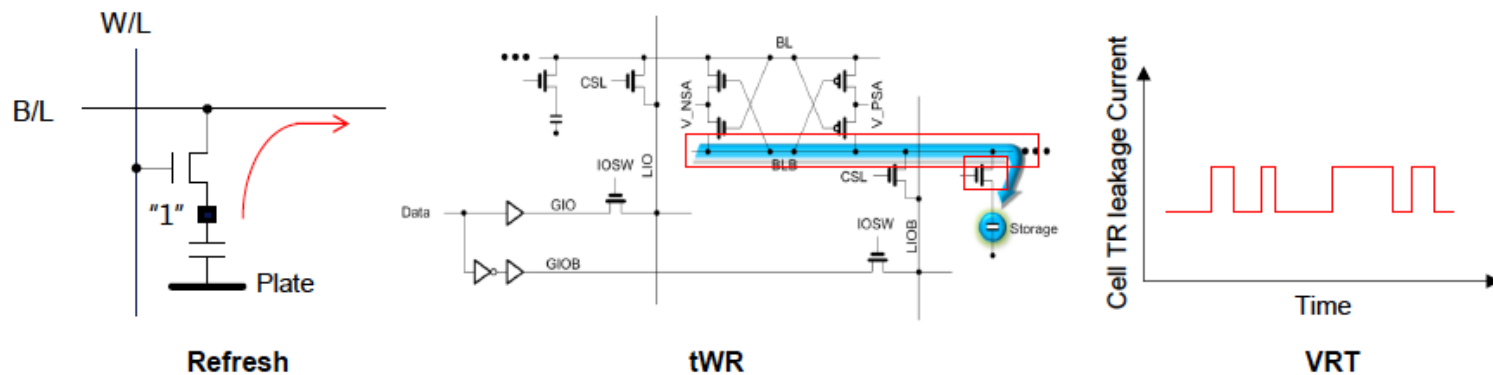
- Difficult to build high-aspect ratio cell capacitors decreasing cell capacitance
- Leakage current of cell access transistors increasing

❖ 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



Call for Intelligent Memory Controllers

DRAM Process Scaling Challenges

❖ Refresh

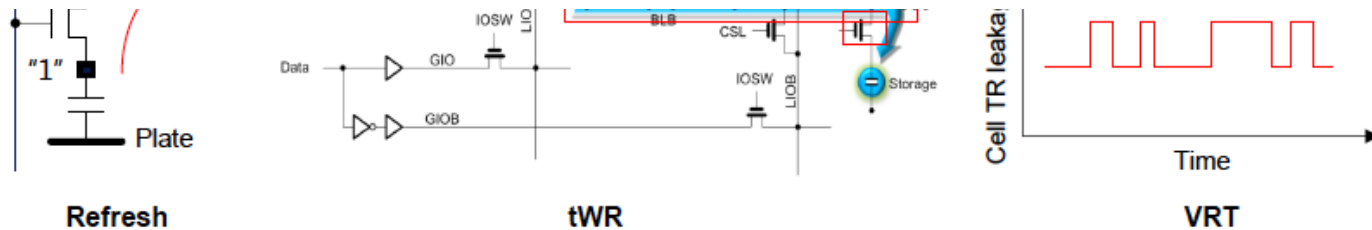
- Difficult to build high-aspect ratio cell capacitors decreasing cell capacitance

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*



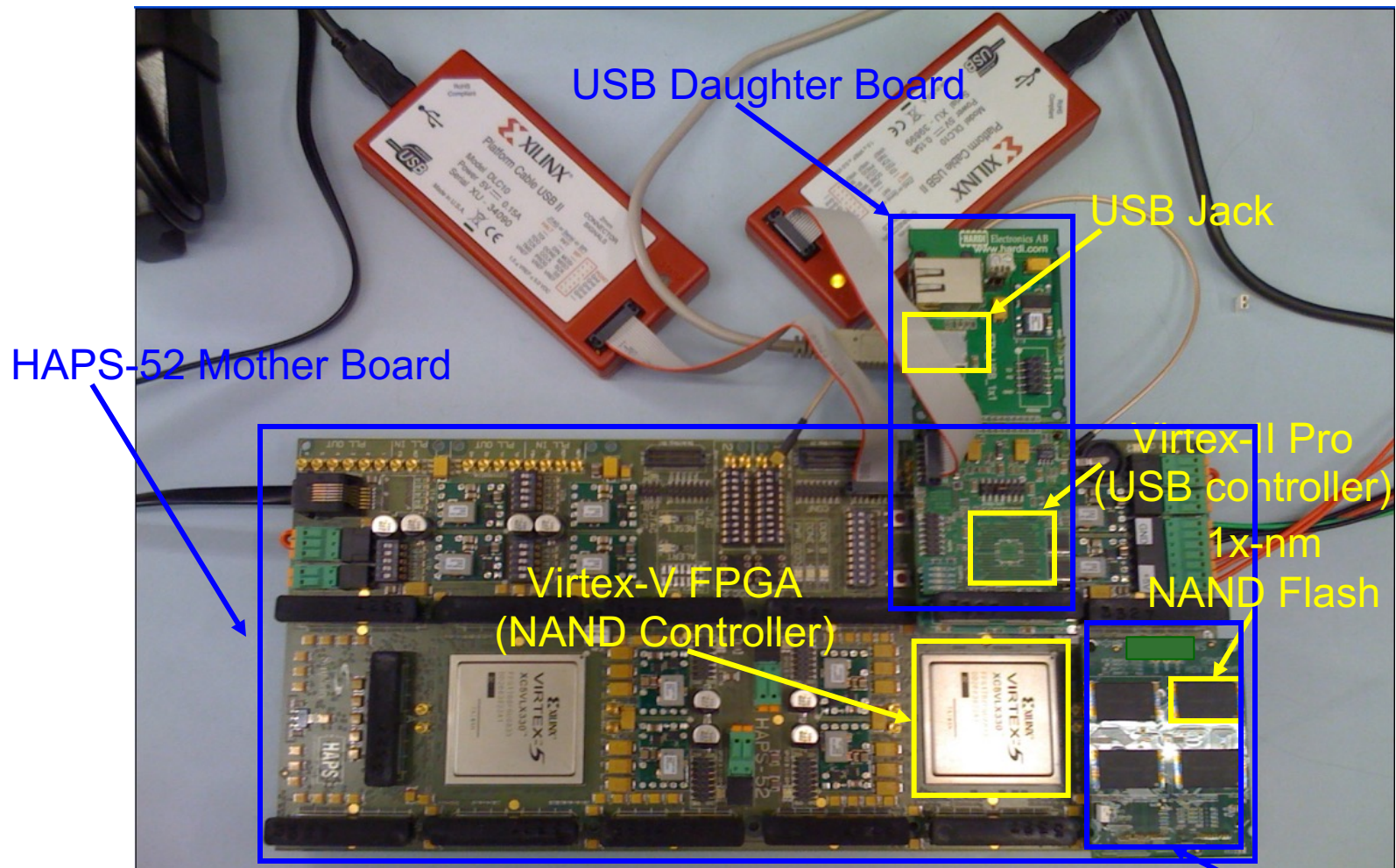
Another Example Intelligent Controller

- Minesh Patel, Geraldo F. de Oliveira Jr., and Onur Mutlu,
"HARP: Practically and Effectively Identifying Uncorrectable Errors in Memory Chips That Use On-Die Error-Correcting Codes"
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](#) (20 minutes)]
[[Lightning Talk Video](#) (1.5 minutes)]
[[HARP Source Code \(Officially Artifact Evaluated with All Badges\)](#)]



HARP: Practically and Effectively Identifying Uncorrectable Errors in Memory Chips That Use On-Die Error-Correcting Codes

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]

NAND Daughter Board

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>

Emerging Memories Also Need Intelligent Controllers

- Benjamin C. Lee, Engin Ipek, Onur Mutlu, and Doug Burger,
"Architecting Phase Change Memory as a Scalable DRAM Alternative"
*Proceedings of the 36th International Symposium on Computer
Architecture (ISCA)*, pages 2-13, Austin, TX, June 2009. Slides (pdf)
***One of the 13 computer architecture papers of 2009 selected as Top
Picks by IEEE Micro. Selected as a CACM Research Highlight.
2022 Persistent Impact Prize.***

Architecting Phase Change Memory as a Scalable DRAM Alternative

Benjamin C. Lee[†] Engin Ipek[†] Onur Mutlu[‡] Doug Burger[†]

[†]Computer Architecture Group
Microsoft Research
Redmond, WA
{blee, ipek, dburger}@microsoft.com

[‡]Computer Architecture Laboratory
Carnegie Mellon University
Pittsburgh, PA
onur@cmu.edu

Intelligent
Memory Controllers
Can Avoid Many Failures
& Enable Better Scaling

Main Memory Needs Intelligent Controllers

Why In-Memory Computation Today?

- **Push from Technology**

- **DRAM Scaling at jeopardy**

- Controllers close to DRAM

- Industry open to new memory architectures

- **Pull from Systems and Applications**

- **Data access is a major system and application bottleneck**

- **Systems are energy limited**

- **Data movement much more energy-hungry than computation**

Three Key Systems & Application Trends

1. Data access is a major bottleneck

- ▣ Applications are increasingly data hungry

2. Energy consumption is a key limiter

3. Data movement energy dominates compute

- ▣ Especially true for off-chip to on-chip movement

Do We Want This?



Or This?



High Performance,

Energy Efficient,

Sustainable

(All at the Same Time)

The Problem

Data access is the major performance and energy bottleneck

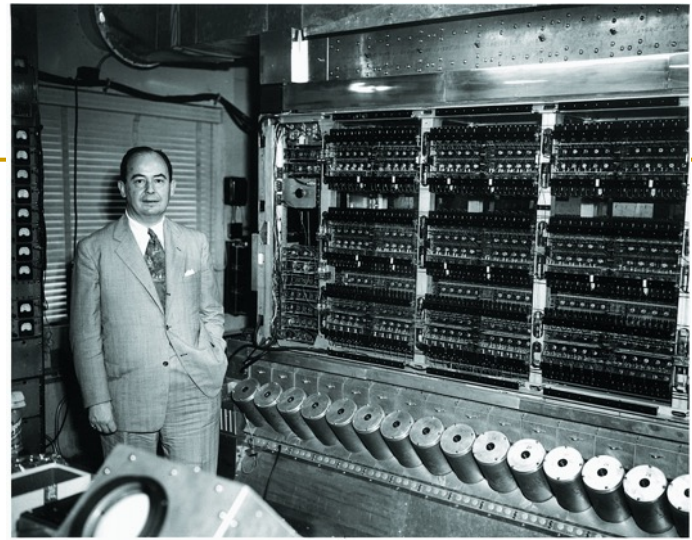
Our current
design principles
cause great energy waste
(and great performance loss)

The Problem

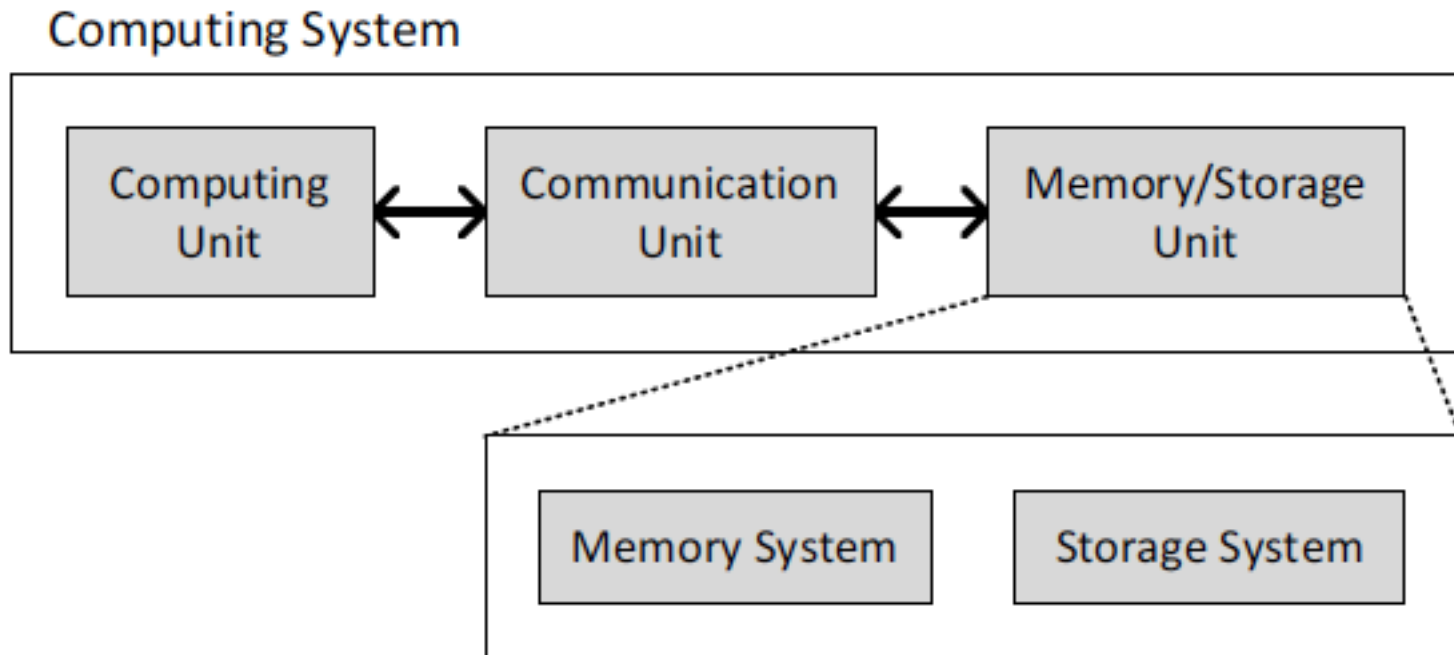
Processing of data
is performed
far away from the data

A Computing System

- Three key components
- Computation
- Communication
- Storage/memory

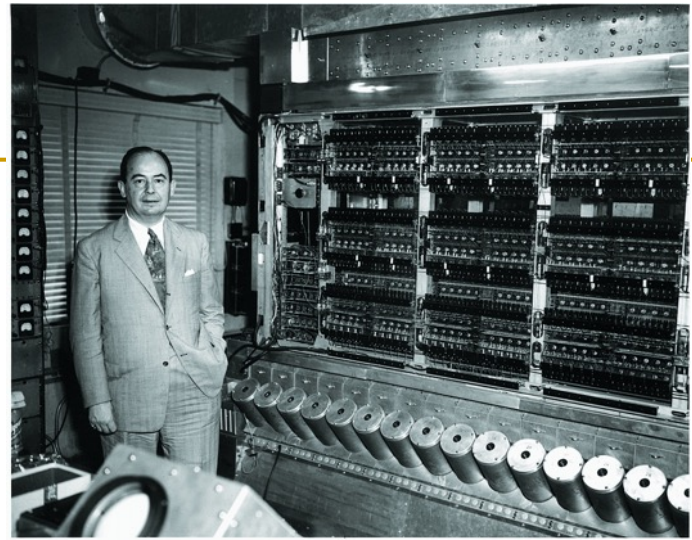


Burks, Goldstein, von Neumann, "Preliminary discussion of the logical design of an electronic computing instrument," 1946.



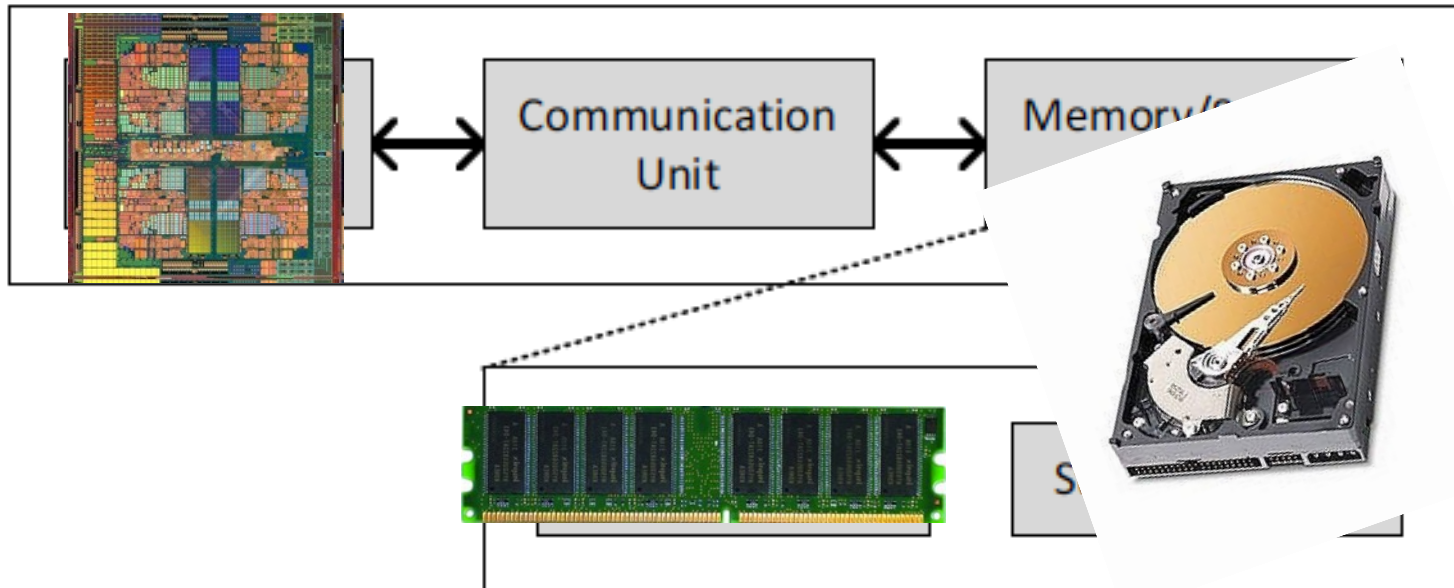
A Computing System

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- Communication
- Storage/memory



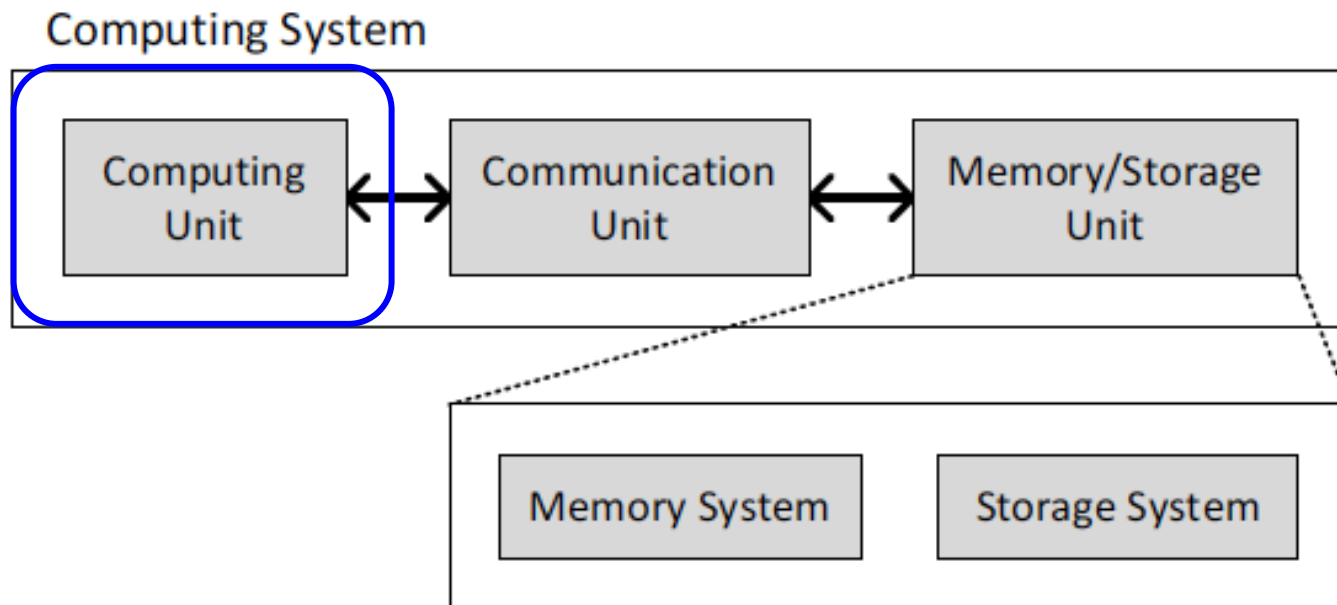
Burks, Goldstein, von Neumann, "Preliminary discussion of the logical design of an electronic computing instrument," 1946.

Computing System



Today's Computing Systems

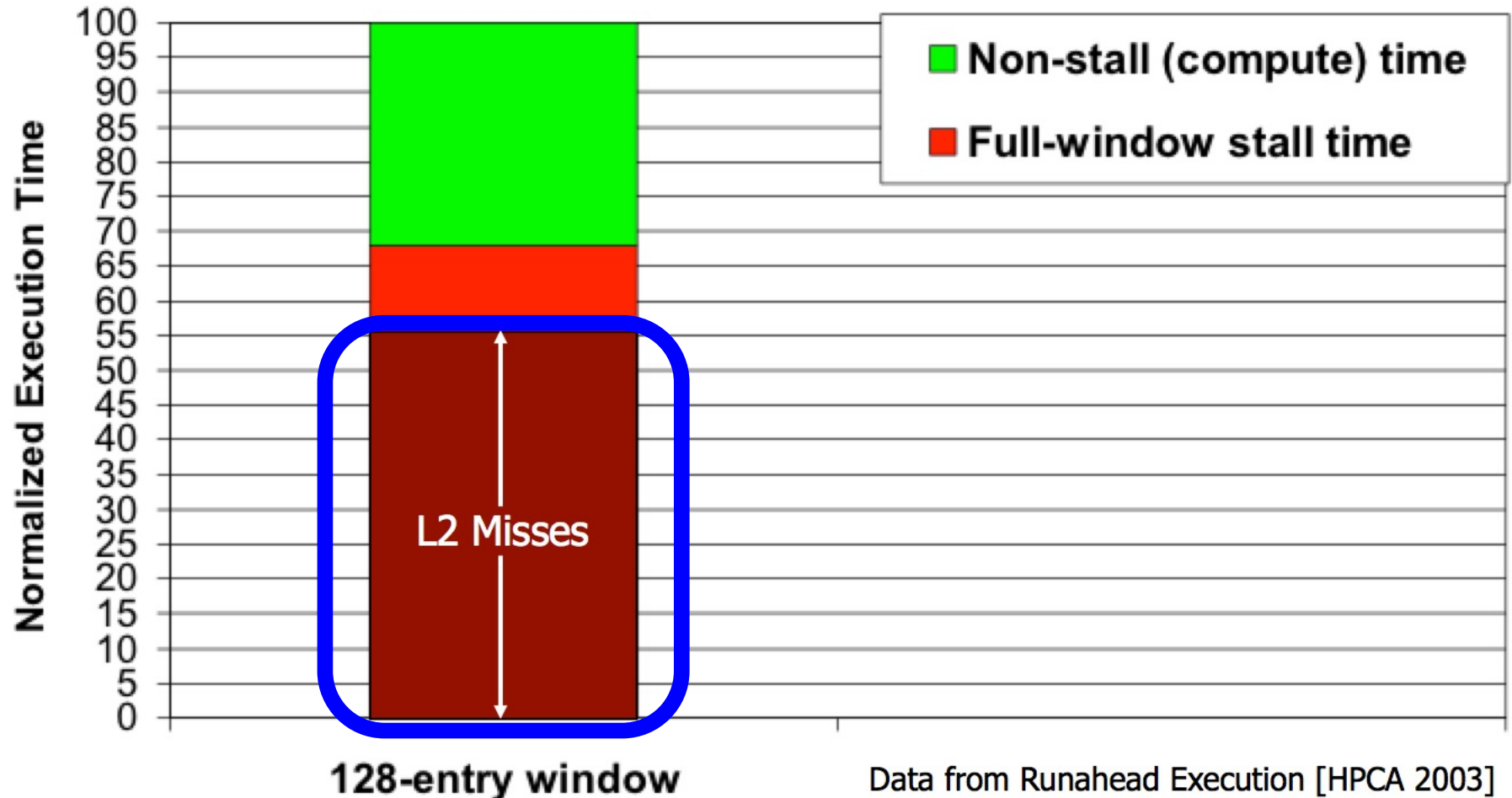
- Are overwhelmingly processor centric
- All data processed in the processor → at great system cost
- Processor is heavily optimized and is considered the master
- Data storage units are dumb and are largely unoptimized



Yet ...

I expect that over the coming decade memory subsystem design will be the *only* important design issue for microprocessors.

- **“It’s the Memory, Stupid!”** (Richard Sites, MPR, 1996)



The Performance Perspective

- Onur Mutlu, Jared Stark, Chris Wilkerson, and Yale N. Patt,
"Runahead Execution: An Alternative to Very Large Instruction Windows for Out-of-order Processors"
Proceedings of the 9th International Symposium on High-Performance Computer Architecture (HPCA), pages 129-140, Anaheim, CA, February 2003. [Slides \(pdf\)](#)
One of the 15 computer arch. papers of 2003 selected as Top Picks by IEEE Micro. HPCA Test of Time Award (awarded in 2021).

Runahead Execution: An Alternative to Very Large Instruction Windows for Out-of-order Processors

Onur Mutlu § Jared Stark † Chris Wilkerson ‡ Yale N. Patt §

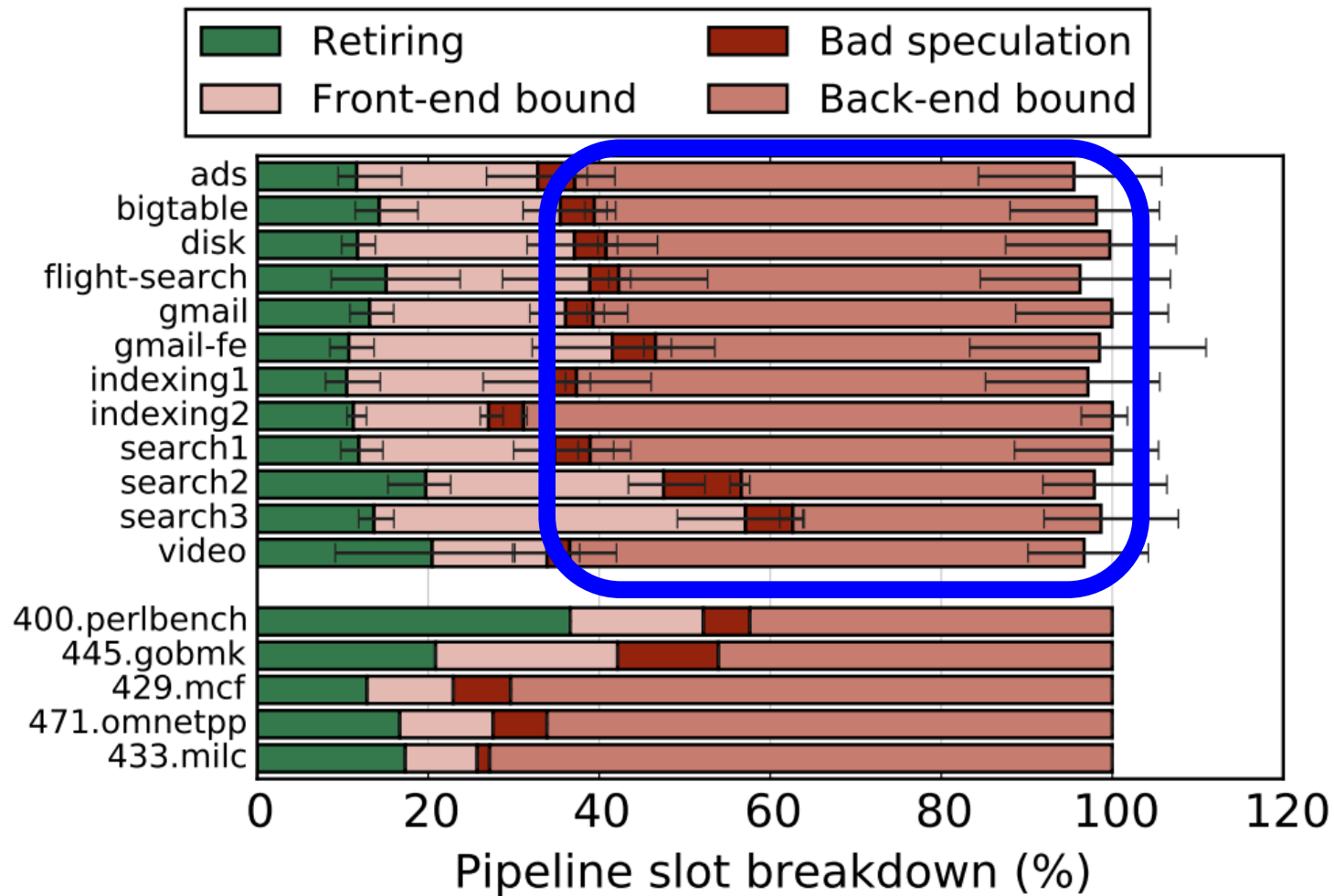
§ECE Department
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‡Desktop Platforms Group
Intel Corporation
chris.wilkerson@intel.com

The Performance Perspective (Today)

- All of Google's Data Center Workloads (2015):



The Performance Perspective (Today)

- All of Google's Data Center Workloads (2015):

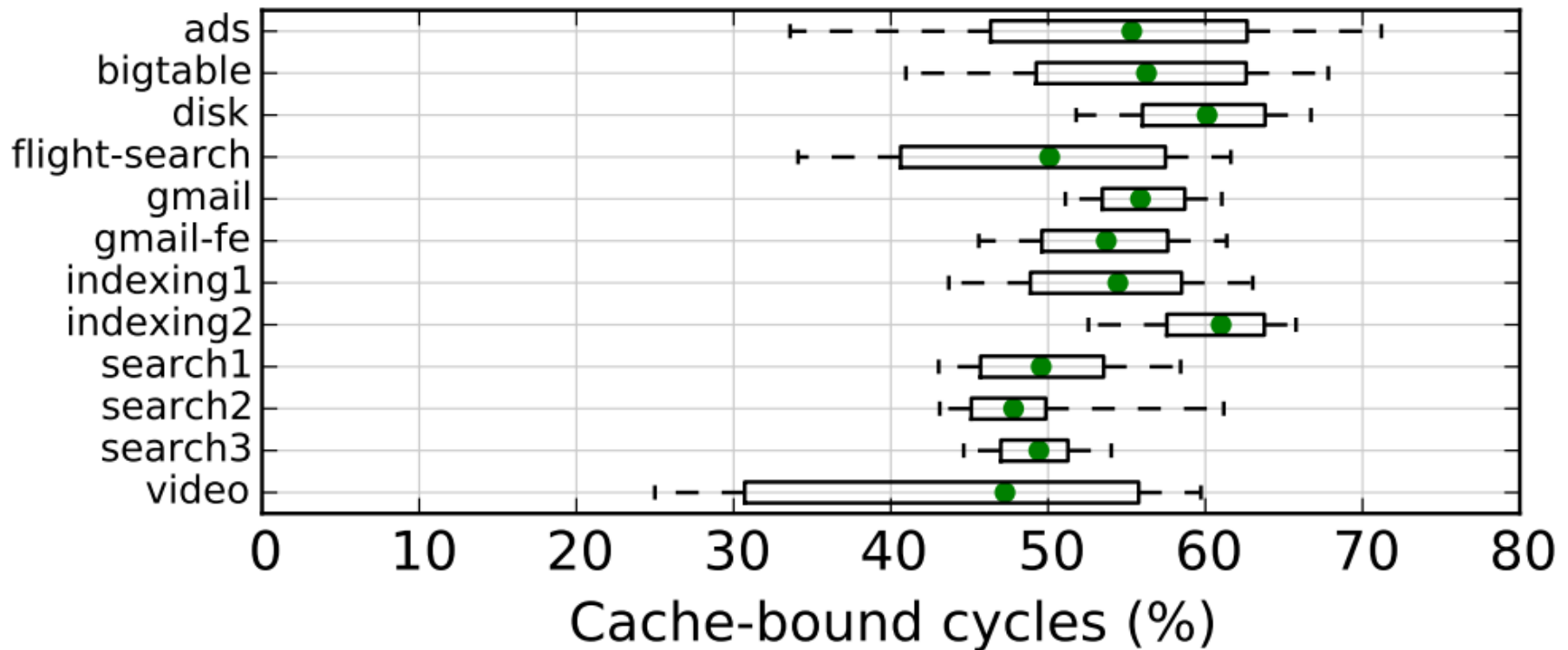


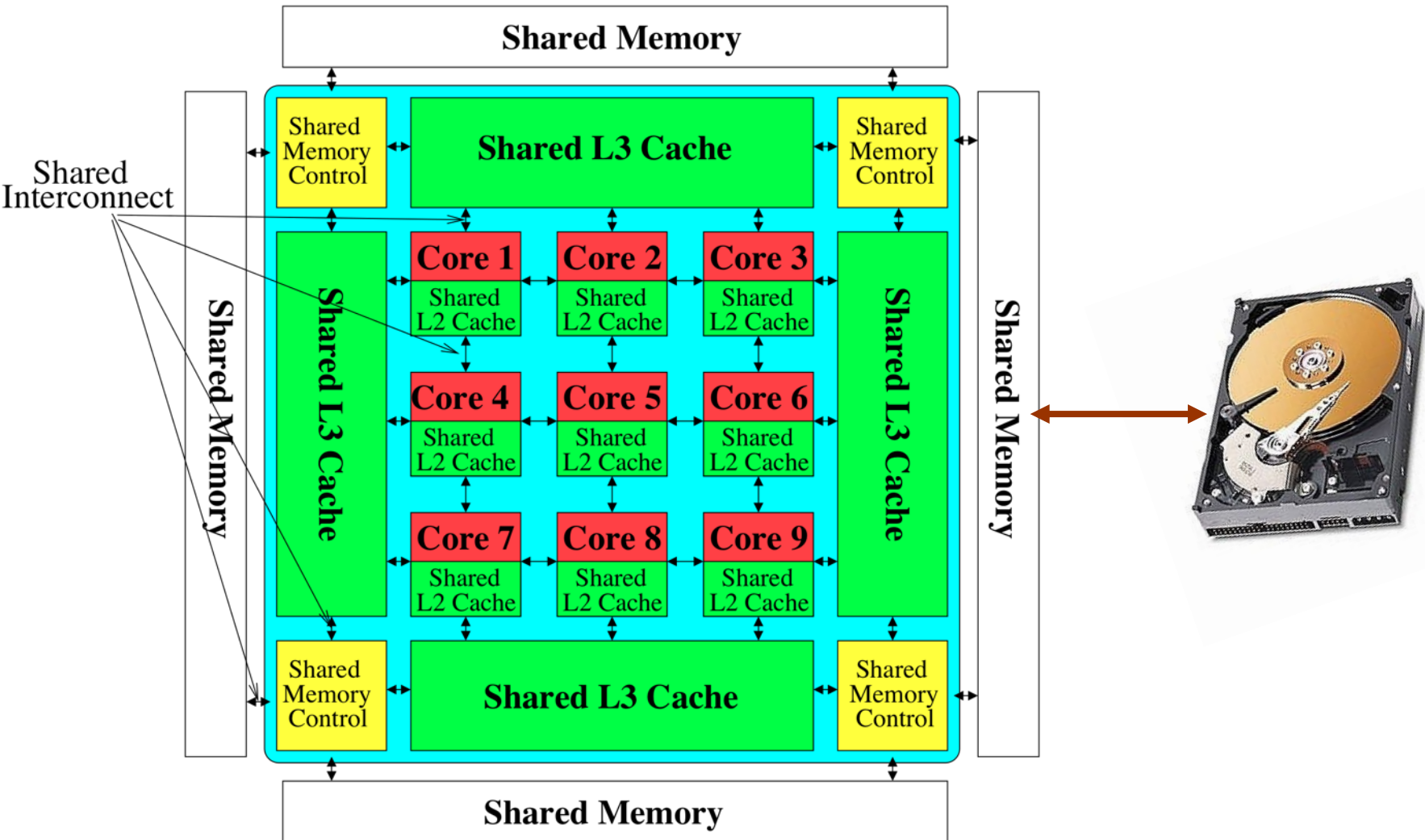
Figure 11: Half of cycles are spent stalled on caches.

Perils of Processor-Centric Design

- **Grossly-imbalanced systems**
 - ❑ Processing done only in **one place**
 - ❑ All else just stores and moves data: **data moves a lot**
 - Energy inefficient
 - Low performance
 - Complex

- **Overly complex and bloated processor (and accelerators)**
 - ❑ To tolerate data access from memory
 - ❑ Complex hierarchies and mechanisms
 - Energy inefficient
 - Low performance
 - Complex

Perils of Processor-Centric Design



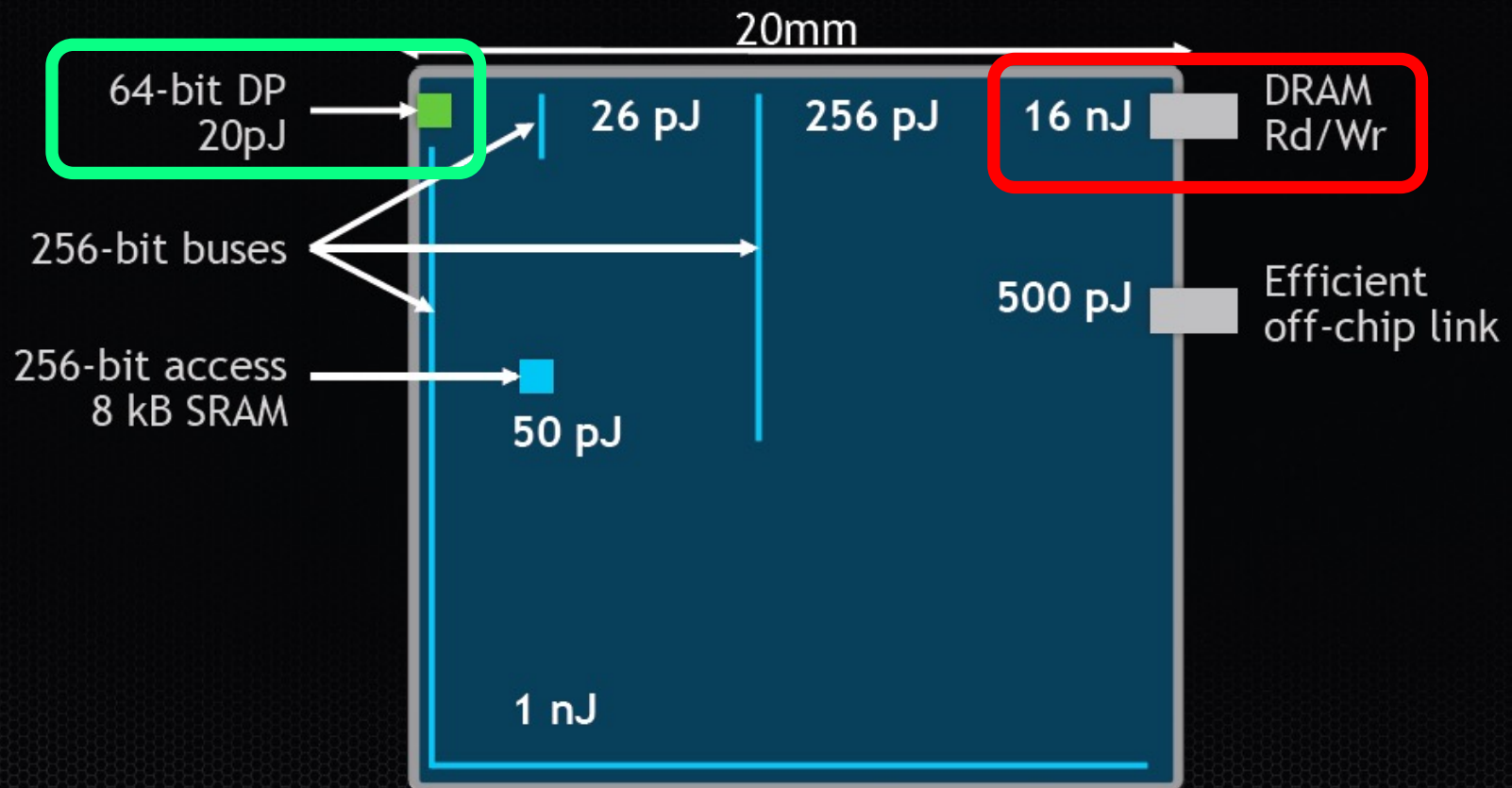
Most of the system is dedicated to storing and moving data

Yet, system is still bottlenecked by memory

The Energy Perspective

Communication Dominates Arithmetic

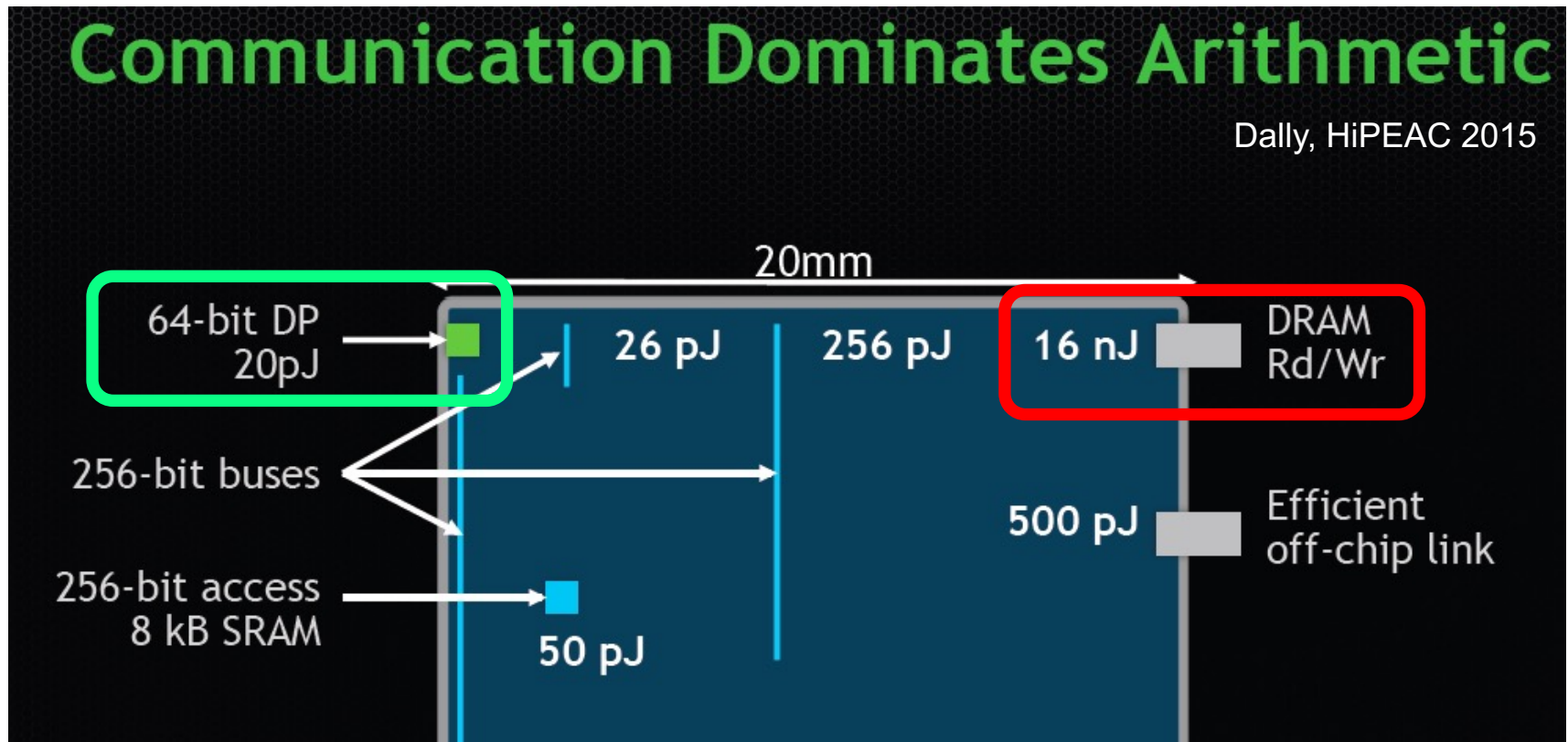
Dally, HiPEAC 2015



Data Movement vs. Computation Energy

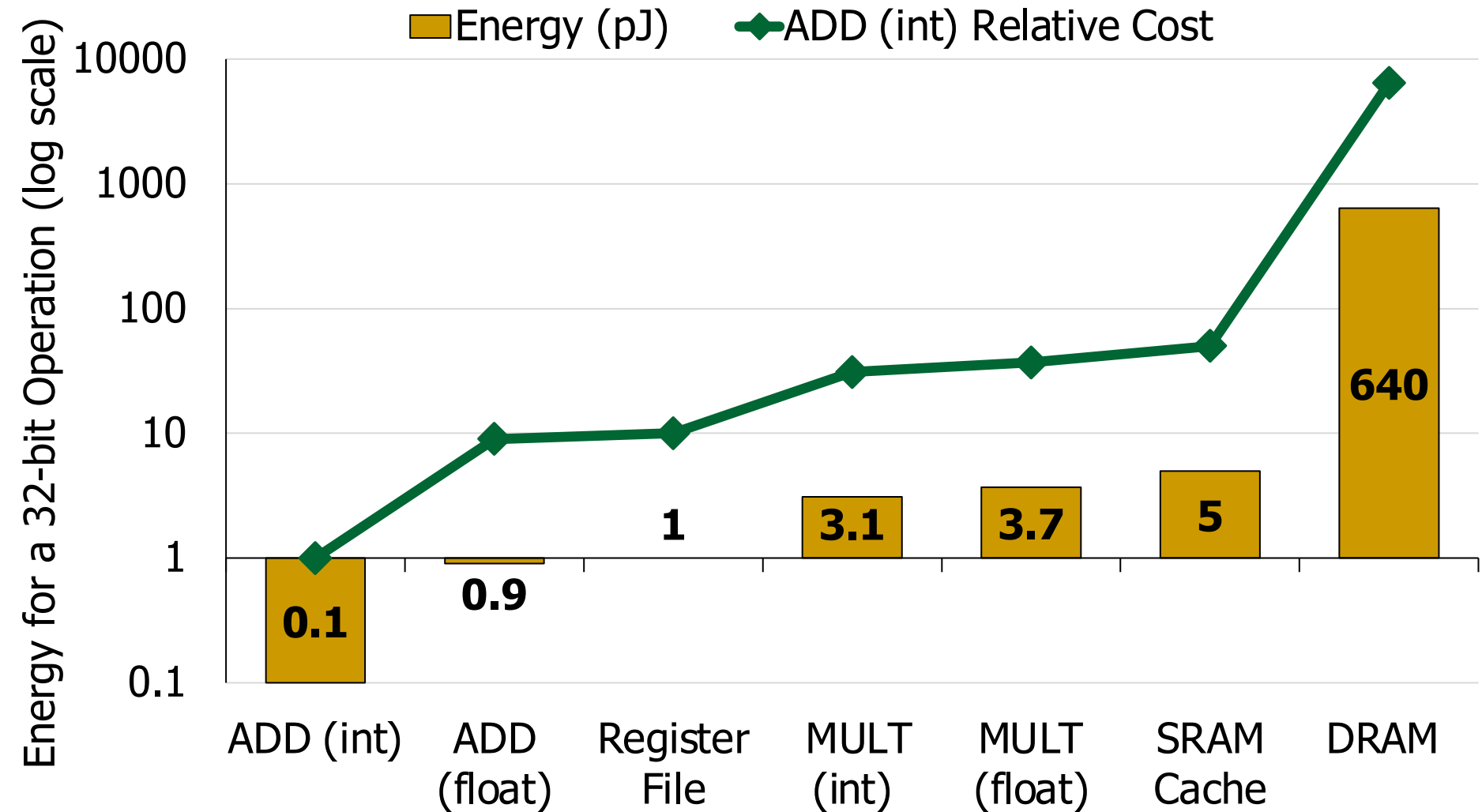
Communication Dominates Arithmetic

Dally, HiPEAC 2015

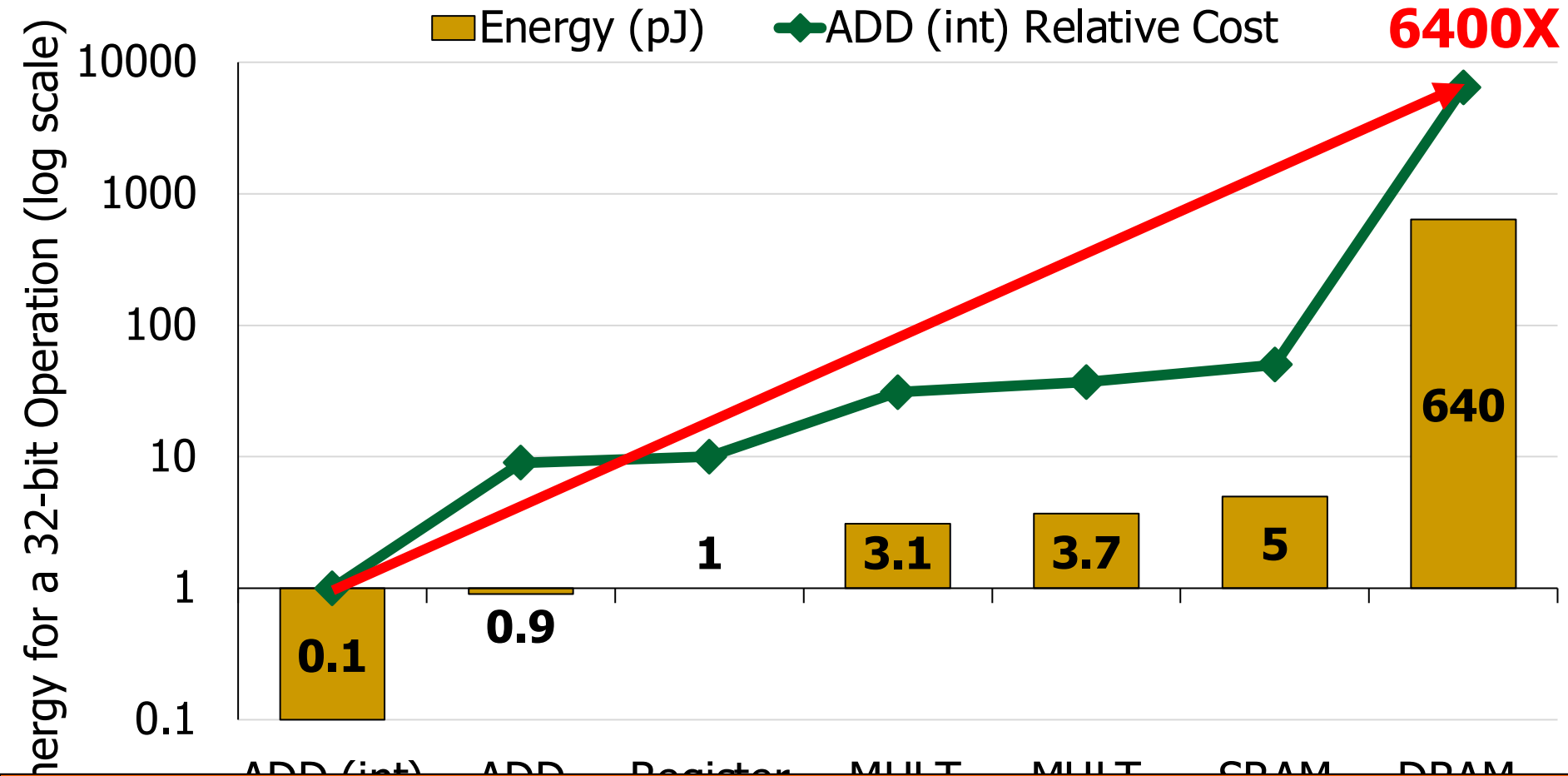


A memory access consumes $\sim 100-1000X$ the energy of a complex addition

Data Movement vs. Computation Energy



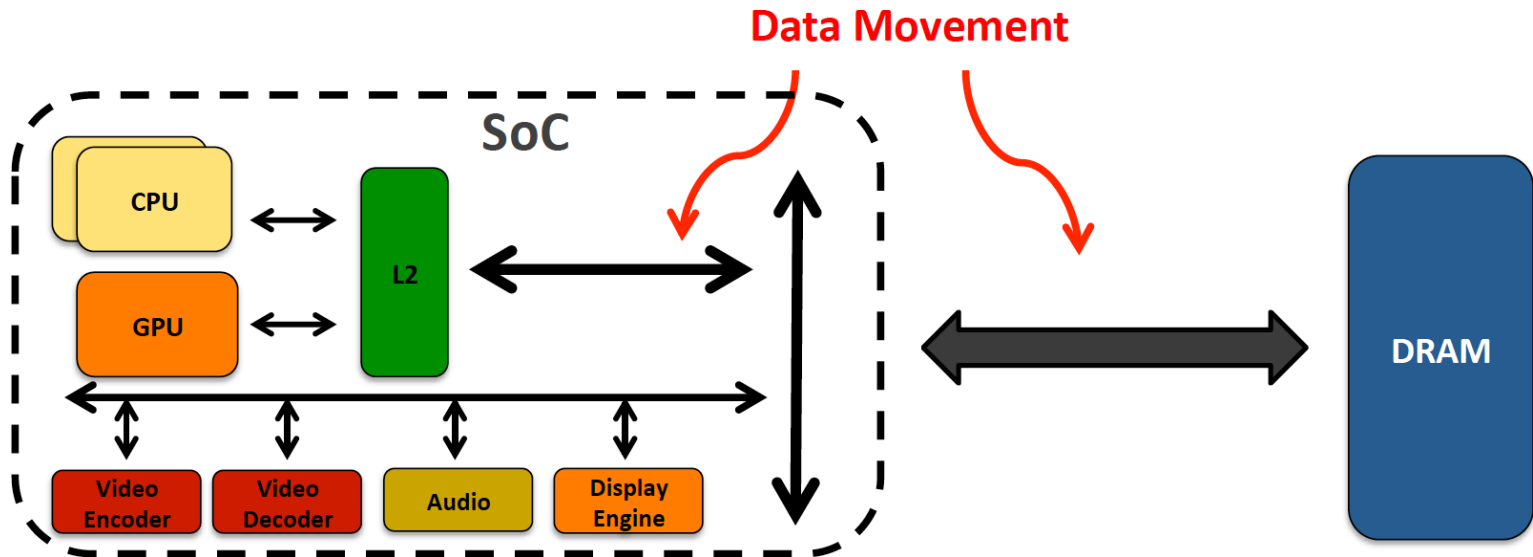
Data Movement vs. Computation Energy



A memory access consumes 6400X the energy of a simple integer addition

Data Movement vs. Computation Energy

- **Data movement** is a major system energy bottleneck
 - ❑ Comprises 41% of mobile system energy during web browsing [2]
 - ❑ Costs ~ 115 times as much energy as an ADD operation [1, 2]



[1]: Reducing data Movement Energy via Online Data Clustering and Encoding (MICRO'16)

[2]: Quantifying the energy cost of data movement for emerging smart phone workloads on mobile platforms (IISWC'14)

Energy Waste in Mobile Devices

- Amirali Boroumand, Saugata Ghose, Youngsok Kim, Rachata Ausavarungnirun, Eric Shiu, Rahul Thakur, Daehyun Kim, Aki Kuusela, Allan Knies, Parthasarathy Ranganathan, and Onur Mutlu, ["Google Workloads for Consumer Devices: Mitigating Data Movement Bottlenecks"](#) *Proceedings of the 23rd International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, Williamsburg, VA, USA, March 2018.

**62.7% of the total system energy
is spent on data movement**

Google Workloads for Consumer Devices: Mitigating Data Movement Bottlenecks

Amirali Boroumand¹

Saugata Ghose¹

Youngsok Kim²

Rachata Ausavarungnirun¹

Eric Shiu³

Rahul Thakur³

Daehyun Kim^{4,3}

Aki Kuusela³

Allan Knies³

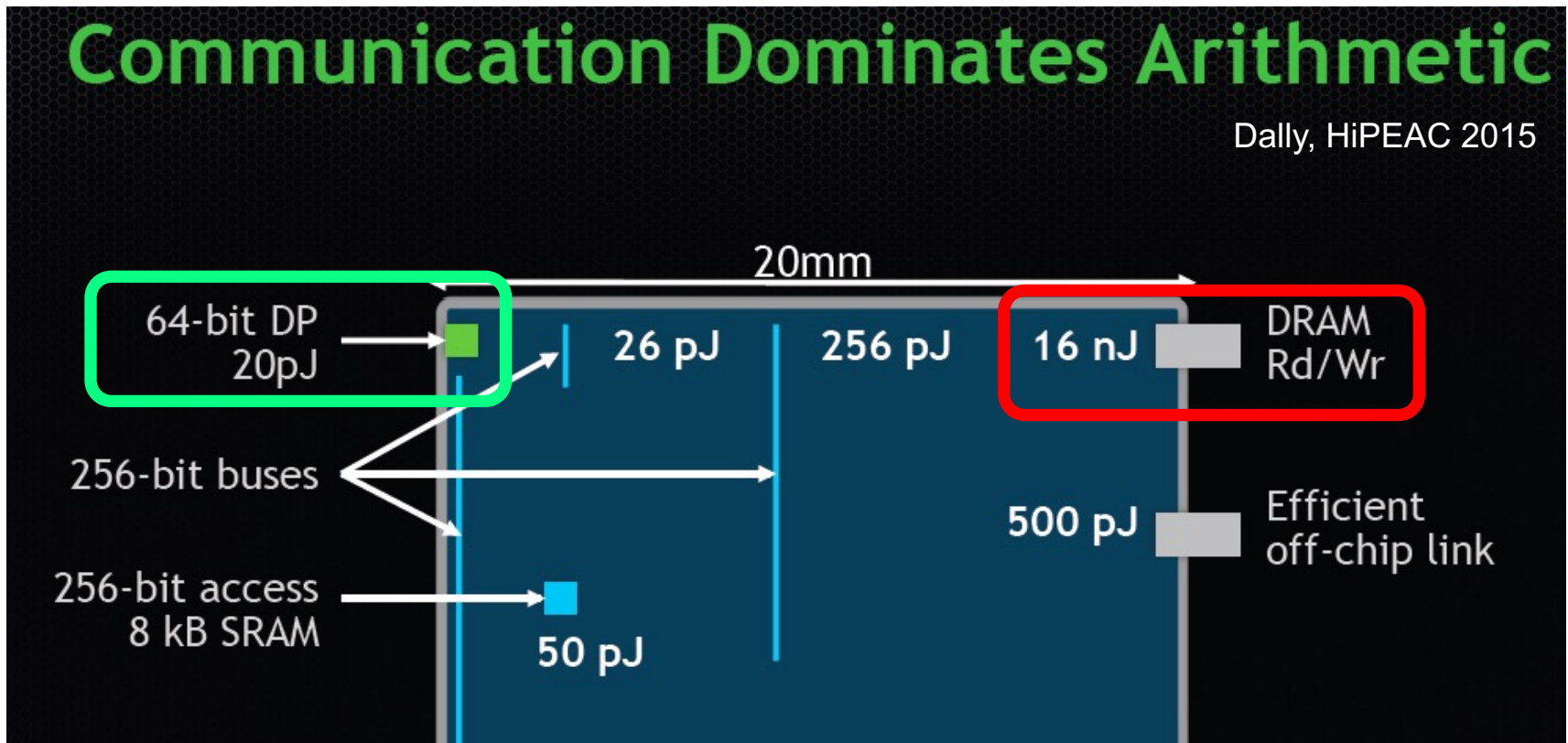
Parthasarathy Ranganathan³

Onur Mutlu^{5,1}

We Do Not Want to Move Data!

Communication Dominates Arithmetic

Dally, HiPEAC 2015

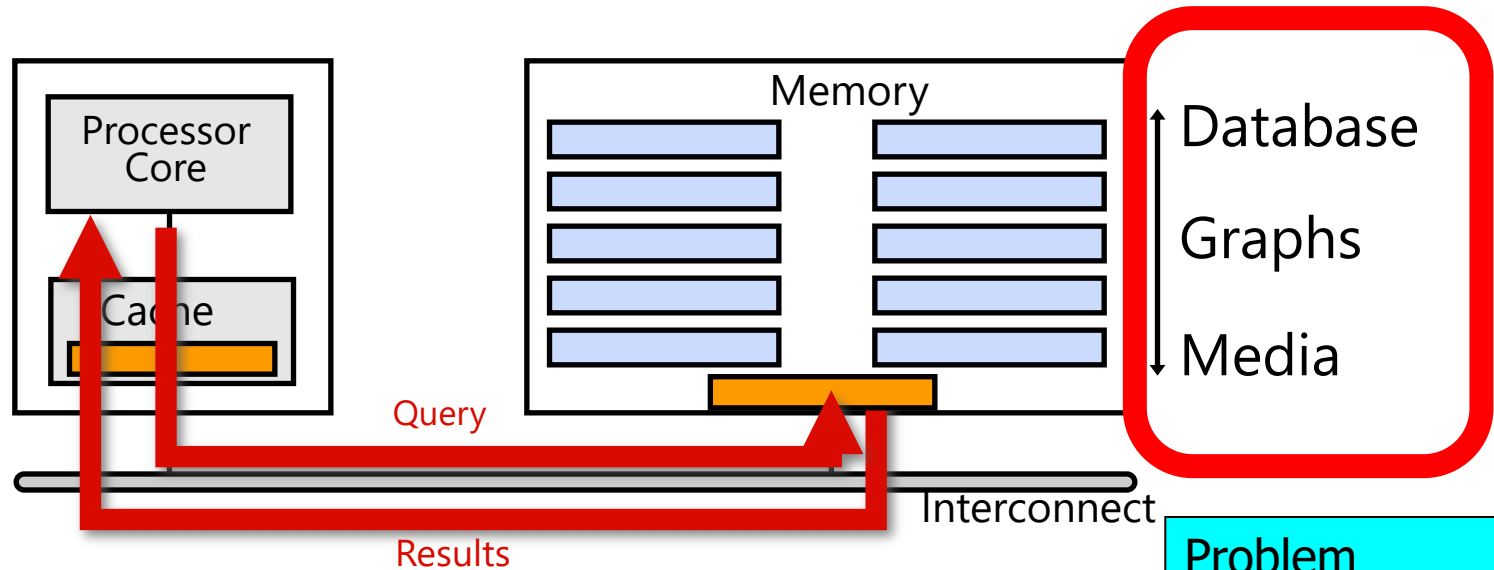


A memory access consumes $\sim 100-1000\times$ the energy of a complex addition

We Need A Paradigm Shift To ...

- Enable computation with minimal data movement
- Compute where it makes sense (where data resides)
- Make computing architectures more data-centric

Goal: Processing Inside Memory



- Many questions ... How do we design the:
 - ❑ compute-capable memory & controllers?
 - ❑ processors & communication units?
 - ❑ software & hardware interfaces?
 - ❑ system software, compilers, languages?
 - ❑ algorithms & theoretical foundations?

Problem
Algorithm
Program/Language
System Software
SW/HW Interface
Micro-architecture
Logic
Devices
Electrons

PIM Review and Open Problems

A Modern Primer on Processing in Memory

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

SAFARI Research Group

^a*ETH Zürich*

^b*Carnegie Mellon University*

^c*University of Illinois at Urbana-Champaign*

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

Onur Mutlu, Saugata Ghose, Juan Gomez-Luna, and Rachata Ausavarungnirun,

"A Modern Primer on Processing in Memory"

*Invited Book Chapter in **Emerging Computing: From Devices to Systems - Looking Beyond Moore and Von Neumann**, Springer, to be published in 2021.*

A Modern Primer on Processing in Memory

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

SAFARI Research Group

^aETH Zürich

^bCarnegie Mellon University

^cUniversity of Illinois at Urbana-Champaign

^dKing Mongkut's University of Technology North Bangkok

Abstract

Modern computing systems are overwhelmingly designed to move data to computation. This design choice goes directly against at least three key trends in computing that cause performance, scalability and energy bottlenecks: (1) data access is a key bottleneck as many important applications are increasingly data-intensive, and memory bandwidth and energy do not scale well, (2) energy consumption is a key limiter in almost all computing platforms, especially server and mobile systems, (3) data movement, especially off-chip to on-chip, is very expensive in terms of bandwidth, energy and latency, much more so than computation. These trends are especially severely-felt in the data-intensive server and energy-constrained mobile systems of today.

At the same time, conventional memory technology is facing many technology scaling challenges in terms of reliability, energy, and performance. As a result, memory system architects are open to organizing memory in different ways and making it more intelligent, at the expense of higher cost. The emergence of 3D-stacked memory plus logic, the adoption of error correcting codes inside the latest DRAM chips, proliferation of different main memory standards and chips, specialized for different purposes (e.g., graphics, low-power, high bandwidth, low latency), and the necessity of designing new solutions to serious reliability and security issues, such as the RowHammer phenomenon, are an evidence of this trend.

This chapter discusses recent research that aims to practically enable computation close to data, an approach we call *processing-in-memory* (PIM). PIM places computation mechanisms in or near where the data is stored (i.e., inside the memory chips, in the logic layer of 3D-stacked memory, or in the memory controllers), so that data movement between the computation units and memory is reduced or eliminated. While the general idea of PIM is not new, we discuss motivating trends in applications as well as memory circuits/technology that greatly exacerbate the need for enabling it in modern computing systems. We examine at least two promising new approaches to designing PIM systems to accelerate important data-intensive applications: (1) *processing using memory* by exploiting analog operational properties of DRAM chips to perform massively-parallel operations in memory, with low-cost changes, (2) *processing near memory* by exploiting 3D-stacked memory technology design to provide high memory bandwidth and low memory latency to in-memory logic. In both approaches, we describe and tackle relevant cross-layer research, design, and adoption challenges in devices, architecture, systems, and programming models. Our focus is on the development of in-memory processing designs that can be adopted in real computing platforms at low cost. We conclude by discussing work on solving key challenges to the practical adoption of PIM.

Keywords: memory systems, data movement, main memory, processing-in-memory, near-data processing, computation-in-memory, processing using memory, processing near memory, 3D-stacked memory, non-volatile memory, energy efficiency, high-performance computing, computer architecture, computing paradigm, emerging technologies, memory scaling, technology scaling, dependable systems, robust systems, hardware security, system security, latency, low-latency computing

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8.8 Security Considerations	30
9 Conclusion and Future Outlook	31

Main memory, built using the Dynamic Random Access Memory (DRAM) technology, is a major component in nearly all computing systems, including servers, cloud platforms, mobile/embedded devices, and sensor systems. Across all of these systems, the data working set sizes of modern applications are rapidly growing, while the need for fast analysis of such data is increasing. Thus, main memory is becoming an increasingly significant bottleneck across a wide variety of computing systems and applications [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. Alleviating the main memory bottleneck requires the memory capacity, energy, cost, and performance to all scale in an efficient manner across technology generations. Unfortunately, it has become increasingly difficult in recent years, especially the past decade, to scale all of these dimensions [1, 2, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49], and thus the main memory bottleneck has been worsening.

A major reason for the main memory bottleneck is the high energy and latency cost associated with *data movement*. In modern computers, to perform any operation on data that resides in main memory, the processor must retrieve the data from main memory. This requires the memory controller to issue commands to a DRAM module across a relatively slow and power-hungry off-chip bus (known as the *memory channel*). The DRAM module sends the requested data across the memory channel, after which the data is placed in the caches and registers. The CPU can perform computation on the data once the data is in its registers. Data movement from the DRAM to the CPU incurs long latency and consumes a significant amount of energy [7, 50, 51, 52, 53, 54]. These costs are often exacerbated by the fact that much of the data brought into the caches is *not reused* by the CPU [52, 53, 55, 56], providing little benefit in return for the high latency and energy cost.

The cost of data movement is a fundamental issue with the *processor-centric* nature of contemporary computer systems. The CPU is considered to be the master in the system, and computation is performed only in the processor (and accelerators). In contrast, data storage and communication units, including the main memory, are treated as unintelligent workers that are incapable of computation. As a result of this processor-centric design paradigm, data moves a lot in the system between the computation units and communication/ storage units so that computation can be done on it. With the increasingly *data-centric* nature of contemporary and emerging appli-

System Desirables

- Self-managing, independent components
- All components intelligent & equal partners
- Easy collaboration & partitioning across all components
- Fine-grained communication of data & tasks
- Seamless caching & translation & protection anywhere
- Execution anywhere without rewriting code
- Flexibility, adaptability, self-optimization

Open minds

We Need to Think Differently
from the Past Approaches

Processing in Memory: Two Approaches

1. Processing using Memory
2. Processing near Memory

Specialization: In-Memory Graph Processing

- Large graphs are everywhere (circa 2015)



36 Million
Wikipedia Pages



1.4 Billion
Facebook Users

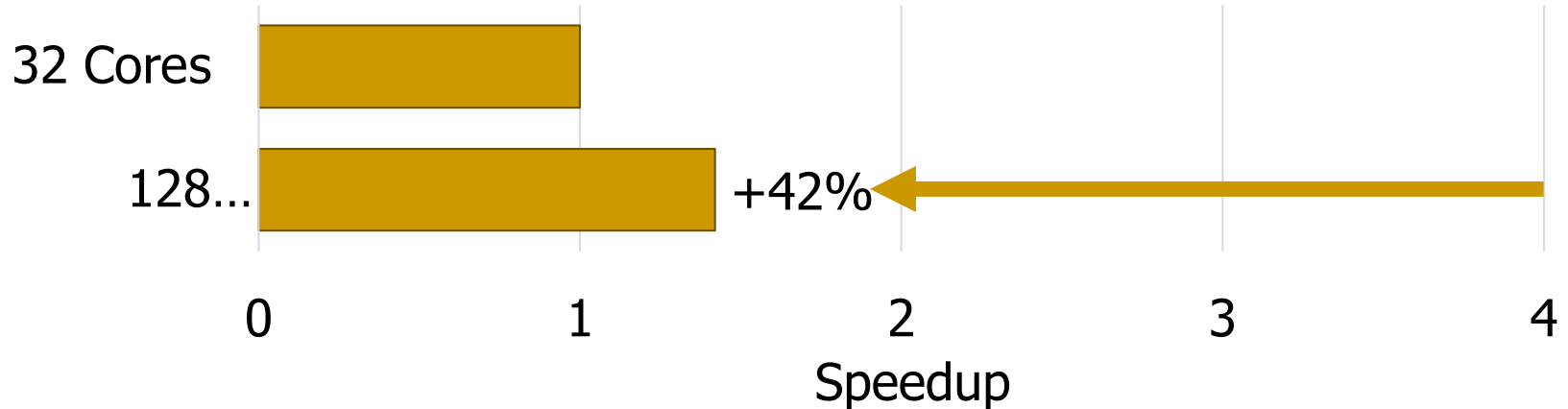


300 Million
Twitter Users



30 Billion
Instagram Photos

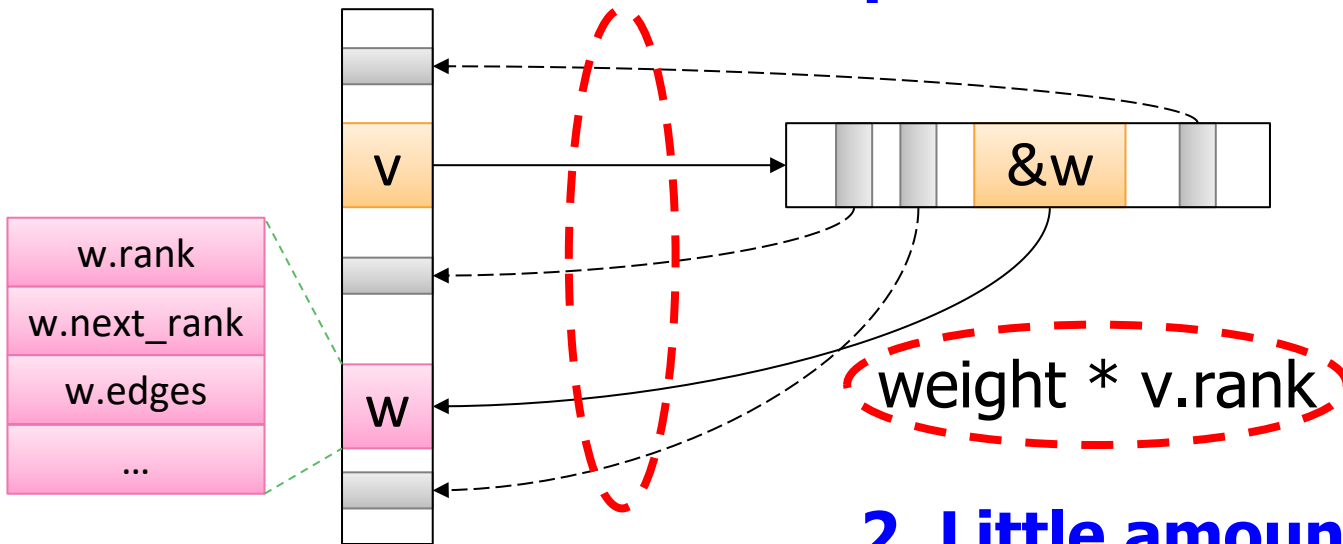
- Scalable large-scale graph processing is challenging



Key Bottlenecks in Graph Processing

```
for (v: graph.vertices) {  
  for (w: v.successors) {  
    w.next_rank += weight * v.rank;  
  }  
}
```

1. Frequent random memory accesses

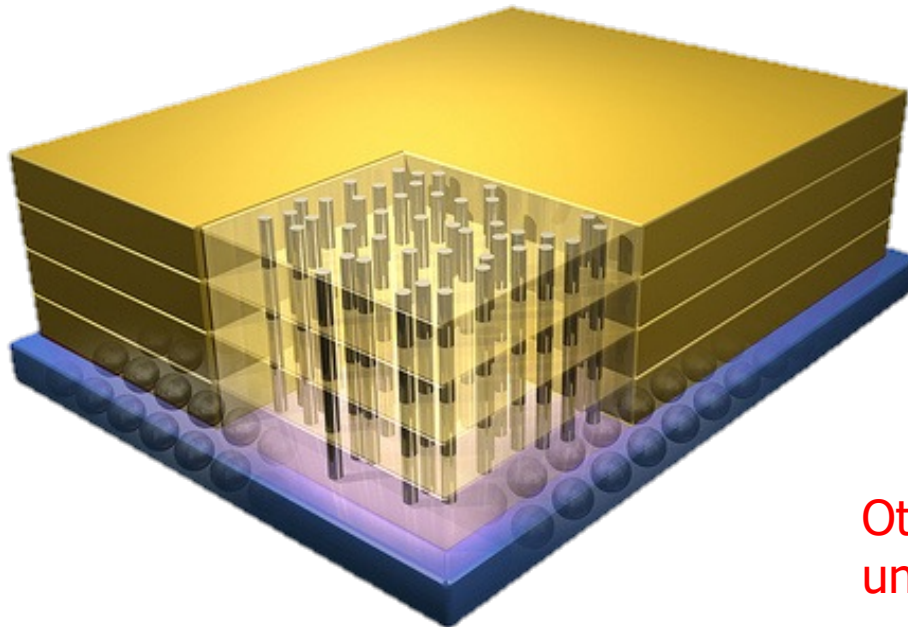


2. Little amount of computation

Opportunity: 3D-Stacked Logic+Memory



Hybrid Memory Cube
C O N S O R T I U M



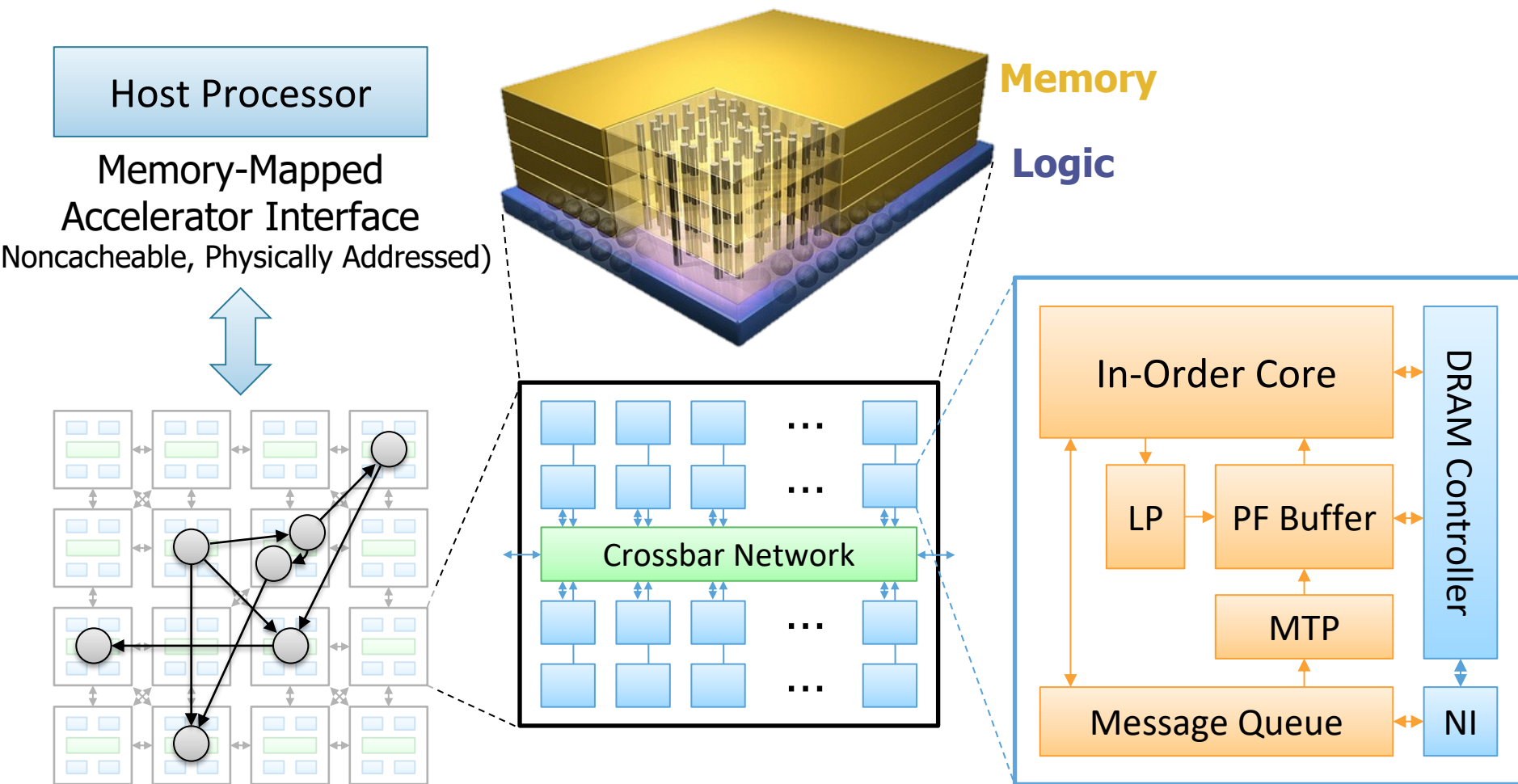
Memory

Logic

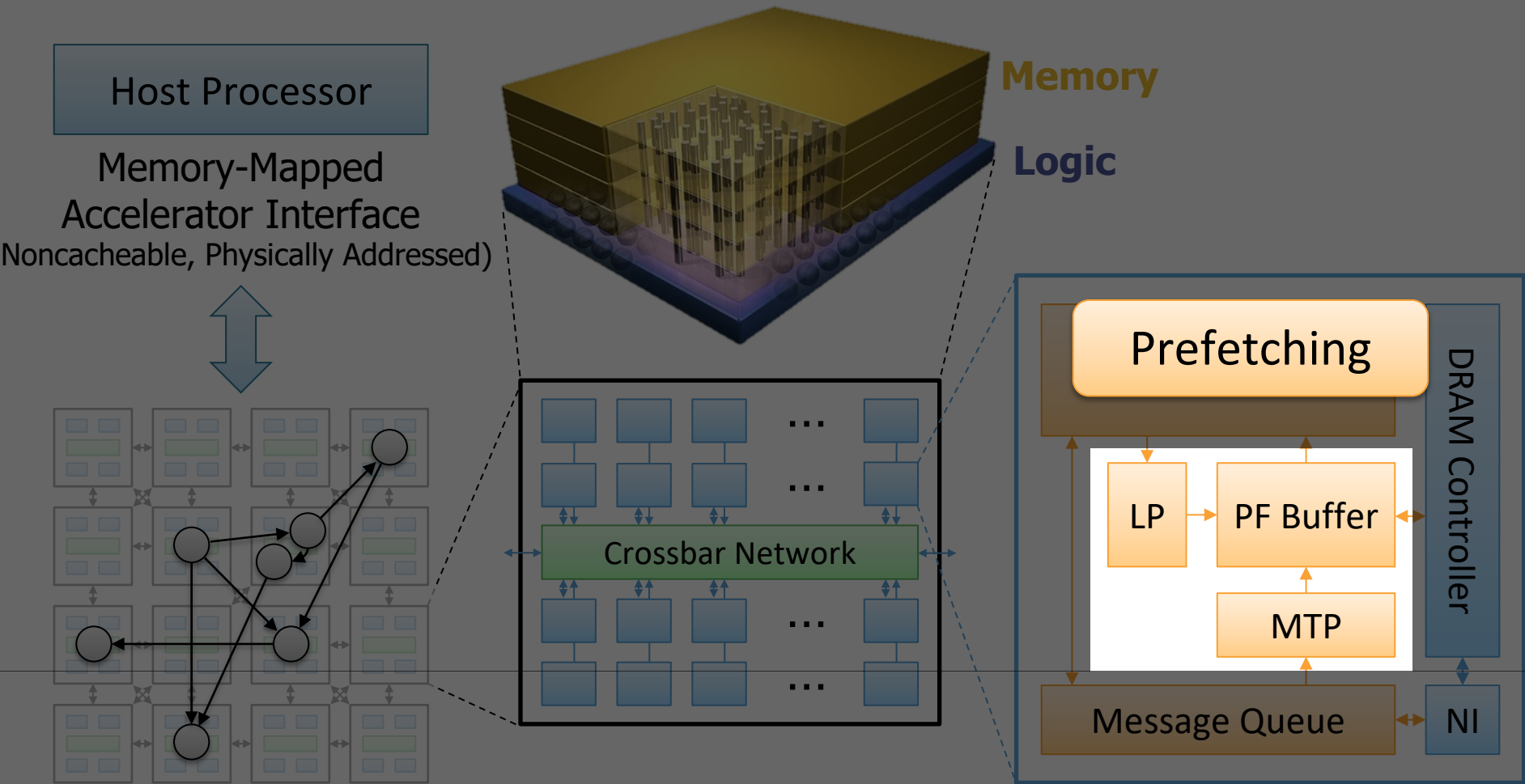
Other "True 3D" technologies
under development

Tesseract System for Graph Processing

Interconnected set of 3D-stacked memory+logic chips with simple cores

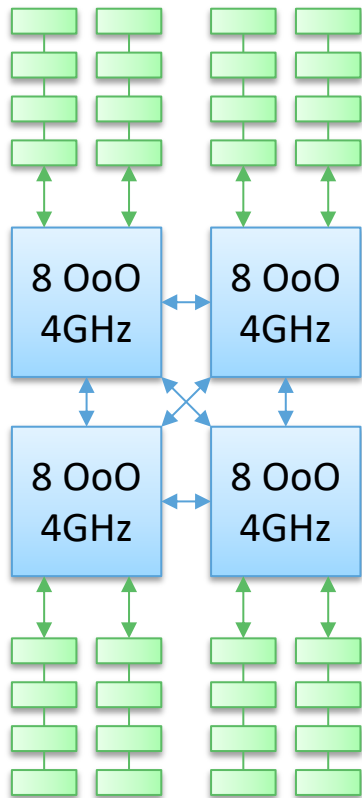


Tesseract System for Graph Processing



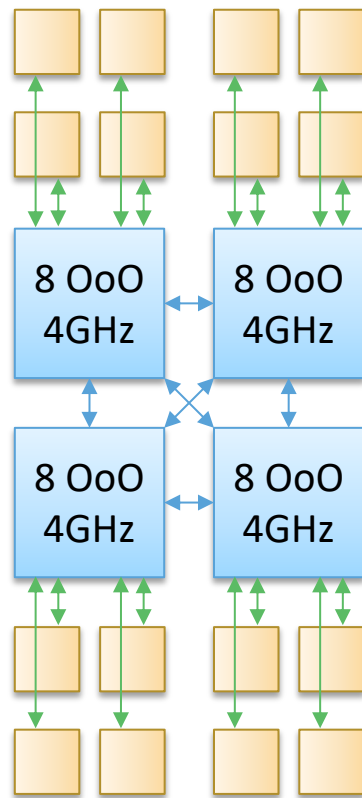
Evaluated Systems

DDR3-OoO



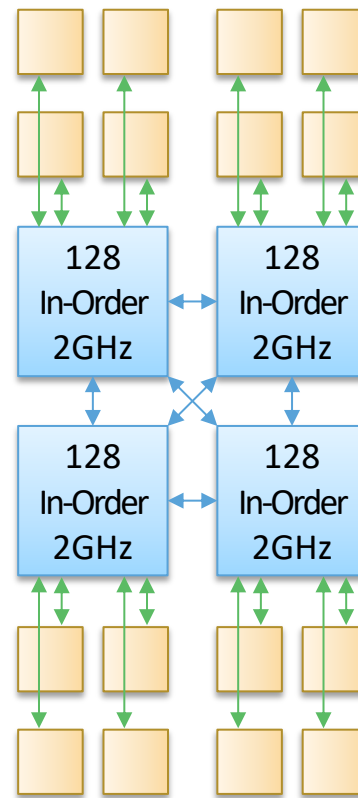
102.4GB/s

HMC-OoO



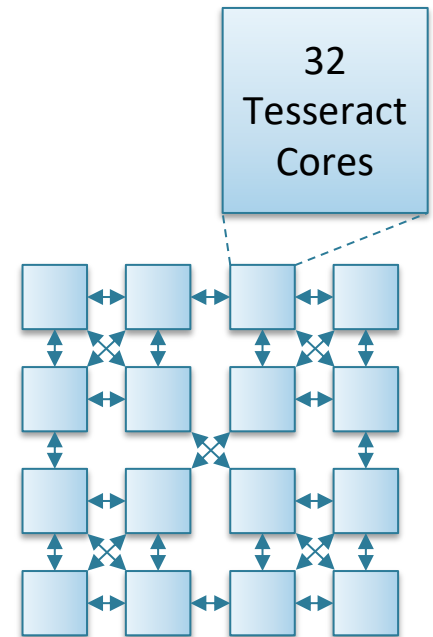
640GB/s

HMC-MC



640GB/s

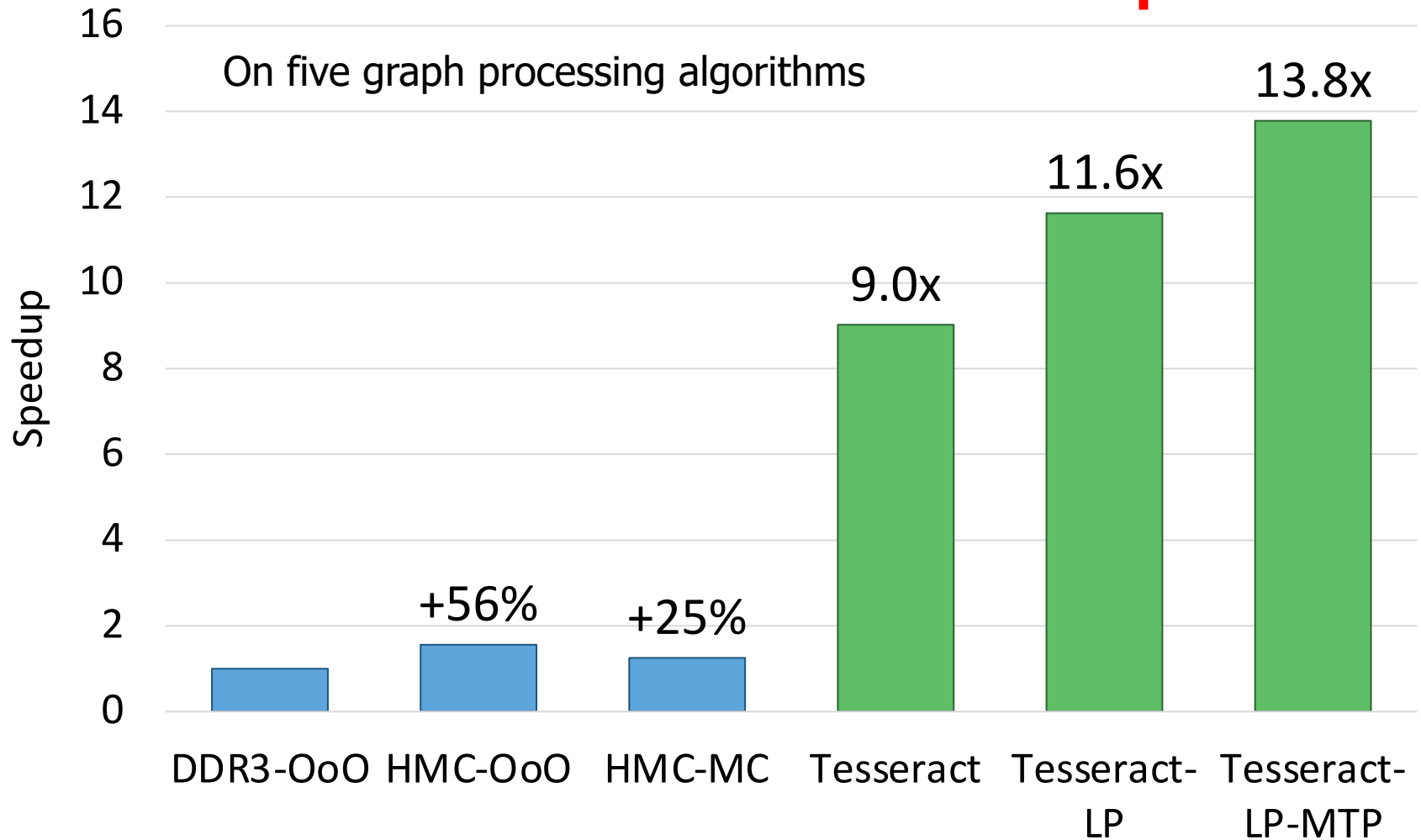
Tesseract



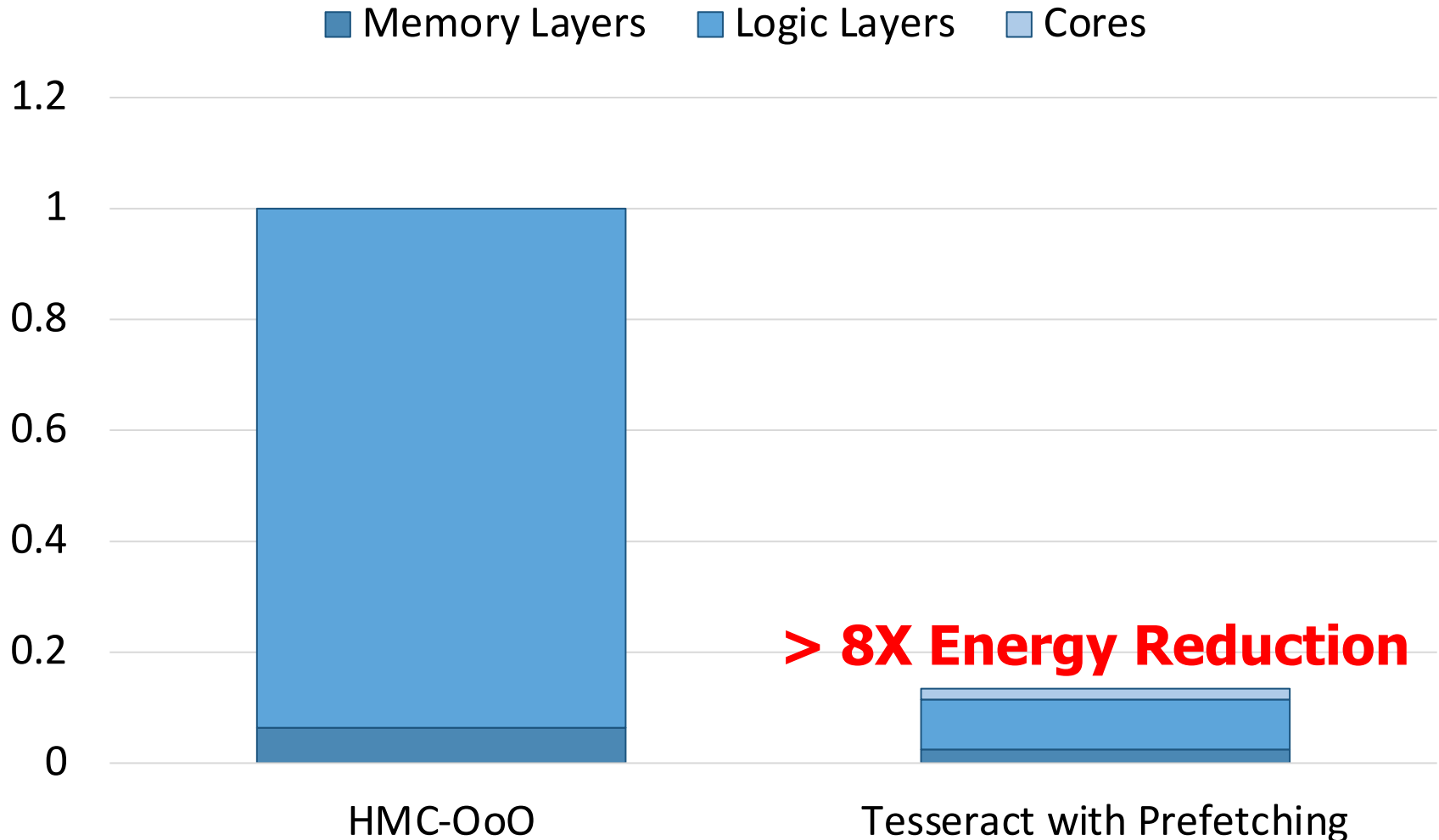
8TB/s

Tesseract Graph Processing Performance

>13X Performance Improvement



Tesseract Graph Processing System Energy



More on Tesseract

- Junwhan Ahn, Sungpack Hong, Sungjoo Yoo, Onur Mutlu, and Kiyoun Choi,
"A Scalable Processing-in-Memory Accelerator for Parallel Graph Processing"
Proceedings of the 42nd International Symposium on Computer Architecture (ISCA), Portland, OR, June 2015.
[Slides (pdf)] [Lightning Session Slides (pdf)]

A Scalable Processing-in-Memory Accelerator for Parallel Graph Processing

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junwhan@snu.ac.kr, sungpack.hong@oracle.com, sungjoo.yoo@gmail.com, onur@cmu.edu, kchoi@snu.ac.kr

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Google Workloads for Consumer Devices: Mitigating Data Movement Bottlenecks

Amirali Boroumand

Saugata Ghose, Youngsok Kim, Rachata Ausavarungnirun,
Eric Shiu, Rahul Thakur, Daehyun Kim, Aki Kuusela,
Allan Knies, Parthasarathy Ranganathan, Onur Mutlu

SAFARI

Carnegie Mellon

Google



SEOUL
NATIONAL
UNIVERSITY

ETH zürich

Consumer Devices



Consumer devices are everywhere!

**Energy consumption is
a first-class concern in consumer devices**



Popular Consumer Workloads



Chrome

Google's web browser



TensorFlow Mobile

Google's machine learning
framework

VP9



Video Playback

Google's **video codec**

VP9

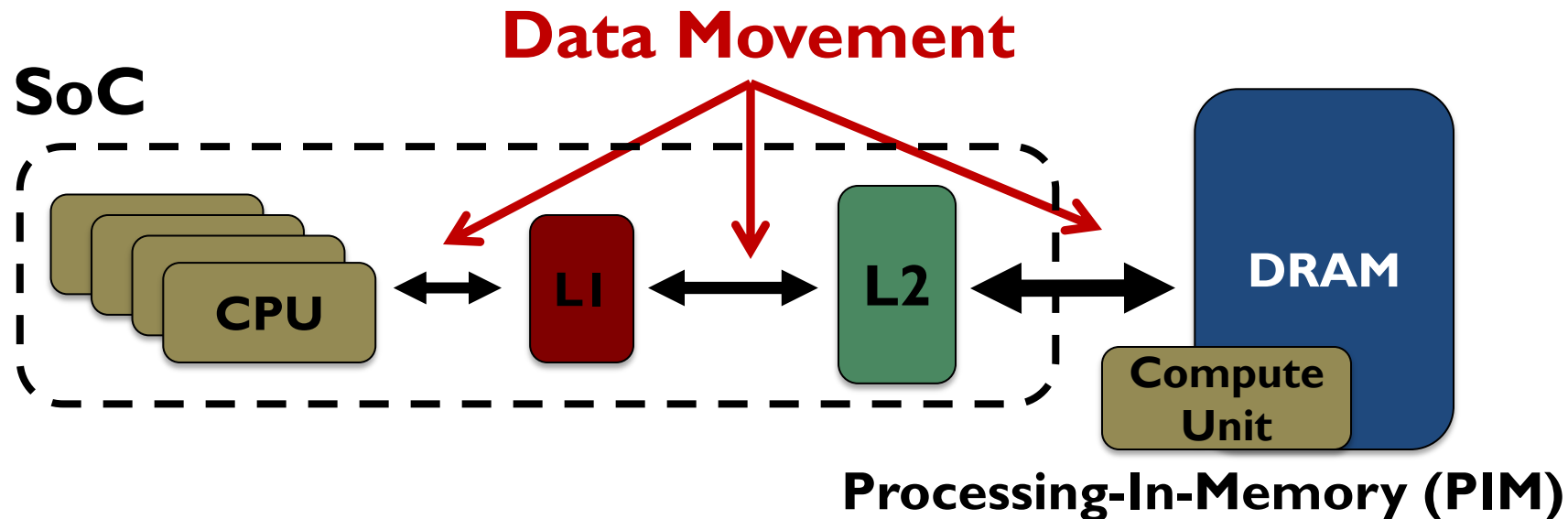


Video Capture

Google's **video codec**

Energy Cost of Data Movement

1st key observation: **62.7%** of the total system energy is spent on **data movement**



Potential solution: move computation **close to data**

Challenge: limited area and energy budget

Using PIM to Reduce Data Movement

2nd key observation: a significant fraction of the **data movement** often comes from **simple functions**

We can design lightweight logic to implement these simple functions in **memory**

Small embedded
low-power core



Small fixed-function
accelerators



Offloading to PIM logic reduces energy and improves performance, on average, by 2.3X and 2.2X

Workload Analysis



Chrome

Google's web browser



TensorFlow Mobile

Google's machine learning
framework



Video Playback

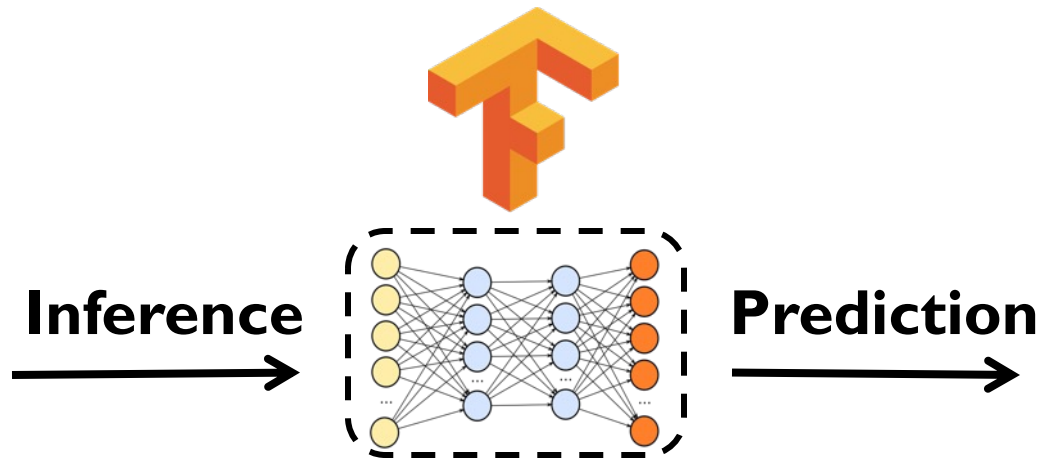
Google's **video codec**



Video Capture

Google's **video codec**

TensorFlow Mobile



57.3% of the inference energy is spent on data movement



54.4% of the **data movement** energy comes from packing/unpacking and quantization

More on PIM for Mobile Devices

- Amirali Boroumand, Saugata Ghose, Youngsok Kim, Rachata Ausavarungnirun, Eric Shiu, Rahul Thakur, Daehyun Kim, Aki Kuusela, Allan Knies, Parthasarathy Ranganathan, and Onur Mutlu,

"Google Workloads for Consumer Devices: Mitigating Data Movement Bottlenecks"

Proceedings of the 23rd International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS), Williamsburg, VA, USA, March 2018.

[[Slides \(pptx\) \(pdf\)](#)] [[Lightning Session Slides \(pptx\) \(pdf\)](#)] [[Poster \(pptx\) \(pdf\)](#)]

[[Lightning Talk Video](#) (2 minutes)]

[[Full Talk Video](#) (21 minutes)]

Google Workloads for Consumer Devices: Mitigating Data Movement Bottlenecks

Amirali Boroumand¹

Saugata Ghose¹

Youngsok Kim²

Rachata Ausavarungnirun¹

Eric Shiu³

Rahul Thakur³

Daehyun Kim^{4,3}

Aki Kuusela³

Allan Knies³

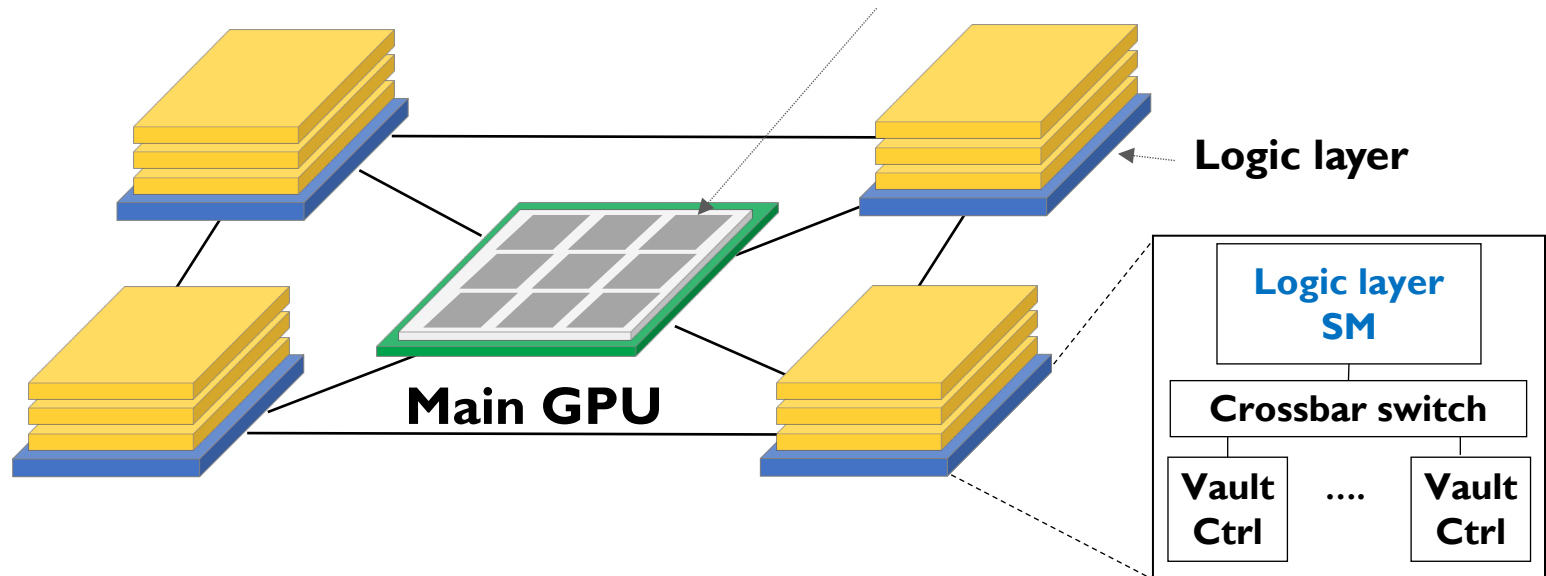
Parthasarathy Ranganathan³

Onur Mutlu^{5,1}

Truly Distributed GPU Processing with PIM

**3D-stacked memory
(memory stack)**

SM (Streaming Multiprocessor)



```
__global__  
void applyScaleFactorsKernel( uint8_T * const out,  
    uint8_T const * const in, const double *factor,  
    size_t const numRows, size_t const numCols )  
{  
    // Work out which pixel we are working on.  
    const int rowIdx = blockIdx.x * blockDim.x + threadIdx.x;  
    const int colIdx = blockIdx.y;  
    const int sliceIdx = threadIdx.z;  
  
    // Check this thread isn't off the image  
    if( rowIdx >= numRows ) return;  
  
    // Compute the index of my element  
    size_t linearIdx = rowIdx + colIdx*numRows +  
        sliceIdx*numRows*numCols;
```

Accelerating GPU Execution with PIM (I)

- Kevin Hsieh, Eiman Ebrahimi, Gwangsun Kim, Niladrish Chatterjee, Mike O'Connor, Nandita Vijaykumar, Onur Mutlu, and Stephen W. Keckler, **"Transparent Offloading and Mapping (TOM): Enabling Programmer-Transparent Near-Data Processing in GPU Systems"**

Proceedings of the 43rd International Symposium on Computer Architecture (ISCA), Seoul, South Korea, June 2016.

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

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

Transparent Offloading and Mapping (TOM): Enabling Programmer-Transparent Near-Data Processing in GPU Systems

Kevin Hsieh[‡] Eiman Ebrahimi[†] Gwangsun Kim* Niladrish Chatterjee[†] Mike O'Connor[†]
Nandita Vijaykumar[‡] Onur Mutlu^{§‡} Stephen W. Keckler[†]

[‡]Carnegie Mellon University [†]NVIDIA ^{*}KAIST [§]ETH Zürich

Accelerating GPU Execution with PIM (II)

- Ashutosh Pattnaik, Xulong Tang, Adwait Jog, Onur Kayiran, Asit K. Mishra, Mahmut T. Kandemir, Onur Mutlu, and Chita R. Das, **"Scheduling Techniques for GPU Architectures with Processing-In-Memory Capabilities"**
Proceedings of the 25th International Conference on Parallel Architectures and Compilation Techniques (PACT), Haifa, Israel, September 2016.

Scheduling Techniques for GPU Architectures with Processing-In-Memory Capabilities

Ashutosh Pattnaik¹ Xulong Tang¹ Adwait Jog² Onur Kayiran³
Asit K. Mishra⁴ Mahmut T. Kandemir¹ Onur Mutlu^{5,6} Chita R. Das¹

¹Pennsylvania State University ²College of William and Mary
³Advanced Micro Devices, Inc. ⁴Intel Labs ⁵ETH Zürich ⁶Carnegie Mellon University

Accelerating Linked Data Structures

- Kevin Hsieh, Samira Khan, Nandita Vijaykumar, Kevin K. Chang, Amirali Boroumand, Saugata Ghose, and Onur Mutlu,
["Accelerating Pointer Chasing in 3D-Stacked Memory: Challenges, Mechanisms, Evaluation"](#)
Proceedings of the 34th IEEE International Conference on Computer Design (ICCD), Phoenix, AZ, USA, October 2016.

Accelerating Pointer Chasing in 3D-Stacked Memory: Challenges, Mechanisms, Evaluation

Kevin Hsieh[†] Samira Khan[‡] Nandita Vijaykumar[†]
Kevin K. Chang[†] Amirali Boroumand[†] Saugata Ghose[†] Onur Mutlu^{§†}
[†]*Carnegie Mellon University* [‡]*University of Virginia* [§]*ETH Zürich*

Accelerating Dependent Cache Misses

- Milad Hashemi, Khubaib, Eiman Ebrahimi, Onur Mutlu, and Yale N. Patt, **"Accelerating Dependent Cache Misses with an Enhanced Memory Controller"**

Proceedings of the 43rd International Symposium on Computer Architecture (ISCA), Seoul, South Korea, June 2016.

[Slides (pptx) (pdf)]

[Lightning Session Slides (pptx) (pdf)]

Accelerating Dependent Cache Misses with an Enhanced Memory Controller

Milad Hashemi*, Khubaib[†], Eiman Ebrahimi[‡], Onur Mutlu[§], Yale N. Patt*

**The University of Texas at Austin [†]Apple [‡]NVIDIA [§]ETH Zürich & Carnegie Mellon University*

Accelerating Runahead Execution

- Milad Hashemi, Onur Mutlu, and Yale N. Patt,
[**"Continuous Runahead: Transparent Hardware Acceleration for Memory Intensive Workloads"**](#)
Proceedings of the 49th International Symposium on Microarchitecture (MICRO), Taipei, Taiwan, October 2016.
[[Slides \(pptx\)](#)] [[pdf](#)] [[Lightning Session Slides \(pdf\)](#)] [[Poster \(pptx\)](#)] [[pdf](#)]

Continuous Runahead: Transparent Hardware Acceleration for Memory Intensive Workloads

Milad Hashemi*, Onur Mutlu[§], Yale N. Patt*

**The University of Texas at Austin* [§]*ETH Zürich*

Accelerating Climate Modeling

- Gagandeep Singh, Dionysios Diamantopoulos, Christoph Hagleitner, Juan Gómez-Luna, Sander Stuijk, Onur Mutlu, and Henk Corporaal,
"NERO: A Near High-Bandwidth Memory Stencil Accelerator for Weather Prediction Modeling"
Proceedings of the 30th International Conference on Field-Programmable Logic and Applications (FPL), Gothenburg, Sweden, September 2020.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (23 minutes)]
Nominated for the Stamatis Vassiliadis Memorial Award.

NERO: A Near High-Bandwidth Memory Stencil Accelerator for Weather Prediction Modeling

Gagandeep Singh^{a,b,c} Dionysios Diamantopoulos^c Christoph Hagleitner^c Juan Gómez-Luna^b
Sander Stuijk^a Onur Mutlu^b Henk Corporaal^a
^aEindhoven University of Technology ^bETH Zürich ^cIBM Research Europe, Zurich

Accelerating Approximate String Matching

- Damla Senol Cali, Gurpreet S. Kalsi, Zülal Bingöl, Can Firtina, Lavanya Subramanian, Jeremie S. Kim, Rachata Ausavarungnirun, Mohammed Alser, Juan Gomez-Luna, Amirali Boroumand, Anant Nori, Allison Scibisz, Sreenivas Subramoney, Can Alkan, Saugata Ghose, and Onur Mutlu, **"GenASM: A High-Performance, Low-Power Approximate String Matching Acceleration Framework for Genome Sequence Analysis"**
Proceedings of the 53rd International Symposium on Microarchitecture (MICRO), Virtual, October 2020.
[[Lightning Talk Video](#) (1.5 minutes)]
[[Lightning Talk Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (18 minutes)]
[[Slides \(pptx\)](#) ([pdf](#))]

GenASM: A High-Performance, Low-Power Approximate String Matching Acceleration Framework for Genome Sequence Analysis

Damla Senol Cali^{†⋈} Gurpreet S. Kalsi[⋈] Zülal Bingöl[▽] Can Firtina[◇] Lavanya Subramanian[‡] Jeremie S. Kim^{◇†}
Rachata Ausavarungnirun[○] Mohammed Alser[◇] Juan Gomez-Luna[◇] Amirali Boroumand[†] Anant Nori[⋈]
Allison Scibisz[†] Sreenivas Subramoney[⋈] Can Alkan[▽] Saugata Ghose^{*†} Onur Mutlu^{◇†▽}
[†]Carnegie Mellon University [⋈]Processor Architecture Research Lab, Intel Labs [▽]Bilkent University [◇]ETH Zürich
[‡]Facebook [○]King Mongkut's University of Technology North Bangkok ^{*}University of Illinois at Urbana-Champaign

Accelerating Sequence-to-Graph Mapping

- Damla Senol Cali, Konstantinos Kanellopoulos, Joel Lindegger, Zülal Bingöl, Gurpreet S. Kalsi, Ziyi Zuo, Can Firtina, Meryem Banu Cavlak, Jeremie Kim, Nika Mansouri Ghiasi, Gagandeep Singh, Juan Gomez-Luna, Nour Almadhoun Alserr, Mohammed Alser, Sreenivas Subramoney, Can Alkan, Saugata Ghose, and Onur Mutlu,
"SeGraM: A Universal Hardware Accelerator for Genomic Sequence-to-Graph and Sequence-to-Sequence Mapping"
Proceedings of the 49th International Symposium on Computer Architecture (ISCA), New York, June 2022.
[[arXiv version](#)]

SeGraM: A Universal Hardware Accelerator for Genomic Sequence-to-Graph and Sequence-to-Sequence Mapping

Damla Senol Cali¹ Konstantinos Kanellopoulos² Joël Lindegger² Zülal Bingöl³
Gurpreet S. Kalsi⁴ Ziyi Zuo⁵ Can Firtina² Meryem Banu Cavlak² Jeremie Kim²
Nika Mansouri Ghiasi² Gagandeep Singh² Juan Gómez-Luna² Nour Almadhoun Alserr²
Mohammed Alser² Sreenivas Subramoney⁴ Can Alkan³ Saugata Ghose⁶ Onur Mutlu²

¹Bionano Genomics ²ETH Zürich ³Bilkent University ⁴Intel Labs
⁵Carnegie Mellon University ⁶University of Illinois Urbana-Champaign

Accelerating Time Series Analysis

- Ivan Fernandez, Ricardo Quisiant, Christina Giannoula, Mohammed Alser, Juan Gómez-Luna, Eladio Gutiérrez, Oscar Plata, and Onur Mutlu,
"NATSA: A Near-Data Processing Accelerator for Time Series Analysis"
Proceedings of the 38th IEEE International Conference on Computer Design (ICCD), Virtual, October 2020.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (10 minutes)]
[[Source Code](#)]

NATSA: A Near-Data Processing Accelerator for Time Series Analysis

Ivan Fernandez[§]

Ricardo Quisiant[§]

Christina Giannoula[†]

Mohammed Alser[‡]

Juan Gómez-Luna[‡]

Eladio Gutiérrez[§]

Oscar Plata[§]

Onur Mutlu[‡]

[§]*University of Malaga*

[†]*National Technical University of Athens*

[‡]*ETH Zürich*

Accelerating Graph Pattern Mining

- Maciej Besta, Raghavendra Kanakagiri, Grzegorz Kwasniewski, Rachata Ausavarungnirun, Jakub Beránek, Konstantinos Kanellopoulos, Kacper Janda, Zur Vonarburg-Shmaria, Lukas Gianinazzi, Ioana Stefan, Juan Gómez-Luna, Marcin Copik, Lukas Kapp-Schwoerer, Salvatore Di Girolamo, Nils Blach, Marek Konieczny, Onur Mutlu, and Torsten Hoefler,

"SISA: Set-Centric Instruction Set Architecture for Graph Mining on Processing-in-Memory Systems"

Proceedings of the 54th International Symposium on Microarchitecture (MICRO), Virtual, October 2021.

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

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

[[Lightning Talk Video](#) (1.5 minutes)]

[[Full arXiv version](#)]

SISA: Set-Centric Instruction Set Architecture for Graph Mining on Processing-in-Memory Systems

Maciej Besta¹, Raghavendra Kanakagiri², Grzegorz Kwasniewski¹, Rachata Ausavarungnirun³, Jakub Beránek⁴, Konstantinos Kanellopoulos¹, Kacper Janda⁵, Zur Vonarburg-Shmaria¹, Lukas Gianinazzi¹, Ioana Stefan¹, Juan Gómez-Luna¹, Marcin Copik¹, Lukas Kapp-Schwoerer¹, Salvatore Di Girolamo¹, Nils Blach¹, Marek Konieczny⁵, Onur Mutlu¹, Torsten Hoefler¹

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Thailand

²IIT Tirupati, India

³King Mongkut's University of Technology North Bangkok,
⁴Technical University of Ostrava, Czech Republic

⁵AGH-UST, Poland

Accelerating HTAP Database Systems

- Amirali Boroumand, Saugata Ghose, Geraldo F. Oliveira, and Onur Mutlu,
"Polynesia: Enabling High-Performance and Energy-Efficient Hybrid Transactional/Analytical Databases with Hardware/Software Co-Design"
Proceedings of the 38th International Conference on Data Engineering (ICDE),
Virtual, May 2022.
[[arXiv version](#)]
[[Slides \(pptx\)](#) ([pdf](#))]
[[Short Talk Slides \(pptx\)](#) ([pdf](#))]

Polynesia: Enabling High-Performance and Energy-Efficient Hybrid Transactional/Analytical Databases with Hardware/Software Co-Design

Amirali Boroumand[†] Saugata Ghose[◇] Geraldo F. Oliveira[‡] Onur Mutlu[‡]
[†]*Google* [◇]*Univ. of Illinois Urbana-Champaign* [‡]*ETH Zürich*

Accelerating Neural Network Inference

- Amirali Boroumand, Saugata Ghose, Berkin Akin, Ravi Narayanaswami, Geraldo F. Oliveira, Xiaoyu Ma, Eric Shiu, and Onur Mutlu,
"Google Neural Network Models for Edge Devices: Analyzing and Mitigating Machine Learning Inference Bottlenecks"
Proceedings of the 30th International Conference on Parallel Architectures and Compilation Techniques (PACT), Virtual, September 2021.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (14 minutes)]

Google Neural Network Models for Edge Devices: Analyzing and Mitigating Machine Learning Inference Bottlenecks

Amirali Boroumand^{†◇}

Geraldo F. Oliveira^{*}

Saugata Ghose[‡]

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Berkin Akin[§]

Eric Shiu[§]

Ravi Narayanaswami[§]

Onur Mutlu^{*†}

[†]*Carnegie Mellon Univ.*

[◇]*Stanford Univ.*

[‡]*Univ. of Illinois Urbana-Champaign*

[§]*Google*

^{*}*ETH Zürich*

Google Neural Network Models for Edge Devices: Analyzing and Mitigating Machine Learning Inference Bottlenecks

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Eric Shiu

Onur Mutlu

PACT 2021

SAFARI

Carnegie Mellon



UNIVERSITY OF
ILLINOIS
URBANA-CHAMPAIGN



ETH zürich

Executive Summary

Context: We extensively analyze a state-of-the-art edge ML accelerator (Google Edge TPU) using 24 Google edge models

- Wide range of models (CNNs, LSTMs, Transducers, RCNNs)

Problem: The Edge TPU accelerator suffers from **three challenges:**

- It operates **significantly below** its peak throughput
- It operates **significantly below** its theoretical energy efficiency
- It **inefficiently** handles memory accesses

Key Insight: These shortcomings arise from **the monolithic design** of the Edge TPU accelerator

- The Edge TPU accelerator design does not account for **layer heterogeneity**

Key Mechanism: A new framework called **Mensa**

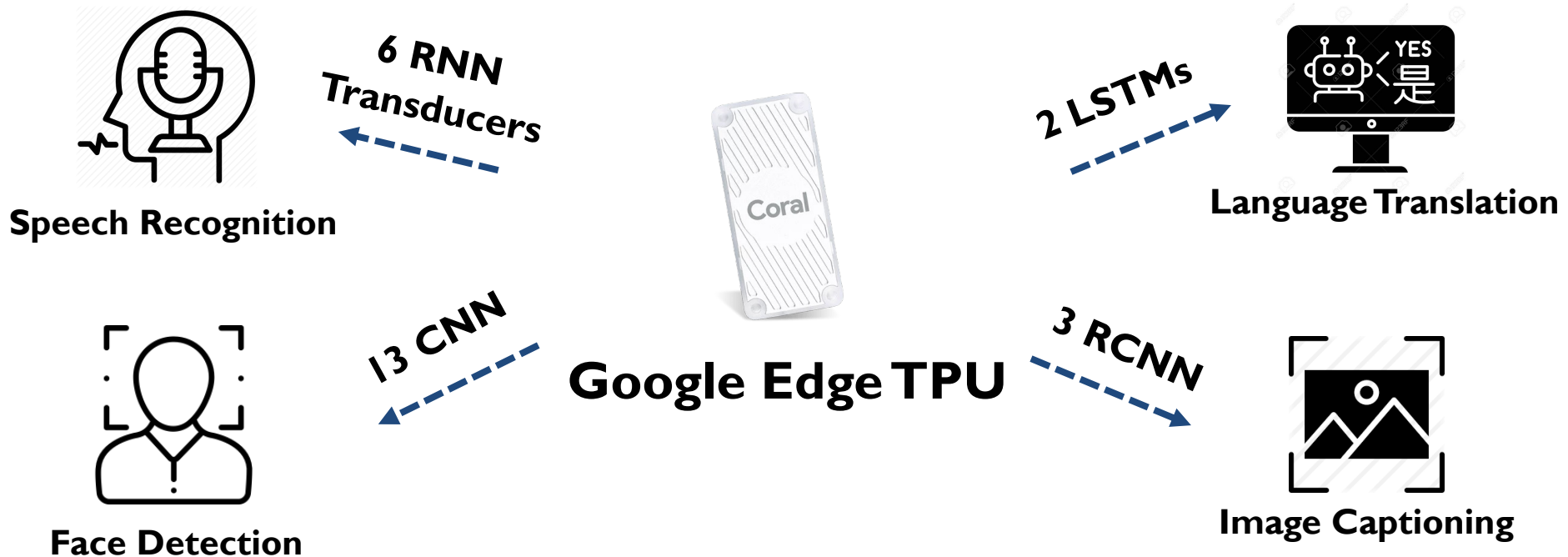
- Mensa consists of heterogeneous accelerators whose dataflow and hardware are specialized for specific families of layers

Key Results: We design a version of Mensa for Google edge ML models

- Mensa improves performance and energy by **3.0X** and **3.1X**
- Mensa reduces cost and improves area efficiency

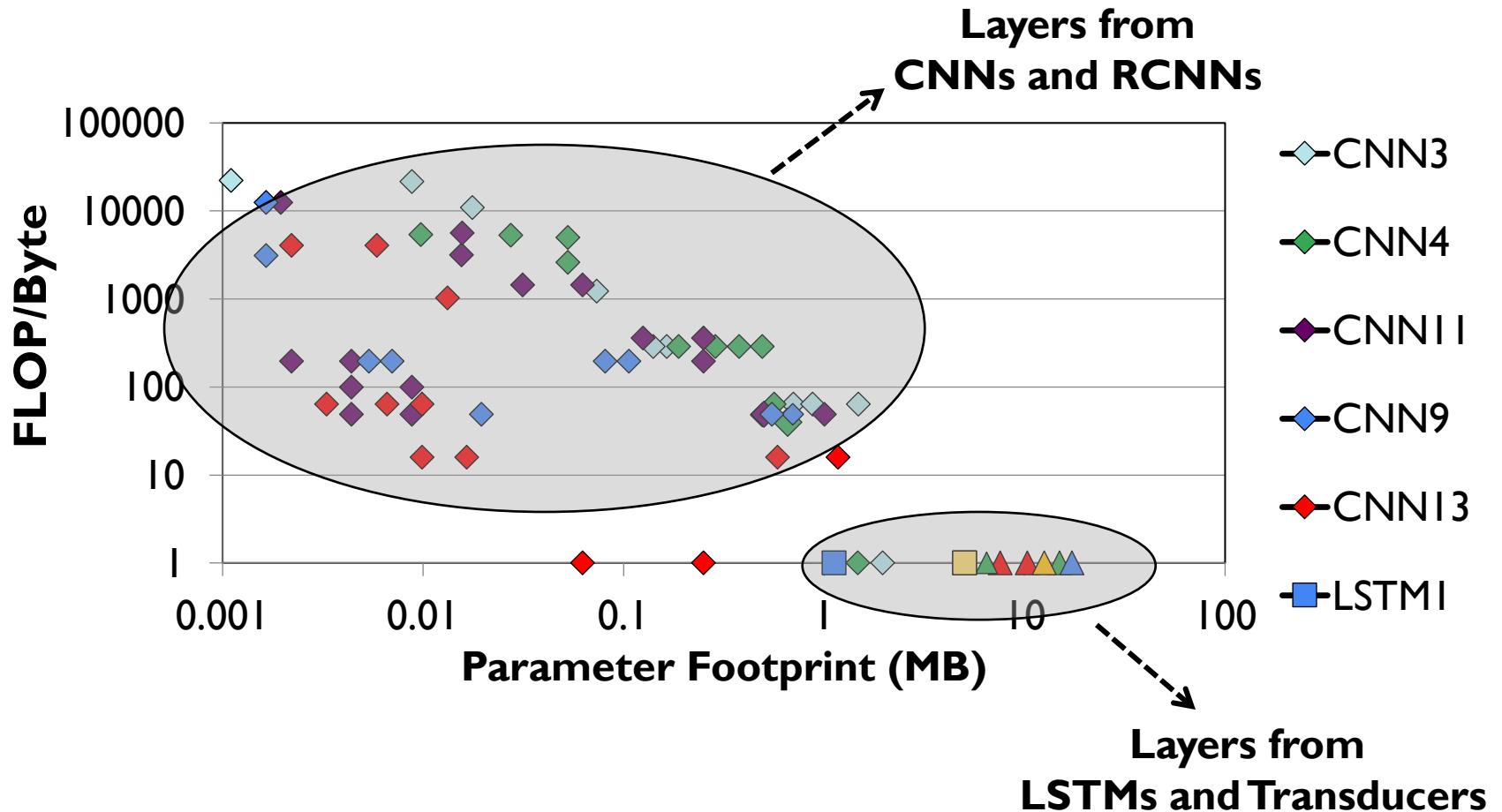
Google Edge Neural Network Models

We analyze inference execution using 24 edge NN models



Diversity Across the Models

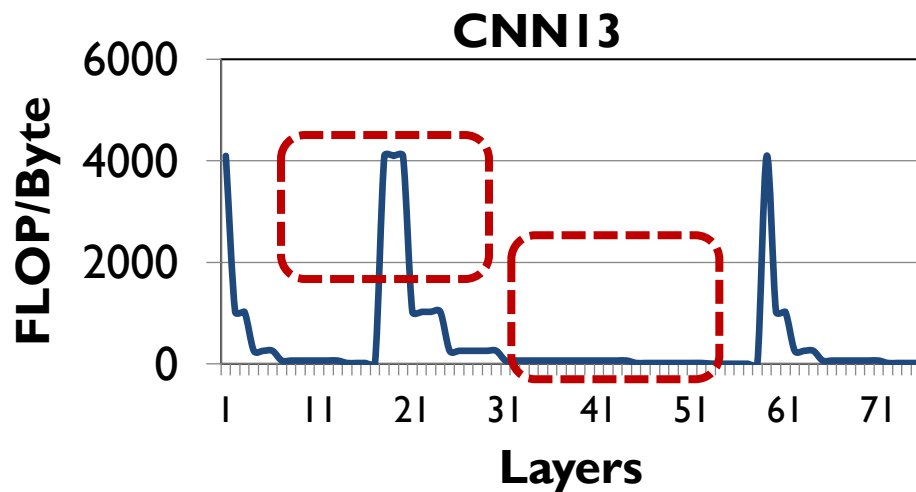
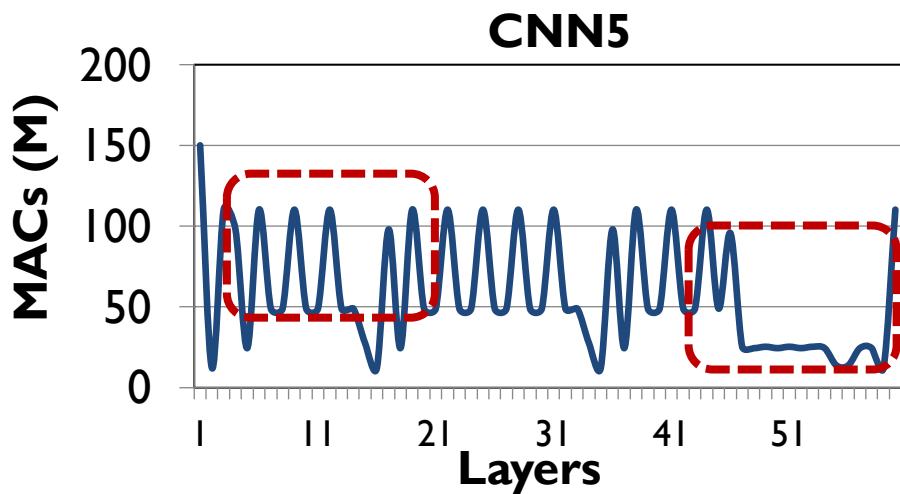
Insight 1: there is **significant variation** in terms of layer characteristics **across the models**



Diversity Within the Models

Insight 2: even **within** each model, layers exhibit **significant variation** in terms of layer characteristics

For example, our analysis of edge **CNN** models shows:



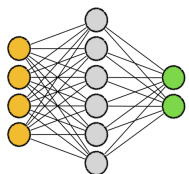
Variation in **MAC intensity**: up to **200x** across layers

Variation in **FLOP/Byte**: up to **244x** across layers

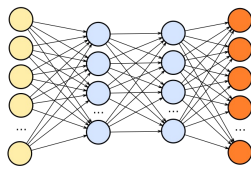
Mensa High-Level Overview

Edge TPU Accelerator

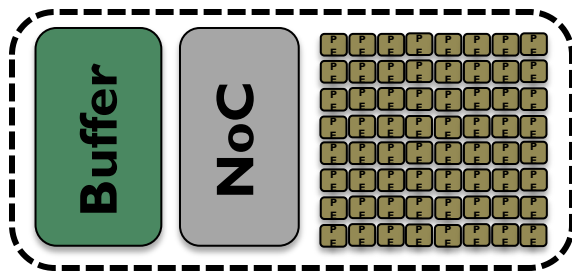
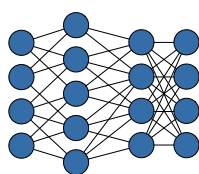
Model A



Model B



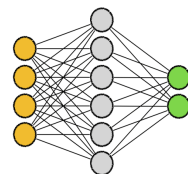
Model C



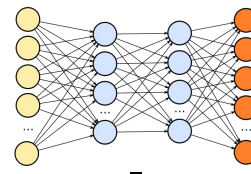
Monolithic Accelerator

Mensa

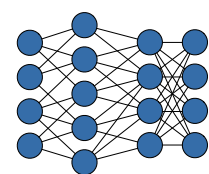
Model A



Model B

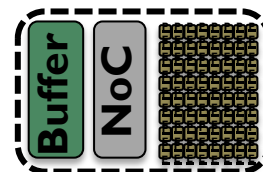


Model C



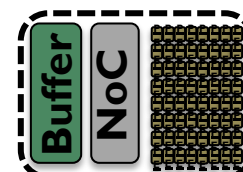
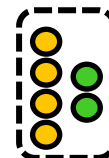
Runtime

Family 1



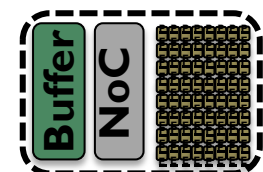
Acc. 1

Family 2



Acc. 2

Family 3



Acc. 3

Mensa: Highly-Efficient ML Inference

- Amirali Boroumand, Saugata Ghose, Berkin Akin, Ravi Narayanaswami, Geraldo F. Oliveira, Xiaoyu Ma, Eric Shiu, and Onur Mutlu,
"Google Neural Network Models for Edge Devices: Analyzing and Mitigating Machine Learning Inference Bottlenecks"
Proceedings of the 30th International Conference on Parallel Architectures and Compilation Techniques (PACT), Virtual, September 2021.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (14 minutes)]

Google Neural Network Models for Edge Devices: Analyzing and Mitigating Machine Learning Inference Bottlenecks

Amirali Boroumand^{†◇}

Geraldo F. Oliveira^{*}

Saugata Ghose[‡]

Xiaoyu Ma[§]

Berkin Akin[§]

Eric Shiu[§]

Ravi Narayanaswami[§]

Onur Mutlu^{*†}

[†]*Carnegie Mellon Univ.*

[◇]*Stanford Univ.*

[‡]*Univ. of Illinois Urbana-Champaign*

[§]*Google*

^{*}*ETH Zürich*

FPGA-based Processing Near Memory

- Gagandeep Singh, Mohammed Alser, Damla Senol Cali, Dionysios Diamantopoulos, Juan Gómez-Luna, Henk Corporaal, and Onur Mutlu, ["FPGA-based Near-Memory Acceleration of Modern Data-Intensive Applications"](#) *IEEE Micro* (**IEEE MICRO**), 2021.

FPGA-based Near-Memory Acceleration of Modern Data-Intensive Applications

Gagandeep Singh[◇] Mohammed Alser[◇] Damla Senol Cali[✕]

Dionysios Diamantopoulos[▽] Juan Gómez-Luna[◇]

Henk Corporaal[★] Onur Mutlu^{◇✕}

[◇]*ETH Zürich* [✕]*Carnegie Mellon University*

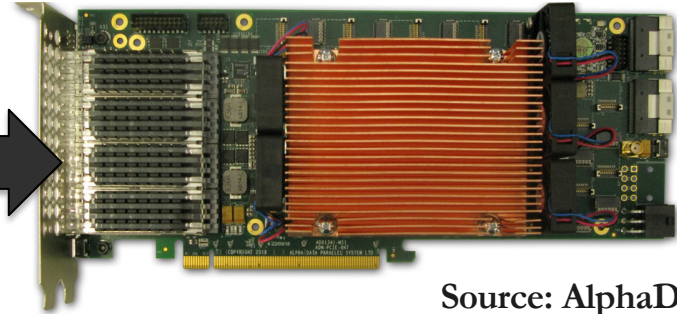
[★]*Eindhoven University of Technology* [▽]*IBM Research Europe*

Near-Memory Acceleration Using FPGAs



Source: IBM

IBM POWER9 CPU



Source: AlphaData

HBM-based FPGA board

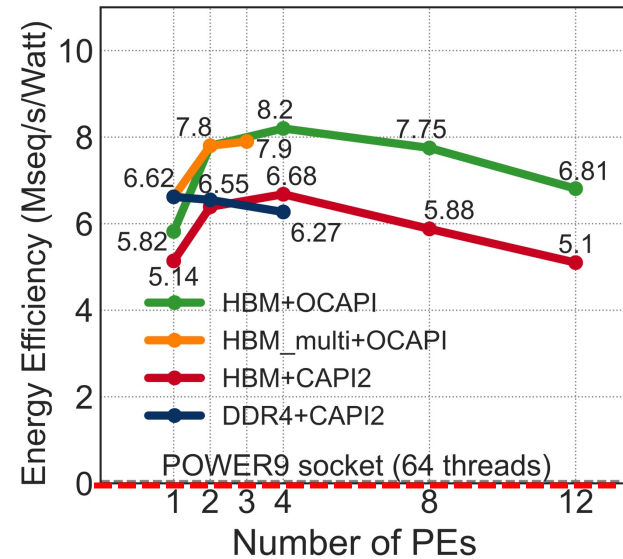
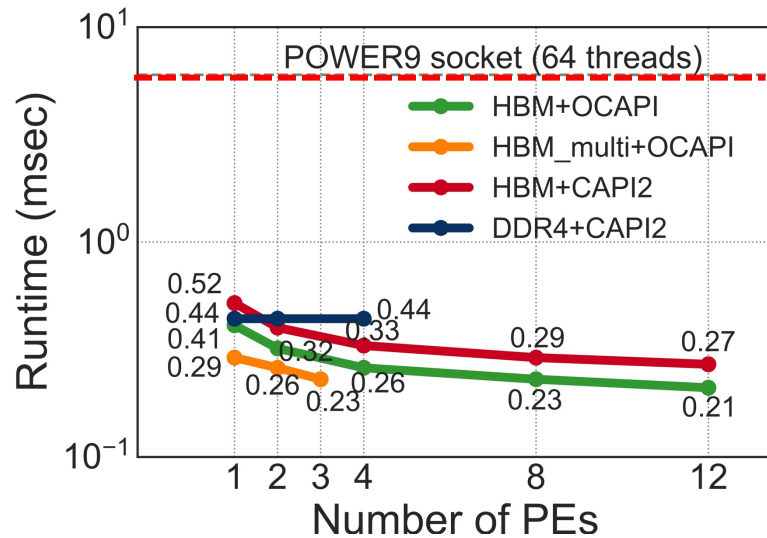
Near-HBM FPGA-based accelerator

Two communication technologies: CAPI2 and OCAPI

Two memory technologies: DDR4 and HBM

Two workloads: Weather Modeling and Genome Analysis

Performance & Energy Greatly Improve

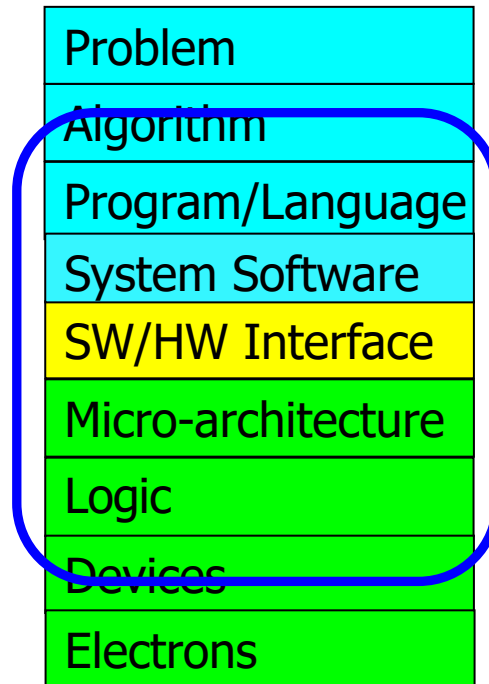


5-27× performance vs. a 16-core (64-thread) IBM POWER9 CPU

12-133× energy efficiency vs. a 16-core (64-thread) IBM POWER9 CPU

HBM alleviates memory bandwidth contention vs. DDR4

We Need to Revisit the Entire Stack



We can get there step by step

PIM Review and Open Problems

A Modern Primer on Processing in Memory

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

SAFARI Research Group

^a*ETH Zürich*

^b*Carnegie Mellon University*

^c*University of Illinois at Urbana-Champaign*

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

Onur Mutlu, Saugata Ghose, Juan Gomez-Luna, and Rachata Ausavarungnirun,
"A Modern Primer on Processing in Memory"
*Invited Book Chapter in **Emerging Computing: From Devices to Systems - Looking Beyond Moore and Von Neumann**, Springer, to be published in 2021.*

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*

[§]*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]

Processing in Memory: Two Approaches

1. Processing using Memory
2. Processing near Memory

Two PIM Approaches

5.2. Two Approaches: Processing Using Memory (PUM) vs. Processing Near Memory (PNM)

Many recent works take advantage of the memory technology innovations that we discuss in Section 5.1 to enable and implement PIM. We find that these works generally take one of two approaches, which are categorized in Table 1: (1) *processing using memory* or (2) *processing near memory*. We briefly describe each approach here. Sections 6 and 7 will provide example approaches and more detail for both.

Table 1: Summary of enabling technologies for the two approaches to PIM used by recent works. Adapted from [309].

Approach	Enabling Technologies
Processing Using Memory	SRAM
	DRAM
	Phase-change memory (PCM)
	Magnetic RAM (MRAM)
Processing Near Memory	Resistive RAM (RRAM)/memristors
	Logic layers in 3D-stacked memory
	Silicon interposers
	Logic in memory controllers

Processing using memory (PUM) exploits the existing memory architecture and the operational principles of the memory circuitry to enable operations within main memory with minimal changes. PUM makes use

Onur Mutlu, Saugata Ghose, Juan Gomez-Luna, and Rachata Ausavarungnirun, ["A Modern Primer on Processing in Memory"](#)

*Invited Book Chapter in **Emerging Computing: From Devices to Systems - Looking Beyond Moore and Von Neumann***, Springer, to be published in 2021.

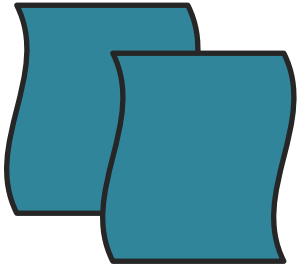
[[Tutorial Video on "Memory-Centric Computing Systems"](#) (1 hour 51 minutes)]

Approach 1: Processing Using Memory

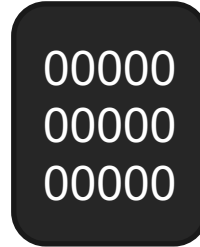
- Take advantage of operational principles of memory to perform **bulk data movement and computation in memory**
 - Can **exploit internal connectivity** to move data
 - Can **exploit analog computation capability**
 - ...
- Examples: RowClone, In-DRAM AND/OR, Gather/Scatter DRAM
 - RowClone: Fast and Efficient In-DRAM Copy and Initialization of Bulk Data (Seshadri et al., MICRO 2013)
 - Fast Bulk Bitwise AND and OR in DRAM (Seshadri et al., IEEE CAL 2015)
 - Gather-Scatter DRAM: In-DRAM Address Translation to Improve the Spatial Locality of Non-unit Strided Accesses (Seshadri et al., MICRO 2015)
 - "Ambit: In-Memory Accelerator for Bulk Bitwise Operations Using Commodity DRAM Technology" (Seshadri et al., MICRO 2017)

Starting Simple: Data Copy and Initialization

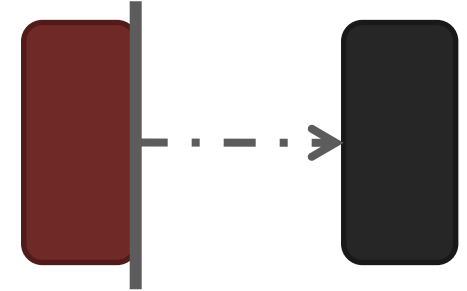
memmove & memcpy: 5% cycles in Google's datacenter [Kanev+ ISCA'15]



Forking



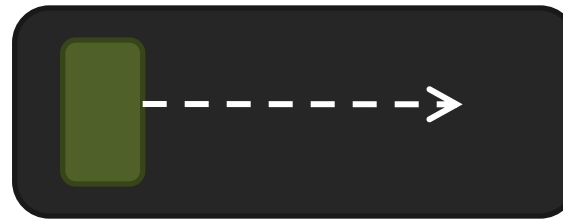
**Zero initialization
(e.g., security)**



Checkpointing



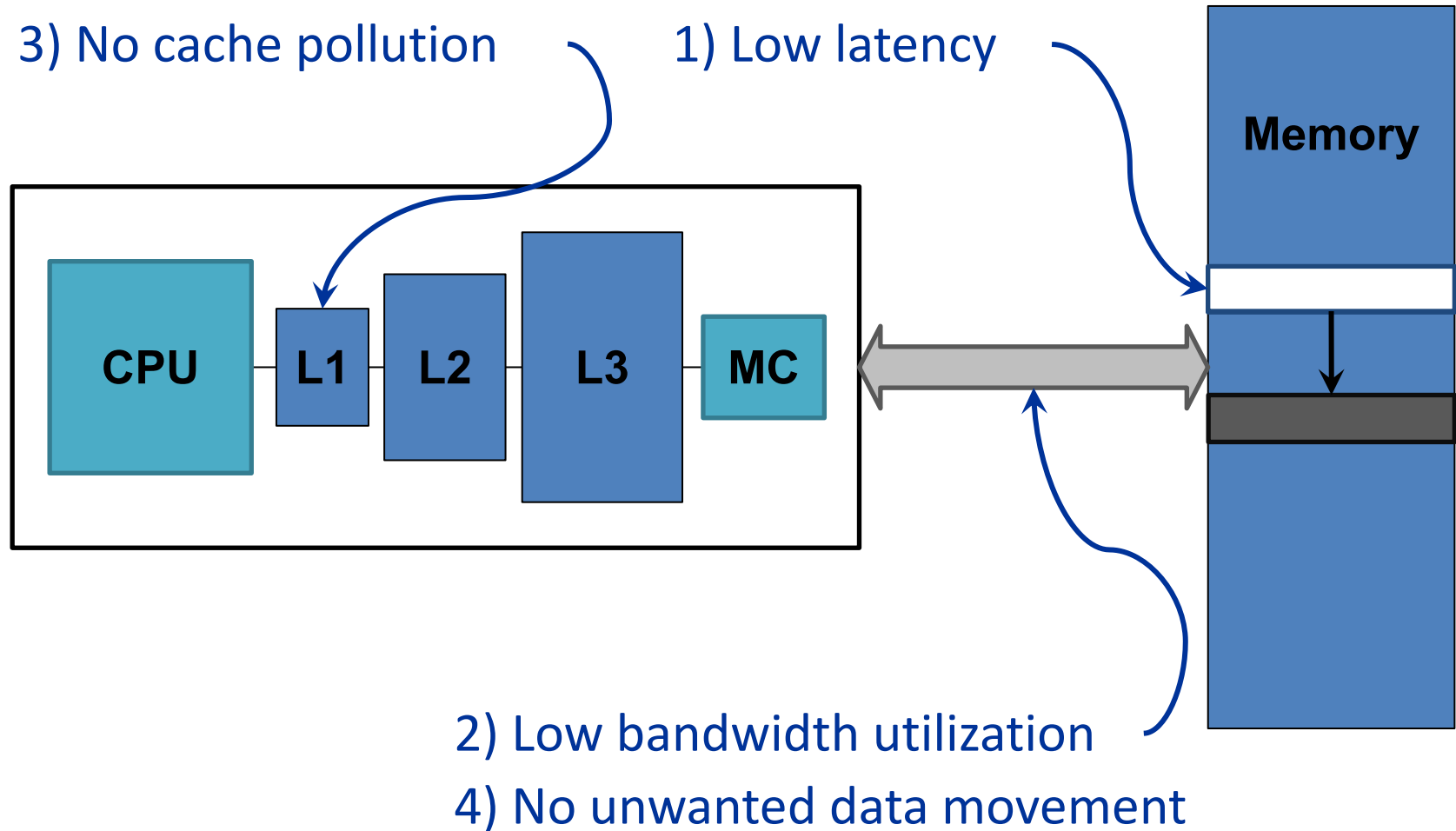
**VM Cloning
Deduplication**



Page Migration

...
Many more

Future Systems: In-Memory Copy

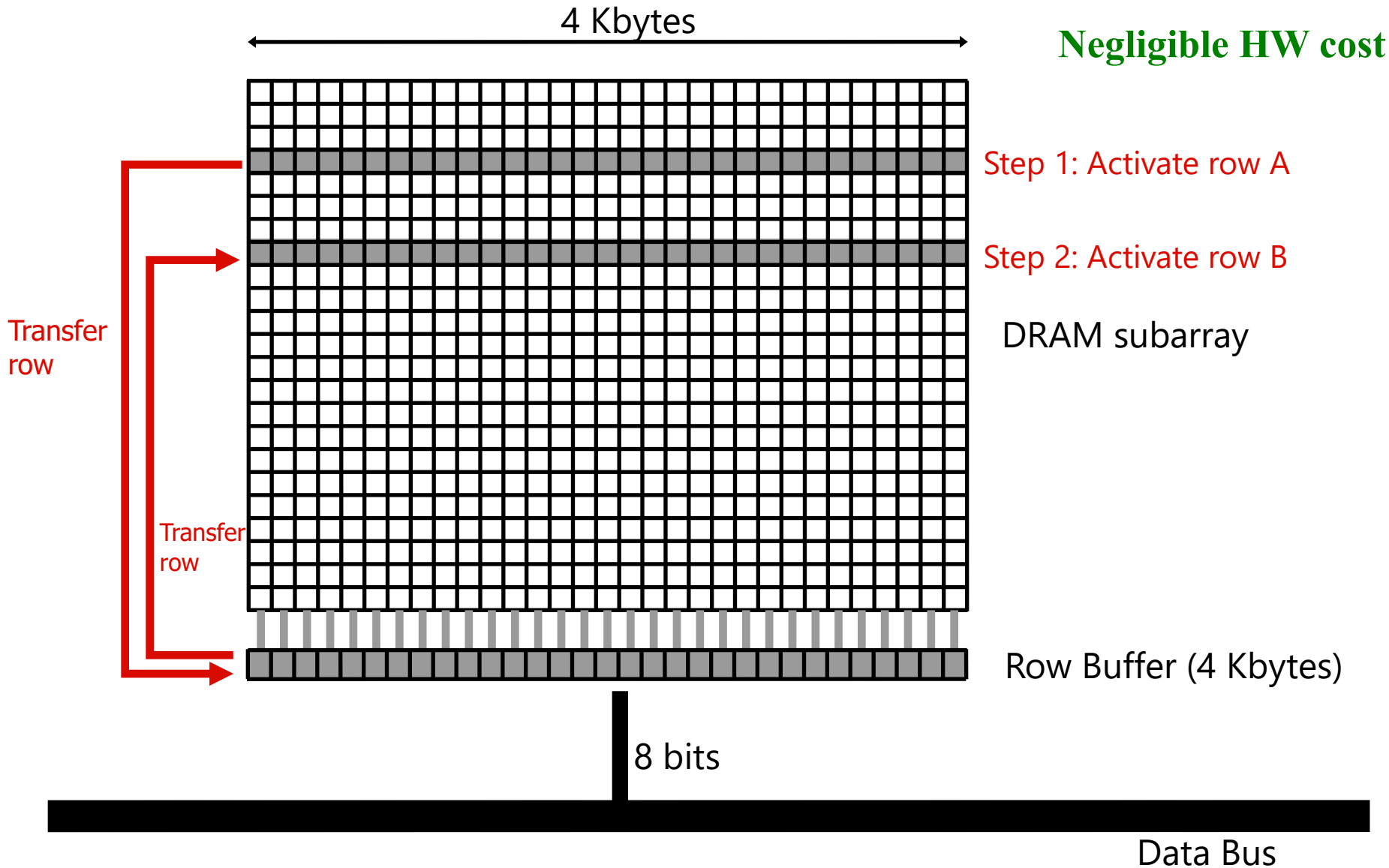


1046ns, 3.6uJ → 90ns, 0.04uJ

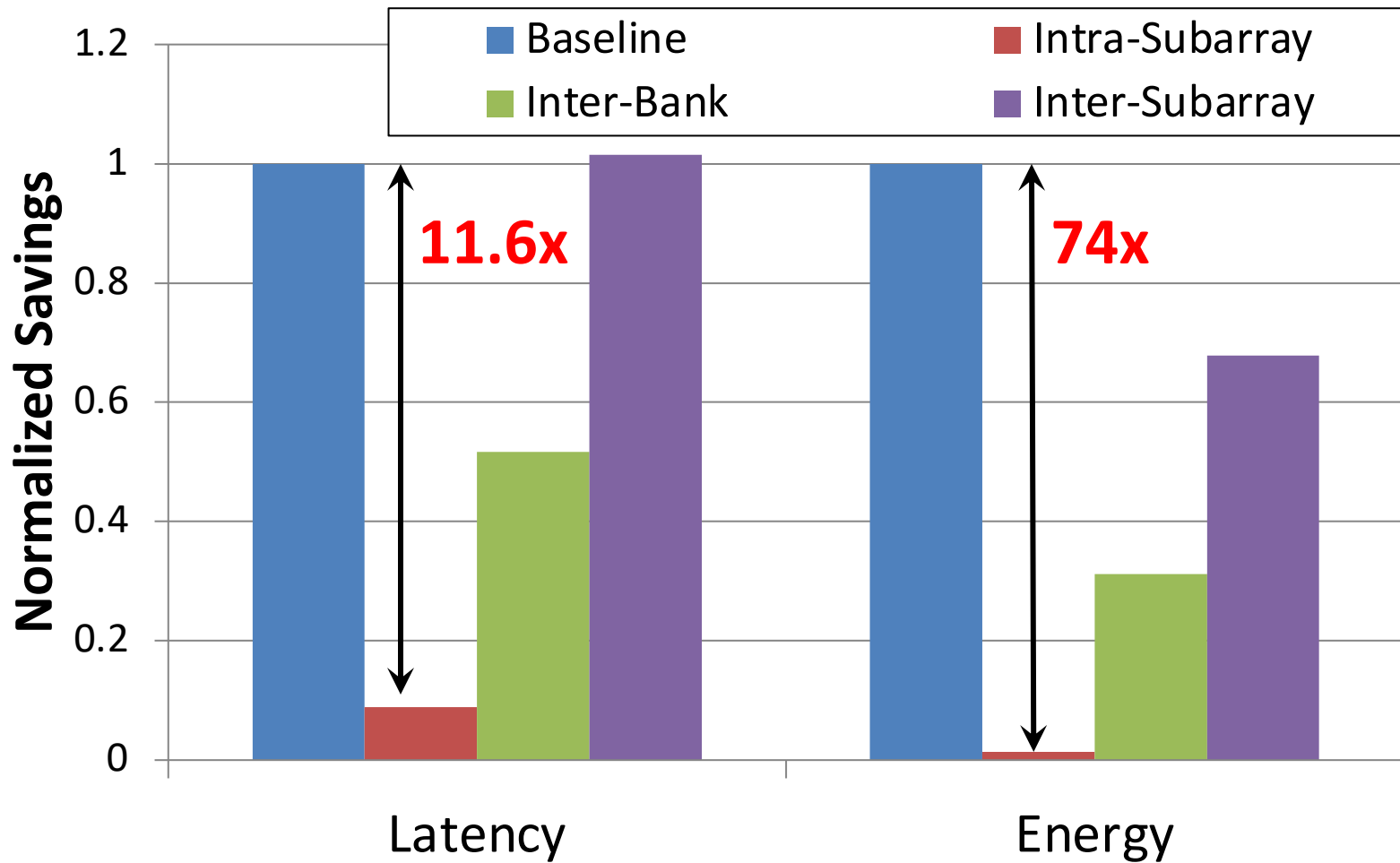
RowClone: In-DRAM Row Copy

Idea: Two consecutive ACTivates

Negligible HW cost



RowClone: Latency and Energy Savings



Seshadri et al., "RowClone: Fast and Efficient In-DRAM Copy and Initialization of Bulk Data," MICRO 2013.

More on RowClone

- Vivek Seshadri, Yoongu Kim, Chris Fallin, Donghyuk Lee, Rachata Ausavarungnirun, Gennady Pekhimenko, Yixin Luo, Onur Mutlu, Michael A. Kozuch, Phillip B. Gibbons, and Todd C. Mowry,
"RowClone: Fast and Energy-Efficient In-DRAM Bulk Data Copy and Initialization"
Proceedings of the 46th International Symposium on Microarchitecture (MICRO), Davis, CA, December 2013. [[Slides \(pptx\)](#)] [[pdf](#)] [[Lightning Session Slides \(pptx\)](#)] [[pdf](#)] [[Poster \(pptx\)](#)] [[pdf](#)]

RowClone: Fast and Energy-Efficient In-DRAM Bulk Data Copy and Initialization

Vivek Seshadri Yoongu Kim Chris Fallin* Donghyuk Lee
vseshadr@cs.cmu.edu yoongukim@cmu.edu cfallin@c1f.net donghyuk1@cmu.edu

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Onur Mutlu Phillip B. Gibbons† Michael A. Kozuch† Todd C. Mowry
onur@cmu.edu phillip.b.gibbons@intel.com michael.a.kozuch@intel.com tcm@cs.cmu.edu

Carnegie Mellon University †Intel Pittsburgh

Real System RowClone Prototype

PiDRAM: A Holistic End-to-end FPGA-based Framework for Processing-in-DRAM

Ataberk Olgun^{§†}

Juan Gómez Luna[§]
Hasan Hassan[§]

Konstantinos Kanellopoulos[§]
Oğuz Ergin[†] Onur Mutlu[§]

Behzad Salami^{§*}

[§]ETH Zürich

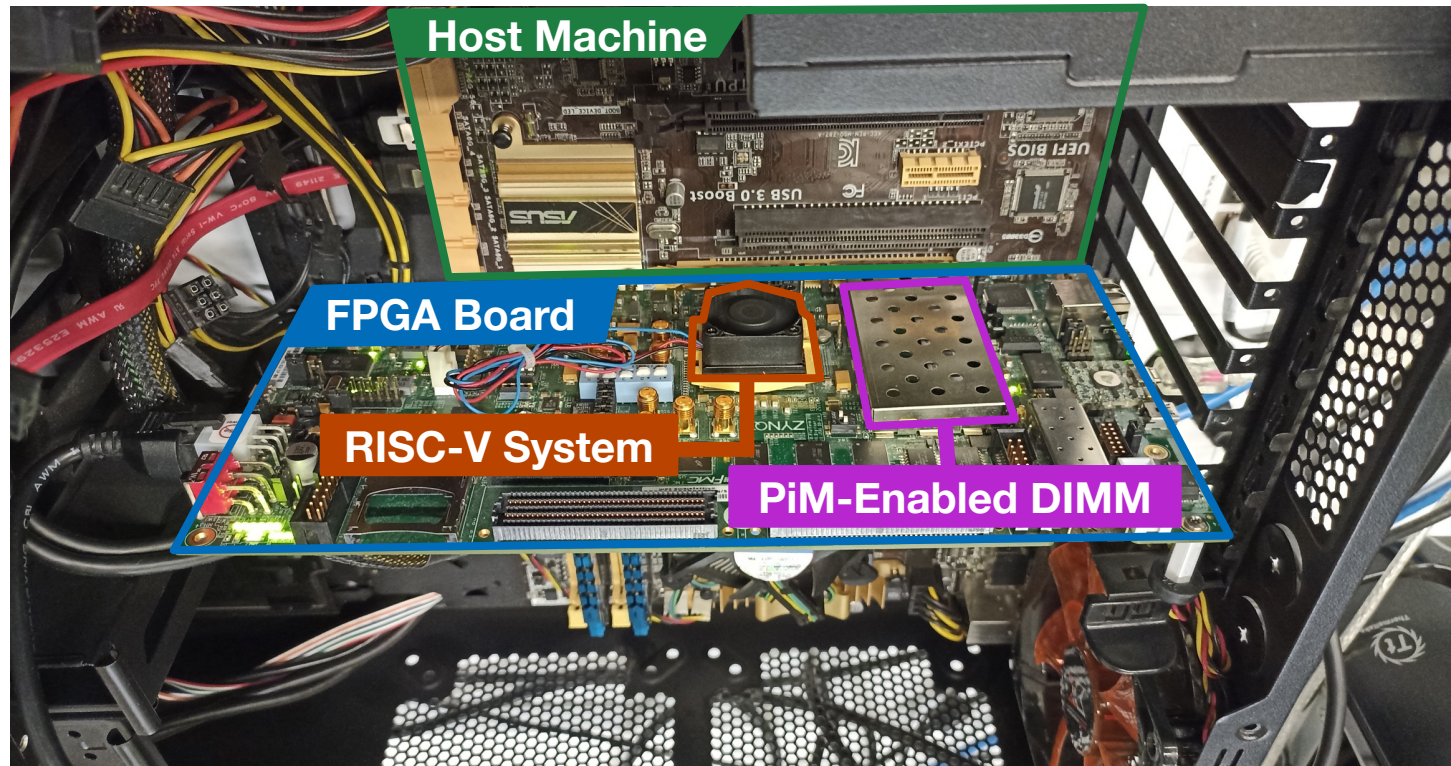
[†]TOBB ETÜ

^{*}BSC

<https://arxiv.org/pdf/2111.00082.pdf>

<https://github.com/cmu-safari/pidram>

Real System RowClone (& PuM) Prototype



<https://arxiv.org/pdf/2111.00082.pdf>

<https://github.com/cmu-safari/pidram>

Lecture on RowClone & Processing using DRAM

Mindset: Memory as an Accelerator

The diagram illustrates a system architecture where memory is treated as an accelerator. On the left, a large gray box represents the system, containing several components: four 'CPU core' blocks, one 'mini-CPU core', one 'video core', one 'imaging core', and four 'GPU (throughput) core' blocks. Below these is a large 'LLC' (Last Level Cache) block, which is connected to a 'Memory Controller' block. The 'Memory Controller' is connected to a 'Memory Bus'. To the right of the system box is a large 'Memory' block. A red rounded rectangle highlights a 'Specialized compute-capability in memory' block within the memory, which is also connected to the 'Memory Bus'. A video player interface is overlaid on the bottom of the diagram, showing a red text overlay: 'Memory similar to a "conventional" accelerator'. The video player also shows a progress bar at 43:48 / 2:03:45 and various control icons.

Onur Mutlu

Memory

Specialized compute-capability in memory

Memory Bus

LLC

Memory Controller

CPU core

mini-CPU core

video core

imaging core

GPU (throughput) core

Memory similar to a "conventional" accelerator

DEPARTMENT OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING (D-ITET)

Seminar in Computer Arch. - Meeting 3: RowClone: In-Memory Data Copy and Initialization (Fall 2021)

292 views • Streamed live on Oct 7, 2021

21 0 SHARE SAVE ...



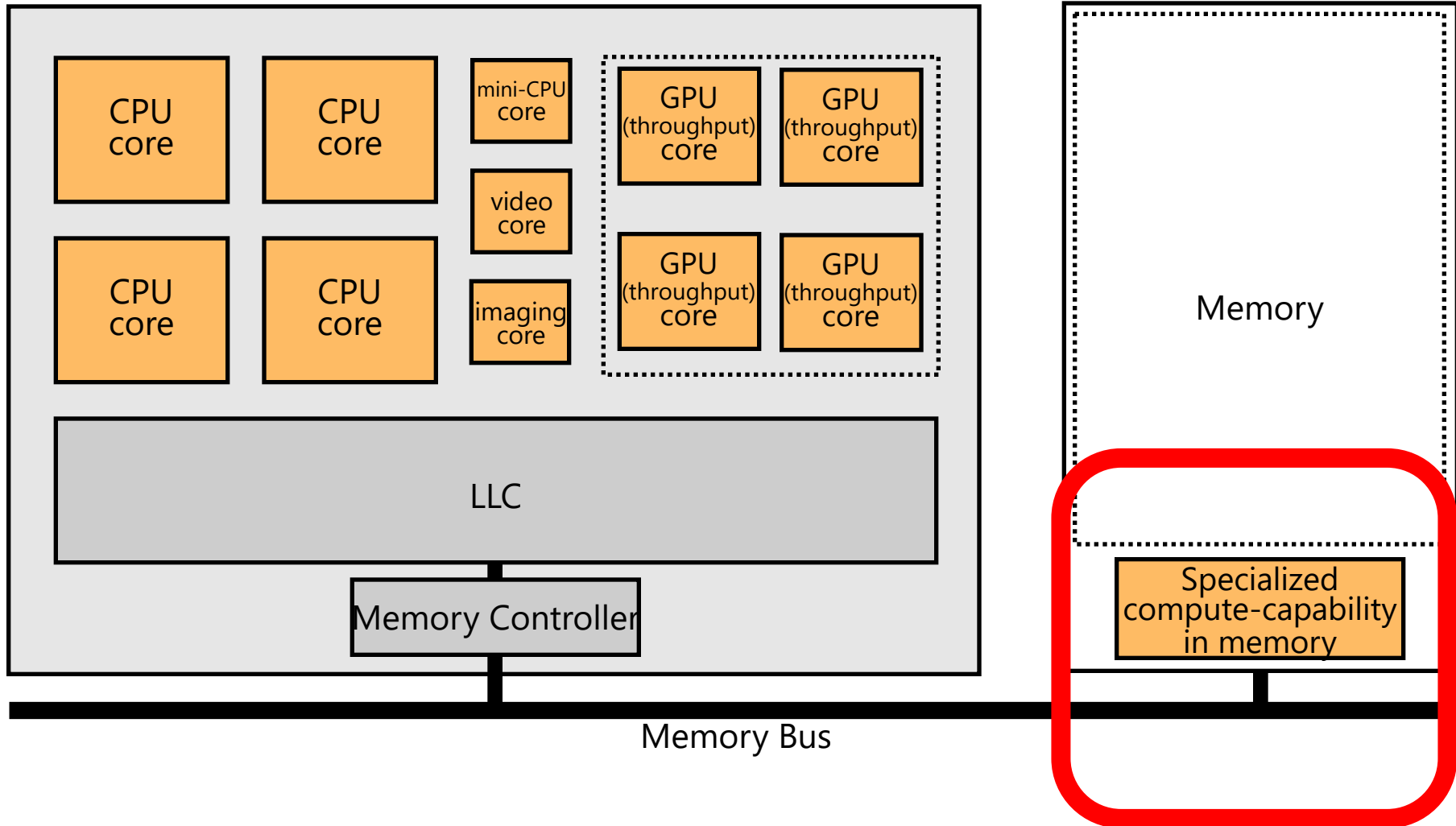
Onur Mutlu Lectures
19.1K subscribers

SUBSCRIBED



https://www.youtube.com/watch?v=n6Pwg1qax_E&list=PL5Q2soXY2Zi_7UBNmC9B8Yr5JSwTG9yH4&index=4

Mindset: Memory as an Accelerator

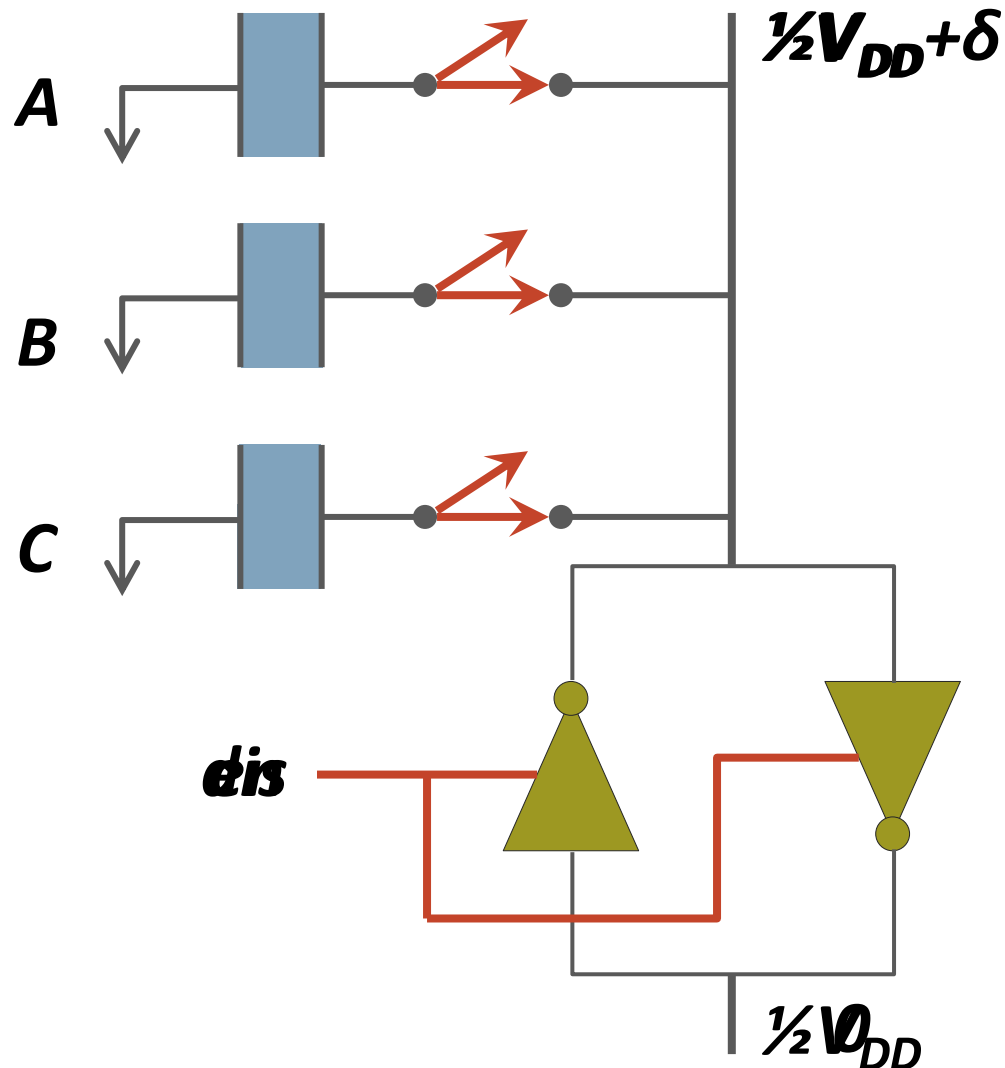


Memory similar to a "conventional" accelerator

(Truly) In-Memory Computation

- We can support in-DRAM 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

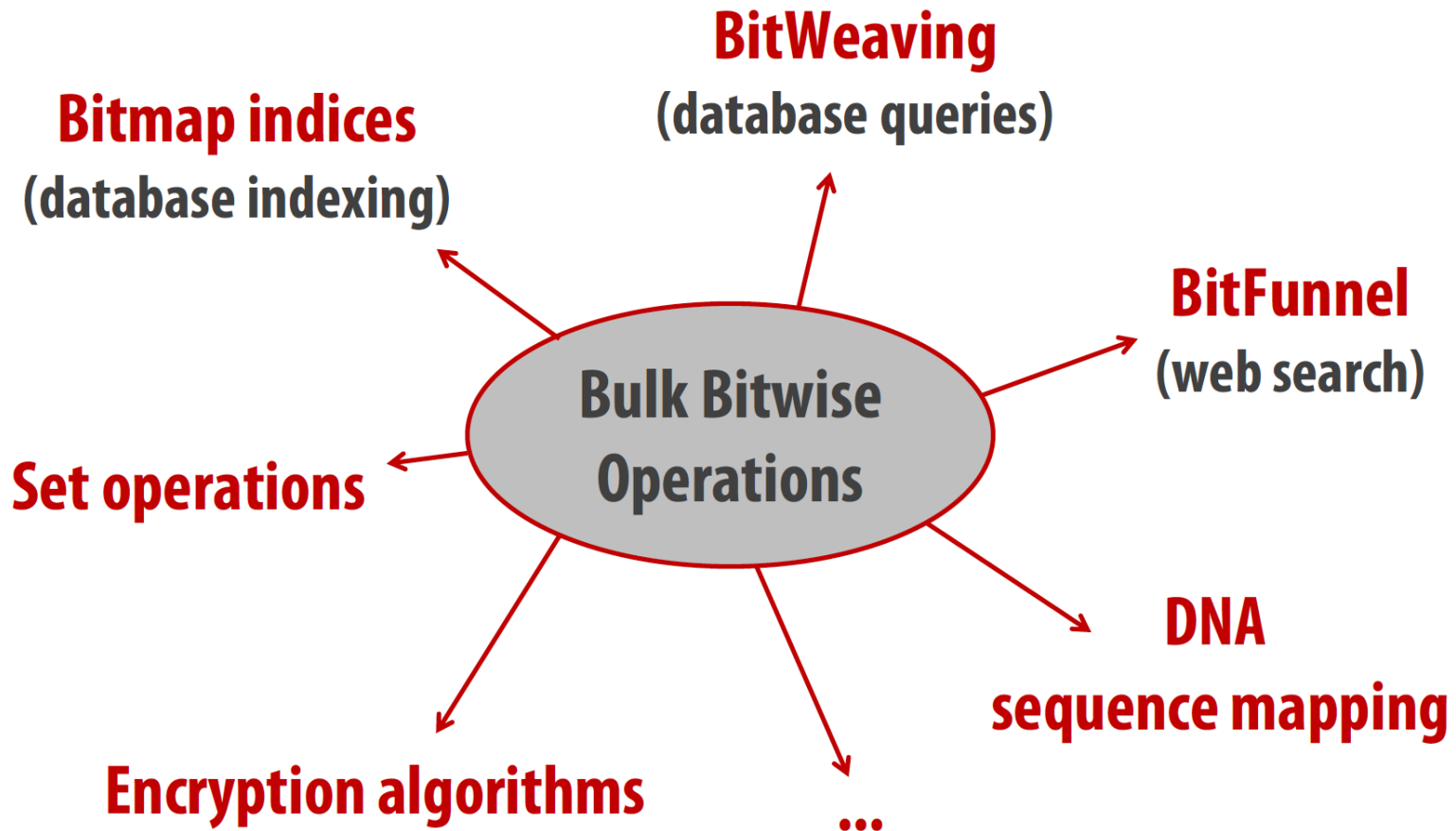
In-DRAM AND/OR: Triple Row Activation



Final State
 $AB + BC + AC$

**$C(A + B) +$
 $\sim C(AB)$**

Bulk Bitwise Operations in Workloads



In-DRAM Acceleration of Database Queries

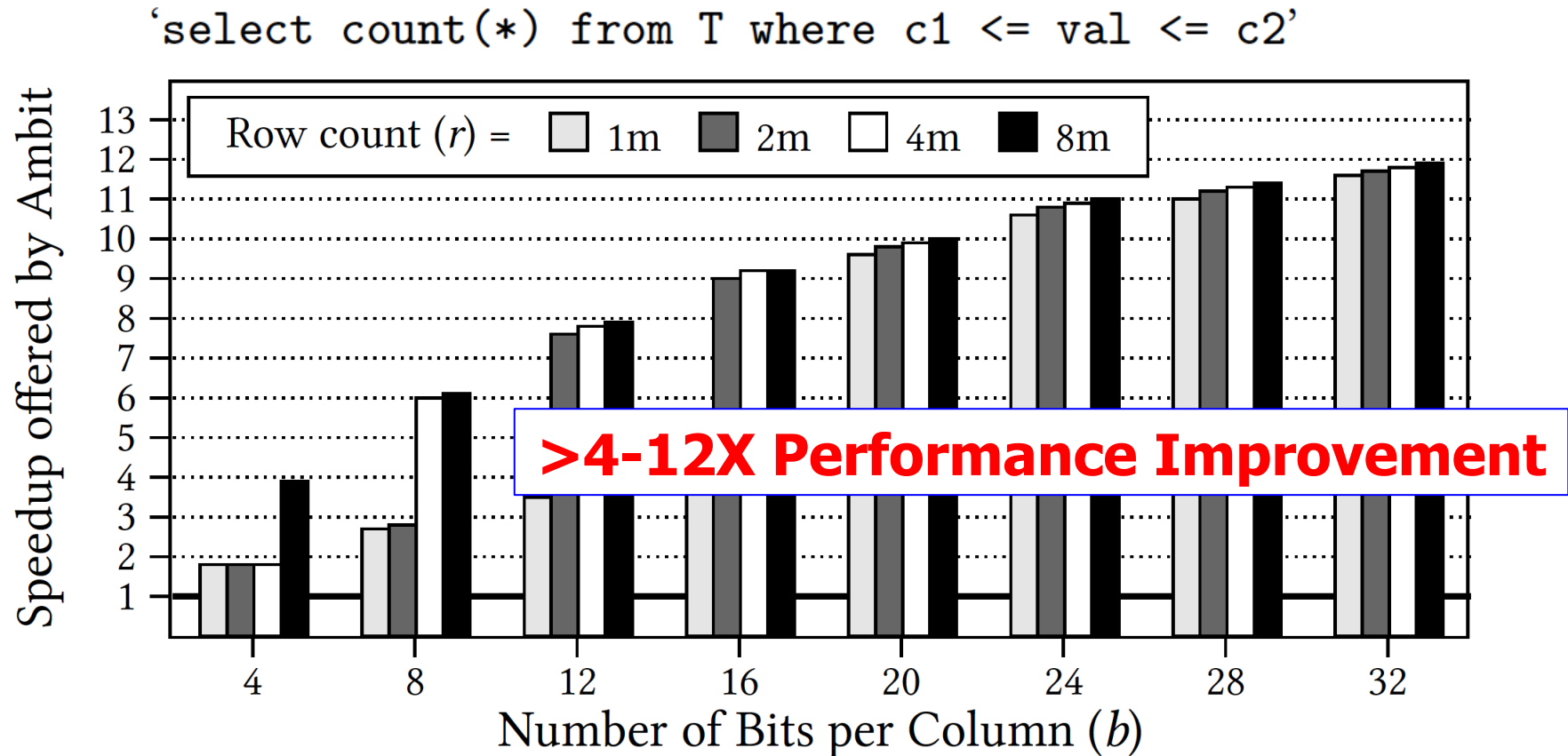


Figure 11: Speedup offered by Ambit over baseline CPU with SIMD for BitWeaving

Seshadri+, "Ambit: In-Memory Accelerator for Bulk Bitwise Operations using Commodity DRAM Technology," MICRO 2017.

More on Ambit

- Vivek Seshadri, Donghyuk Lee, Thomas Mullins, Hasan Hassan, Amirali Boroumand, Jeremie Kim, Michael A. Kozuch, Onur Mutlu, Phillip B. Gibbons, and Todd C. Mowry,
["Ambit: In-Memory Accelerator for Bulk Bitwise Operations Using Commodity DRAM Technology"](#)
Proceedings of the 50th International Symposium on Microarchitecture (MICRO), Boston, MA, USA, October 2017.
[\[Slides \(pptx\) \(pdf\)\]](#) [\[Lightning Session Slides \(pptx\) \(pdf\)\]](#) [\[Poster \(pptx\) \(pdf\)\]](#)

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

In-DRAM Bulk Bitwise Execution

- 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

SIMDRAM Framework

- Nastaran Hajinazar, Geraldo F. Oliveira, Sven Gregorio, Joao Dinis Ferreira, Nika Mansouri Ghiasi, Minesh Patel, Mohammed Alser, Saugata Ghose, Juan Gomez-Luna, and Onur Mutlu, **["SIMDRAM: An End-to-End Framework for Bit-Serial SIMD Computing in DRAM"](#)** *Proceedings of the 26th International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, Virtual, March-April 2021.
[[2-page Extended Abstract](#)]
[[Short Talk Slides \(pptx\)](#) ([pdf](#))]
[[Talk Slides \(pptx\)](#) ([pdf](#))]
[[Short Talk Video](#) (5 mins)]
[[Full Talk Video](#) (27 mins)]

SIMDRAM: A Framework for Bit-Serial SIMD Processing using DRAM

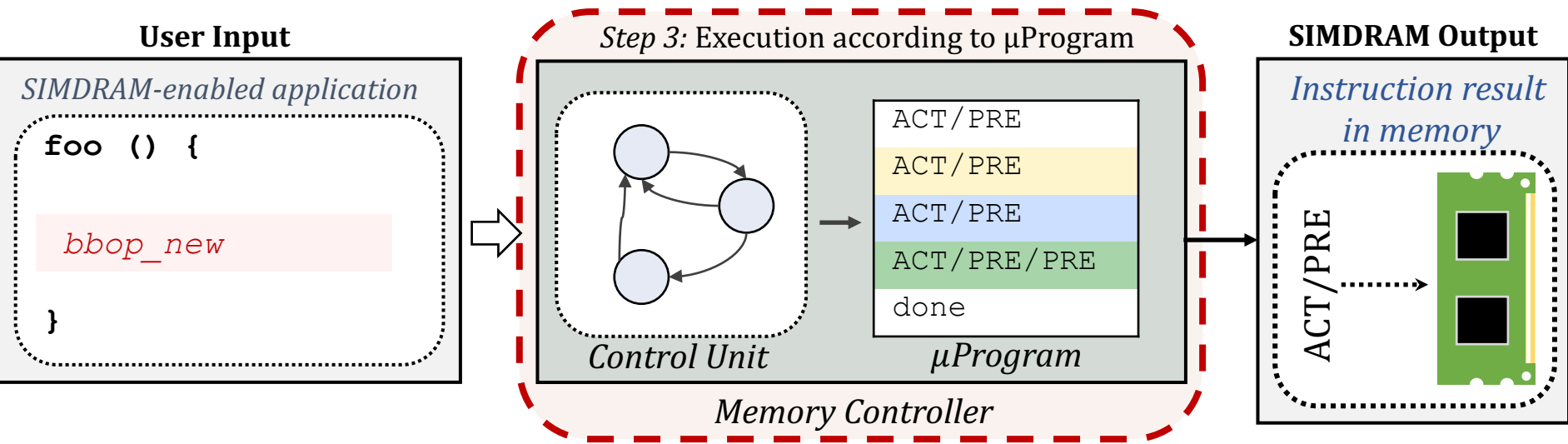
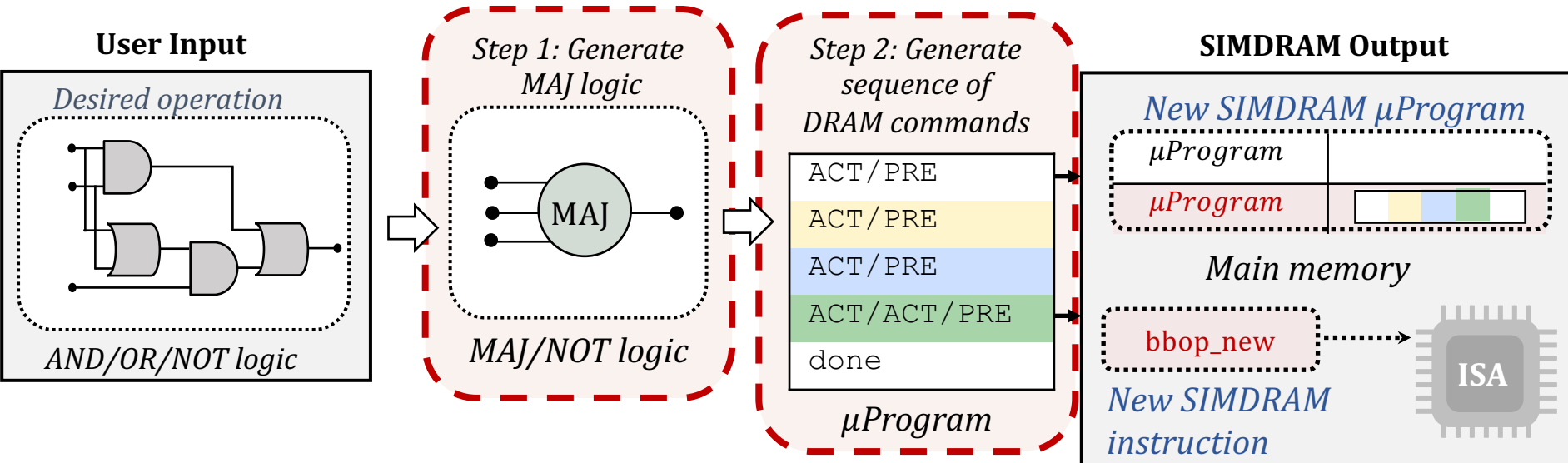
*Nastaran Hajinazar ^{1,2}	*Geraldo F. Oliveira ¹	Sven Gregorio ¹	João Dinis Ferreira ¹
Nika Mansouri Ghiasi ¹	Minesh Patel ¹	Mohammed Alser ¹	Saugata Ghose ³
	Juan Gómez-Luna ¹	Onur Mutlu ¹	

¹ETH Zürich

²Simon Fraser University

³University of Illinois at Urbana–Champaign

SIMDRAM Framework: Overview



SIMDRAM Key Results

Evaluated on:

- 16 complex in-DRAM operations
- 7 commonly-used real-world applications

SIMDRAM provides:

- **88×** and **5.8×** the **throughput** of a **CPU** and a **high-end GPU**, respectively, over **16 operations**
- **257×** and **31×** the **energy efficiency** of a **CPU** and a **high-end GPU**, respectively, over **16 operations**
- **21×** and **2.1×** the **performance** of a **CPU** and a **high-end GPU**, over **seven real-world applications**

SAFARI

More on SIMD RAM

- Nastaran Hajinazar, Geraldo F. Oliveira, Sven Gregorio, Joao Dinis Ferreira, Nika Mansouri Ghiasi, Minesh Patel, Mohammed Alser, Saugata Ghose, Juan Gomez-Luna, and Onur Mutlu, [**"SIMDRAM: An End-to-End Framework for Bit-Serial SIMD Computing in DRAM"**](#) *Proceedings of the 26th International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS)*, Virtual, March-April 2021.
[[2-page Extended Abstract](#)]
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[[Talk Slides \(pptx\)](#) ([pdf](#))]
[[Short Talk Video](#) (5 mins)]
[[Full Talk Video](#) (27 mins)]

SIMDRAM: A Framework for Bit-Serial SIMD Processing using DRAM

*Nastaran Hajinazar ^{1,2}	*Geraldo F. Oliveira ¹	Sven Gregorio ¹	João Dinis Ferreira ¹
Nika Mansouri Ghiasi ¹	Minesh Patel ¹	Mohammed Alser ¹	Saugata Ghose ³
	Juan Gómez-Luna ¹	Onur Mutlu ¹	

¹ETH Zürich

²Simon Fraser University

³University of Illinois at Urbana–Champaign

In-DRAM Physical Unclonable Functions

- Jeremie S. Kim, Minesh Patel, Hasan Hassan, and Onur Mutlu,
"The DRAM Latency PUF: Quickly Evaluating Physical Unclonable Functions by Exploiting the Latency-Reliability Tradeoff in Modern DRAM Devices"
Proceedings of the 24th International Symposium on High-Performance Computer Architecture (HPCA), Vienna, Austria, February 2018.
[[Lightning Talk Video](#)]
[[Slides \(pptx\)](#)] [[pdf](#)] [[Lightning Session Slides \(pptx\)](#)] [[pdf](#)]
[[Full Talk Lecture Video](#) (28 minutes)]

The DRAM Latency PUF:

Quickly Evaluating Physical Unclonable Functions

by Exploiting the Latency-Reliability Tradeoff in Modern Commodity DRAM Devices

Jeremie S. Kim^{†§}

Minesh Patel[§]

Hasan Hassan[§]

Onur Mutlu^{§†}

[†]Carnegie Mellon University

[§]ETH Zürich

In-DRAM True Random Number Generation

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

Proceedings of the 25th International Symposium on High-Performance Computer Architecture (HPCA), Washington, DC, USA, February 2019.

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

[[Full Talk Video](#) (21 minutes)]

[[Full Talk Lecture Video](#) (27 minutes)]

Top Picks Honorable Mention by IEEE Micro.

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

Jeremie S. Kim^{‡§}

Minesh Patel[§]

Hasan Hassan[§]

Lois Orosa[§]

Onur Mutlu^{§‡}

[‡]Carnegie Mellon University

[§]ETH Zürich

In-DRAM True Random Number Generation

- Ataberk Olgun, Minesh Patel, A. Giray Yaglikci, Haocong Luo, Jeremie S. Kim, F. Nisa Bostanci, Nandita Vijaykumar, Oguz Ergin, and Onur Mutlu,
"QUAC-TRNG: High-Throughput True Random Number Generation Using Quadruple Row Activation in Commodity DRAM Chips"
Proceedings of the 48th International Symposium on Computer Architecture (ISCA), Virtual, June 2021.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Short Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (25 minutes)]
[[SAFARI Live Seminar Video](#) (1 hr 26 mins)]

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

Ataberk Olgun^{§†}

Minesh Patel[§]

A. Giray Yağlıkçı[§]

Haocong Luo[§]

Jeremie S. Kim[§]

F. Nisa Bostanci^{§†}

Nandita Vijaykumar^{§⊙}

Oğuz Ergin[†]

Onur Mutlu[§]

[§]ETH Zürich

[†]TOBB University of Economics and Technology

[⊙]University of Toronto

In-DRAM True Random Number Generation

- F. Nisa Bostanci, Ataberk Olgun, Lois Orosa, A. Giray Yaglikci, Jeremie S. Kim, Hasan Hassan, Oguz Ergin, and Onur Mutlu,

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

Proceedings of the 28th International Symposium on High-Performance Computer Architecture (HPCA), Virtual, April 2022.

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

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

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

F. Nisa Bostanci^{†§}

Ataberk Olgun^{†§}

Lois Orosa[§]

A. Giray Yağlıkçı[§]

Jeremie S. Kim[§]

Hasan Hassan[§]

Oğuz Ergin[†]

Onur Mutlu[§]

[†]*TOBB University of Economics and Technology*

[§]*ETH Zürich*

Processing in Memory: Adoption Challenges

1. Processing using Memory
2. Processing near Memory

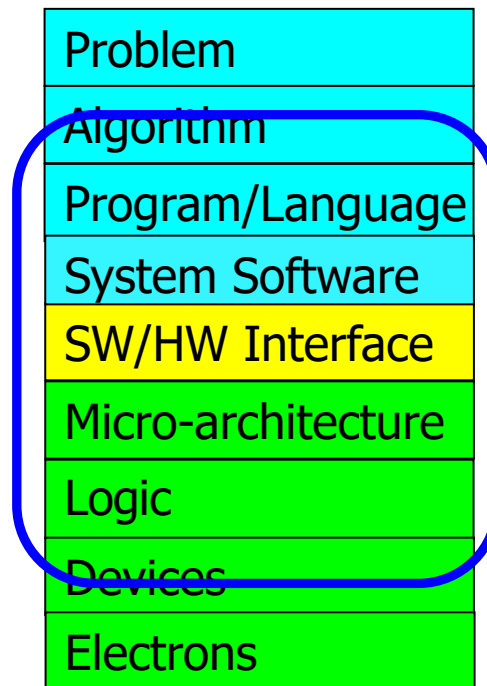
How to Enable Adoption of Processing in Memory

Potential Barriers to Adoption of PIM

1. **Applications & software** for PIM
2. Ease of **programming** (interfaces and compiler/HW support)
3. **System** and **security** support: coherence, synchronization, virtual memory, isolation, communication interfaces, ...
4. **Runtime** and **compilation** systems for adaptive scheduling, data mapping, access/sharing control, ...
5. **Infrastructures** to assess benefits and feasibility

All can be solved with change of mindset

We Need to Revisit the Entire Stack



We can get there step by step

Adoption: Accelerating Key Applications (I)

- Mohammed Alser, Zülal Bingöl, Damla Senol Cali, Jeremie Kim, Saugata Ghose, Can Alkan, and Onur Mutlu,
["Accelerating Genome Analysis: A Primer on an Ongoing Journey"](#)
[IEEE Micro \(IEEE MICRO\)](#), Vol. 40, No. 5, pages 65-75, September/October 2020.
[[Slides \(pptx\)\(pdf\)](#)]
[[Talk Video \(1 hour 2 minutes\)](#)]

Accelerating Genome Analysis: A Primer on an Ongoing Journey

Mohammed Alser

ETH Zürich

Zülal Bingöl

Bilkent University

Damla Senol Cali

Carnegie Mellon University

Jeremie Kim

ETH Zurich and Carnegie Mellon University

Saugata Ghose

University of Illinois at Urbana–Champaign and
Carnegie Mellon University

Can Alkan

Bilkent University

Onur Mutlu

ETH Zurich, Carnegie Mellon University, and
Bilkent University

Adoption: Accelerating Key Applications (II)

- Nika Mansouri Ghiasi, Jisung Park, Harun Mustafa, Jeremie Kim, Ataberk Olgun, Arvid Gollwitzer, Damla Senol Cali, Can Firtina, Haiyu Mao, Nour Almadhoun Alserr, Rachata Ausavarungnirun, Nandita Vijaykumar, Mohammed Alser, and Onur Mutlu,
"GenStore: A High-Performance and Energy-Efficient In-Storage Computing System for Genome Sequence Analysis"
Proceedings of the 27th International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS), Virtual, February-March 2022.
[[Lightning Talk Slides \(pptx\)](#)] ([pdf](#))
[[Lightning Talk Video](#) (90 seconds)]

GenStore: A High-Performance In-Storage Processing System for Genome Sequence Analysis

Nika Mansouri Ghiasi¹ Jisung Park¹ Harun Mustafa¹ Jeremie Kim¹ Ataberk Olgun¹
Arvid Gollwitzer¹ Damla Senol Cali² Can Firtina¹ Haiyu Mao¹ Nour Almadhoun Alserr¹
Rachata Ausavarungnirun³ Nandita Vijaykumar⁴ Mohammed Alser¹ Onur Mutlu¹

¹ETH Zürich ²Bionano Genomics ³KMUTNB ⁴University of Toronto

Adoption: Accelerating Key Applications (III)

- Junwhan Ahn, Sungpack Hong, Sungjoo Yoo, Onur Mutlu, and Kiyoun Choi,
"A Scalable Processing-in-Memory Accelerator for Parallel Graph Processing"
Proceedings of the 42nd International Symposium on Computer Architecture (ISCA), Portland, OR, June 2015.
[Slides (pdf)] [Lightning Session Slides (pdf)]

A Scalable Processing-in-Memory Accelerator for Parallel Graph Processing

Junwhan Ahn Sungpack Hong[§] Sungjoo Yoo Onur Mutlu[†] Kiyoun Choi
junwhan@snu.ac.kr, sungpack.hong@oracle.com, sungjoo.yoo@gmail.com, onur@cmu.edu, kchoi@snu.ac.kr

Seoul National University [§]Oracle Labs [†]Carnegie Mellon University

Adoption: Accelerating Key Applications (IV)

- Maciej Besta, Raghavendra Kanakagiri, Grzegorz Kwasniewski, Rachata Ausavarungnirun, Jakub Beránek, Konstantinos Kanellopoulos, Kacper Janda, Zur Vonarburg-Shmaria, Lukas Gianinazzi, Ioana Stefan, Juan Gómez-Luna, Marcin Copik, Lukas Kapp-Schwoerer, Salvatore Di Girolamo, Nils Blach, Marek Konieczny, Onur Mutlu, and Torsten Hoefler,

"SISA: Set-Centric Instruction Set Architecture for Graph Mining on Processing-in-Memory Systems"

Proceedings of the 54th International Symposium on Microarchitecture (MICRO), Virtual, October 2021.

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

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

[[Lightning Talk Video](#) (1.5 minutes)]

[[Full arXiv version](#)]

SISA: Set-Centric Instruction Set Architecture for Graph Mining on Processing-in-Memory Systems

Maciej Besta¹, Raghavendra Kanakagiri², Grzegorz Kwasniewski¹, Rachata Ausavarungnirun³, Jakub Beránek⁴, Konstantinos Kanellopoulos¹, Kacper Janda⁵, Zur Vonarburg-Shmaria¹, Lukas Gianinazzi¹, Ioana Stefan¹, Juan Gómez-Luna¹, Marcin Copik¹, Lukas Kapp-Schwoerer¹, Salvatore Di Girolamo¹, Nils Blach¹, Marek Konieczny⁵, Onur Mutlu¹, Torsten Hoefler¹

¹ETH Zurich, Switzerland
Thailand

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³King Mongkut's University of Technology North Bangkok,
⁴Technical University of Ostrava, Czech Republic

⁵AGH-UST, Poland

Adoption: Accelerating Key Applications (V)

- Amirali Boroumand, Saugata Ghose, Berkin Akin, Ravi Narayanaswami, Geraldo F. Oliveira, Xiaoyu Ma, Eric Shiu, and Onur Mutlu,
"Google Neural Network Models for Edge Devices: Analyzing and Mitigating Machine Learning Inference Bottlenecks"
Proceedings of the 30th International Conference on Parallel Architectures and Compilation Techniques (PACT), Virtual, September 2021.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (14 minutes)]

Google Neural Network Models for Edge Devices: Analyzing and Mitigating Machine Learning Inference Bottlenecks

Amirali Boroumand^{†◇}

Geraldo F. Oliveira^{*}

Saugata Ghose[‡]

Xiaoyu Ma[§]

Berkin Akin[§]

Eric Shiu[§]

Ravi Narayanaswami[§]

Onur Mutlu^{*†}

[†]*Carnegie Mellon Univ.*

[◇]*Stanford Univ.*

[‡]*Univ. of Illinois Urbana-Champaign*

[§]*Google*

^{*}*ETH Zürich*

Adoption: Accelerating Key Applications (VI)

- Gagandeep Singh, Dionysios Diamantopoulos, Christoph Hagleitner, Juan Gómez-Luna, Sander Stuijk, Onur Mutlu, and Henk Corporaal,

"NERO: A Near High-Bandwidth Memory Stencil Accelerator for Weather Prediction Modeling"

Proceedings of the 30th International Conference on Field-Programmable Logic and Applications (FPL), Gothenburg, Sweden, September 2020.

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

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

[[Talk Video](#) (23 minutes)]

Nominated for the Stamatis Vassiliadis Memorial Award.

NERO: A Near High-Bandwidth Memory Stencil Accelerator for Weather Prediction Modeling

Gagandeep Singh^{a,b,c}

Dionysios Diamantopoulos^c

Christoph Hagleitner^c

Juan Gómez-Luna^b

Sander Stuijk^a

Onur Mutlu^b

Henk Corporaal^a

^aEindhoven University of Technology

^bETH Zürich

^cIBM Research Europe, Zurich

Adoption: Accelerating Key Applications (VII)

- Ivan Fernandez, Ricardo Quisiant, Christina Giannoula, Mohammed Alser, Juan Gómez-Luna, Eladio Gutiérrez, Oscar Plata, and Onur Mutlu,
"NATSA: A Near-Data Processing Accelerator for Time Series Analysis"
Proceedings of the 38th IEEE International Conference on Computer Design (ICCD), Virtual, October 2020.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (10 minutes)]
[[Source Code](#)]

NATSA: A Near-Data Processing Accelerator for Time Series Analysis

Ivan Fernandez[§]

Ricardo Quisiant[§]

Christina Giannoula[†]

Mohammed Alser[‡]

Juan Gómez-Luna[‡]

Eladio Gutiérrez[§]

Oscar Plata[§]

Onur Mutlu[‡]

[§]*University of Malaga*

[†]*National Technical University of Athens*

[‡]*ETH Zürich*

Adoption: Accelerating Key Applications (VIII)

- Damla Senol Cali, Gurpreet S. Kalsi, Zulal Bingol, Can Firtina, Lavanya Subramanian, Jeremie S. Kim, Rachata Ausavarungnirun, Mohammed Alser, Juan Gomez-Luna, Amirali Boroumand, Anant Nori, Allison Scibisz, Sreenivas Subramoney, Can Alkan, Saugata Ghose, and Onur Mutlu, **"GenASM: A High-Performance, Low-Power Approximate String Matching Acceleration Framework for Genome Sequence Analysis"**
Proceedings of the 53rd International Symposium on Microarchitecture (MICRO), Virtual, October 2020.
[[Lighting Talk Video](#) (1.5 minutes)]
[[Lightning Talk Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (18 minutes)]
[[Slides \(pptx\)](#) ([pdf](#))]

GenASM: A High-Performance, Low-Power Approximate String Matching Acceleration Framework for Genome Sequence Analysis

Damla Senol Cali[†]✕ Gurpreet S. Kalsi[✕] Zülal Bingöl[▽] Can Firtina[◇] Lavanya Subramanian[‡] Jeremie S. Kim[◇]†
Rachata Ausavarungnirun[○] Mohammed Alser[◇] Juan Gomez-Luna[◇] Amirali Boroumand[†] Anant Nori[✕]
Allison Scibisz[†] Sreenivas Subramoney[✕] Can Alkan[▽] Saugata Ghose^{*†} Onur Mutlu[◇]†[▽]
[†]Carnegie Mellon University [✕]Processor Architecture Research Lab, Intel Labs [▽]Bilkent University [◇]ETH Zürich
[‡]Facebook [○]King Mongkut's University of Technology North Bangkok ^{*}University of Illinois at Urbana-Champaign

Adoption: Accelerating Key Applications (IX)

- Damla Senol Cali, Konstantinos Kanellopoulos, Joel Lindegger, Zülal Bingöl, Gurpreet S. Kalsi, Ziyi Zuo, Can Firtina, Meryem Banu Cavlak, Jeremie Kim, Nika Mansouri Ghiasi, Gagandeep Singh, Juan Gomez-Luna, Nour Almadhoun Alserr, Mohammed Alser, Sreenivas Subramoney, Can Alkan, Saugata Ghose, and Onur Mutlu,
"SeGraM: A Universal Hardware Accelerator for Genomic Sequence-to-Graph and Sequence-to-Sequence Mapping"
Proceedings of the 49th International Symposium on Computer Architecture (ISCA), New York, June 2022.
[[arXiv version](#)]

SeGraM: A Universal Hardware Accelerator for Genomic Sequence-to-Graph and Sequence-to-Sequence Mapping

Damla Senol Cali¹ Konstantinos Kanellopoulos² Joël Lindegger² Zülal Bingöl³
Gurpreet S. Kalsi⁴ Ziyi Zuo⁵ Can Firtina² Meryem Banu Cavlak² Jeremie Kim²
Nika Mansouri Ghiasi² Gagandeep Singh² Juan Gómez-Luna² Nour Almadhoun Alserr²
Mohammed Alser² Sreenivas Subramoney⁴ Can Alkan³ Saugata Ghose⁶ Onur Mutlu²

¹Bionano Genomics ²ETH Zürich ³Bilkent University ⁴Intel Labs

⁵Carnegie Mellon University ⁶University of Illinois Urbana-Champaign

Adoption: Accelerating Key Applications (X)

- Amirali Boroumand, Saugata Ghose, Geraldo F. Oliveira, and Onur Mutlu,
"Polynesia: Enabling High-Performance and Energy-Efficient Hybrid Transactional/Analytical Databases with Hardware/Software Co-Design"
Proceedings of the 38th International Conference on Data Engineering (ICDE),
Virtual, May 2022.
[[arXiv version](#)]
[[Slides \(pptx\)](#) ([pdf](#))]
[[Short Talk Slides \(pptx\)](#) ([pdf](#))]

Polynesia: Enabling High-Performance and Energy-Efficient Hybrid Transactional/Analytical Databases with Hardware/Software Co-Design

Amirali Boroumand[†] Saugata Ghose[◇] Geraldo F. Oliveira[‡] Onur Mutlu[‡]
[†]*Google* [◇]*Univ. of Illinois Urbana-Champaign* [‡]*ETH Zürich*

Adoption: How to Keep It Simple?

- Junwhan Ahn, Sungjoo Yoo, Onur Mutlu, and Kiyoungh Choi, **"PIM-Enabled Instructions: A Low-Overhead, Locality-Aware Processing-in-Memory Architecture"** *Proceedings of the 42nd International Symposium on Computer Architecture (ISCA)*, Portland, OR, June 2015.
[[Slides \(pdf\)](#)] [[Lightning Session Slides \(pdf\)](#)]

PIM-Enabled Instructions: A Low-Overhead, Locality-Aware Processing-in-Memory Architecture

Junwhan Ahn Sungjoo Yoo Onur Mutlu[†] Kiyoungh Choi

junwhan@snu.ac.kr, sungjoo.yoo@gmail.com, onur@cmu.edu, kchoi@snu.ac.kr

Seoul National University

[†]Carnegie Mellon University

Adoption: How to Maintain Coherence? (I)

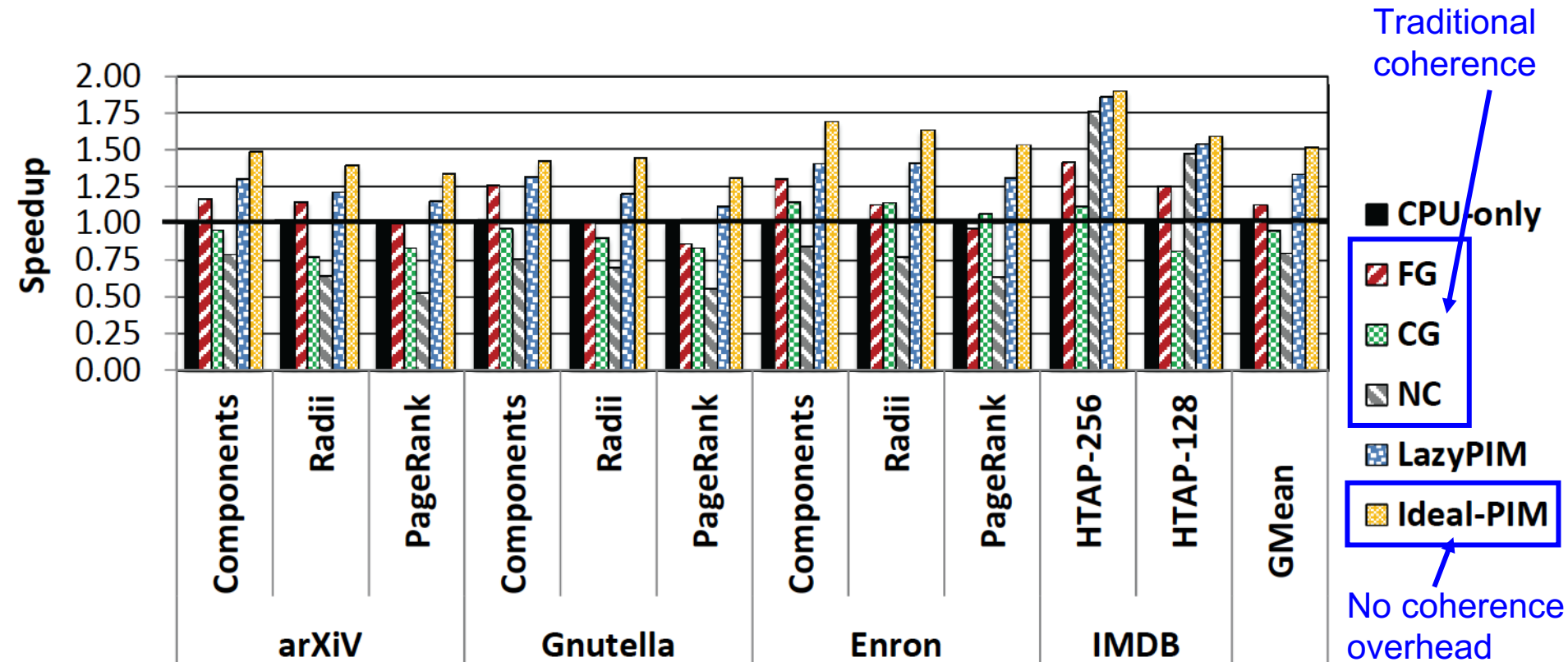
- Amirali Boroumand, Saugata Ghose, Minesh Patel, Hasan Hassan, Brandon Lucia, Kevin Hsieh, Krishna T. Malladi, Hongzhong Zheng, and Onur Mutlu,
"**LazyPIM: An Efficient Cache Coherence Mechanism for Processing-in-Memory**"
IEEE Computer Architecture Letters (**CAL**), June 2016.

LazyPIM: An Efficient Cache Coherence Mechanism for Processing-in-Memory

Amirali Boroumand[†], Saugata Ghose[†], Minesh Patel[†], Hasan Hassan^{†§}, Brandon Lucia[†],
Kevin Hsieh[†], Krishna T. Malladi^{*}, Hongzhong Zheng^{*}, and Onur Mutlu^{††}

[†]Carnegie Mellon University ^{*}Samsung Semiconductor, Inc. [§]TOBB ETÜ [‡]ETH Zürich

Challenge: Coherence for Hybrid CPU-PIM Apps



Adoption: How to Maintain Coherence? (II)

- Amirali Boroumand, Saugata Ghose, Minesh Patel, Hasan Hassan, Brandon Lucia, Kevin Hsieh, Krishna T. Malladi, Hongzhong Zheng, and Onur Mutlu,
"CoNDA: Efficient Cache Coherence Support for Near-Data Accelerators"

Proceedings of the 46th International Symposium on Computer Architecture (ISCA), Phoenix, AZ, USA, June 2019.

CoNDA: Efficient Cache Coherence Support for Near-Data Accelerators

Amirali Boroumand[†]

Saugata Ghose[†]

Minesh Patel[★]

Hasan Hassan[★]

Brandon Lucia[†]

Rachata Ausavarungnirun^{†‡}

Kevin Hsieh[†]

Nastaran Hajinazar^{◇†}

Krishna T. Malladi[§]

Hongzhong Zheng[§]

Onur Mutlu^{★†}

[†]Carnegie Mellon University

[★]ETH Zürich

[‡]KMUTNB

[◇]Simon Fraser University

[§]Samsung Semiconductor, Inc.

Adoption: How to Support Synchronization?

- Christina Giannoula, Nandita Vijaykumar, Nikela Papadopoulou, Vasileios Karakostas, Ivan Fernandez, Juan Gómez-Luna, Lois Orosa, Nectarios Koziris, Georgios Goumas, Onur Mutlu, **"SynCron: Efficient Synchronization Support for Near-Data-Processing Architectures"**
Proceedings of the 27th International Symposium on High-Performance Computer Architecture (HPCA), Virtual, February-March 2021.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Short Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (21 minutes)]
[[Short Talk Video](#) (7 minutes)]

SynCron: Efficient Synchronization Support for Near-Data-Processing Architectures

Christina Giannoula^{†‡} Nandita Vijaykumar^{*‡} Nikela Papadopoulou[†] Vasileios Karakostas[†] Ivan Fernandez^{§‡}
Juan Gómez-Luna[‡] Lois Orosa[‡] Nectarios Koziris[†] Georgios Goumas[†] Onur Mutlu[‡]
[†]*National Technical University of Athens* [‡]*ETH Zürich* ^{*}*University of Toronto* [§]*University of Malaga*

Adoption: How to Support Virtual Memory?

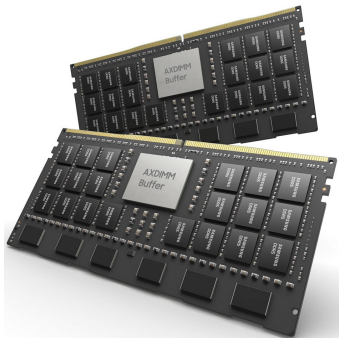
- Kevin Hsieh, Samira Khan, Nandita Vijaykumar, Kevin K. Chang, Amirali Boroumand, Saugata Ghose, and Onur Mutlu,
["Accelerating Pointer Chasing in 3D-Stacked Memory: Challenges, Mechanisms, Evaluation"](#)
Proceedings of the 34th IEEE International Conference on Computer Design (ICCD), Phoenix, AZ, USA, October 2016.

Accelerating Pointer Chasing in 3D-Stacked Memory: Challenges, Mechanisms, Evaluation

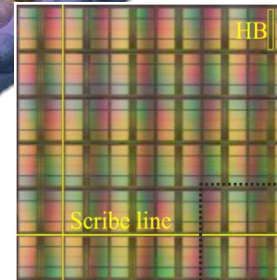
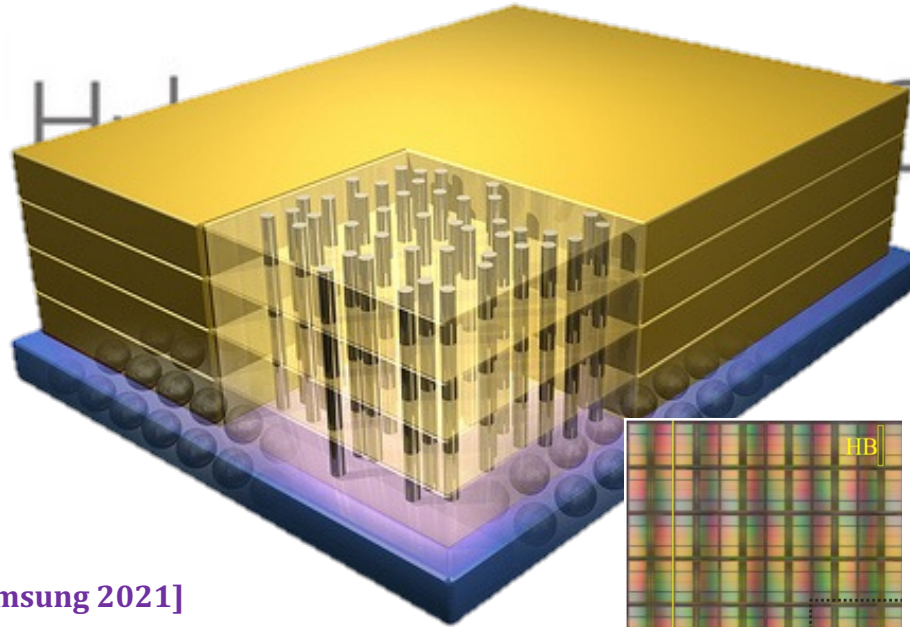
Kevin Hsieh[†] Samira Khan[‡] Nandita Vijaykumar[†]
Kevin K. Chang[†] Amirali Boroumand[†] Saugata Ghose[†] Onur Mutlu^{§†}
[†]Carnegie Mellon University [‡]University of Virginia [§]ETH Zürich

Processing-in-Memory in the Real World

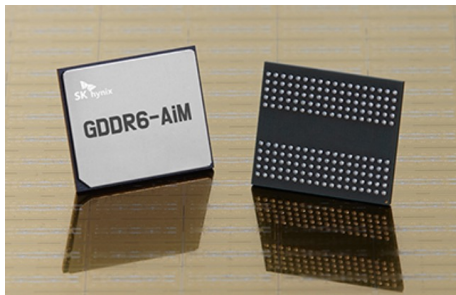
Processing-in-Memory Landscape Today



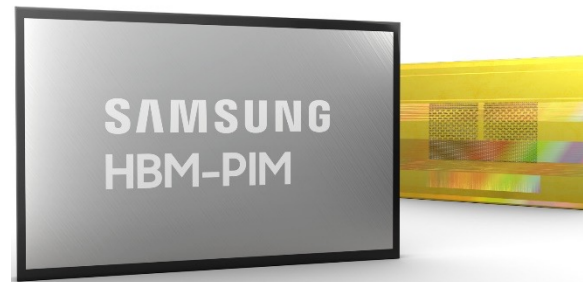
[Samsung 2021]



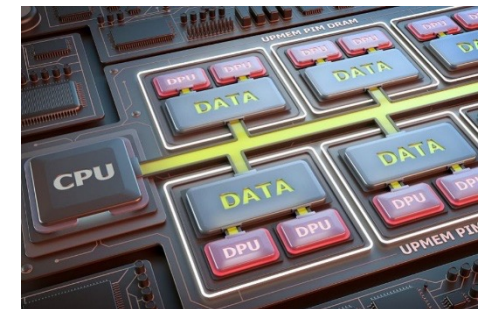
[Alibaba 2022]



[SK Hynix 2022]



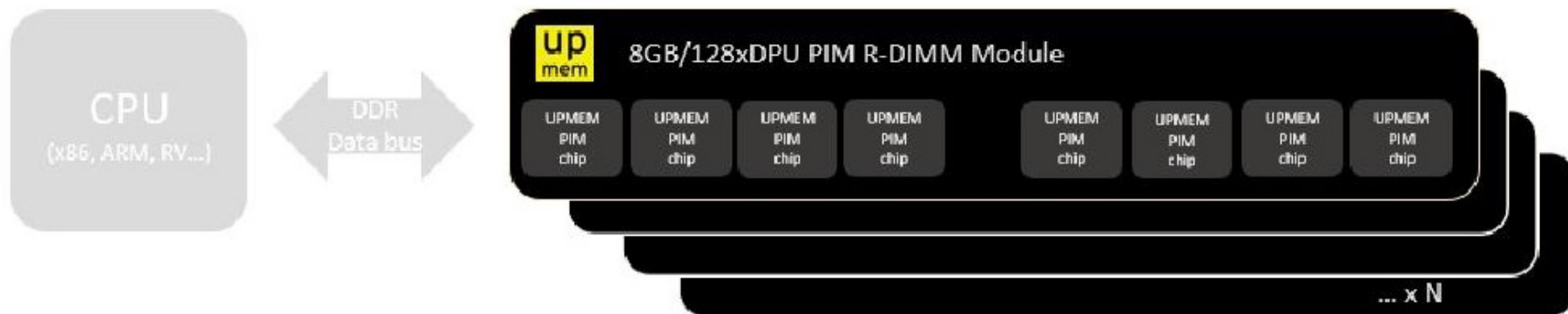
[Samsung 2021]



[UPMEM 2019]

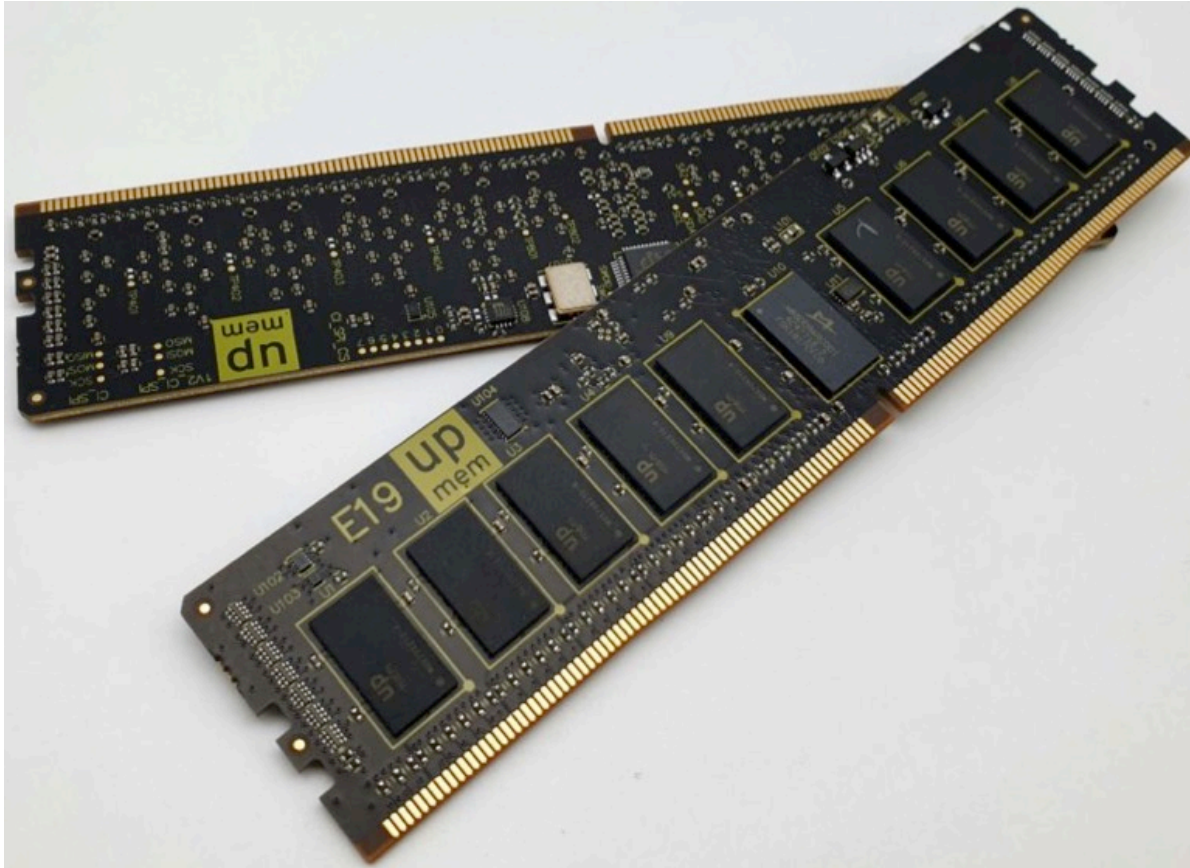
UPMEM Processing-in-DRAM Engine (2019)

- **Processing in DRAM Engine**
- Includes **standard DIMM modules**, with a **large number of DPU processors** combined with DRAM chips.
- Replaces **standard DIMMs**
 - DDR4 R-DIMM modules
 - 8GB+128 DPUs (16 PIM chips)
 - Standard 2x-nm DRAM process
 - **Large amounts of** compute & memory bandwidth

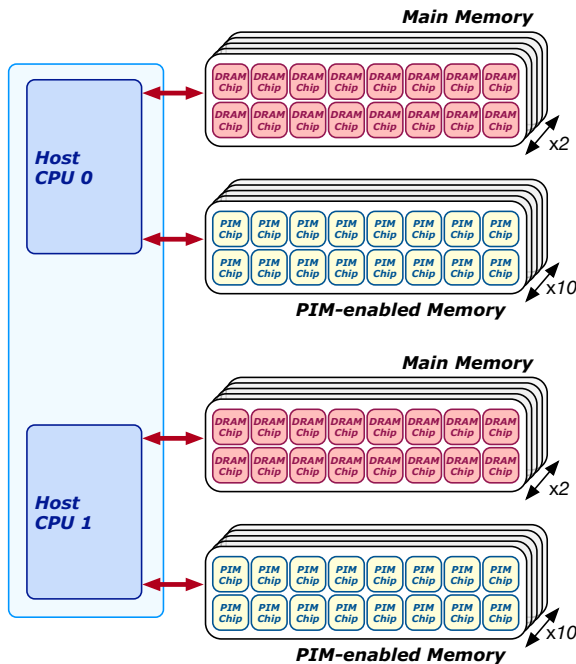


UPMEM Memory Modules

- E19: 8 chips DIMM (1 rank). DPUs @ 267 MHz
- P21: 16 chips DIMM (2 ranks). DPUs @ 350 MHz



2,560-DPU Processing-in-Memory System



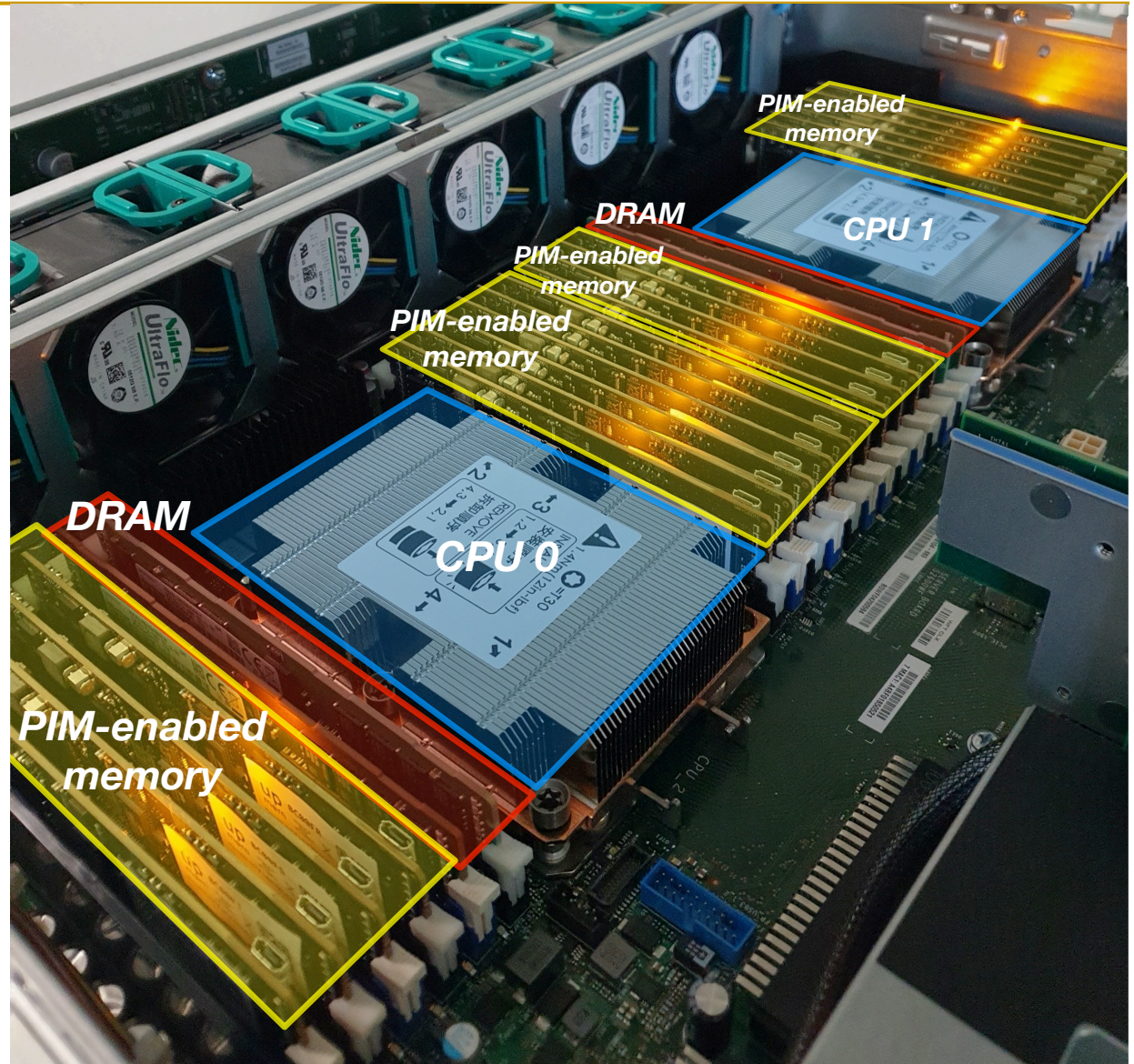
Benchmarking a New Paradigm: An Experimental Analysis of a Real Processing-in-Memory Architecture

JUAN GÓMEZ-LUNA, ETH Zürich, Switzerland
 IZZAT EL HAJJ, American University of Beirut, Lebanon
 IVAN FERNANDEZ, ETH Zürich, Switzerland and University of Malaga, Spain
 CHRISTINA GIANNOULA, ETH Zürich, Switzerland and NTUA, Greece
 GERALDO F. OLIVEIRA, ETH Zürich, Switzerland
 ONUR MUTLU, ETH Zürich, Switzerland

Many modern workloads, such as neural networks, databases, and graph processing, are fundamentally memory-bound. For such workloads, the data movement between main memory and CPU cores imposes a significant overhead in terms of both latency and energy. A major reason is that this communication happens through a narrow bus with high latency and limited bandwidth, and the low data reuse in memory-bound workloads is insufficient to amortize the cost of main memory access. Fundamentally addressing this *data movement bottleneck* requires a paradigm where the memory system assumes an active role in computing by integrating processing capabilities. This paradigm is known as *processing-in-memory (PIM)*.

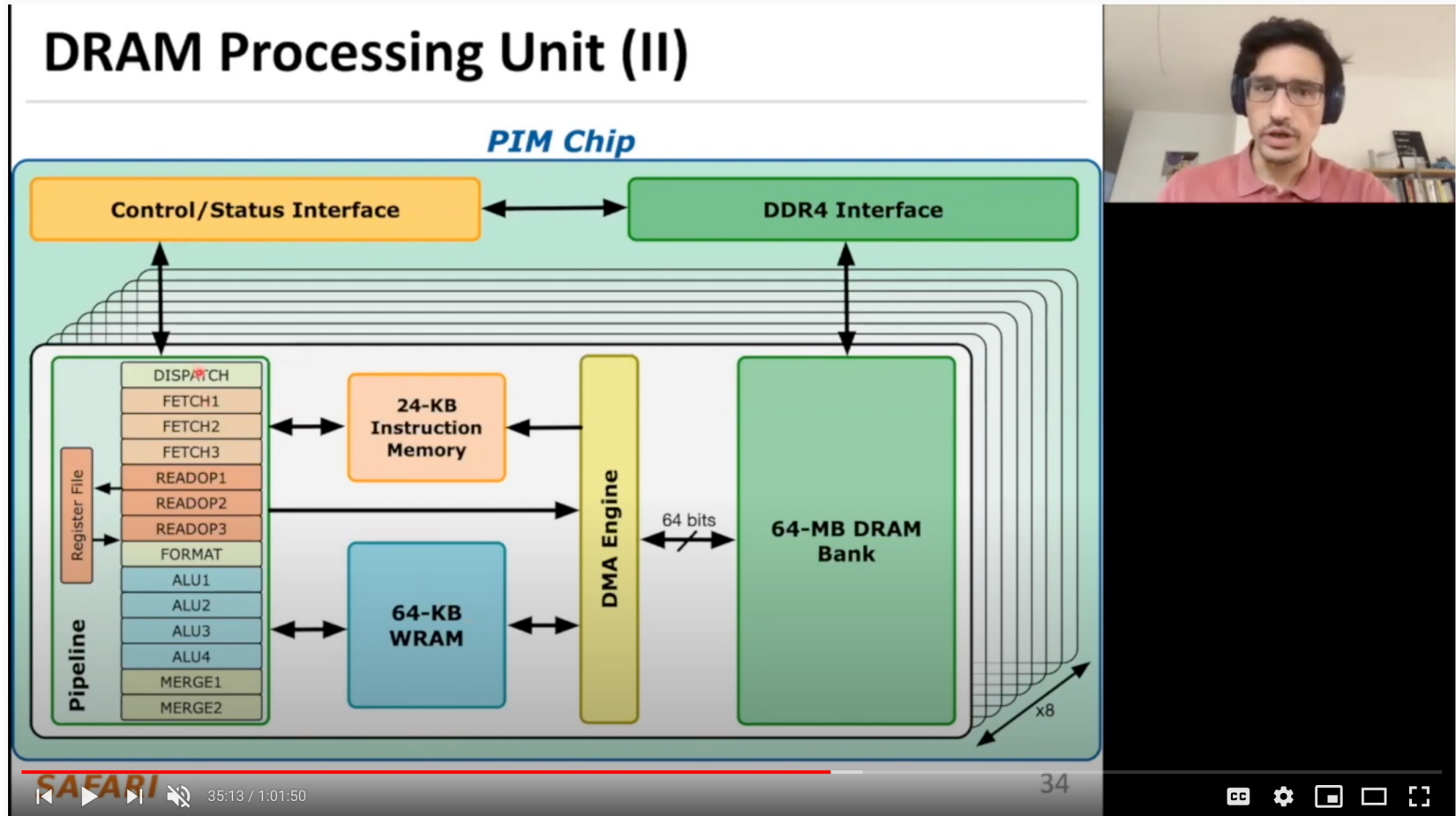
Recent research explores different forms of PIM architectures, motivated by the emergence of new 3D-stacked memory technologies that integrate memory with a logic layer where processing elements can be easily placed. Past works evaluate these architectures in simulation or, at best, with simplified hardware prototypes. In contrast, the UPMEM company has designed and manufactured the first publicly-available real-world PIM architecture. The UPMEM PIM architecture combines traditional DRAM memory arrays with general-purpose in-order cores, called *DRAM Processing Units (DPUs)*, integrated in the same chip.

This paper provides the first comprehensive analysis of the first publicly-available real-world PIM architecture. We make two key contributions. First, we conduct an experimental characterization of the UPMEM-based PIM system using microbenchmarks to assess various architecture limits such as compute throughput and memory bandwidth, yielding new insights. Second, we present *PrIM (Processing-In-Memory benchmarks)*, a benchmark suite of 16 workloads from different application domains (e.g., dense/sparse linear algebra, databases, data analytics, graph processing, neural networks, bioinformatics, image processing), which we identify as memory-bound. We evaluate the performance and scaling characteristics of PrIM benchmarks on the UPMEM PIM architecture, and compare their performance and energy consumption to their state-of-the-art CPU and GPU counterparts. Our extensive evaluation conducted on two real UPMEM-based PIM systems with 640 and 2,560 DPUs provides new insights about suitability of different workloads to the PIM system, programming recommendations for software designers, and suggestions and hints for hardware and architecture designers of future PIM systems.



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

More on the UPMEM PIM System



ETH ZÜRICH HAUPTGEBÄUDE

Computer Architecture - Lecture 12d: Real Processing-in-DRAM with UPMEM (ETH Zürich, Fall 2020)

1,120 views • Oct 31, 2020

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Onur Mutlu Lectures
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ANALYTICS

EDIT VIDEO

<https://www.youtube.com/watch?v=Sscy1Wrr22A&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=26>

Experimental Analysis of the UPMEM PIM Engine

Benchmarking a New Paradigm: An Experimental Analysis of a Real Processing-in-Memory Architecture

JUAN GÓMEZ-LUNA, ETH Zürich, Switzerland

IZZAT EL HAJJ, American University of Beirut, Lebanon

IVAN FERNANDEZ, ETH Zürich, Switzerland and University of Malaga, Spain

CHRISTINA GIANNOULA, ETH Zürich, Switzerland and NTUA, Greece

GERALDO F. OLIVEIRA, ETH Zürich, Switzerland

ONUR MUTLU, ETH Zürich, Switzerland

Many modern workloads, such as neural networks, databases, and graph processing, are fundamentally memory-bound. For such workloads, the data movement between main memory and CPU cores imposes a significant overhead in terms of both latency and energy. A major reason is that this communication happens through a narrow bus with high latency and limited bandwidth, and the low data reuse in memory-bound workloads is insufficient to amortize the cost of main memory access. Fundamentally addressing this *data movement bottleneck* requires a paradigm where the memory system assumes an active role in computing by integrating processing capabilities. This paradigm is known as *processing-in-memory* (PIM).

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UPMEM PIM System Summary & Analysis

- Juan Gomez-Luna, Izzat El Hajj, Ivan Fernandez, Christina Giannoula, Geraldo F. Oliveira, and Onur Mutlu,
"Benchmarking Memory-Centric Computing Systems: Analysis of Real Processing-in-Memory Hardware"
*Invited Paper at Workshop on Computing with Unconventional Technologies (**CUT**), Virtual, October 2021.*
[[arXiv version](#)]
[[PrIM Benchmarks Source Code](#)]
[[Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (37 minutes)]
[[Lightning Talk Video](#) (3 minutes)]

Benchmarking Memory-Centric Computing Systems: Analysis of Real Processing-in-Memory Hardware

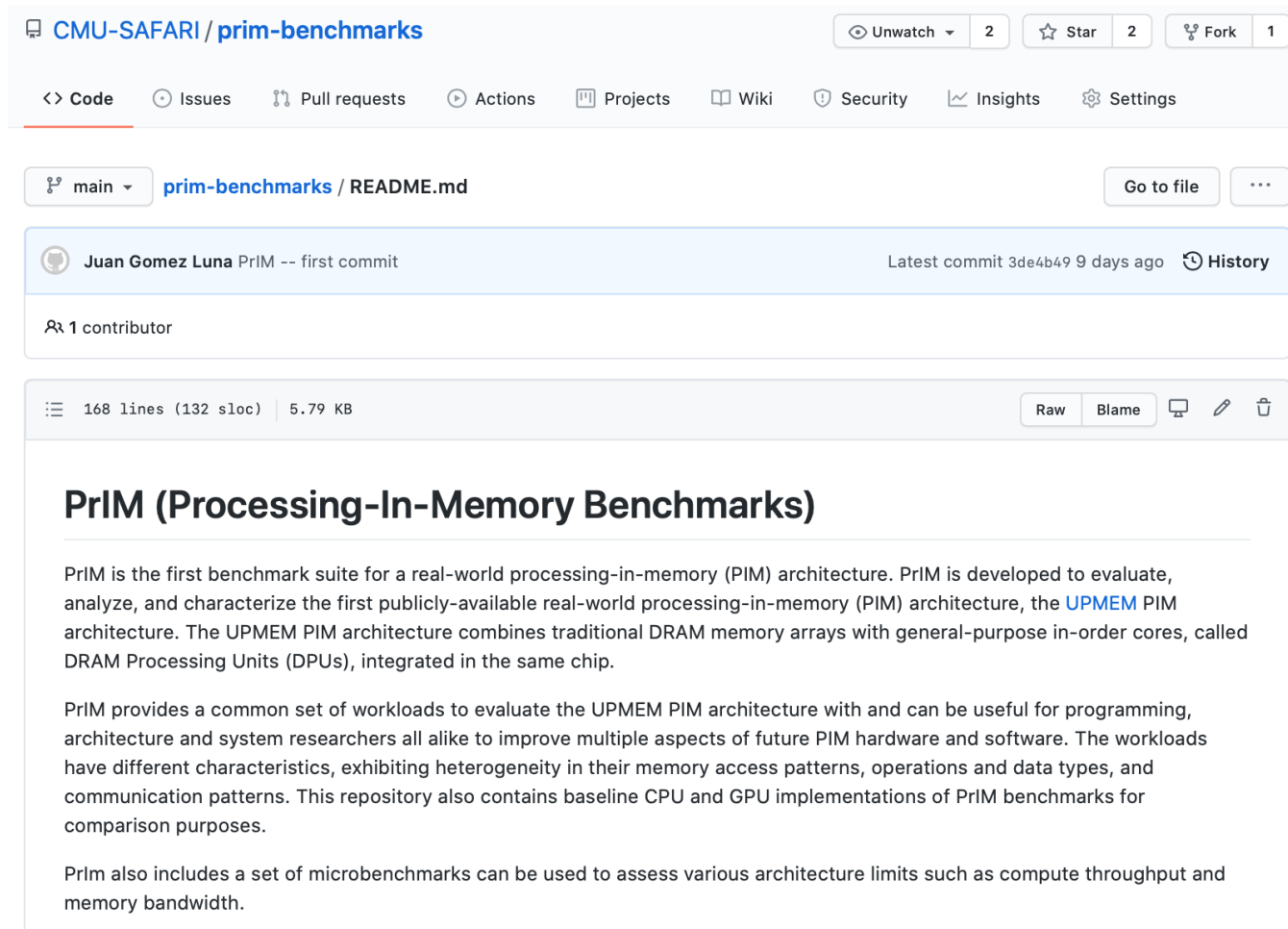
Juan Gómez-Luna	Izzat El Hajj	Ivan Fernandez	Christina Giannoula	Geraldo F. Oliveira	Onur Mutlu
<i>ETH Zürich</i>	<i>American University of Beirut</i>	<i>University of Malaga</i>	<i>National Technical University of Athens</i>	<i>ETH Zürich</i>	<i>ETH Zürich</i>

PrIM Benchmarks: Application Domains

Domain	Benchmark	Short name
Dense linear algebra	Vector Addition	VA
	Matrix-Vector Multiply	GEMV
Sparse linear algebra	Sparse Matrix-Vector Multiply	SpMV
Databases	Select	SEL
	Unique	UNI
Data analytics	Binary Search	BS
	Time Series Analysis	TS
Graph processing	Breadth-First Search	BFS
Neural networks	Multilayer Perceptron	MLP
Bioinformatics	Needleman-Wunsch	NW
Image processing	Image histogram (short)	HST-S
	Image histogram (large)	HST-L
Parallel primitives	Reduction	RED
	Prefix sum (scan-scan-add)	SCAN-SSA
	Prefix sum (reduce-scan-scan)	SCAN-RSS
	Matrix transposition	TRNS

PrIM Benchmarks are Open Source

- All microbenchmarks, benchmarks, and scripts
- <https://github.com/CMU-SAFARI/prim-benchmarks>



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Juan Gomez Luna PrIM -- first commit Latest commit 3de4b49 9 days ago History

1 contributor

168 lines (132 sloc) 5.79 KB Raw Blame

PrIM (Processing-In-Memory Benchmarks)

PrIM is the first benchmark suite for a real-world processing-in-memory (PIM) architecture. PrIM is developed to evaluate, analyze, and characterize the first publicly-available real-world processing-in-memory (PIM) architecture, the [UPMEM](#) PIM architecture. The UPMEM PIM architecture combines traditional DRAM memory arrays with general-purpose in-order cores, called DRAM Processing Units (DPUs), integrated in the same chip.

PrIM provides a common set of workloads to evaluate the UPMEM PIM architecture with and can be useful for programming, architecture and system researchers all alike to improve multiple aspects of future PIM hardware and software. The workloads have different characteristics, exhibiting heterogeneity in their memory access patterns, operations and data types, and communication patterns. This repository also contains baseline CPU and GPU implementations of PrIM benchmarks for comparison purposes.

PrIM also includes a set of microbenchmarks can be used to assess various architecture limits such as compute throughput and memory bandwidth.

Understanding a Modern PIM Architecture

Benchmarking a New Paradigm: Experimental Analysis and Characterization of a Real Processing-in-Memory System

**JUAN GÓMEZ-LUNA¹, IZZAT EL HAJJ², IVAN FERNANDEZ^{1,3}, CHRISTINA GIANNOULA^{1,4},
GERALDO F. OLIVEIRA¹, AND ONUR MUTLU¹**

¹ETH Zürich

²American University of Beirut

³University of Malaga

⁴National Technical University of Athens

Corresponding author: Juan Gómez-Luna (e-mail: juang@ethz.ch).

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

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

Understanding a Modern PIM Architecture



The video player shows a seminar titled "Understanding a Modern Processing-in-Memory Architecture: Benchmarking and Experimental Characterization". The speaker is Juan Gómez Luna, with co-speakers Izzat El Hajj, Ivan Fernandez, Christina Giannoula, Geraldo F. Oliveira, and Onur Mutlu. The video includes links to an arXiv paper and a GitHub repository. The player interface shows a progress bar at 2:26 / 2:57:10, and the video is from the channel "Onur Mutlu Lectures" with 18.7K subscribers. The video has 2,579 views and was streamed live on Jul 12, 2021. The video player includes standard controls like play, pause, and volume, as well as social media sharing options.

Understanding a Modern Processing-in-Memory Architecture: Benchmarking and Experimental Characterization

Juan Gómez Luna, Izzat El Hajj,
Ivan Fernandez, Christina Giannoula,
Geraldo F. Oliveira, Onur Mutlu

<https://arxiv.org/pdf/2105.03814.pdf>
<https://github.com/CMU-SAFARI/prim-benchmarks>

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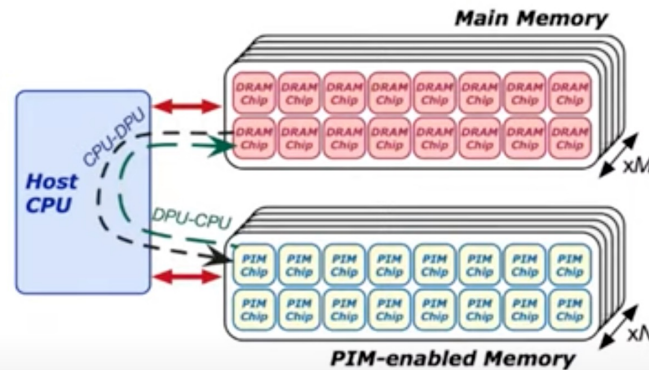
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More on Analysis of the UPMEM PIM Engine

Inter-DPU Communication

- There is **no direct communication channel between DPUs**



- Inter-DPU communication takes place via the host CPU using CPU-DPU and DPU-CPU transfers
- Example communication patterns:
 - Merging of partial results to obtain the final result
 - Only DPU-CPU transfers
 - Redistribution of intermediate results for further computation
 - DPU-CPU transfers and CPU-DPU transfers



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Talk Title: Understanding a Modern Processing-in-Memory Architecture: Benchmarking and Experimental Characterization
Dr. Juan Gómez-Luna, SAFARI Research Group, D-ITET, ETH Zurich

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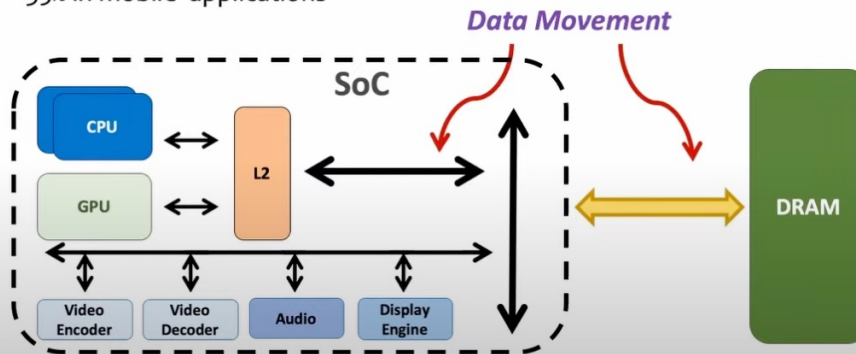
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More on Analysis of the UPMEM PIM Engine

Data Movement in Computing Systems

- **Data movement** dominates **performance** and is a major system **energy bottleneck**
- **Total system energy**: data movement accounts for
 - 62% in consumer applications*,
 - 40% in scientific applications*,
 - 35% in mobile applications*



* Boroumand et al., "Google Workloads for Consumer Devices: Mitigating Data Movement Bottlenecks," ASPLOS 2018

* Kestor et al., "Quantifying the Energy Cost of Data Movement in Scientific Applications," IISWC 2013

* Pandiyan and Wu, "Quantifying the energy cost of data movement for emerging smart phone workloads on mobile platforms," IISWC 2014

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3

Understanding a Modern Processing-in-Memory Arch: Benchmarking & Experimental Characterization; 21m

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More on PRIM Benchmarks

- Juan Gomez-Luna, Izzat El Hajj, Ivan Fernandez, Christina Giannoula, Geraldo F. Oliveira, and Onur Mutlu,
"Benchmarking a New Paradigm: An Experimental Analysis of a Real Processing-in-Memory Architecture"

*Preprint in **arXiv**, 9 May 2021.*

[[arXiv preprint](#)]

[[PrIM Benchmarks Source Code](#)]

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

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

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UPMEM PIM System Summary & Analysis

- Juan Gomez-Luna, Izzat El Hajj, Ivan Fernandez, Christina Giannoula, Geraldo F. Oliveira, and Onur Mutlu,
"Benchmarking Memory-Centric Computing Systems: Analysis of Real Processing-in-Memory Hardware"
*Invited Paper at Workshop on Computing with Unconventional Technologies (**CUT**), Virtual, October 2021.*
[[arXiv version](#)]
[[PrIM Benchmarks Source Code](#)]
[[Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (37 minutes)]
[[Lightning Talk Video](#) (3 minutes)]

Benchmarking Memory-Centric Computing Systems: Analysis of Real Processing-in-Memory Hardware

Juan Gómez-Luna
ETH Zürich

Izzat El Hajj
*American University
of Beirut*

Ivan Fernandez
*University
of Malaga*

Christina Giannoula
*National Technical
University of Athens*

Geraldo F. Oliveira
ETH Zürich

Onur Mutlu
ETH Zürich

FPGA-based Processing Near Memory

- Gagandeep Singh, Mohammed Alser, Damla Senol Cali, Dionysios Diamantopoulos, Juan Gómez-Luna, Henk Corporaal, and Onur Mutlu, ["FPGA-based Near-Memory Acceleration of Modern Data-Intensive Applications"](#) *IEEE Micro* (**IEEE MICRO**), to appear, 2021.

FPGA-based Near-Memory Acceleration of Modern Data-Intensive Applications

Gagandeep Singh[◇] Mohammed Alser[◇] Damla Senol Cali[✕]

Dionysios Diamantopoulos[▽] Juan Gómez-Luna[◇]

Henk Corporaal^{*} Onur Mutlu^{◇✕}

[◇]*ETH Zürich* [✕]*Carnegie Mellon University*

^{*}*Eindhoven University of Technology* [▽]*IBM Research Europe*

DAMOV Analysis Methodology & Workloads

DAMOV: A New Methodology and Benchmark Suite for Evaluating Data Movement Bottlenecks

GERALDO F. OLIVEIRA, ETH Zürich, Switzerland

JUAN GÓMEZ-LUNA, ETH Zürich, Switzerland

LOIS OROSA, ETH Zürich, Switzerland

SAUGATA GHOSE, University of Illinois at Urbana–Champaign, USA

NANDITA VIJAYKUMAR, University of Toronto, Canada

IVAN FERNANDEZ, University of Malaga, Spain & ETH Zürich, Switzerland

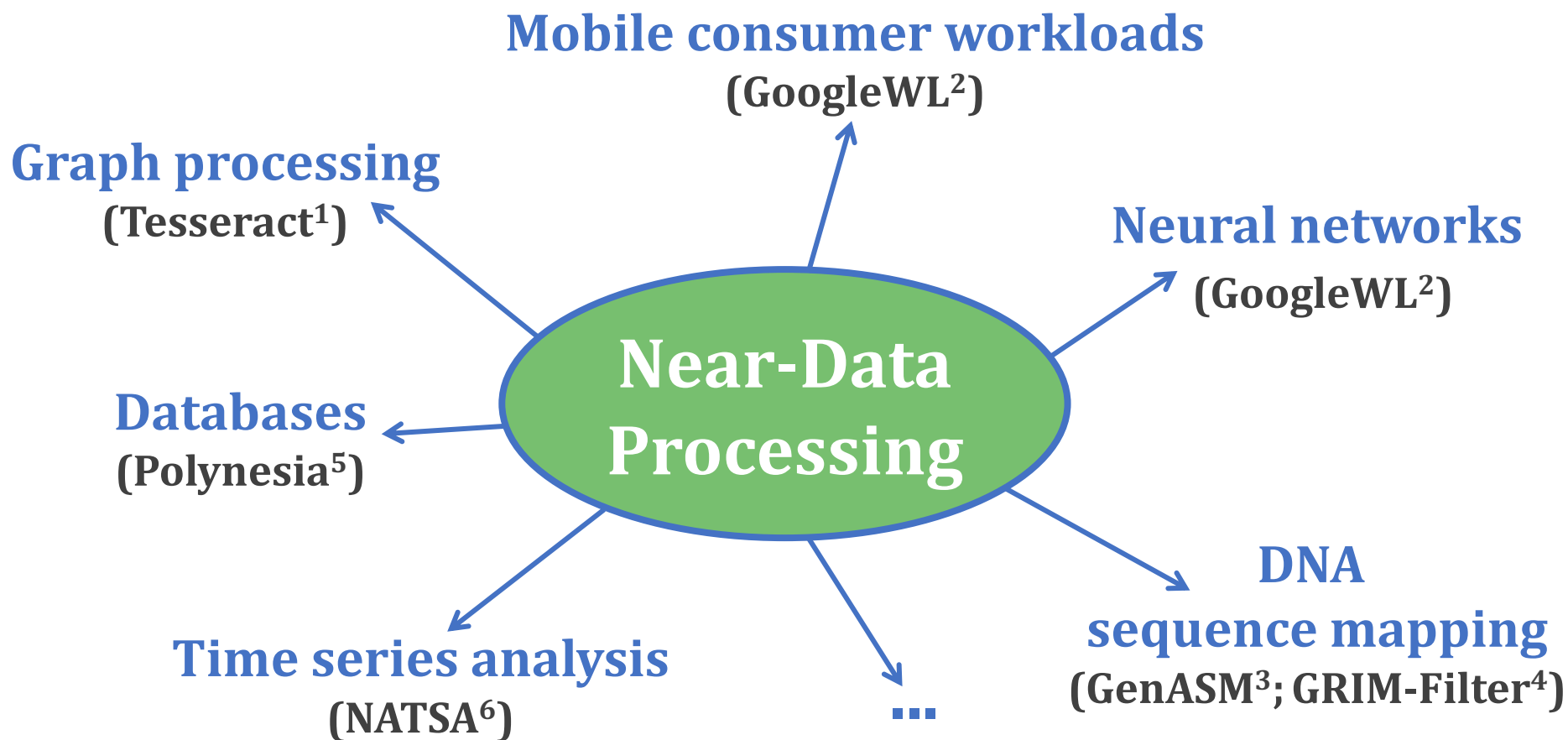
MOHAMMAD SADROSADATI, Institute for Research in Fundamental Sciences (IPM), Iran & ETH Zürich, Switzerland

ONUR MUTLU, ETH Zürich, Switzerland

Data movement between the CPU and main memory is a first-order obstacle against improving performance, scalability, and energy efficiency in modern systems. Computer systems employ a range of techniques to reduce overheads tied to data movement, spanning from traditional mechanisms (e.g., deep multi-level cache hierarchies, aggressive hardware prefetchers) to emerging techniques such as Near-Data Processing (NDP), where some computation is moved close to memory. Prior NDP works investigate the root causes of data movement bottlenecks using different profiling methodologies and tools. However, there is still a lack of understanding about the key metrics that can identify different data movement bottlenecks and their relation to traditional and emerging data movement mitigation mechanisms. Our goal is to methodically identify potential sources of data movement over a broad set of applications and to comprehensively compare traditional compute-centric data movement mitigation techniques (e.g., caching and prefetching) to more memory-centric techniques (e.g., NDP), thereby developing a rigorous understanding of the best techniques to mitigate each source of data movement.

With this goal in mind, we perform the first large-scale characterization of a wide variety of applications, across a wide range of application domains, to identify fundamental program properties that lead to data movement to/from main memory. We develop the first systematic methodology to classify applications based on the sources contributing to data movement bottlenecks. From our large-scale characterization of 77K functions across 345 applications, we select 144 functions to form the first open-source benchmark suite (DAMOV) for main memory data movement studies. We select a diverse range of functions that (1) represent different types of data movement bottlenecks, and (2) come from a wide range of application domains. Using NDP as a case study, we identify new insights about the different data movement bottlenecks and use these insights to determine the most suitable data movement mitigation mechanism for a particular application. We open-source DAMOV and the complete source code for our new characterization methodology at <https://github.com/CMU-SAFARI/DAMOV>.

When to Employ Near-Data Processing?



[1] Ahn+, "A Scalable Processing-in-Memory Accelerator for Parallel Graph Processing," ISCA, 2015

[2] Boroumand+, "Google Workloads for Consumer Devices: Mitigating Data Movement Bottlenecks," ASPLOS, 2018

[3] Cali+, "GenASM: A High-Performance, Low-Power Approximate String Matching Acceleration Framework for Genome Sequence Analysis," MICRO, 2020

[4] Kim+, "GRIM-Filter: Fast Seed Location Filtering in DNA Read Mapping Using Processing-in-Memory Technologies," BMC Genomics, 2018

[5] Boroumand+, "Polynesia: Enabling Effective Hybrid Transactional/Analytical Databases with Specialized Hardware/Software Co-Design," arXiv:2103.00798 [cs.AR], 2021

[6] Fernandez+, "NATSA: A Near-Data Processing Accelerator for Time Series Analysis," ICCD, 2020

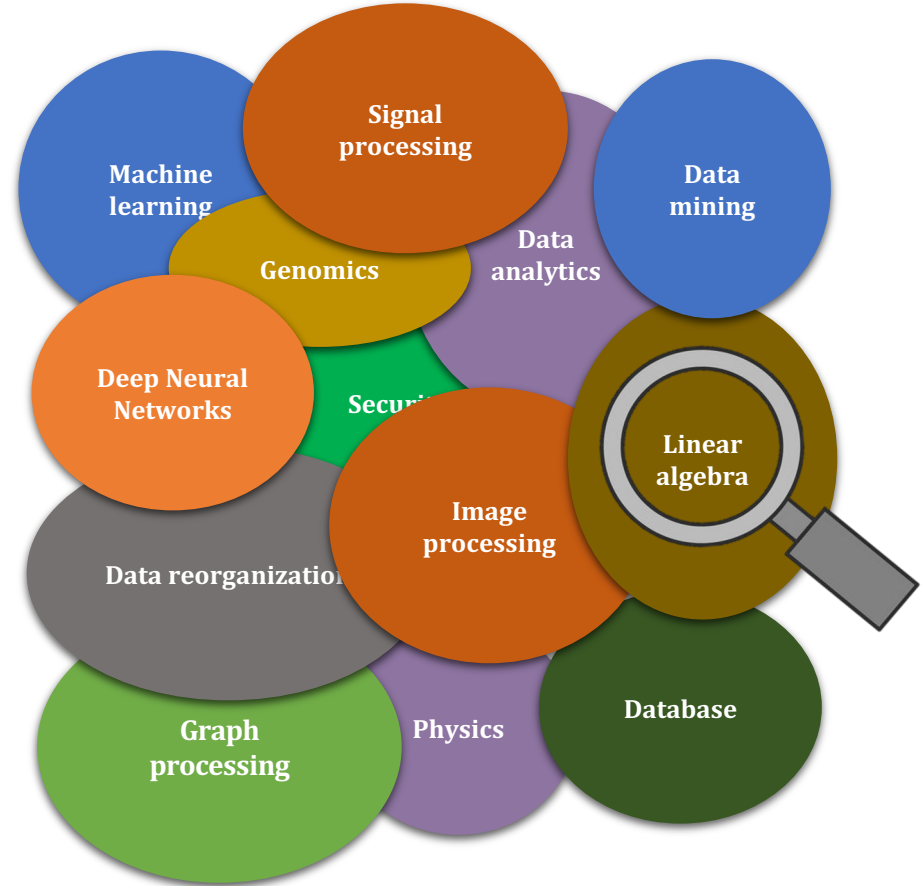
Step 1: Application Profiling

- We analyze 345 applications from distinct domains:

- Graph Processing
- Deep Neural Networks
- Physics
- High-Performance Computing
- Genomics
- Machine Learning
- Databases
- Data Reorganization
- Image Processing
- Map-Reduce
- Benchmarking
- Linear Algebra

...

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Step 3: Memory Bottleneck Analysis

**Six classes of
data movement bottlenecks:**

each class $\leftrightarrow$ data movement
mitigation mechanism

Memory Bottleneck Class

1a: *DRAM
Bandwidth*

1b: *DRAM Latency*

1c: *L1/L2
Cache Capacity*

2a: *L3 Cache
Contention*

2b: *L1 Cache
Capacity*

2c: *Compute-Bound*

DAMOV is Open Source

- We open-source our **benchmark suite** and our **toolchain**

CMU-SAFARI / DAMOV

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About



DAMOV is a benchmark suite and a methodical framework targeting the study of data movement bottlenecks in modern applications. It is intended to study new architectures, such as near-data processing. Described by Oliveira et al. (preliminary version at <https://arxiv.org/pdf/2105.03725.pdf>)

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DAMOV: A New Methodology and Benchmark Suite for Evaluating Data Movement Bottlenecks

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The DAMOV benchmark suite is the first open-source benchmark suite for main memory data movement-related studies, based on our systematic characterization methodology. This suite consists of 144 functions representing different sources of data movement bottlenecks and can be used as a baseline benchmark set for future data-movement mitigation research. The applications in the DAMOV benchmark suite belong to popular benchmark suites, including [BWA](#), [Chai](#), [Darknet](#), [GASE](#), [Hardware Effects](#), [Hashjoin](#), [HPCC](#), [HPCG](#), [Ligra](#), [PARSEC](#), [Parboil](#), [PolyBench](#), [Phoenix](#), [Rodinia](#), [SPLASH-2](#), [STREAM](#).

DAMOV-SIM

DAMOV
Benchmarks

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DAMOV is Open Source

- We open-source our [benchmark suite](#) and our [toolchain](#)

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About

DAMOV is a benchmark suite and a

Get DAMOV at:

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

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DAMOV: A New Methodology and Benchmark Suite for Evaluating Data Movement Bottlenecks

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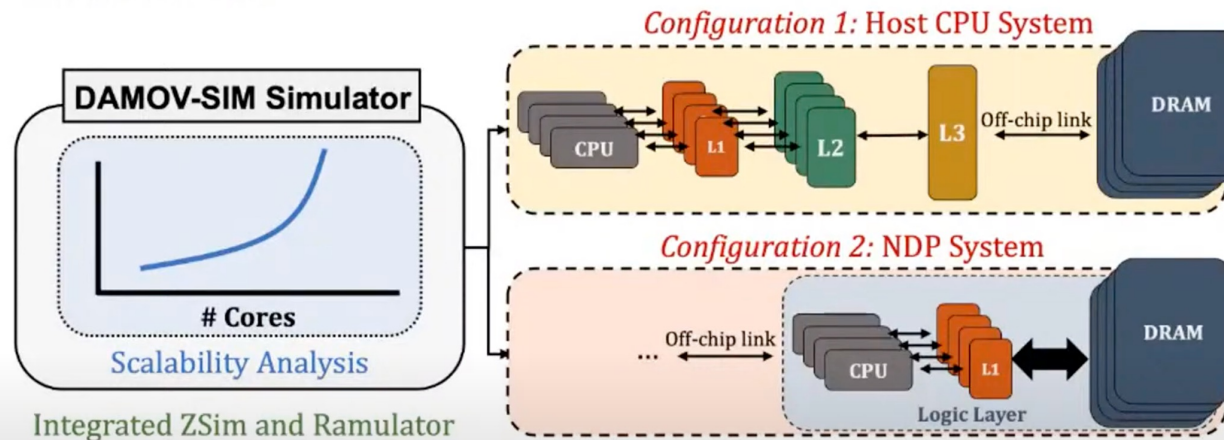
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More on DAMOV Analysis Methodology & Workloads

Step 3: Memory Bottleneck Classification (2/)

- **Goal:** identify the specific sources of data movement bottlenecks



- **Scalability Analysis:**
 - 1, 4, 16, 64, and 256 out-of-order/in-order host and NDP CPU cores
 - 3D-stacked memory as main memory

SAFARI DAMOV-SIM: <https://github.com/CMU-SAFARI/DAMOV> 30

SAFARI Live Seminar: DAMOV: A New Methodology & Benchmark Suite for Data Movement Bottlenecks

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https://www.youtube.com/watch?v=GWideVyo0nM&list=PL5Q2soXY2Zi_tOTAYm--dYByNPL7JhwR9&index=3

More on DAMOV Methods & Benchmarks

- Geraldo F. Oliveira, Juan Gomez-Luna, Lois Orosa, Saugata Ghose, Nandita Vijaykumar, Ivan fernandez, Mohammad Sadrosadati, and Onur Mutlu,
"DAMOV: A New Methodology and Benchmark Suite for Evaluating Data Movement Bottlenecks"
IEEE Access, 8 September 2021.
Preprint in arXiv, 8 May 2021.
[[arXiv preprint](#)]
[[IEEE Access version](#)]
[[DAMOV Suite and Simulator Source Code](#)]
[[SAFARI Live Seminar Video](#) (2 hrs 40 mins)]
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DAMOV: A New Methodology and Benchmark Suite for Evaluating Data Movement Bottlenecks

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MOHAMMAD SADROSADATI, ETH Zürich, Switzerland

ONUR MUTLU, ETH Zürich, Switzerland

Coming Up: SpMV on Real PIM Systems

- Appears in SIGMETRICS 2022

***SparseP*: Towards Efficient Sparse Matrix Vector Multiplication on Real Processing-In-Memory Systems**

CHRISTINA GIANNOULA, ETH Zürich, Switzerland and National Technical University of Athens, Greece

IVAN FERNANDEZ, ETH Zürich, Switzerland and University of Malaga, Spain

JUAN GÓMEZ-LUNA, ETH Zürich, Switzerland

NECTARIOS KOZIRIS, National Technical University of Athens, Greece

GEORGIOS GOUMAS, National Technical University of Athens, Greece

ONUR MUTLU, ETH Zürich, Switzerland

<https://arxiv.org/pdf/2201.05072.pdf>

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

Coming Up: SpMV on Real PIM Systems



The video player displays a presentation slide for 'SparseP'. The slide features a green network diagram at the top, followed by the title 'SparseP' in large blue letters. Below the title is the subtitle 'Towards Efficient Sparse Matrix Vector Multiplication on Real Processing-In-Memory Architectures'. The presenter's name, 'Christina Giannoula', is listed in red, followed by the names of other contributors: 'Ivan Fernandez, Juan Gomez-Luna, Nectarios Koziris, Georgios Goumas, Onur Mutlu'. At the bottom of the slide are logos for 'SAFARI', 'ETH zürich', 'CSLab', and 'UNIVERSITY OF MALAGA'. A small video inset in the top right corner shows the presenter, Christina Giannoula. The video player controls at the bottom show a play button, a progress bar at 0:02 / 55:25, and various icons for volume, subtitles, and settings.

Christina Giannoula

SparseP

Towards Efficient Sparse Matrix Vector Multiplication
on Real Processing-In-Memory Architectures

Christina Giannoula
Ivan Fernandez, Juan Gomez-Luna,
Nectarios Koziris, Georgios Goumas, Onur Mutlu

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Samsung Function-in-Memory DRAM (2021)



Samsung Develops Industry's First High Bandwidth Memory with AI Processing Power

Korea on February 17, 2021

Audio



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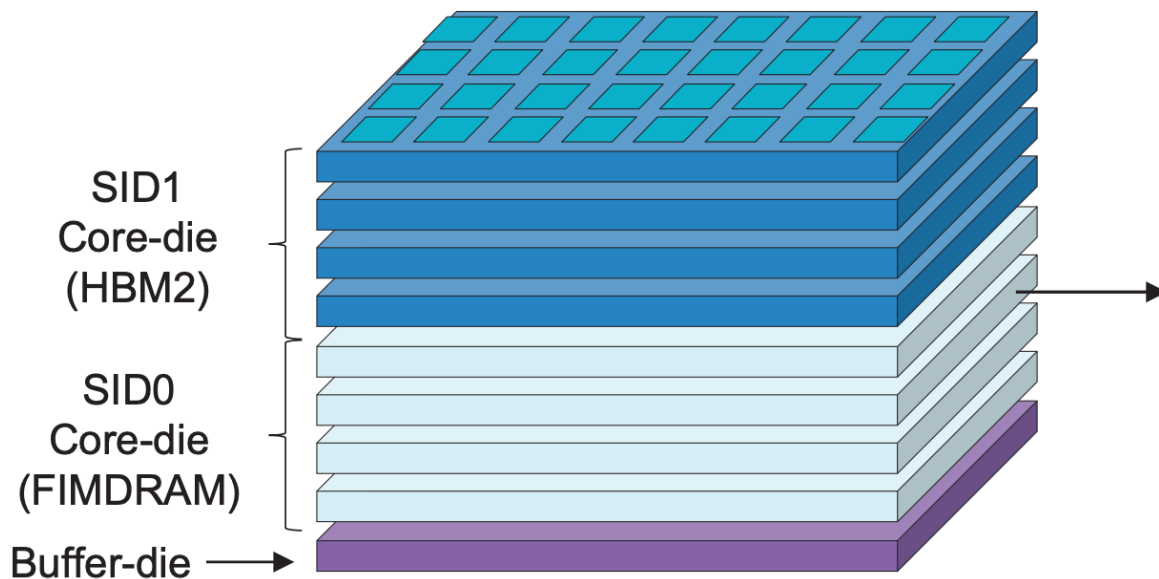
The new architecture will deliver over twice the system performance and reduce energy consumption by more than 70%

Samsung Electronics, the world leader in advanced memory technology, today announced that it has developed the industry's first High Bandwidth Memory (HBM) integrated with artificial intelligence (AI) processing power – the HBM-PIM. The new processing-in-memory (PIM) architecture brings powerful AI computing capabilities inside high-performance memory, to accelerate large-scale processing in data centers, high performance computing (HPC) systems and AI-enabled mobile applications.

Kwangil Park, senior vice president of Memory Product Planning at Samsung Electronics stated, "Our groundbreaking HBM-PIM is the industry's first programmable PIM solution tailored for diverse AI-driven workloads such as HPC, training and inference. We plan to build upon this breakthrough by further collaborating with AI solution providers for even more advanced PIM-powered applications."

Samsung Function-in-Memory DRAM (2021)

■ FIMDRAM based on HBM2



[3D Chip Structure of HBM with FIMDRAM]

Chip Specification

128DQ / 8CH / 16 banks / BL4

32 PCU blocks (1 FIM block/2 banks)

1.2 TFLOPS (4H)

**FP16 ADD /
Multiply (MUL) /
Multiply-Accumulate (MAC) /
Multiply-and- Add (MAD)**

ISSCC 2021 / SESSION 25 / DRAM / 25.4

25.4 A 20nm 6GB Function-In-Memory DRAM, Based on HBM2 with a 1.2TFLOPS Programmable Computing Unit Using Bank-Level Parallelism, for Machine Learning Applications

Young-Cheon Kwon¹, Suk Han Lee¹, Jaehoon Lee¹, Sang-Hyuk Kwon¹, Je Min Ryu¹, Jong-Pil Son¹, Seongil O¹, Hak-Soo Yu¹, Haesuk Lee¹, Soo Young Kim¹, Youngmin Cho¹, Jin Guk Kim¹, Jongyoon Choi¹, Hyun-Sung Shin¹, Jin Kim¹, BengSeng Phuah¹, HyoungMin Kim¹, Myeong Jun Song¹, Ahn Choi¹, Daeho Kim¹, SooYoung Kim¹, Eun-Bong Kim¹, David Wang², Shinhaeng Kang¹, Yuhwan Ro³, Seungwoo Seo³, JoonHo Song³, Jaeyoun Youn¹, Kyomin Sohn¹, Nam Sung Kim¹

¹Samsung Electronics, Hwaseong, Korea

²Samsung Electronics, San Jose, CA

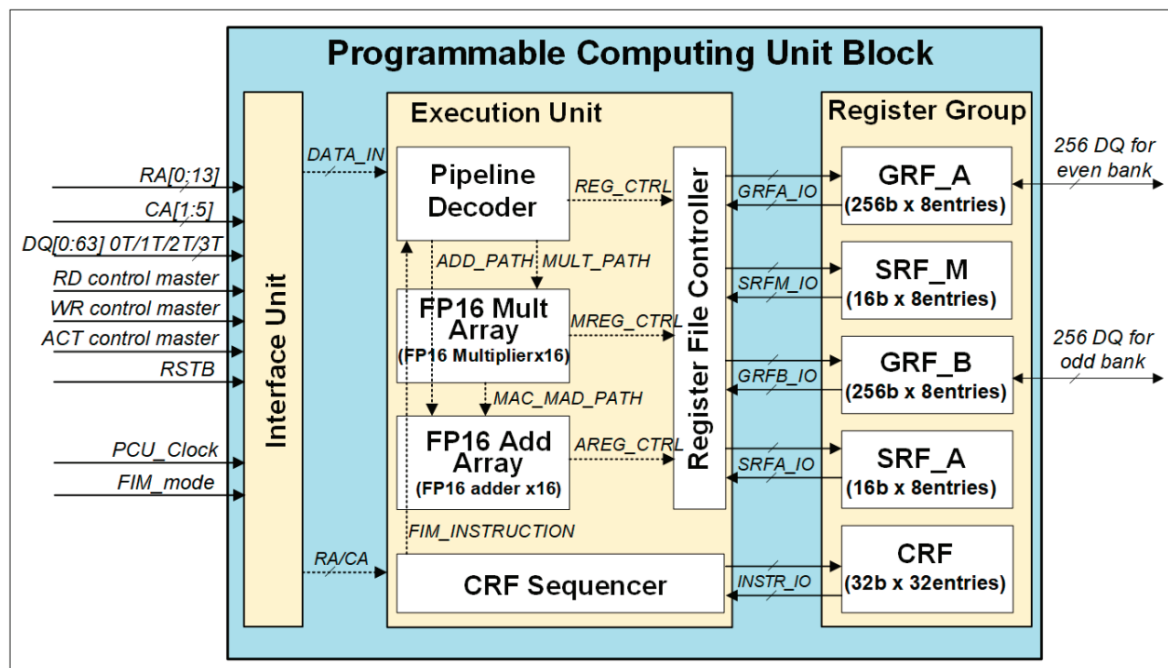
³Samsung Electronics, Suwon, Korea

Samsung Function-in-Memory DRAM (2021)

Programmable Computing Unit

■ Configuration of PCU block

- Interface unit to control data flow
- Execution unit to perform operations
- Register group
 - 32 entries of CRF for instruction memory
 - 16 GRF for weight and accumulation
 - 16 SRF to store constants for MAC operations



[Block diagram of PCU in FIMDRAM]

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¹Samsung Electronics, Hwaseong, Korea
²Samsung Electronics, San Jose, CA
³Samsung Electronics, Suwon, Korea

Samsung Function-in-Memory DRAM (2021)

[Available instruction list for FIM operation]

Type	CMD	Description
Floating Point	ADD	FP16 addition
	MUL	FP16 multiplication
	MAC	FP16 multiply-accumulate
	MAD	FP16 multiply and add
Data Path	MOVE	Load or store data
	FILL	Copy data from bank to GRFs
Control Path	NOP	Do nothing
	JUMP	Jump instruction
	EXIT	Exit instruction

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¹Samsung Electronics, Hwaseong, Korea

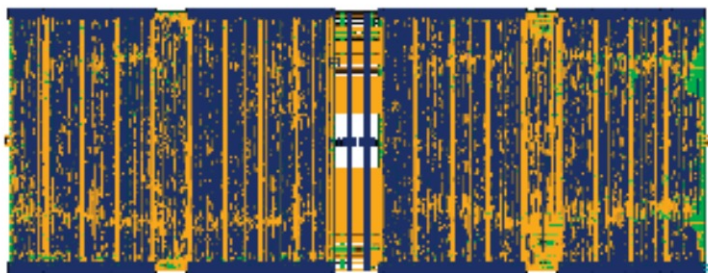
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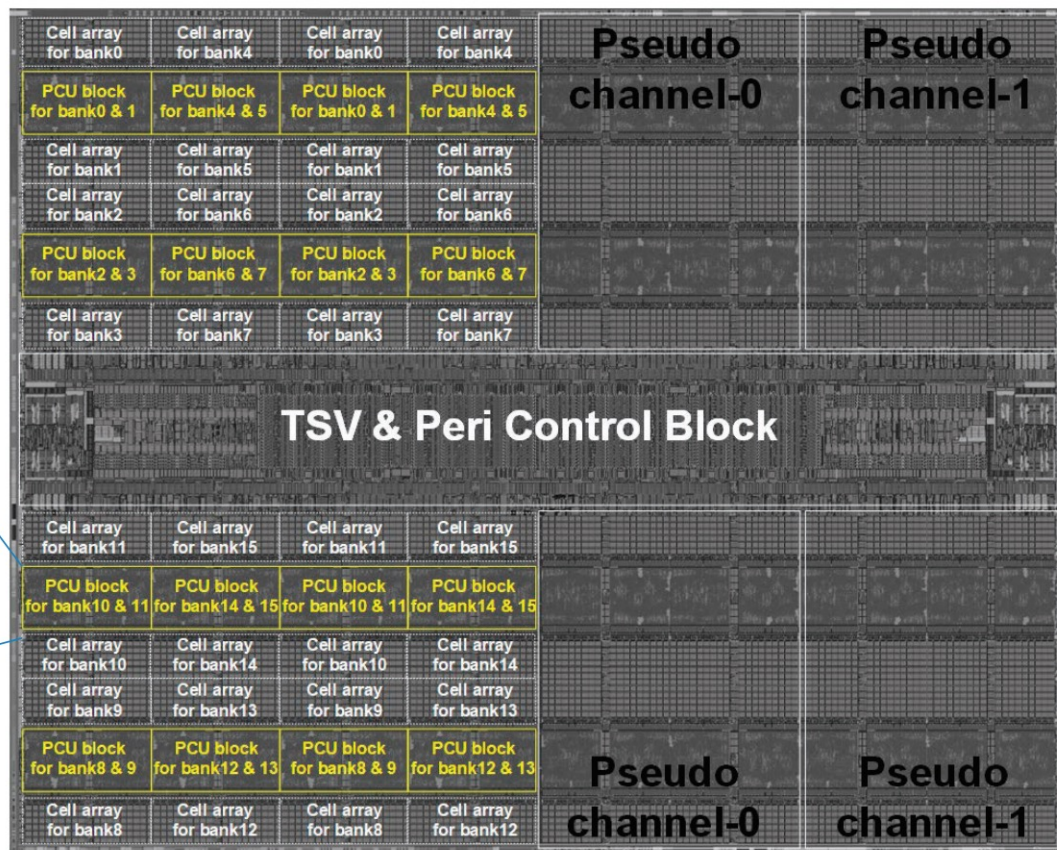
Samsung Function-in-Memory DRAM (2021)

Chip Implementation

- Mixed design methodology to implement FIMDRAM
 - Full-custom + Digital RTL



[Digital RTL design for PCU block]



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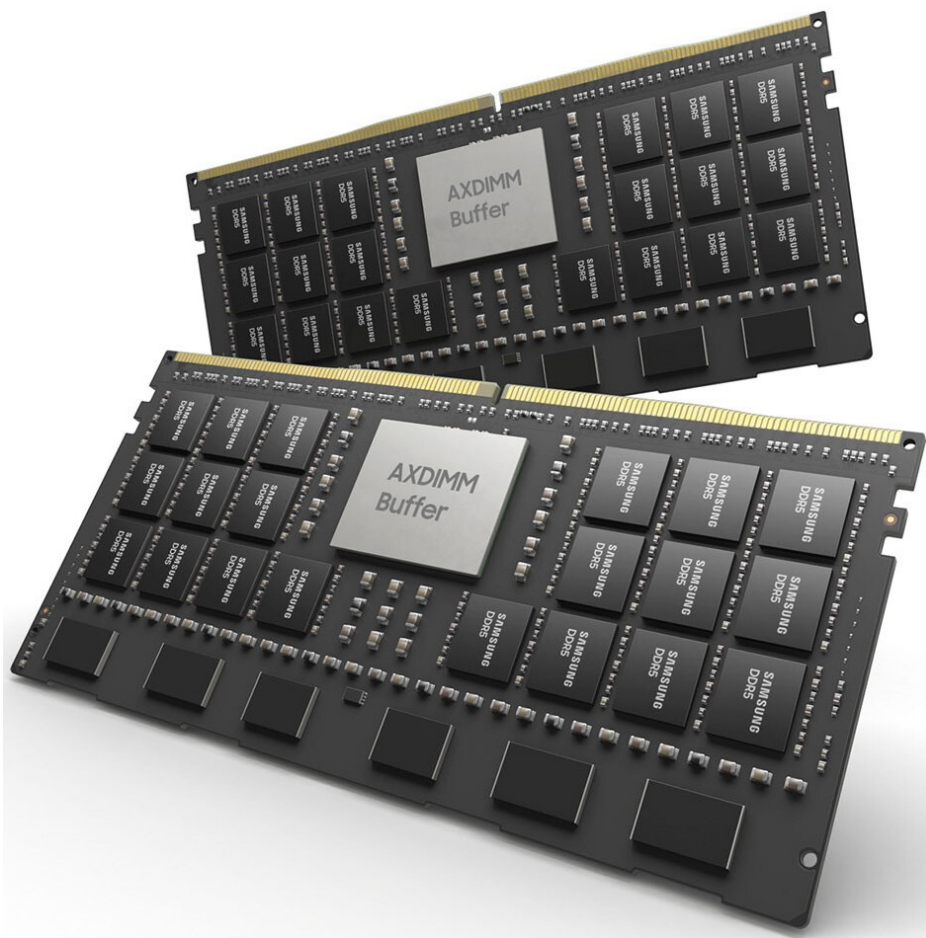
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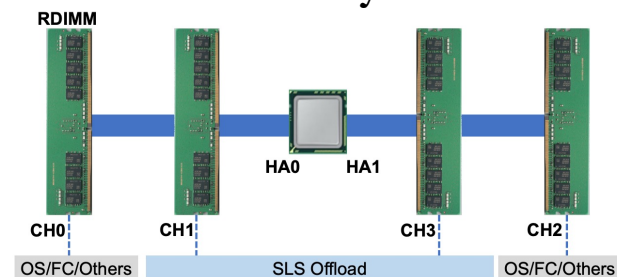
³Samsung Electronics, Suwon, Korea

Samsung AxDIMM (2021)

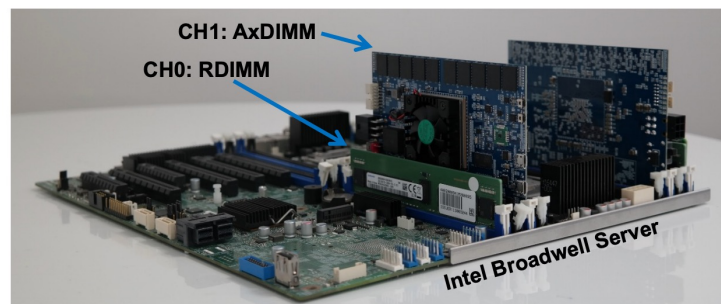
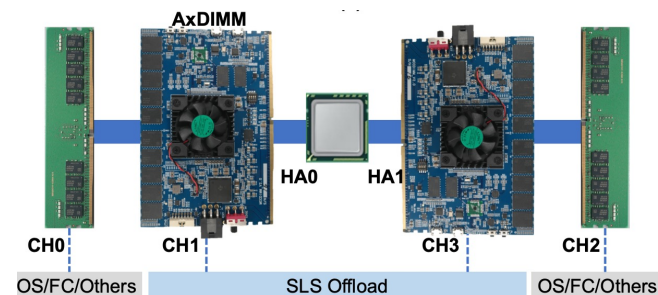
- DDRx-PIM
 - DLRM recommendation system



Baseline System



AxDIMM System



SK Hynix Accelerator-in-Memory (2022)

SK hynix Develops PIM, Next-Generation AI Accelerator

February 16, 2022



Seoul, February 16, 2022

SK hynix (or “the Company”, www.skhynix.com) announced on February 16 that it has developed PIM*, a next-generation memory chip with computing capabilities.

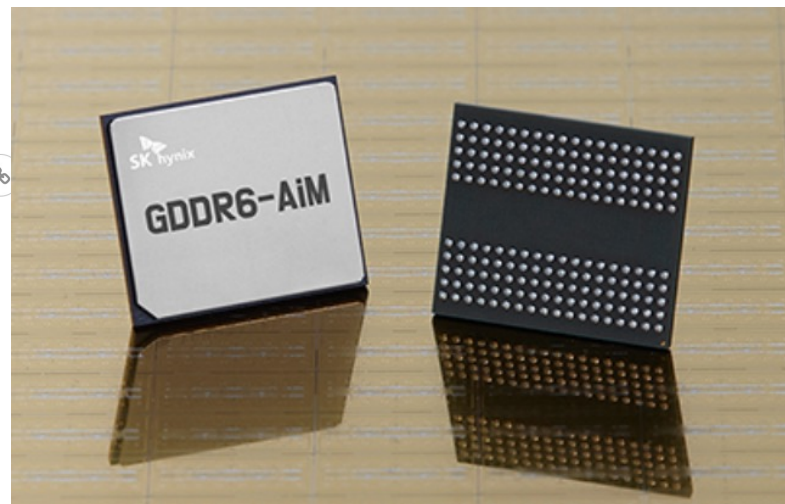
**PIM(Processing In Memory): A next-generation technology that provides a solution for data congestion issues for AI and big data by adding computational functions to semiconductor memory*

It has been generally accepted that memory chips store data and CPU or GPU, like human brain, process data. SK hynix, following its challenge to such notion and efforts to pursue innovation in the next-generation smart memory, has found a breakthrough solution with the development of the latest technology.

SK hynix plans to showcase its PIM development at the world’s most prestigious semiconductor conference, 2022 ISSCC*, in San Francisco at the end of this month. The company expects continued efforts for innovation of this technology to bring the memory-centric computing, in which semiconductor memory plays a central role, a step closer to the reality in devices such as smartphones.

**ISSCC: The International Solid-State Circuits Conference will be held virtually from Feb. 20 to Feb. 24 this year with a theme of “Intelligent Silicon for a Sustainable World”*

For the first product that adopts the PIM technology, SK hynix has developed a sample of GDDR6-AiM (Accelerator* in memory). The GDDR6-AiM adds computational functions to GDDR6* memory chips, which process data at 16Gbps. A combination of GDDR6-AiM with CPU or GPU instead of a typical DRAM makes certain computation speed 16 times faster. GDDR6-AiM is widely expected to be adopted for machine learning, high-performance computing, and big data computation and storage.



11.1 A 1nm 1.25V 8Gb, 16Gb/s/pin GDDR6-based Accelerator-in-Memory supporting 1TFLOPS MAC Operation and Various Activation Functions for Deep-Learning Applications

Seongju Lee, SK hynix, Icheon, Korea

In Paper 11.1, SK Hynix describes a 1nm, GDDR6-based accelerator-in-memory with a command set for deep-learning operation. The 8Gb design achieves a peak throughput of 1TFLOPS with 1GHz MAC operations and supports major activation functions to improve accuracy.

AliBaba PIM Recommendation System (2022)

ISSCC 2022 / February 24, 2022 / 8:30 AM

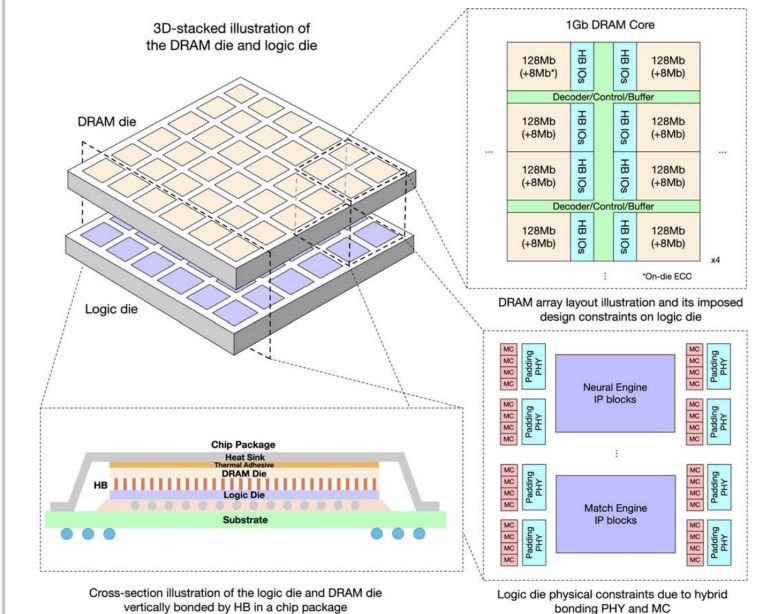


Figure 29.1.2: Illustration of 3D-stacked chip, cross-illustration of package, DRAM array layout and design blocks on logic die.

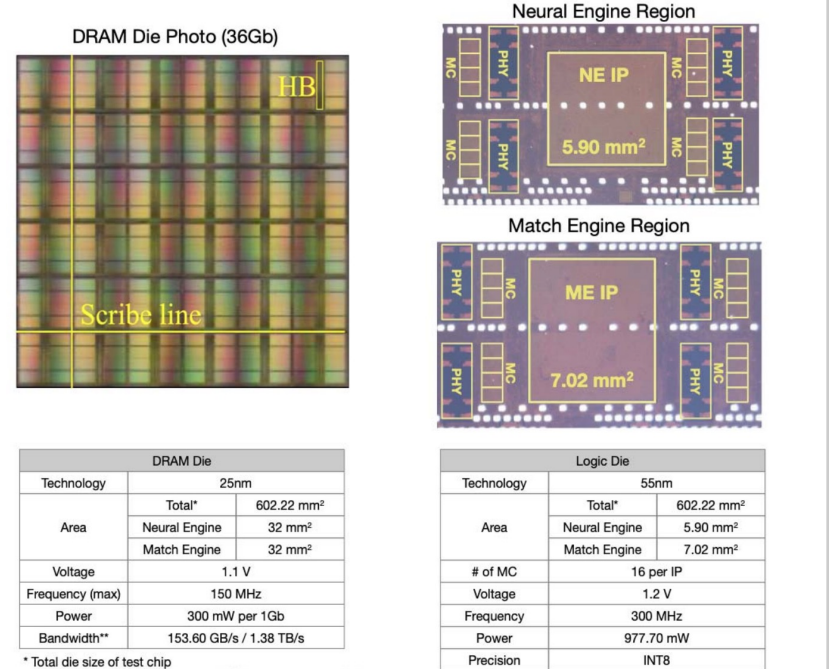


Figure 29.1.7: Die micrographs of DRAM die, NE and ME. Detailed specifications of DRAM die and logic die.

29.1 184QPS/W 64Mb/mm² 3D Logic-to-DRAM Hybrid Bonding with Process-Near-Memory Engine for Recommendation System

Dimin Niu¹, Shuangchen Li¹, Yuhao Wang¹, Wei Han¹, Zhe Zhang², Yijin Guan², Tianchan Guan³, Fei Sun¹, Fei Xue¹, Lide Duan¹, Yuanwei Fang¹, Hongzhong Zheng¹, Xiping Jiang⁴, Song Wang⁴, Fengguo Zuo⁴, Yubing Wang⁴, Bing Yu⁴, Qiwei Ren⁴, Yuan Xie¹

Future: Enable New Medical/Health Platforms

Nanopore sequencing technology and tools for genome assembly: computational analysis of the current state, bottlenecks and future directions

Damla Senol Cali ✉, Jeremie S Kim, Saugata Ghose, Can Alkan, Onur Mutlu

Briefings in Bioinformatics, bby017, <https://doi.org/10.1093/bib/bby017>

Published: 02 April 2018 **Article history** ▼



Oxford Nanopore MinION

Senol Cali+, “**Nanopore Sequencing Technology and Tools for Genome Assembly: Computational Analysis of the Current State, Bottlenecks and Future Directions**,” *Briefings in Bioinformatics*, 2018.

[[Preliminary arxiv.org version](#)]

Future of Genome Sequencing & Analysis

Mohammed Alser, Zülal Bingöl, Damla Senol Cali, Jeremie Kim, Saugata Ghose, Can Alkan, Onur Mutlu
["Accelerating Genome Analysis: A Primer on an Ongoing Journey"](#) IEEE Micro, August 2020.



MinION from ONT

Accelerating Genome Analysis: A Primer on an Ongoing Journey

Sept.-Oct. 2020, pp. 65-75, vol. 40

DOI Bookmark: [10.1109/MM.2020.3013728](https://doi.org/10.1109/MM.2020.3013728)

FPGA-Based Near-Memory Acceleration of Modern Data-Intensive Applications

July-Aug. 2021, pp. 39-48, vol. 41

DOI Bookmark: [10.1109/MM.2021.3088396](https://doi.org/10.1109/MM.2021.3088396)



SmidgION from ONT

Detailed Lectures on PIM (I)

- **Computer Architecture, Fall 2020, Lecture 6**
 - **Computation in Memory** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=oGcZAGwfEUE&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=12>
- **Computer Architecture, Fall 2020, Lecture 7**
 - **Near-Data Processing** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=j2GIigqn1Qw&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=13>
- **Computer Architecture, Fall 2020, Lecture 11a**
 - **Memory Controllers** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=TeG773OgiMQ&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=20>
- **Computer Architecture, Fall 2020, Lecture 12d**
 - **Real Processing-in-DRAM with UPMEM** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=Sscy1Wrr22A&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=25>

Detailed Lectures on PIM (II)

- **Computer Architecture, Fall 2020, Lecture 15**
 - **Emerging Memory Technologies** (ETH Zürich, Fall 2020)
 - https://www.youtube.com/watch?v=AIE1rD9G_YU&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=28
- **Computer Architecture, Fall 2020, Lecture 16a**
 - **Opportunities & Challenges of Emerging Memory Technologies** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=pmLszWGmMGQ&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=29>
- **Computer Architecture, Fall 2020, Guest Lecture**
 - **In-Memory Computing: Memory Devices & Applications** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=wNmQqHiEZnk&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=41>

Latest Longer & Detailed Tutorial on PIM

- Onur Mutlu,
"Memory-Centric Computing"
Education Class at Embedded Systems Week (ESWEEK),
Virtual, 9 October 2021.
[Slides (pptx) (pdf)]
[Abstract (pdf)]
[Talk Video (2 hours, including Q&A)]
[Invited Paper at DATE 2021]
["A Modern Primer on Processing in Memory" paper]

<https://www.youtube.com/watch?v=N1Ac1ov1JOM>

Memory-Centric Computing

Onur Mutlu

omutlu@gmail.com

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

9 October 2021

ESWEEK Education Class

SAFARI

ETH zürich

Carnegie Mellon



1:08 / 2:00:10



Embedded Systems Week (ESWEEK) 2021 Lecture - Memory-Centric Computing - Onur Mutlu - 9 October 2021

509 views • Premiered Dec 6, 2021

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Onur Mutlu Lectures
20.7K subscribers

<https://www.youtube.com/watch?v=N1Ac1ov1JOM>

ANALYTICS

EDIT VIDEO

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

228

Fundamentally Energy-Efficient **(Data-Centric)** Computing Architectures

Fundamentally High-Performance **(Data-Centric)** Computing Architectures

Computing Architectures with Minimal Data Movement

Unfortunately, Little or No
Time for the Next Two Parts

Data-Driven **(Self-Optimizing)** **Computing Architectures**

Data-Aware (Expressive)

Computing Architectures

More Info in This Longer Tutorial...

- Onur Mutlu,

"Memory-Centric Computing Systems"

Invited Tutorial at *66th International Electron Devices Meeting (IEDM)*, Virtual, 12 December 2020.

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

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

[[Tutorial Video](#) (1 hour 51 minutes)]

[[Executive Summary Video](#) (2 minutes)]

[[Abstract and Bio](#)]

[[Related Keynote Paper from VLSI-DAT 2020](#)]

[[Related Review Paper on Processing in Memory](#)]

<https://www.youtube.com/watch?v=H3sEaINPBOE>

Memory-Centric Computing Systems



Onur Mutlu

omutlu@gmail.com

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

12 December 2020

IEDM Tutorial

SAFARI

ETH zürich

Carnegie Mellon



0:06 / 1:51:05



IEDM 2020 Tutorial: Memory-Centric Computing Systems, Onur Mutlu, 12 December 2020

1,641 views • Dec 23, 2020

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13.9K subscribers

<https://www.youtube.com/watch?v=H3sEaINPBOE>

ANALYTICS

EDIT VIDEO

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

Concluding Remarks

Concluding Remarks

- We must design systems to be truly balanced, high-performance, and **energy-efficient** → intelligent systems
 - **Data-centric, data-driven, data-aware**
- Enable computation capability inside and close to memory
- This can
 - Lead to **orders-of-magnitude** improvements
 - **Enable new applications & computing platforms**
 - **Enable better understanding of nature**
 - ...
- Future of **truly memory-centric computing** is bright
 - We need to do research & design across the computing stack

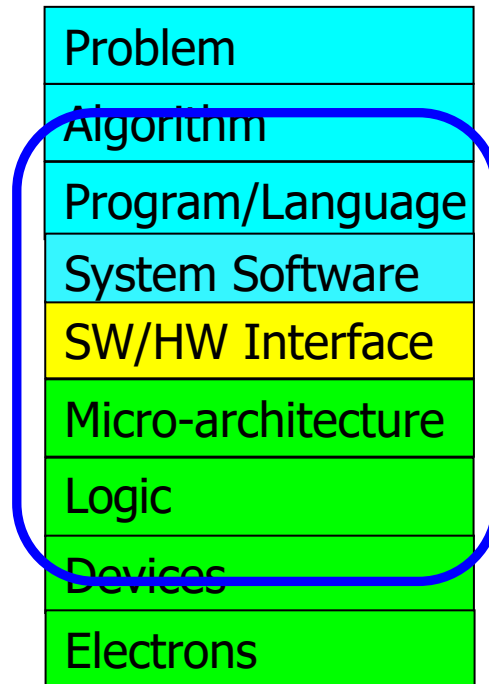
Data-centric

Data-driven

Data-aware



We Need to Revisit the Entire Stack



We can get there step by step

We Need to Exploit Good Principles

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

Open minds

A Blueprint for Fundamentally Better Architectures

- Onur Mutlu,
"Intelligent Architectures for Intelligent Computing Systems"
*Invited Paper in Proceedings of the Design, Automation, and Test in Europe Conference (**DATE**), Virtual, February 2021.*
[Slides (pptx) (pdf)]
[IEDM Tutorial Slides (pptx) (pdf)]
[Short DATE Talk Video (11 minutes)]
[Longer IEDM Tutorial Video (1 hr 51 minutes)]

Intelligent Architectures for Intelligent Computing Systems

Onur Mutlu
ETH Zurich
omutlu@gmail.com

Funding Acknowledgments

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

Acknowledgments

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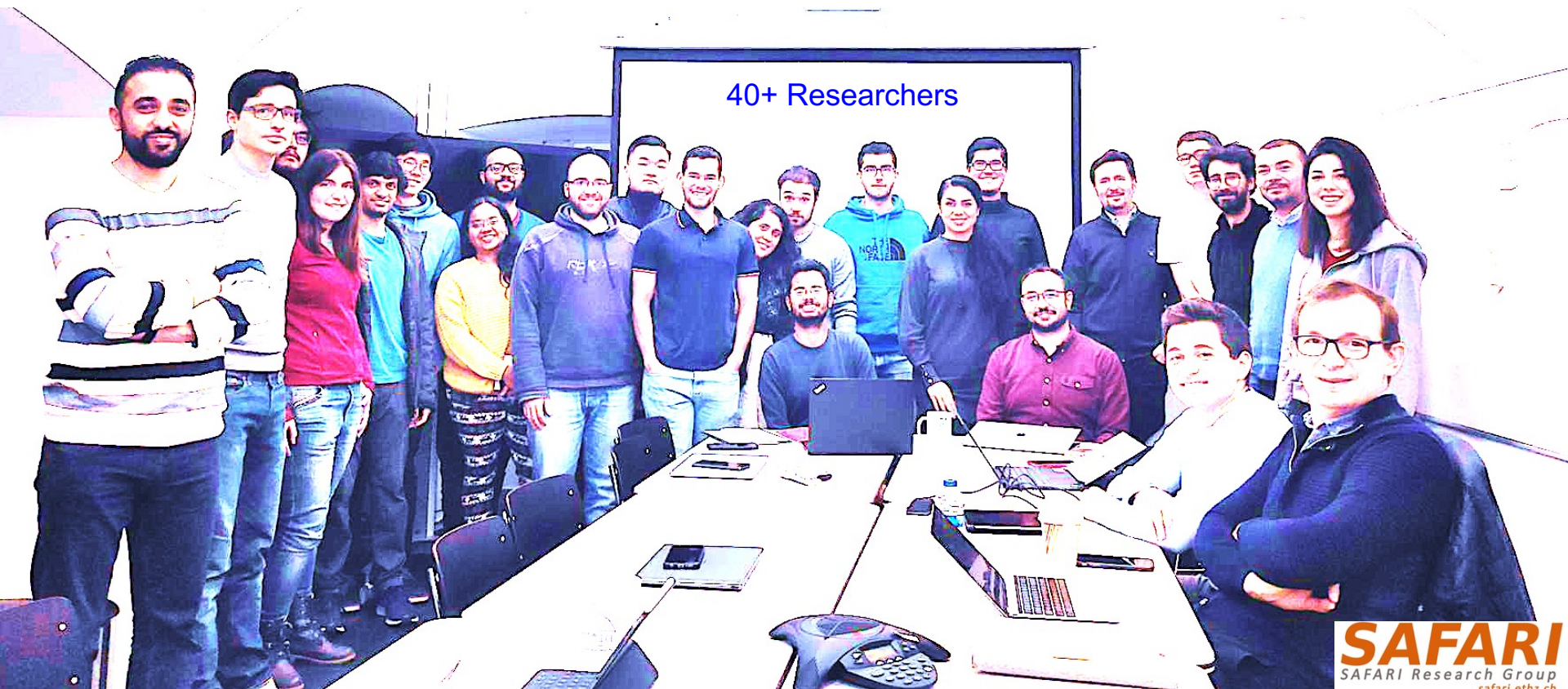
Think BIG, Aim HIGH!

<https://safari.ethz.ch>

Onur Mutlu's SAFARI Research Group

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

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



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SAFARI Newsletter December 2021 Edition

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

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Think Big, Aim High

ETH zürich



View in your browser
December 2021



Referenced Papers, Talks, Artifacts

- All are available at

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

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

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

Open Source Tools: SAFARI GitHub



SAFARI Research Group at ETH Zurich and Carnegie Mellon University

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

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

🏠 Overview 📁 Repositories 71 📁 Projects 📁 Packages 👤 Teams 1 👤 People 44 ⚙ Settings

Pinned

Customize pins

📁 ramulator Public

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

🔴 C++ ☆ 311 🍷 161

📁 prim-benchmarks Public

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

⬛ C ☆ 53 🍷 21

📁 DAMOV Public

DAMOV is a benchmark suite and a methodical framework targeting the study of data movement bottlenecks in modern applications. It is intended to study new architectures, such as near-data processin...

🔴 C++ ☆ 26 🍷 4

📁 SneakySnake Public

SneakySnake🐍 is the first and the only pre-alignment filtering algorithm that works efficiently and fast on modern CPU, FPGA, and GPU architectures. It greatly (by more than two orders of magnitude...

🔵 VHDL ☆ 41 🍷 8

📁 MQSim Public

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

🔴 C++ ☆ 146 🍷 93

📁 rowhammer Public

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

⬛ C ☆ 189 🍷 41

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

Comp Arch (Fall'21)

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

- Computer Architecture FS20: Course Webpage
- Computer Architecture FS20: Lecture Videos
- Digitaltechnik SS21: Course Webpage
- Digitaltechnik SS21: Lecture Videos
- Moodle
- HotCRP
- Verilog Practice Website (HDLBits)

Fall 2021 Edition:

- <https://safari.ethz.ch/architecture/fall2021/doku.php?id=schedule>

Fall 2020 Edition:

- <https://safari.ethz.ch/architecture/fall2020/doku.php?id=schedule>

Youtube Livestream (2021):

- https://www.youtube.com/watch?v=4yfkM_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF

Youtube Livestream (2020):

- <https://www.youtube.com/watch?v=c3mPdZA-Fmc&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN>

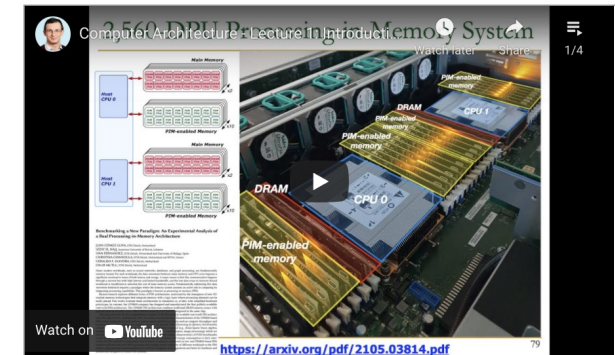
Master's level course

- 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

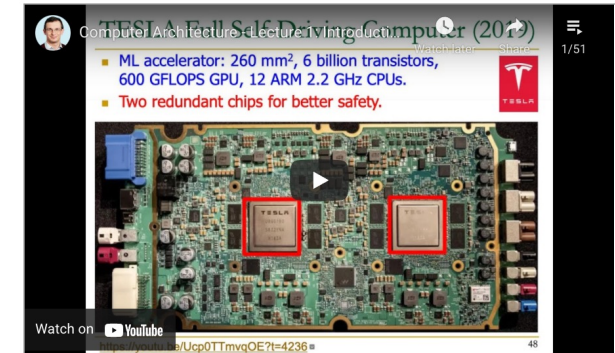
<https://www.youtube.com/onurmutlulectures>

Lecture Video Playlist on YouTube

Livestream Lecture Playlist



Recorded Lecture Playlist



Fall 2021 Lectures & Schedule

Week	Date	Livestream	Lecture	Readings	Lab	HW
W1	30.09 Thu.	YouTube Live	L1: Introduction and Basics PDF PPT	Required Mentioned	Lab 1 Out	HW 0 Out
	01.10 Fri.	YouTube Live	L2: Trends, Tradeoffs and Design Fundamentals PDF PPT	Required Mentioned		
W2	07.10 Thu.	YouTube Live	L3a: Memory Systems: Challenges and Opportunities PDF PPT	Described Suggested		HW 1 Out
			L3b: Course Info & Logistics PDF PPT			
			L3c: Memory Performance Attacks PDF PPT	Described Suggested		
	08.10 Fri.	YouTube Live	L4a: Memory Performance Attacks PDF PPT	Described Suggested	Lab 2 Out	
			L4b: Data Retention and Memory Refresh PDF PPT	Described Suggested		
			L4c: RowHammer PDF PPT	Described Suggested		

PIM Course (Fall'21)

Fall 2021 Edition:

- https://safari.ethz.ch/projects_and_seminars/fall2021/doku.php?id=processing_in_memory

Youtube Livestream:

- https://www.youtube.com/watch?v=9e4Chnwdovo&list=PL5Q2soXY2Zi-841fUYYUK9EsXKhQKRPyX

Project course

- Taken by Bachelor's/Master's students
- Processing-in-Memory lectures
- Hands-on research exploration
- Many research readings

PIM Review and Open Problems
Processing in Memory Course: Meeting 1: Ex...

Watch later Share 1/10

A Modern Primer on Processing in Memory

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

SAFARI Research Group

^aETH Zürich
^bCarnegie Mellon University
^cUniversity of Illinois at Urbana-Champaign
^dKing Mongkut's University of Technology North Bangkok

Onur Mutlu, Saugata Ghose, Juan Gomez-Luna, and Rachata Ausavarungnirun, "A Modern Primer on Processing in Memory" Invited Book Chapter in *Emerging Computing: From Devices to Systems - Looking Beyond Moore and Von Neumann*, Springer, to be published in 2021.

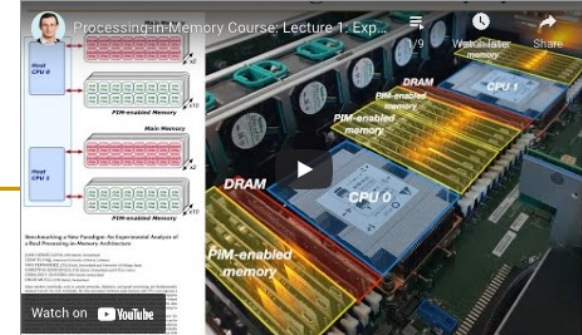
Watch on YouTube

<https://arxiv.org/pdf/1903.03988.pdf> 108

Fall 2021 Meetings/Schedule

Week	Date	Livestream	Meeting	Learning Materials	Assignments
W1	05.10 Tue.	YouTube Live	M1: P&S PIM Course Presentation PDF (PDF) PPT (PPT)	Required Materials Recommended Materials	HW 0 Out
W2	12.10 Tue.	YouTube Live	M2: Real-World PIM Architectures PDF (PDF) PPT (PPT)		
W3	19.10 Tue.	YouTube Live	M3: Real-World PIM Architectures II PDF (PDF) PPT (PPT)		
W4	26.10 Tue.	YouTube Live	M4: Real-World PIM Architectures III PDF (PDF) PPT (PPT)		
W5	02.11 Tue.	YouTube Live	M5: Real-World PIM Architectures IV PDF (PDF) PPT (PPT)		
W6	09.11 Tue.	YouTube Live	M6: End-to-End Framework for Processing-using-Memory PDF (PDF) PPT (PPT)		
W7	16.11 Tue.	YouTube Live	M7: How to Evaluate Data Movement Bottlenecks PDF (PDF) PPT (PPT)		
W8	23.11 Tue.	YouTube Live	M8: Programming PIM Architectures PDF (PDF) PPT (PPT)		
W9	30.11 Tue.	YouTube Live	M9: Benchmarking and Workload Suitability on PIM PDF (PDF) PPT (PPT)		
W10	07.12 Tue.	YouTube Live	M10: Bit-Serial SIMD Processing using DRAM PDF (PDF) PPT (PPT)		

PIM Course (Current)



Recorded Lecture Playlist



Spring 2022 Meetings/Schedule

Week	Date	Livestream	Meeting	Learning Materials	Assignments
W1	10.03 Thu.	Live	M1: P&S PIM Course Presentation (PDF) (PPT)	Required Materials Recommended Materials	HW 0 Out
W2	15.03 Tue.		Hands-on Project Proposals		
	17.03 Thu.	Premiere	M2: Real-world PIM: UPMEM PIM (PDF) (PPT)		
W3	24.03 Thu.	Live	M3: Real-world PIM: Microbenchmarking of UPMEM PIM (PDF) (PPT)		
W4	31.03 Thu.	Live	M4: Real-world PIM: Samsung HBM-PIM (PDF) (PPT)		
W5	07.04 Thu.	Live	M5: How to Evaluate Data Movement Bottlenecks (PDF) (PPT)		
W6	14.04 Thu.	Live	M6: Real-world PIM: SK Hynix A1M (PDF) (PPT)		
W7	21.04 Thu.	Premiere	M7: Programming PIM Architectures (PDF) (PPT)		
W8	28.04 Thu.	Premiere	M8: Benchmarking and Workload Suitability on PIM (PDF) (PPT)		
W9	05.05 Thu.	Premiere	M9: Real-world PIM: Samsung AxDIMM (PDF) (PPT)		
W10	12.05 Thu.		M10: Real-world PIM: Alibaba HB-PNM (PDF) (PPT)		

Spring 2022 Edition:

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

Youtube Livestream:

- https://www.youtube.com/watch?v=9e4Chnwdovo&list=PL5Q2soXY2Zi-841fUYYUK9EsXKhQKRPyX

Project course

- Taken by Bachelor's/Master's students
- Processing-in-Memory lectures
- Hands-on research exploration
- Many research readings

Memory-Centric Computing

Onur Mutlu

omutlu@gmail.com

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

19 June 2022

HipChips Workshop Keynote (with ISCA 2022)

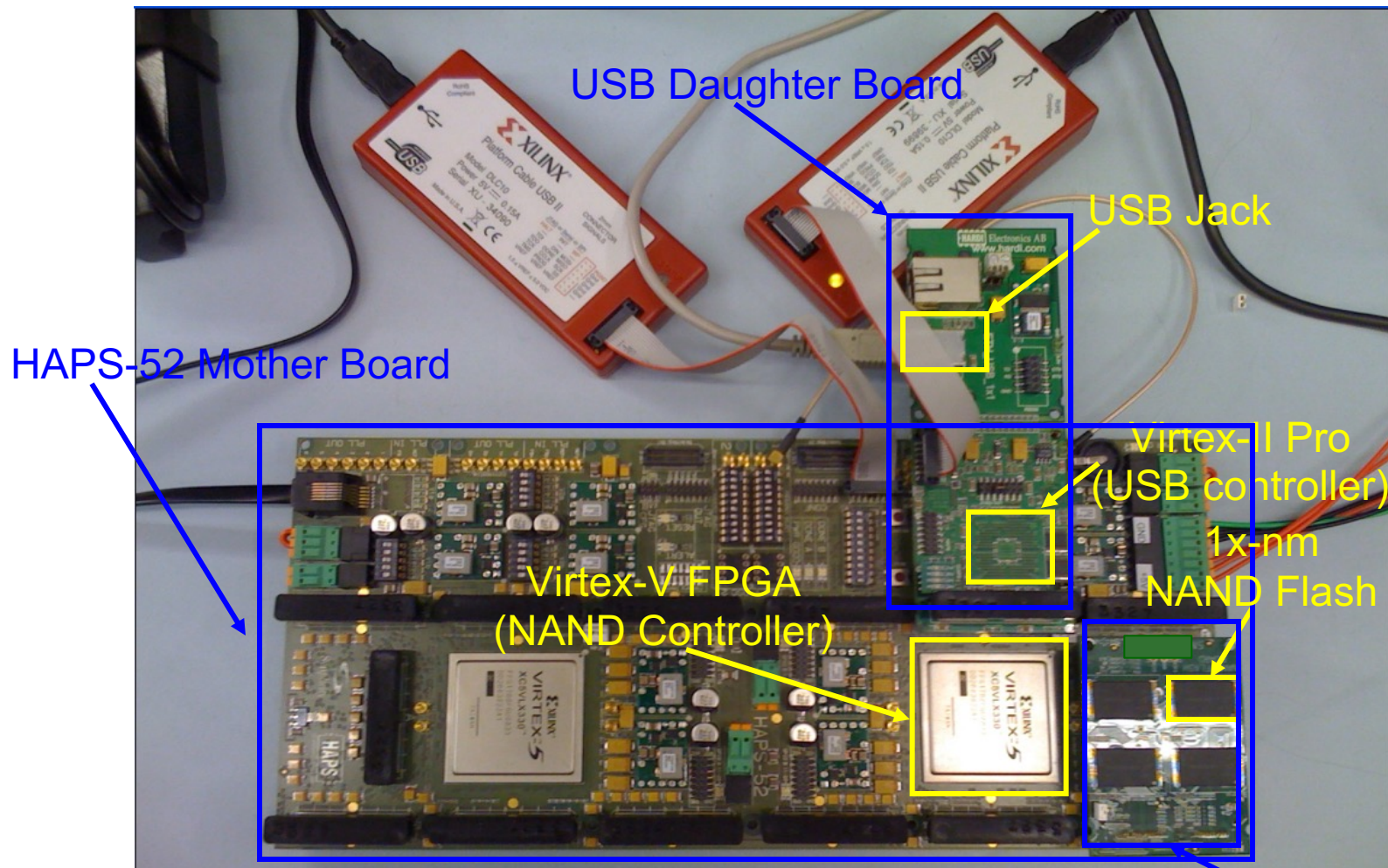
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Backup Slides

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>

System Desirables

- Self-managing, independent components
- All components intelligent & equal partners
- Easy collaboration & partitioning across all components
- Fine-grained communication of data & tasks
- Seamless caching & translation & protection anywhere
- Execution anywhere without rewriting code
- Flexibility, adaptability, self-optimization

Open minds

SAFARI Research Group

SAFARI Newsletter April 2020 Edition

- <https://safari.ethz.ch/safari-newsletter-april-2020/>



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Think Big, Aim High



Dear SAFARI friends,

2019 and the first three months of 2020 have been very positive eventful times for SAFARI.

SAFARI Newsletter January 2021 Edition

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



Newsletter
January 2021

*Think Big, Aim High, and
Have a Wonderful 2021!*



Dear SAFARI friends,

Happy New Year! We are excited to share our group highlights with you in this second edition of the SAFARI newsletter (You can find the first edition from April 2020 [here](#)). 2020 has

SAFARI Newsletter December 2021 Edition

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

SAFARI
SAFARI Research Group

Think Big, Aim High

ETH zürich



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December 2021



A Talk on Impactful Research & Teaching



The video player shows a presentation slide with the following content:

Applying to Grad School
& Doing Impactful Research

Onur Mutlu
omutlu@gmail.com
<https://people.inf.ethz.ch/omutlu>
13 June 2020
Undergraduate Architecture Mentoring Workshop @ ISCA 2021

Logos at the bottom of the slide: SAFARI, ETH zürich, Carnegie Mellon.

Below the video player, the YouTube interface shows:

Arch. Mentoring Workshop @ISCA'21 - Applying to Grad School & Doing Impactful Research - Onur Mutlu

1,563 views • Premiered Jun 16, 2021

Onur Mutlu Lectures
17.2K subscribers

Panel talk at Undergraduate Architecture Mentoring Workshop at ISCA 2021
(<https://sites.google.com/wisc.edu/uar...>)

Engagement icons: 74 likes, 1 comment, SHARE, SAVE, and a menu icon.

Buttons: ANALYTICS, EDIT VIDEO

An Interview on Computing Futures



Interview with Onur Mutlu @ ISCA 2019 on computing research & education (after Maurice Wilkes Award)

6,749 views • Oct 19, 2019

195 0 SHARE SAVE ...



Onur Mutlu Lectures
19.1K subscribers

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EDIT VIDEO

Latest Longer & Detailed Tutorial on PIM

- Onur Mutlu,
"Memory-Centric Computing"
Education Class at Embedded Systems Week (ESWEEK),
Virtual, 9 October 2021.
[Slides (pptx) (pdf)]
[Abstract (pdf)]
[Talk Video (2 hours, including Q&A)]
[Invited Paper at DATE 2021]
["A Modern Primer on Processing in Memory" paper]

<https://www.youtube.com/watch?v=N1Ac1ov1JOM>

Memory-Centric Computing

Onur Mutlu

omutlu@gmail.com

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

9 October 2021

ESWEEK Education Class

SAFARI

ETH zürich

Carnegie Mellon



1:08 / 2:00:10



Embedded Systems Week (ESWEEK) 2021 Lecture - Memory-Centric Computing - Onur Mutlu - 9 October 2021

509 views • Premiered Dec 6, 2021

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ANALYTICS

EDIT VIDEO

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

265

Detailed Lectures on PIM (I)

- **Computer Architecture, Fall 2020, Lecture 6**
 - **Computation in Memory** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=oGcZAGwfEUE&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=12>
- **Computer Architecture, Fall 2020, Lecture 7**
 - **Near-Data Processing** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=j2GIigqn1Qw&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=13>
- **Computer Architecture, Fall 2020, Lecture 11a**
 - **Memory Controllers** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=TeG773OgiMQ&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=20>
- **Computer Architecture, Fall 2020, Lecture 12d**
 - **Real Processing-in-DRAM with UPMEM** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=Sscy1Wrr22A&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=25>

Detailed Lectures on PIM (II)

- **Computer Architecture, Fall 2020, Lecture 15**
 - **Emerging Memory Technologies** (ETH Zürich, Fall 2020)
 - https://www.youtube.com/watch?v=AIE1rD9G_YU&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=28
- **Computer Architecture, Fall 2020, Lecture 16a**
 - **Opportunities & Challenges of Emerging Memory Technologies** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=pmLszWGmMGQ&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=29>
- **Computer Architecture, Fall 2020, Guest Lecture**
 - **In-Memory Computing: Memory Devices & Applications** (ETH Zürich, Fall 2020)
 - <https://www.youtube.com/watch?v=wNmQqHiEZnk&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=41>



Computer Architecture - Fall 2021

Recent Changes Media Manager Sitemap

Trace: • readings • start • **schedule**
schedule

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Announcements

Materials

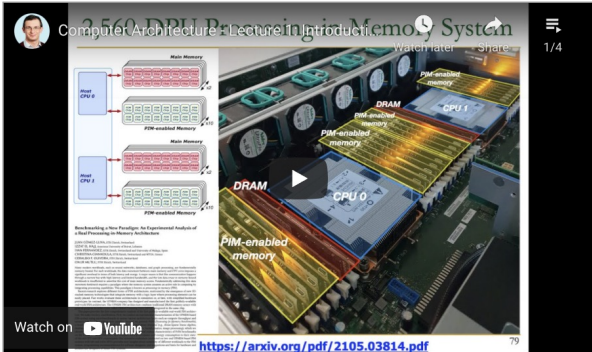
- Lectures/Schedule
- Lecture Buzzwords
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Resources

- Computer Architecture FS20: Course Webpage
- Computer Architecture FS20: Lecture Videos
- Digitaltechnik SS21: Course Webpage
- Digitaltechnik SS21: Lecture Videos
- Moodle
- HotCRP
- Verilog Practice Website (HDLBits)

Lecture Video Playlist on YouTube

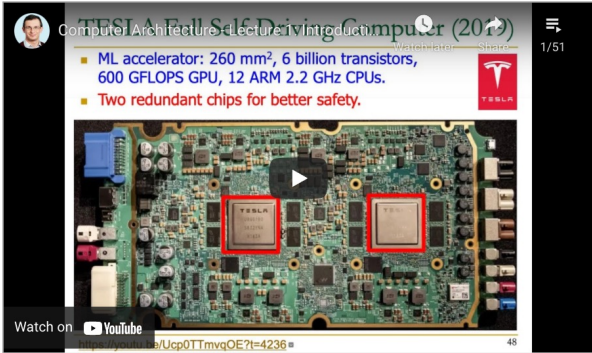
🔗 Livestream Lecture Playlist



2.560 DPU Processing in a Memory System

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

Recorded Lecture Playlist



TESLA Full Self-Driving Computer (2019)

Watch on  <https://www.youtube.com/watch?v=Ucp0TTmvqOE>

Fall 2021 Lectures & Schedule

Week	Date	Livestream	Lecture	Readings	Lab	HW
W1	30.09 Thu.	 Live	L1: Introduction and Basics PDF PPT	Required Mentioned	Lab 1 Out	HW 0 Out
	01.10 Fri.	 Live	L2: Trends, Tradeoffs and Design Fundamentals PDF PPT	Required Mentioned		
W2	07.10 Thu.	 Live	L3a: Memory Systems: Challenges and Opportunities PDF PPT	Described Suggested		HW 1 Out
			L3b: Course Info & Logistics PDF PPT			
			L3c: Memory Performance Attacks PDF PPT			
	08.10 Fri.	 Live	L4a: Memory Performance Attacks PDF PPT	Described Suggested	Lab 2 Out	
			L4b: Data Retention and Memory Refresh PDF PPT			
			L4c: RowHammer PDF PPT	Described Suggested		

□ <https://safari.ethz.ch/architecture/fall2021/doku.php?id=schedule>

□ https://www.youtube.com/watch?v=4yfkM_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF

- ❑ 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

PIM Course (Current)

Fall 2021 Edition:

- https://safari.ethz.ch/projects_and_seminars/fall2021/doku.php?id=processing_in_memory

Youtube Livestream:

- <https://www.youtube.com/watch?v=9e4Chnwdovo&list=PL5Q2soXY2Zi-841fUYYUK9EsXKhQKRPyX>

Project course

- Taken by Bachelor's/Master's students
- Processing-in-Memory lectures
- Hands-on research exploration
- Many research readings

PIM Review and Open Problems
Processing in Memory Course: Meeting 1: Ex...

Watch later Share 1/10

A Modern Primer on Processing in Memory

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

SAFARI Research Group

^aETH Zürich
^bCarnegie Mellon University
^cUniversity of Illinois at Urbana-Champaign
^dKing Mongkut's University of Technology North Bangkok

Onur Mutlu, Saugata Ghose, Juan Gomez-Luna, and Rachata Ausavarungnirun, "A Modern Primer on Processing in Memory" Invited Book Chapter in *Emerging Computing: From Devices to Systems - Looking Beyond Moore and Von Neumann*, Springer, to be published in 2021.

Watch on YouTube <https://arxiv.org/pdf/1903.03988.pdf> 108

Fall 2021 Meetings/Schedule

Week	Date	Livestream	Meeting	Learning Materials	Assignments
W1	05.10 Tue.	You Tube Live	M1: P&S PIM Course Presentation PDF (PDF) PPT (PPT)	Required Materials Recommended Materials	HW 0 Out
W2	12.10 Tue.	You Tube Live	M2: Real-World PIM Architectures PDF (PDF) PPT (PPT)		
W3	19.10 Tue.	You Tube Live	M3: Real-World PIM Architectures II PDF (PDF) PPT (PPT)		
W4	26.10 Tue.	You Tube Live	M4: Real-World PIM Architectures III PDF (PDF) PPT (PPT)		
W5	02.11 Tue.	You Tube Live	M5: Real-World PIM Architectures IV PDF (PDF) PPT (PPT)		
W6	09.11 Tue.	You Tube Live	M6: End-to-End Framework for Processing-using-Memory PDF (PDF) PPT (PPT)		
W7	16.11 Tue.	You Tube Live	M7: How to Evaluate Data Movement Bottlenecks PDF (PDF) PPT (PPT)		
W8	23.11 Tue.	You Tube Live	M8: Programming PIM Architectures PDF (PDF) PPT (PPT)		
W9	30.11 Tue.	You Tube Live	M9: Benchmarking and Workload Suitability on PIM PDF (PDF) PPT (PPT)		
W10	07.12 Tue.	You Tube Live	M10: Bit-Serial SIMD Processing using DRAM PDF (PDF) PPT (PPT)		



Onur Mutlu Lectures

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Computer Architecture - Lecture 1: Introduction and Basics

36K views • 3 years ago

Computer Architecture - Lecture 1: Introduction and Basics

31K views • 1 year ago

Computer Architecture - Lecture 1: Introduction and Basics

30K views • 8 months ago

Design of Digital Circuits - Lecture 1: Introduction and Basics

22K views • 2 years ago

Computer Architecture - Lecture 2: Fundamentals, Memory Hierarchy

17K views • 3 years ago

First Course in Computer Architecture & Digital Design 2021-2013

Livestream - Digital Design and Computer Architecture - ETH Zurich

Onur Mutlu Lectures

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Digital Design & Computer Architecture - ETH Zurich

Onur Mutlu Lectures

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Design of Digital Circuits - ETH Zurich - Spring 2019

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Design of Digital Circuits - ETH Zurich - Spring 2018

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Digital Circuits and Computer Architecture - ETH Zurich

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Spring 2015 -- Computer Architecture Lectures -- Carnegie Mellon

Onur Mutlu Lectures

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Advanced Computer Architecture Courses 2020-2012

Computer Architecture - ETH Zurich - Fall 2020

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Computer Architecture - ETH Zurich - Fall 2019

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Computer Architecture - ETH Zurich - Fall 2018

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Computer Architecture - ETH Zurich - Fall 2017

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Fall 2015 - 740 Computer Architecture

Carnegie Mellon Computer Architecture

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Fall 2013 - 740 Computer Architecture - Carnegie Mellon

Carnegie Mellon Computer Architecture

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Special Courses on Memory Systems

Memory Technology Lectures

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Champéry Winter School 2020 - Memory Systems and Memory

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Perugia NiPS Summer School 2019

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SAMOS Tutorial 2019 - Memory Systems

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TU Wien 2019 - Memory Systems and Memory-Centric

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ACACES 2018 Lectures -- Memory Systems and Memory

Onur Mutlu Lectures

VIEW FULL PLAYLIST

Data-Driven Architectures

Corollaries: Architectures Today ...

- Architectures are **terrible at dealing with data**
 - ❑ Designed to mainly store and move data vs. to compute
 - ❑ They are **processor-centric** as opposed to **data-centric**
- Architectures are **terrible at taking advantage of vast amounts of data** (and metadata) available to them
 - ❑ Designed to make simple decisions, ignoring lots of data
 - ❑ They make **human-driven decisions** vs. **data-driven** decisions
- Architectures are **terrible at knowing and exploiting different properties of application data**
 - ❑ Designed to treat all data as the same
 - ❑ They make **component-aware decisions** vs. **data-aware**

Exploiting Data to Design Intelligent Architectures

System Architecture Design Today

- Human-driven
 - Humans design the policies (how to do things)
- Many (too) simple, short-sighted policies all over the system
- No automatic data-driven policy learning
- (Almost) no learning: cannot take lessons from past actions

**Can we design
fundamentally intelligent architectures?**

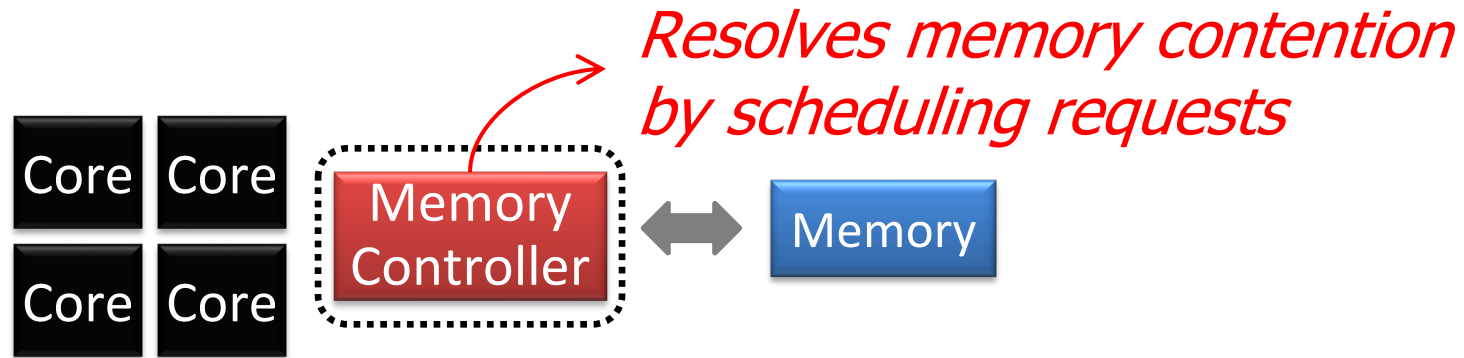
An Intelligent Architecture

- Data-driven
 - Machine learns the “best” policies (how to do things)
- Sophisticated, workload-driven, changing, far-sighted policies
- Automatic data-driven policy learning
- All controllers are intelligent data-driven agents

How do we start?

Self-Optimizing Memory Controllers

Memory Controller



How to schedule requests to maximize system performance?

Why are Memory Controllers Difficult to Design?

- Need to obey **DRAM timing constraints** for correctness
 - There are many (50+) timing constraints in DRAM
 - tWTR: Minimum number of cycles to wait before issuing a read command after a write command is issued
 - tRC: Minimum number of cycles between the issuing of two consecutive activate commands to the same bank
 - ...
- Need to **keep track of many resources** to prevent conflicts
 - Channels, banks, ranks, data bus, address bus, row buffers, ...
- Need to handle **DRAM refresh**
- Need to **manage power** consumption
- Need to **optimize performance & QoS** (in the presence of constraints)
 - Reordering is not simple
 - Fairness and QoS needs complicates the scheduling problem
- ...

Many Memory Timing Constraints

Latency	Symbol	DRAM cycles	Latency	Symbol	DRAM cycles
Precharge	t_{RP}	11	Activate to read/write	t_{RCD}	11
Read column address strobe	CL	11	Write column address strobe	CWL	8
Additive	AL	0	Activate to activate	t_{RC}	39
Activate to precharge	t_{RAS}	28	Read to precharge	t_{RTP}	6
Burst length	t_{BL}	4	Column address strobe to column address strobe	t_{CCD}	4
Activate to activate (different bank)	t_{RRD}	6	Four activate windows	t_{FAW}	24
Write to read	t_{WTR}	6	Write recovery	t_{WR}	12

Table 4. DDR3 1600 DRAM timing specifications

- From Lee et al., “[DRAM-Aware Last-Level Cache Writeback: Reducing Write-Caused Interference in Memory Systems](#),” HPS Technical Report, April 2010.

Many Memory Timing Constraints

- Kim et al., "A Case for Exploiting Subarray-Level Parallelism (SALP) in DRAM," ISCA 2012.
- Lee et al., "Tiered-Latency DRAM: A Low Latency and Low Cost DRAM Architecture," HPCA 2013.

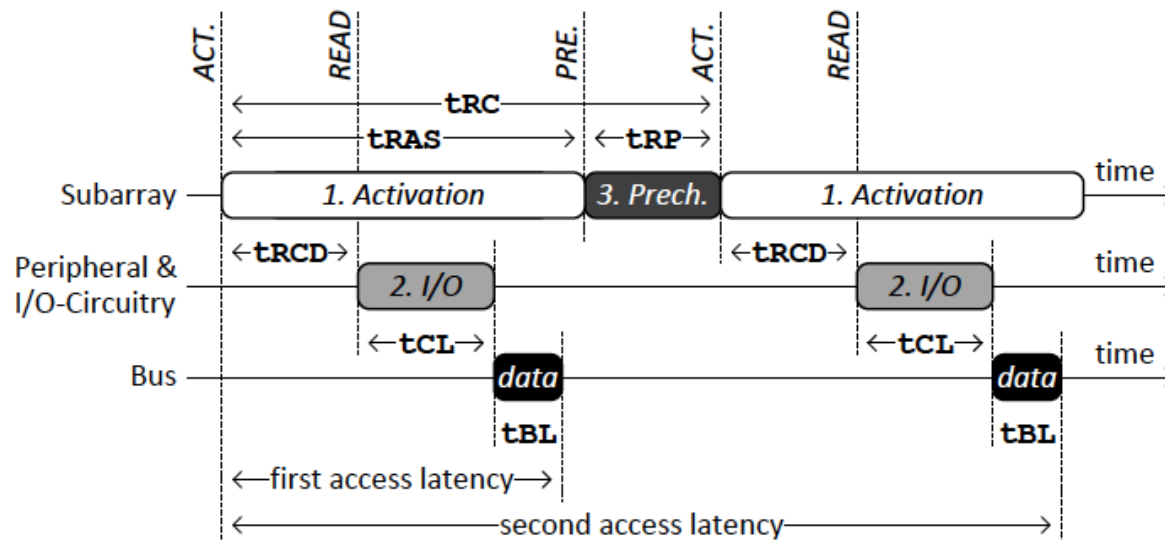
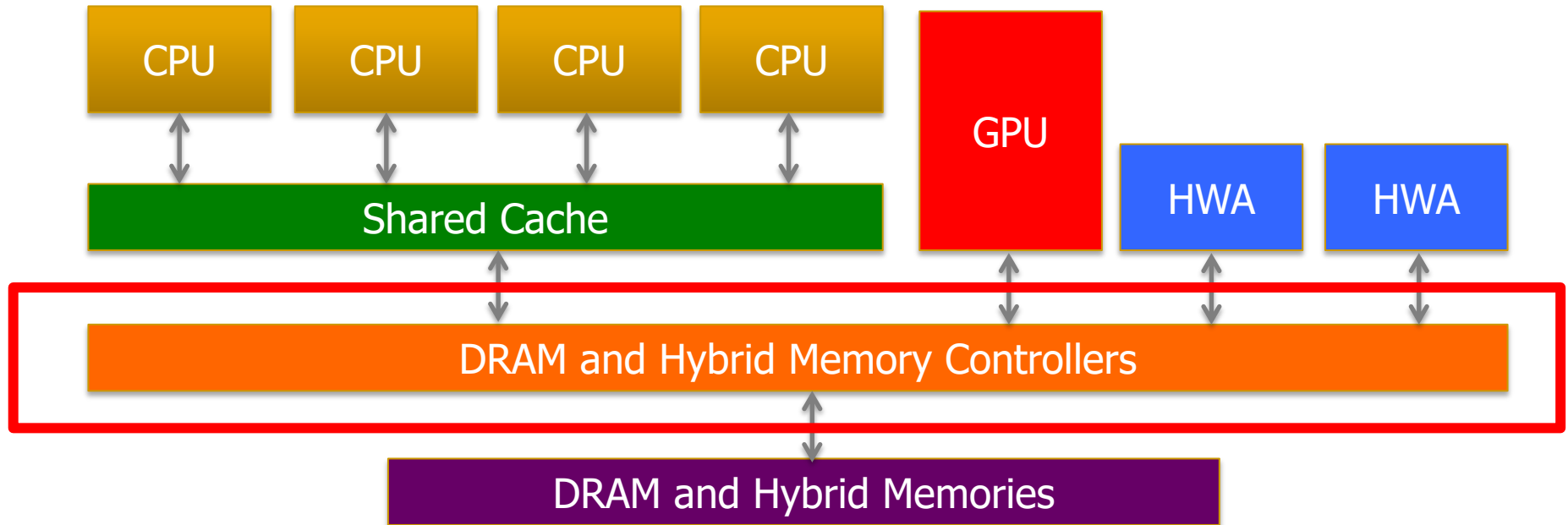


Figure 5. Three Phases of DRAM Access

Table 2. Timing Constraints (DDR3-1066) [43]

Phase	Commands	Name	Value
1	ACT $\rightarrow$ READ	t_{RCD}	15ns
	ACT $\rightarrow$ WRITE		
	ACT $\rightarrow$ PRE	t_{RAS}	37.5ns
2	READ $\rightarrow$ <i>data</i>	t_{CL}	15ns
	WRITE $\rightarrow$ <i>data</i>	t_{CWL}	11.25ns
	<i>data burst</i>	t_{BL}	7.5ns
3	PRE $\rightarrow$ ACT	t_{RP}	15ns
1 & 3	ACT $\rightarrow$ ACT	t_{RC} ($t_{\text{RAS}}+t_{\text{RP}}$)	52.5ns

Memory Controller Design Is Becoming More Difficult



- Heterogeneous agents: CPUs, GPUs, and HWAs
- Main memory interference between CPUs, GPUs, HWAs
- Many timing constraints for various memory types
- Many goals at the same time: performance, fairness, QoS, energy efficiency, ...

Reality and Dream

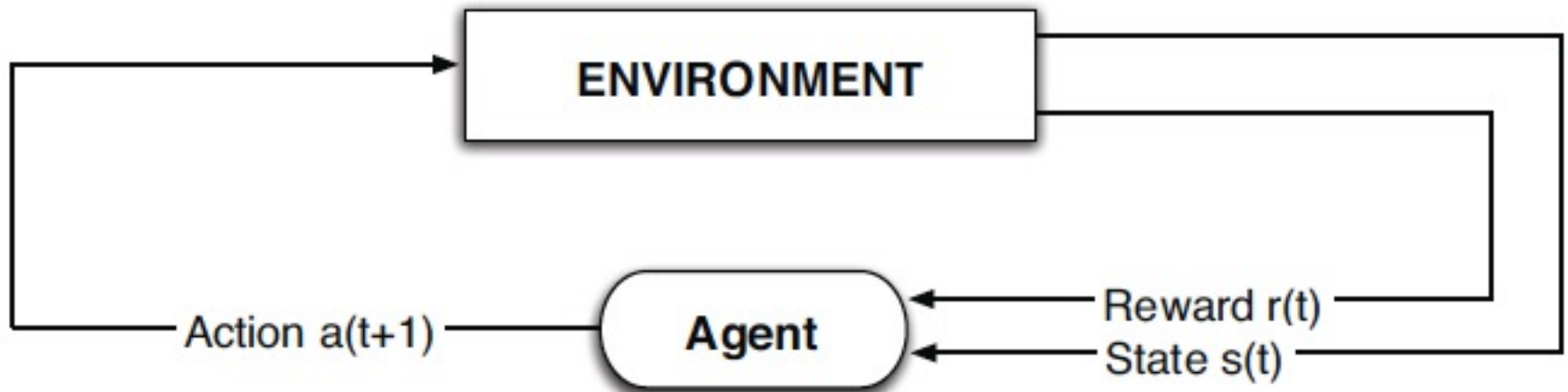
- **Reality**: It difficult to design a policy that maximizes performance, QoS, energy-efficiency, ...
 - Too many things to think about
 - Continuously changing workload and system behavior

- **Dream**: Wouldn't it be nice if the DRAM controller automatically found a good scheduling policy on its own?

Self-Optimizing DRAM Controllers

- Problem: DRAM controllers are difficult to design
 - It is difficult for human designers to design a policy that can adapt itself very well to different workloads and different system conditions
- Idea: A memory controller that adapts its scheduling policy to workload behavior and system conditions using machine learning.
- Observation: Reinforcement learning maps nicely to memory control.
- Design: Memory controller is a reinforcement learning agent
 - It dynamically and continuously learns and employs the best scheduling policy to maximize long-term performance.

Self-Optimizing DRAM Controllers

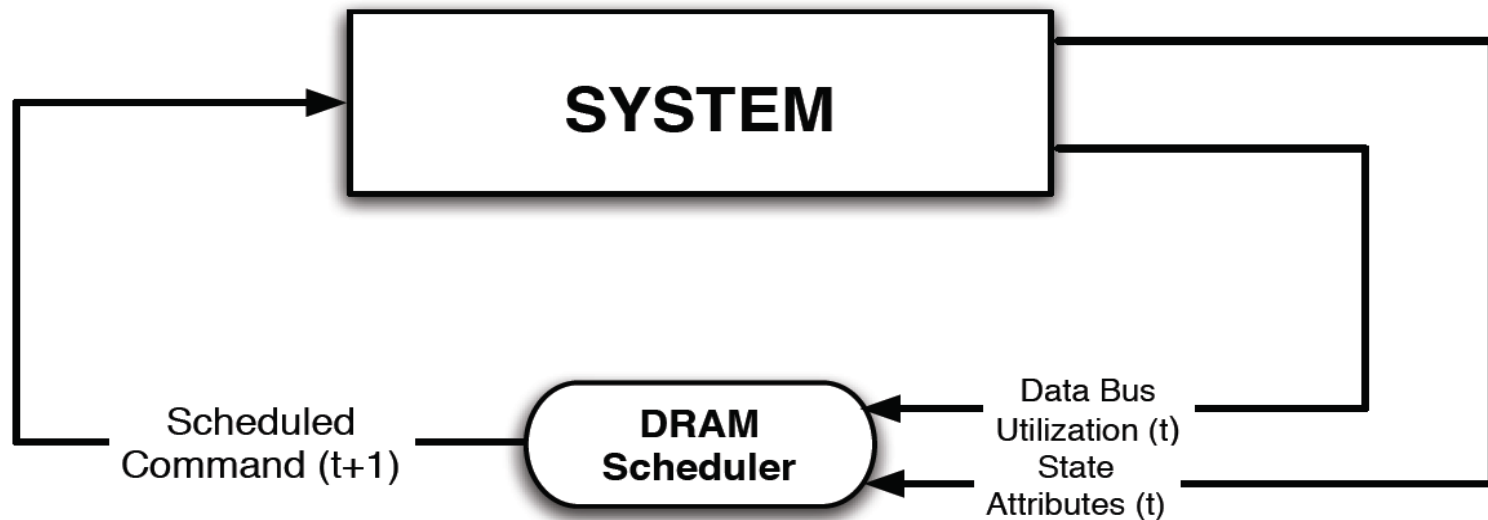


Goal: Learn to choose actions to maximize $r_0 + \gamma r_1 + \gamma^2 r_2 + \dots$ ($0 \leq \gamma < 1$)

Figure 2: (a) Intelligent agent based on reinforcement learning principles;

Self-Optimizing DRAM Controllers

- Dynamically adapt the memory scheduling policy via interaction with the system at runtime
 - Associate system states and actions (commands) with long term reward values: each action at a given state leads to a learned reward
 - Schedule command with highest estimated long-term reward value in each state
 - Continuously update reward values for $\langle \text{state}, \text{action} \rangle$ pairs based on feedback from system



Self-Optimizing DRAM Controllers

- Engin Ipek, Onur Mutlu, José F. Martínez, and Rich Caruana,
"Self Optimizing Memory Controllers: A Reinforcement Learning Approach"

Proceedings of the 35th International Symposium on Computer Architecture (ISCA), pages 39-50, Beijing, China, June 2008.

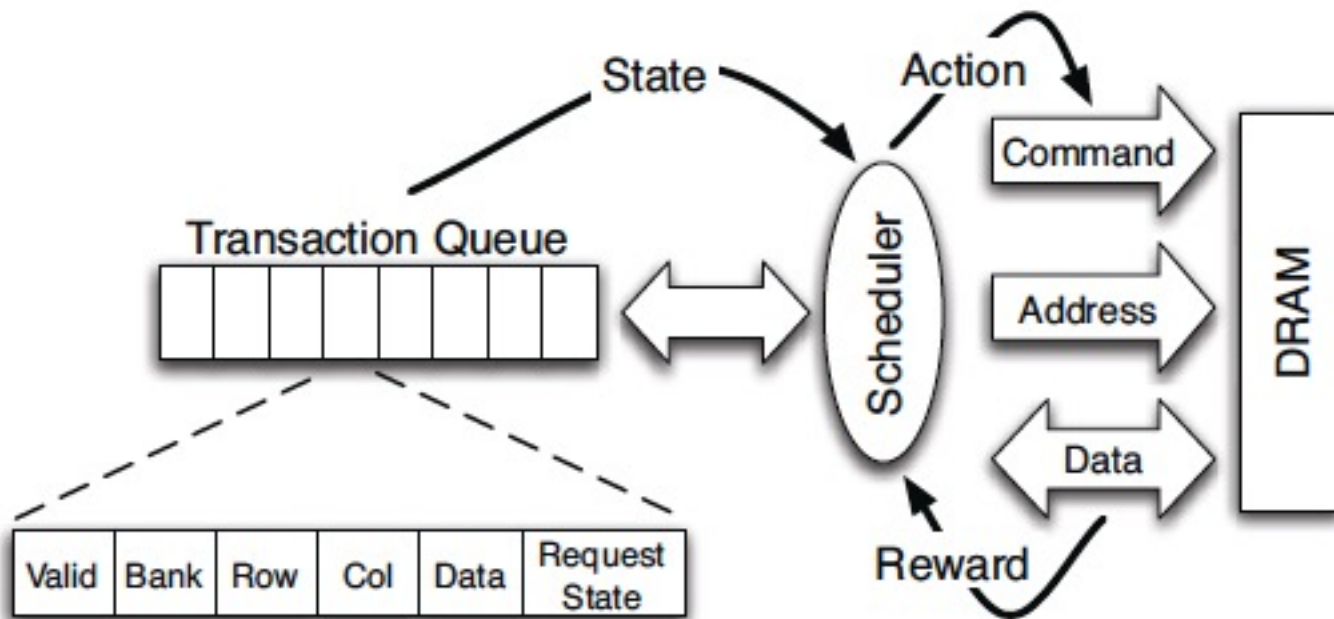


Figure 4: High-level overview of an RL-based scheduler.

States, Actions, Rewards

❖ Reward function

- +1 for scheduling Read and Write commands
- 0 at all other times

Goal is to maximize long-term data bus utilization

❖ State attributes

- Number of reads, writes, and load misses in transaction queue
- Number of pending writes and ROB heads waiting for referenced row
- Request's relative ROB order

❖ Actions

- Activate
- Write
- Read - load miss
- Read - store miss
- Precharge - pending
- Precharge - preemptive
- NOP

Performance Results

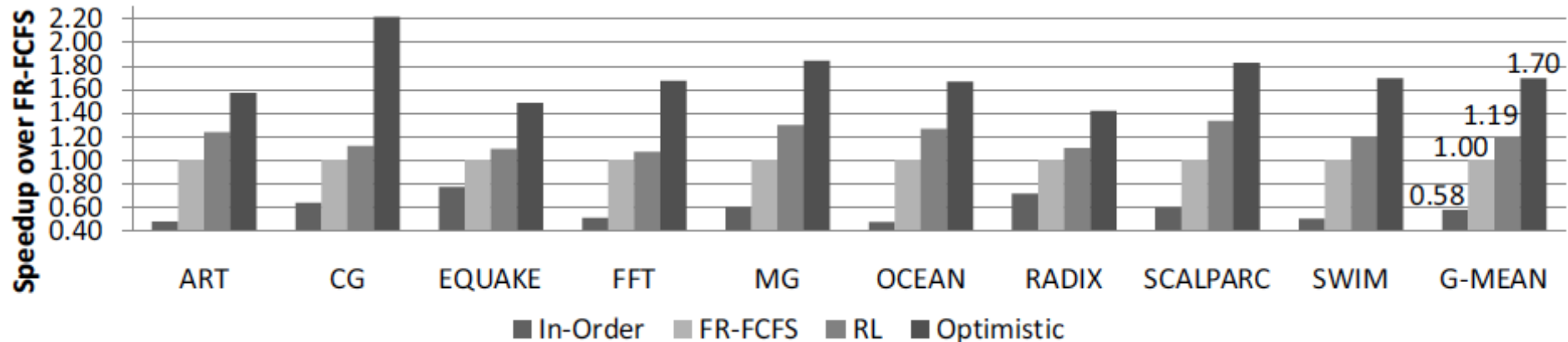


Figure 7: Performance comparison of in-order, FR-FCFS, RL-based, and optimistic memory controllers

Large, robust performance improvements over many human-designed policies

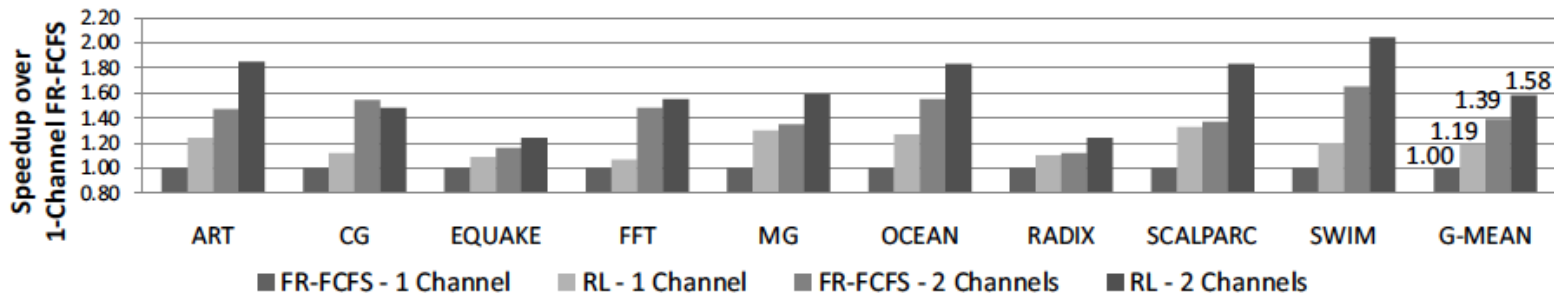


Figure 15: Performance comparison of FR-FCFS and RL-based memory controllers on systems with 6.4GB/s and 12.8GB/s peak DRAM bandwidth

Self Optimizing DRAM Controllers

+ Continuous learning in the presence of changing environment

+ Reduced designer burden in finding a good scheduling policy.

Designer specifies:

1) What system variables might be useful

2) What target to optimize, but not how to optimize it

-- How to specify different objectives? (e.g., fairness, QoS, ...)

-- Hardware complexity?

-- Design mindset and flow

More on Self-Optimizing DRAM Controllers

- Engin Ipek, Onur Mutlu, José F. Martínez, and Rich Caruana,
"Self Optimizing Memory Controllers: A Reinforcement Learning Approach"
Proceedings of the 35th International Symposium on Computer Architecture (ISCA), pages 39-50, Beijing, China, June 2008.

Self-Optimizing Memory Controllers: A Reinforcement Learning Approach

Engin İpek^{1,2} Onur Mutlu² José F. Martínez¹ Rich Caruana¹

¹Cornell University, Ithaca, NY 14850 USA

²Microsoft Research, Redmond, WA 98052 USA

Self-Optimizing Memory Prefetchers

- Rahul Bera, Konstantinos Kanellopoulos, Anant Nori, Taha Shahroodi, Sreenivas Subramoney, and Onur Mutlu,

"Pythia: A Customizable Hardware Prefetching Framework Using Online Reinforcement Learning"

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](#) (20 minutes)]

[[Lightning Talk Video](#) (1.5 minutes)]

[[Pythia Source Code \(Officially Artifact Evaluated with All Badges\)](#)]

[[arXiv version](#)]

Pythia: A Customizable Hardware Prefetching Framework Using Online Reinforcement Learning

Rahul Bera¹ Konstantinos Kanellopoulos¹ Anant V. Nori² Taha Shahroodi^{3,1}
Sreenivas Subramoney² Onur Mutlu¹

¹ETH Zürich

²Processor Architecture Research Labs, Intel Labs

³TU Delft



Pythia

A Customizable Hardware Prefetching Framework Using Online Reinforcement Learning

Rahul Bera, Konstantinos Kanellopoulos, Anant V. Nori,
Taha Shahroodi, Sreenivas Subramoney, Onur Mutlu

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



Executive Summary

- **Background:** Prefetchers predict addresses of future memory requests by associating memory access patterns with program context (called **feature**)
- **Problem:** Three key shortcomings of prior prefetchers:
 - Predict mainly using a **single program feature**
 - Lack **inherent system awareness** (e.g., memory bandwidth usage)
 - Lack **in-silicon customizability**
- **Goal:** Design a prefetching framework that:
 - Learns from **multiple features** and **inherent system-level feedback**
 - Can be **customized in silicon** to use different features and/or prefetching objectives
- **Contribution:** Pythia, which formulates prefetching as reinforcement learning problem
 - Takes **adaptive** prefetch decisions using multiple features and system-level feedback
 - Can be **customized in silicon** for target workloads via simple configuration registers
 - Proposes **a realistic and practical** implementation of RL algorithm in hardware
- **Key Results:**
 - Evaluated using a wide range of workloads from SPEC CPU, PARSEC, Ligra, Cloudsuite
 - Outperforms best prefetcher (in 1-core config.) by **3.4%, 7.7% and 17%** in 1/4/bw-constrained cores
 - Up to **7.8% more performance** over basic Pythia across Ligra workloads via simple customization

Key Shortcomings in Prior Prefetchers

- We observe **three key shortcomings** that significantly limit performance benefits of prior prefetchers

1 Predict mainly using a **single program feature**

2 Lack inherent **system awareness**

3 Lack **in-silicon customizability**

Our Goal

A **prefetching framework** that can:

1. Learn to prefetch using **multiple features** and **inherent system-level feedback** information
2. Be **easily customized in silicon** to use different features and/or change prefetcher's objectives

Our Proposal



Pythia

Formulates prefetching as a
reinforcement learning problem

Basics of Reinforcement Learning (RL)

- Algorithmic approach to learn to take an **action** in a given **situation** to maximize a numerical **reward**

Agent

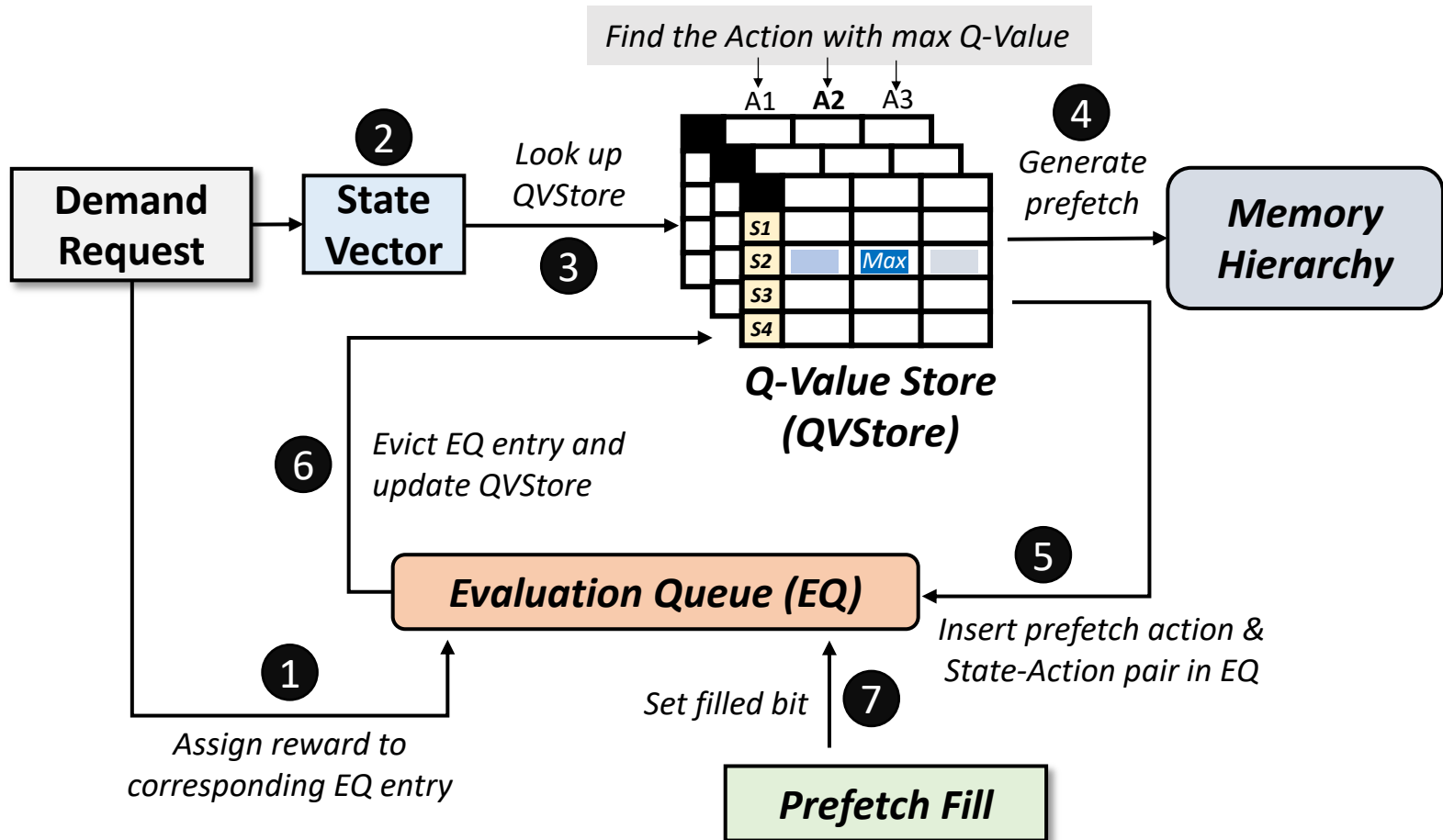
Environment

- Agent stores **Q-values** for *every* state-action pair
 - **Expected return** for taking an action in a state
 - Given a state, selects action that provides **highest** Q-value

Formulating Prefetching as RL

Pythia Overview

- **Q-Value Store**: Records Q-values for *all* state-action pairs
- **Evaluation Queue**: A FIFO queue of recently-taken actions



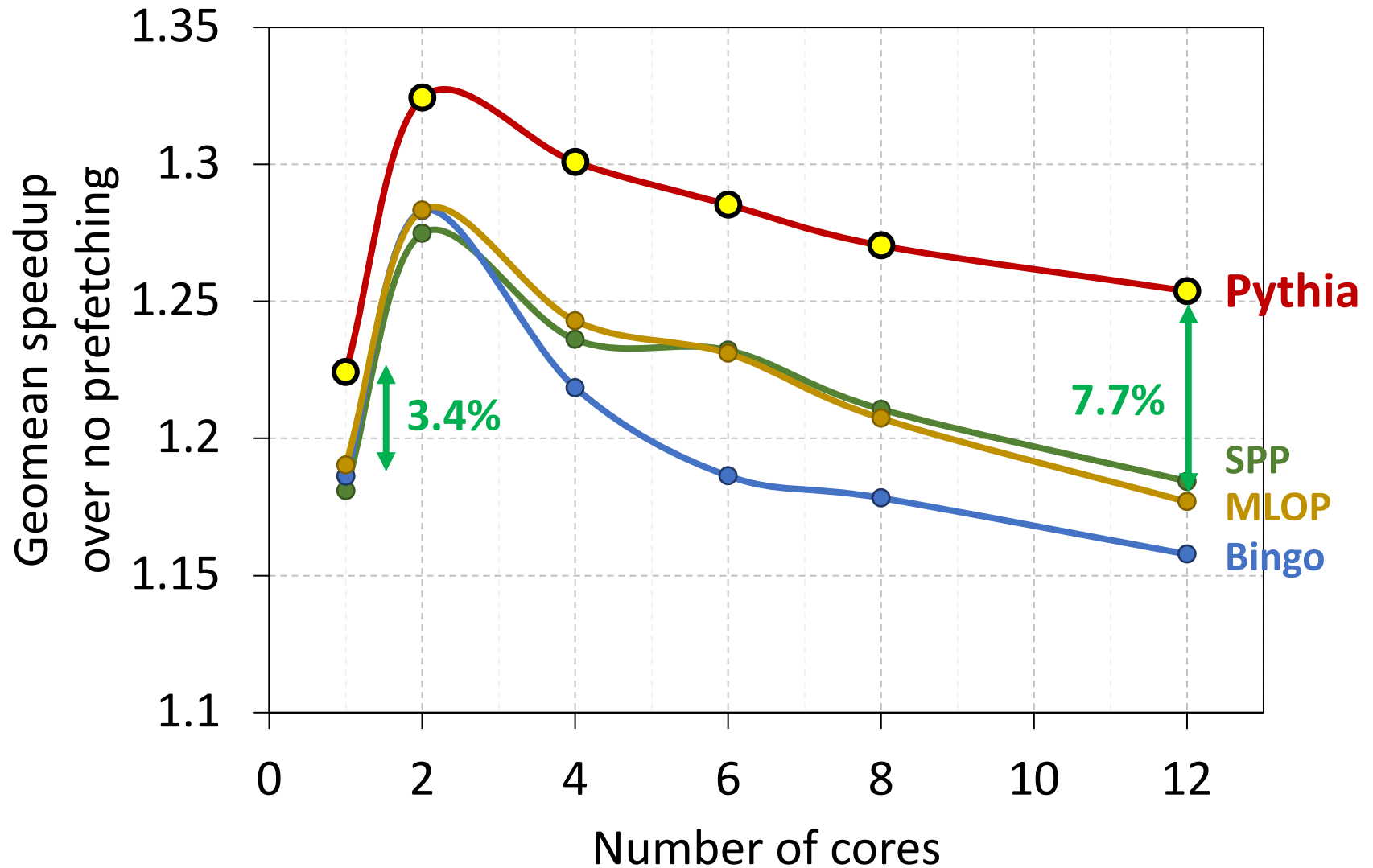
Simulation Methodology

- **Champsim** [3] trace-driven simulator
- **150** single-core memory-intensive workload traces
 - SPEC CPU2006 and CPU2017
 - PARSEC 2.1
 - Ligra
 - Cloudsuite
- Homogeneous and heterogeneous multi-core mixes
- **Five** state-of-the-art prefetchers
 - SPP [Kim+, MICRO'16]
 - Bingo [Bakhshalipour+, HPCA'19]
 - MLOP [Shakerinava+, 3rd Prefetching Championship, 2019]
 - SPP+DSPatch [Bera+, MICRO'19]
 - SPP+PPF [Bhatia+, ISCA'20]

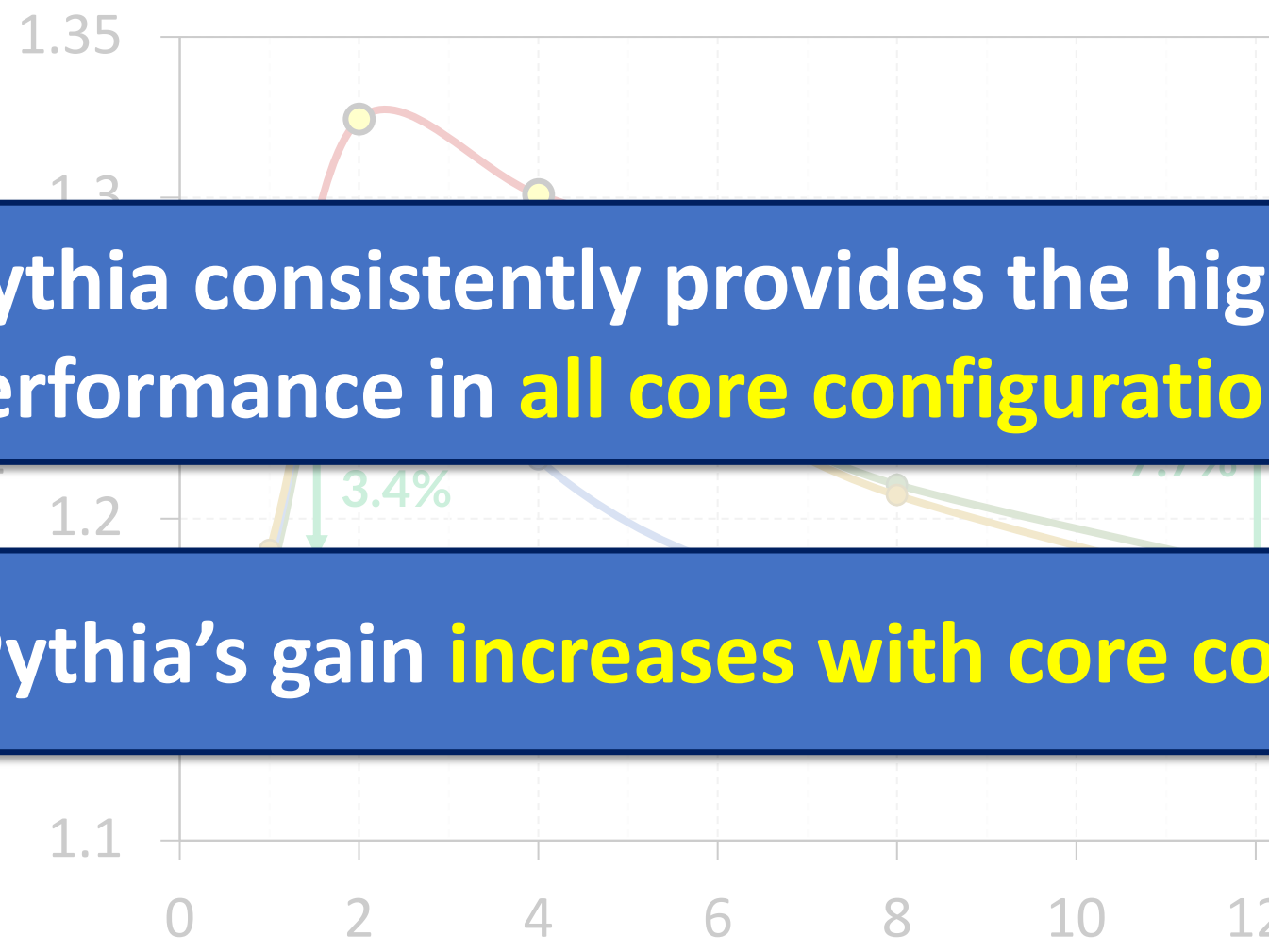
Basic Pythia Configuration

- Derived from **automatic design-space exploration**
- **State:** 2 features
 - PC+Delta
 - Sequence of last-4 deltas
- **Actions:** 16 prefetch offsets
 - Ranging between -6 to +32. Including 0.
- **Rewards:**
 - $R_{AT} = +20$; $R_{AL} = +12$; $R_{NP-H} = -2$; $R_{NP-L} = -4$;
 - $R_{IN-H} = -14$; $R_{IN-L} = -8$; $R_{CL} = -12$

Performance with Varying Core Count



Performance with Varying Core Count

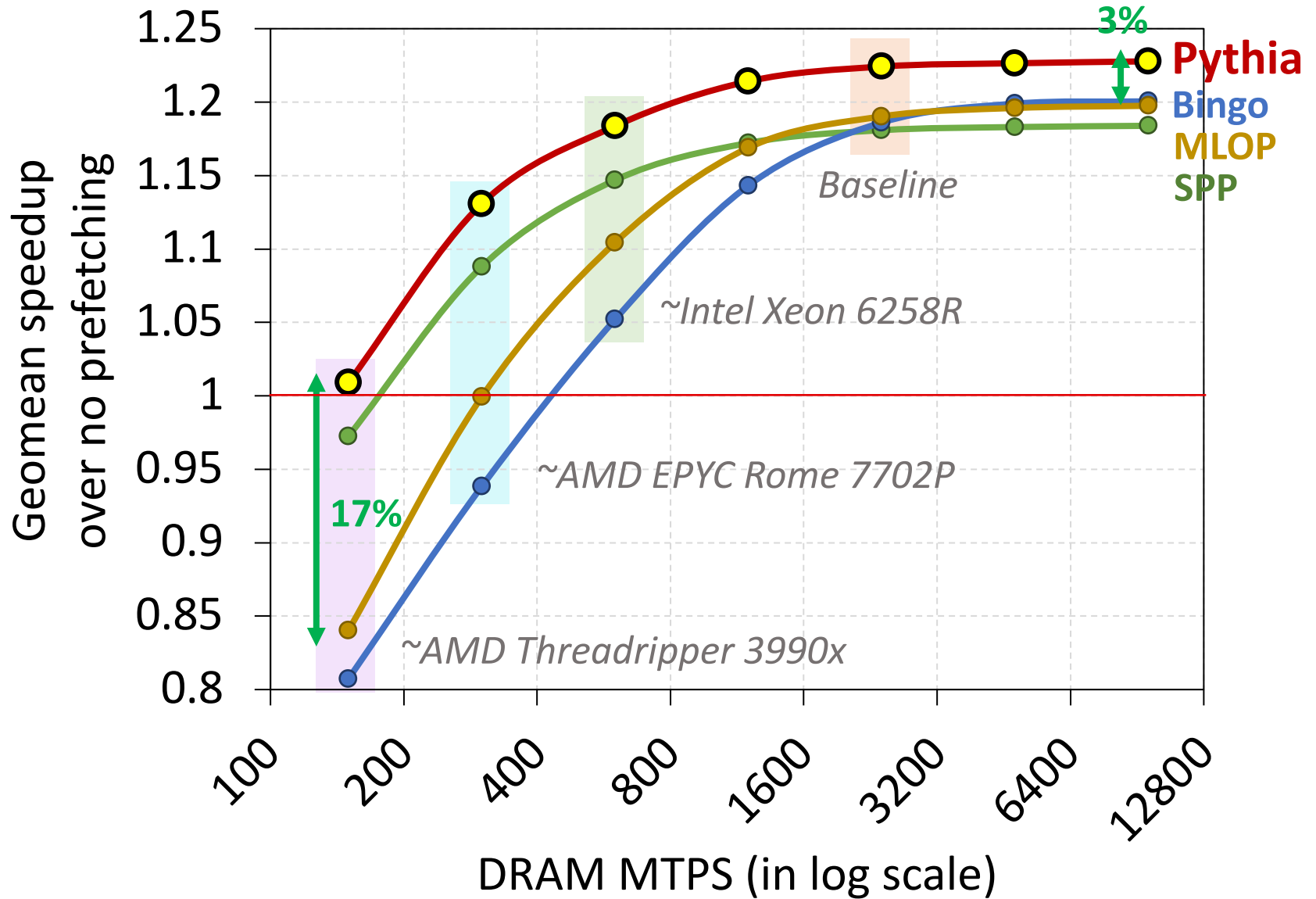


The graph shows performance on the y-axis (ranging from 1.1 to 1.35) against the number of cores on the x-axis (ranging from 0 to 12). Pythia (red line) starts at ~1.28 at 2 cores, peaks at ~1.32 at 4 cores, and then declines. Other models (blue, green, orange lines) show lower performance, with a green line showing a 3.4% gain at 8 cores. A vertical green line at 12 cores is labeled 'SDD'.

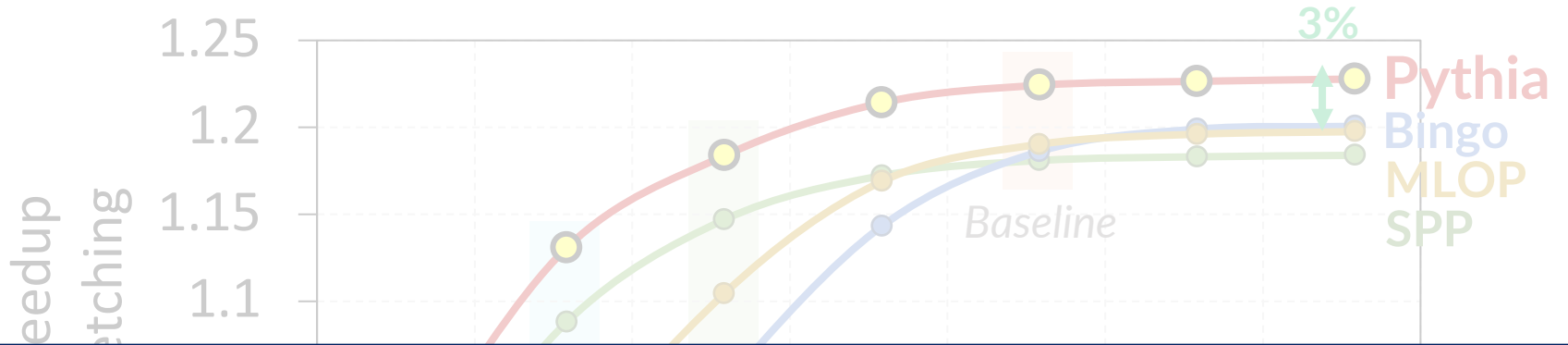
1. Pythia consistently provides the highest performance in **all core configurations**

2. Pythia's gain **increases with core count**

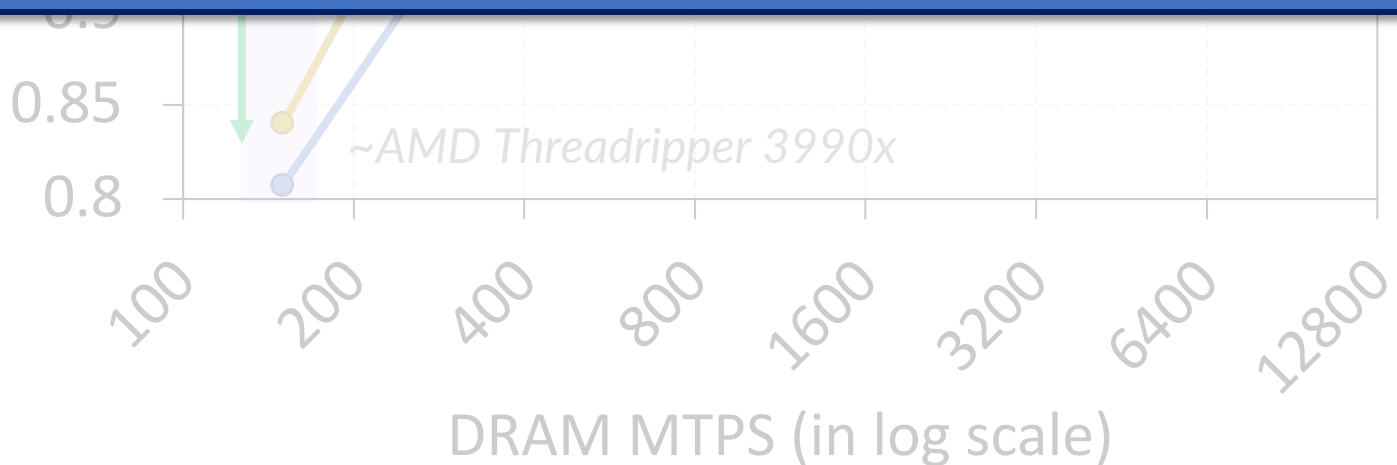
Performance with Varying DRAM Bandwidth



Performance with Varying DRAM Bandwidth



Pythia outperforms prior best prefetchers for a wide range of DRAM bandwidth configurations



Pythia's Overhead

- **25.5 KB** of total metadata storage **per core**
 - Only simple tables
- We also model functionally-accurate Pythia with full complexity in **Chisel** [4] HDL



1.03% area overhead



0.4% power overhead



Satisfies prediction latency

of a desktop-class 4-core Skylake processor (Xeon D2132IT, 60W)

More in the Paper

- Performance comparison with **unseen traces**
 - Pythia provides equally high performance benefits

• Comparison against **multi-level prefetchers**

Pythia: A Customizable Hardware Prefetching Framework Using Online Reinforcement Learning

Rahul Bera¹ Konstantinos Kanellopoulos¹ Anant V. Nori² Taha Shahroodi^{3,1}
Sreenivas Subramoney² Onur Mutlu¹

¹ETH Zürich

²Processor Architecture Research Labs, Intel Labs

³TU Delft

<https://arxiv.org/pdf/2109.12021.pdf>

- **Performance sensitivity** towards different features and hyperparameter values

- Detailed single-core and four-core performance

Pythia is Open Source



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

- MICRO'21 **artifact evaluated**
- **Champsim source** code + **Chisel** modeling code
- **All traces** used for evaluation

The screenshot shows the GitHub repository for CMU-SAFARI/Pythia. The repository is public and has 3 unwatchers, 7 stars, and 2 forks. The main navigation bar includes links to Code, Issues, Pull requests, Actions, Projects, Wiki, Security, Insights, and Settings. The repository is currently on the master branch, with 1 branch and 5 tags. The commit history table shows the following entries:

Commit	Message	Time
f96dee9	Updated README	2 days ago
	branch	Initial commit for MICRO'21 artifact evaluation (2 months ago)
	config	Initial commit for MICRO'21 artifact evaluation (2 months ago)
	experiments	Added chart visualization in Excel template (2 months ago)
	inc	Updated README (6 days ago)
	prefetcher	Initial commit for MICRO'21 artifact evaluation (2 months ago)
	replacement	Initial commit for MICRO'21 artifact evaluation (2 months ago)
	scripts	Added md5 checksum for all artifact traces to verify download (2 months ago)
	src	Initial commit for MICRO'21 artifact evaluation (2 months ago)
	tracer	Initial commit for MICRO'21 artifact evaluation (2 months ago)
	.gitignore	Initial commit for MICRO'21 artifact evaluation (2 months ago)
	CITATION.cff	Added citation file (6 days ago)
	LICENSE	Updated LICENSE (2 months ago)
	LICENSE.champsim	Initial commit for MICRO'21 artifact evaluation (2 months ago)

The right sidebar contains the 'About' section, which describes Pythia as a customizable hardware prefetching framework using online reinforcement learning, as described in the MICRO 2021 paper by Bera and Kanellopoulos et al. It includes a link to the arXiv paper (arxiv.org/pdf/2109.12021.pdf) and a list of tags: machine-learning, reinforcement-learning, computer-architecture, prefetcher, microarchitecture, cache-replacement, branch-predictor, champsim-simulator, and champsim-tracer. Below the 'About' section are links to the README, View license, and Cite this repository. The 'Releases' section shows 5 releases.



Pythia

A Customizable Hardware Prefetching Framework Using Online Reinforcement Learning

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



Self-Optimizing Memory Prefetchers

- Rahul Bera, Konstantinos Kanellopoulos, Anant Nori, Taha Shahroodi, Sreenivas Subramoney, and Onur Mutlu,
"Pythia: A Customizable Hardware Prefetching Framework Using Online Reinforcement Learning"

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](#) (20 minutes)]

[[Lightning Talk Video](#) (1.5 minutes)]

[[Pythia Source Code \(Officially Artifact Evaluated with All Badges\)](#)]

[[arXiv version](#)]

Pythia: A Customizable Hardware Prefetching Framework Using Online Reinforcement Learning

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Self-Optimizing Hybrid Storage Systems

- To appear in ISCA 2022

Sibyl: Adaptive and Extensible Data Placement in Hybrid Storage Systems Using Online Reinforcement Learning

Gagandeep Singh¹ Rakesh Nadig¹ Jisung Park¹ Rahul Bera¹ Nastaran Hajinazar¹
David Novo³ Juan Gómez-Luna¹ Sander Stuijk² Henk Corporaal² Onur Mutlu¹

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<https://arxiv.org/pdf/2205.07394.pdf>

Sibyl:

Adaptive and Extensible Data Placement in Hybrid Storage Systems Using Online Reinforcement Learning

Gagandeep Singh, Rakesh Nadig, Jisung Park, Rahul Bera, Nastaran Hajinazar,
David Novo, Juan Gómez-Luna, Onur Mutlu

Executive Summary

Background: Hybrid storage systems (HSSs) complement different storage technologies to extend the overall capacity and reduce the system cost with minimal effect on the application performance

Problem: Accurately identify the performance-critical data of an application and placing it in the “best-fit” storage device. Three key shortcomings of prior data placement policies (heuristic-based and supervised learning-based) of hybrid storage systems:

- Lack of **adaptability**
- Lack of **device awareness (e.g., read/write latencies of each device)**
- Lack of **extensibility**

Goal: Develop a new, efficient, and high performance data-placement mechanism for hybrid storage systems that can:

- Dynamically derive an adaptive data-placement strategy by **continuously learning and adapting** to the **application and underlying device characteristics**
- **Easily extensible** to incorporate a wide range of hybrid storage configurations.

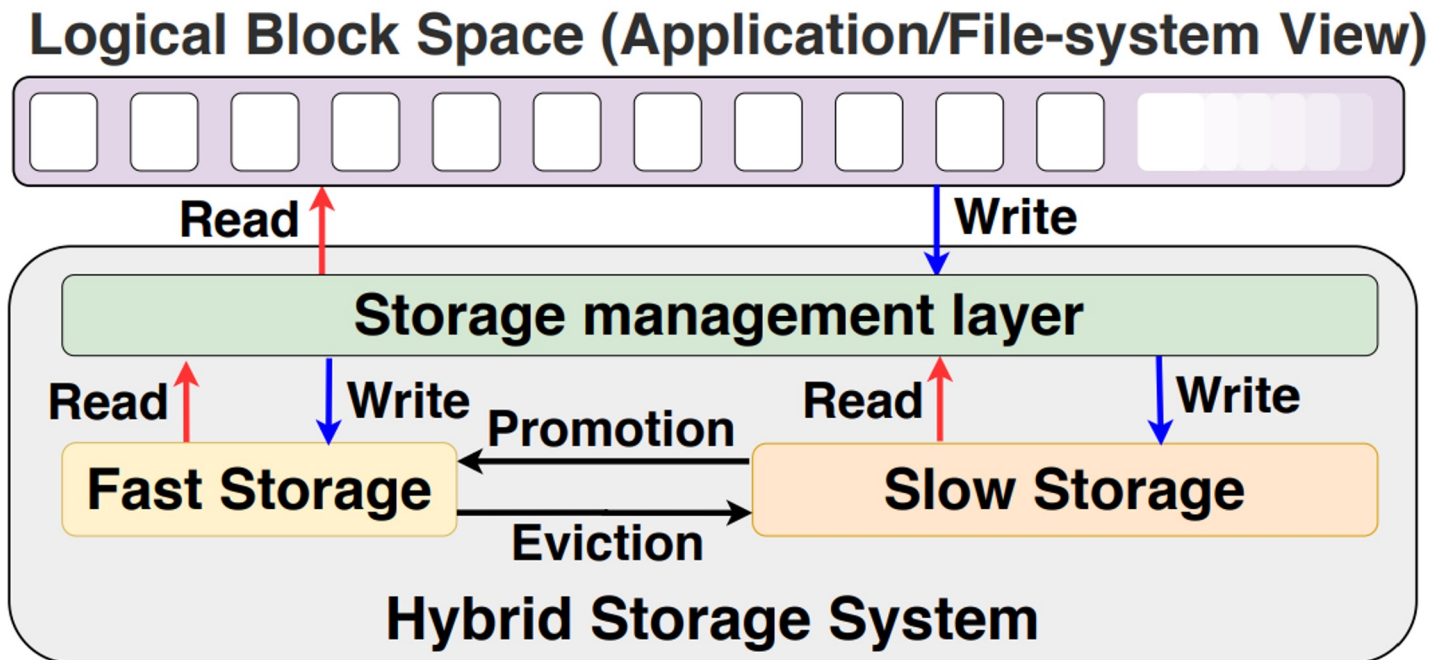
Key Idea: Sibyl, an online reinforcement learning-based self-optimizing mechanism for data placement that:

- **Dynamically learns** from past experiences and **continuously adapts** its policy to improve long-term performance by interacting with the hybrid storage system
- **Learns the asymmetry in the read/write latencies** present in modern hybrid storage devices while **taking into account** the **inherent characteristics of an application**

Key Results: Sibyl is evaluated on a real system with multiple device configurations

- Evaluated using a **wide range of workloads** from MSR Cambridge and Filebench
- In a performance (cost) optimized hybrid storage configuration, Sibyl provides up to **21.6% (19.9%)** performance improvement compared to prior data placement policies
- On a tri-hybrid storage system, Sibyl outperforms a heuristics-based policy by **23.9% -48.2%**
- Sibyl achieves **80%** performance of an oracle policy with storage overhead of **124.4 KiB**

Hybrid Storage Systems



Key Shortcomings of Prior Data Placement Techniques

We observe **three key shortcomings** that significantly limit performance benefits of data-placement techniques

Lack of **adaptability**

Lack of **device awareness**

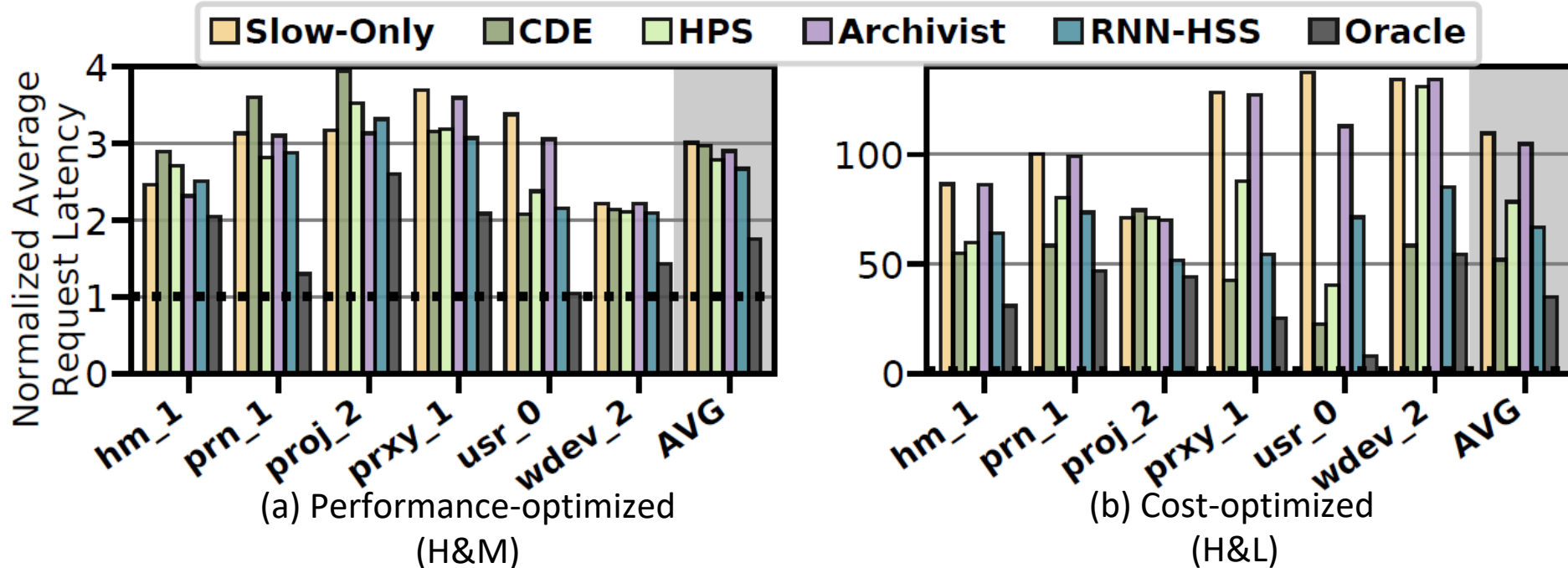
Lack of **extensibility**

Lack of Adaptability (1/2)

- Prior heuristic-based techniques consider only a **few characteristics** (e.g., access frequency) to perform data placement
- **Statically tuned characteristics** (based on **fixed thresholds**) are ineffective when used on a wide range of applications and system configurations
- Supervised learning techniques need **labeled data** and **frequent retraining** to adapt to varying workloads and system conditions

Prior techniques offer **41.1% lower performance** compared to an Oracle policy

Lack of Adaptability (2/2)



CDE shows an average performance gap of 41.1% (32.6%) to Oracle for H&M (H&L)

HPS shows an average performance gap of 37.2% (55.5%) to Oracle for H&M (H&L)

Lack of Device Awareness

Prior data placement techniques:

- **do not adapt** well to changes in underlying device characteristics (e.g., storage read latency)
- **do not consider the data migration cost** between storage devices while making a data placement decision
- **are highly inefficient** in hybrid storage systems that have devices with significantly different read/write latencies

Lack of Extensibility

- Prior data placement techniques are typically **designed** for a hybrid storage system with **only two storage devices**
- **Significant effort** is required to extend the data placement policies for more than two devices

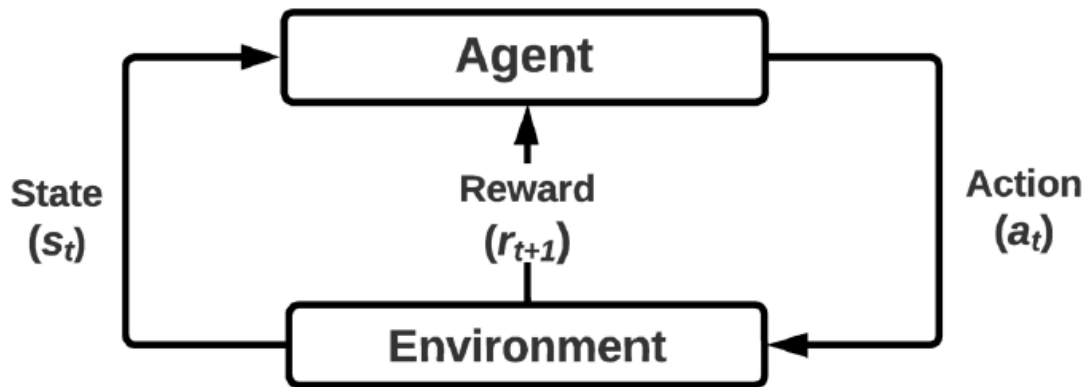
Compared to a RL-based solution, a heuristic-based policy provides **48.2% lower performance** when extended from two to three devices

Our Goal

A **data-placement mechanism** that can

- dynamically derive an adaptive data-placement strategy by **continuously learning** and **adapting** to the application and underlying device characteristics
- be **easily extended** to incorporate a wide range of hybrid storage configurations

Basics of Reinforcement Learning



- RL is a framework for decision making
 - An **autonomous agent observes** the current **state** of the environment
 - It **interacts** with the environment by taking **actions**
 - Agent is **rewarded** or **penalized** based on the consequences of its actions
 - Agent tries to maximize the cumulative reward

Applying RL to Data Placement

Key factors in applying RL for data placement in a hybrid storage system

- RL agent needs to be **aware of:**
 - **asymmetry in read/write latencies** of a storage device
 - **differences in latencies** across hybrid storage devices
 - **application access patterns**
- Data placement module should decide which actions to reward and penalize (credit assignment)
- Low implementation overhead

RL State

- Feature selection is performed to select only the most correlated features that affect data placement
- Divide the states into a small number of bins to reduce the state space

Feature	Description	# of bins	Encoding (bits)
$size_t$	Size of the requested page (in pages)	8	8
$type_t$	Type of the current request (read/write)	2	4
$intr_t$	Access interval of the requested page	64	8
cnt_t	Access count of the requested page	64	8
cap_t	Remaining capacity in the fast storage device	8	8
$curr_t$	Current placement of the requested page (fast/slow)	2	4

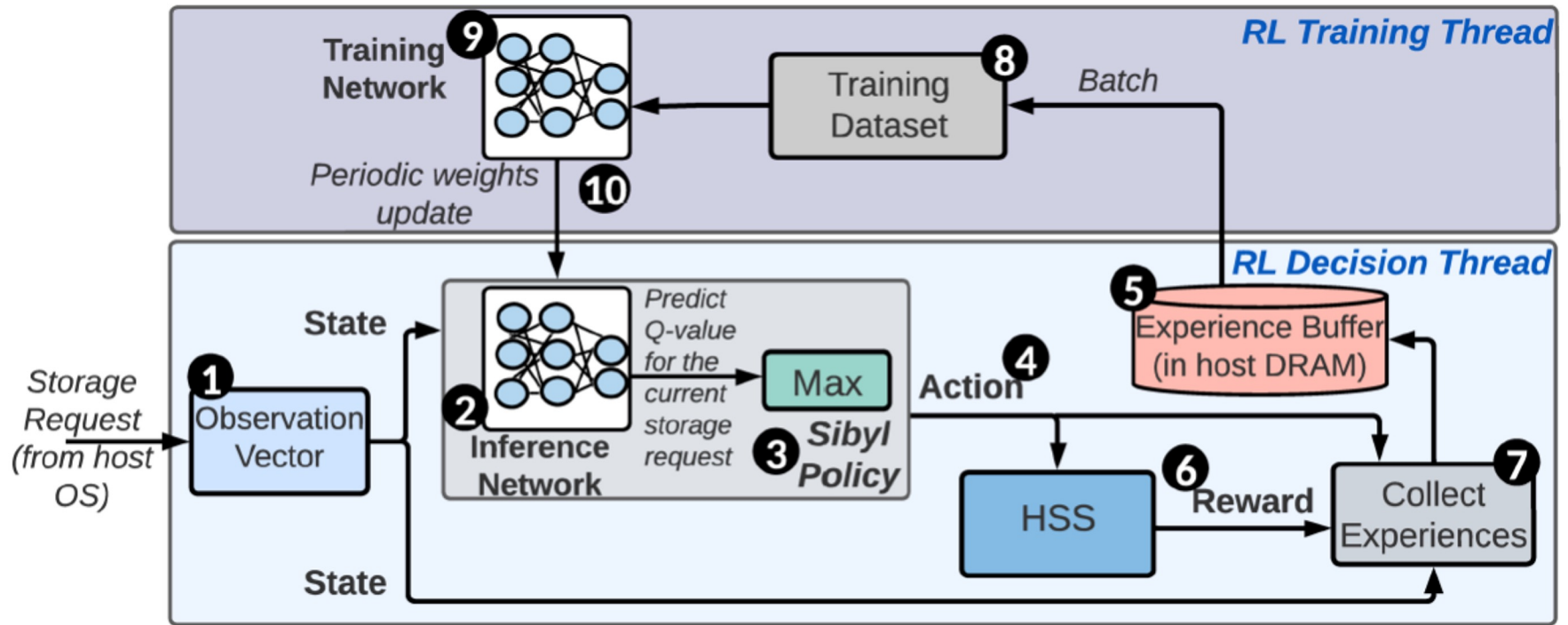
Reward

- For every action at time-step t , Sibyl gets a reward from the environment at time-step $t + 1$
- **Reward** acts as a **feedback** to the agent's past action
- **Request latency** faithfully captures the status of the hybrid storage system
- **Penalty** value is chosen to prevent the agent from aggressively servicing all the requests from the faster device

$$R = \begin{cases} \frac{1}{L_t} & \text{if no eviction} \\ \max(0, \frac{1}{L_t} - R_p) & \text{if an eviction happens} \end{cases}$$

L_t = latency of the request
 R_p = eviction penalty

Overview of Sibyl



The two threads run asynchronously to prevent training delay from affecting the inference time

Hyper-parameter Tuning

- Different hyper-parameter configurations were chosen using the design of experiments (DoE) technique

Hyper-parameter	Design Space	Chosen Value
Discount factor (γ)	0-1	0.9
Learning rate (α)	$1e^{-5} - 1e^0$	$1e^{-4}$
Exploration rate (ϵ)	0-1	0.001
Batch size	64-256	128
Experience buffer size (e_{EB})	10-10000	1000

Evaluation Methodology

- Evaluated on a **real system** with different hybrid storage configurations
- Hybrid storage system constitutes one contiguous logical block address space
- A custom block driver was implemented to manage the I/O requests to the storage devices
- We evaluate **three** different hybrid storage configurations
 - Performance-optimized (H&M)
 - Cost-optimized (H&L)
 - Tri-hybrid storage system

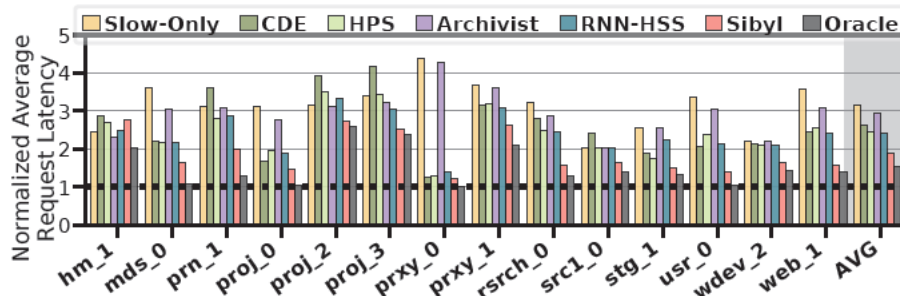
Evaluation Methodology

Host System	AMD Ryzen 7 2700G [146], 8-cores@3.5 GHz, 8×64/32 KiB L1-I/D, 4 MiB L2, 8 MiB L3, 16 GiB RDIMM DDR4 2666 MHz	
Storage Devices	Characteristics	
H: Intel Optane SSD P4800X [94]	375 GB, PCIe 3.0 NVMe, SLC, R/W: 2.4/2 GB/s, random R/W: 550000/500000 IOPS	
M: Intel SSD D3-S4510 [96]	1.92 TB, SATA TLC (3D), R/W: 550/510 MB/s, random R/W: 895000/21000 IOPS	
L: Seagate HDD ST1000DM010 [98]	1 TB, SATA 6Gb/s 7200 RPM Max. Sustained Transfer Rate: 210 MB/s	
L _{SSD} : ADATA SU630 SSD [99]	960 GB, SATA 6 Gb/s, TLC, Max R/W: 520/450 MB/s	
HSS Configurations	Fast Device	Slow Device
H&M (Performance-oriented)	high-end (H)	middle-end (M)
H&L (Cost-oriented)	high-end (H)	low-end (L)

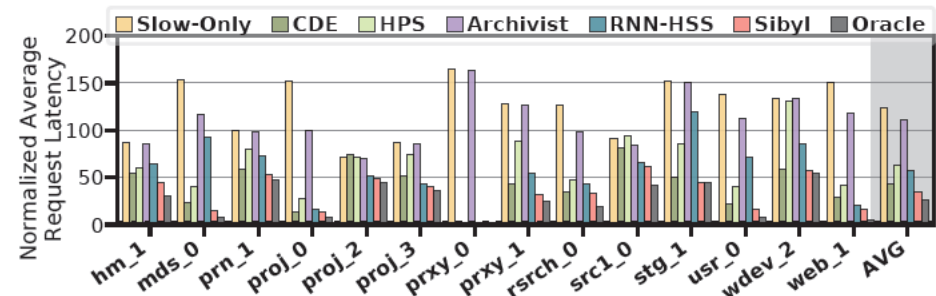
Evaluation Methodology

- 18 different workloads from MSR Cambridge and FileBench suites
- Sibyl is compared against **four baselines**
 - Heuristic-based policies
 - Cold data eviction (CDE) [Matsui et. al., "Design of Hybrid SSDs With Storage Class Memory and NAND Flash Memory," IEEE 2017]
 - History Page Scheduler (HPS) [Meswani et.al., "Heterogeneous Memory Architectures: A HW/SW Approach for Mixing Die-stacked and Off-package Memories," HPCA, 2015]
 - Supervised learning-based policies
 - Recurrent neural network (RNN)-based technique adapted from Kleio [Doudali et.al., "Kleio: A Hybrid Memory Page Scheduler with Machine Intelligence," HPDC, 2019]
 - Neural network-based classifier based on Archivist [Ren et.al., "Archivist: A Machine Learning Assisted Data Placement Mechanism for Hybrid Storage Systems," ICCD, 2019]

Latency Improvement



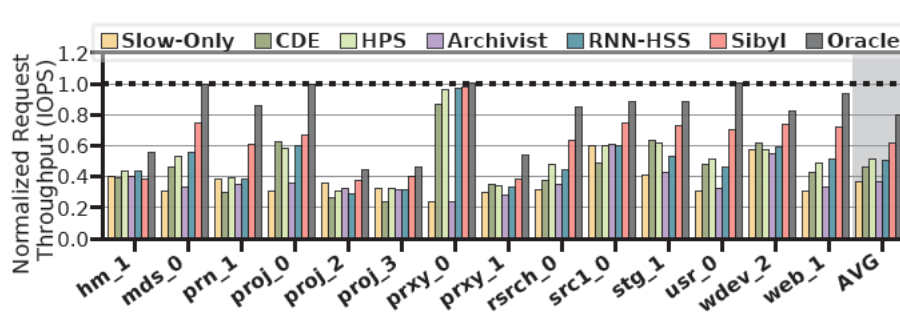
(a) Performance-optimized
(H&M)



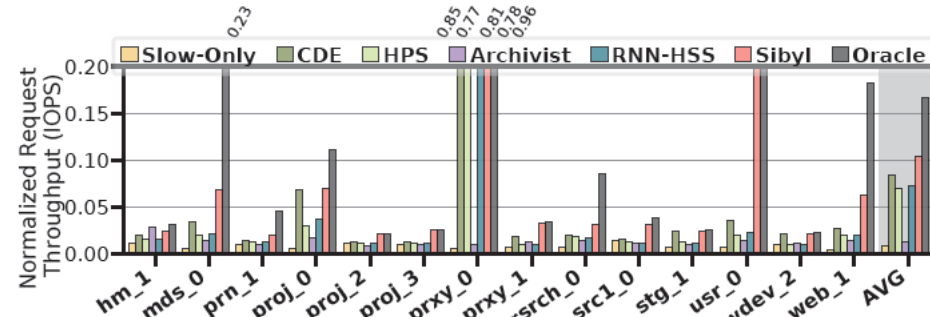
(b) Cost-optimized
(H&L)

Configuration	CDE	HPS	Archivist	RNN-HSS
H&M	28.1%	23.2%	36.1%	21.6%
H&L	19.9%	45.9%	68.8%	34.1%

Throughput Improvement



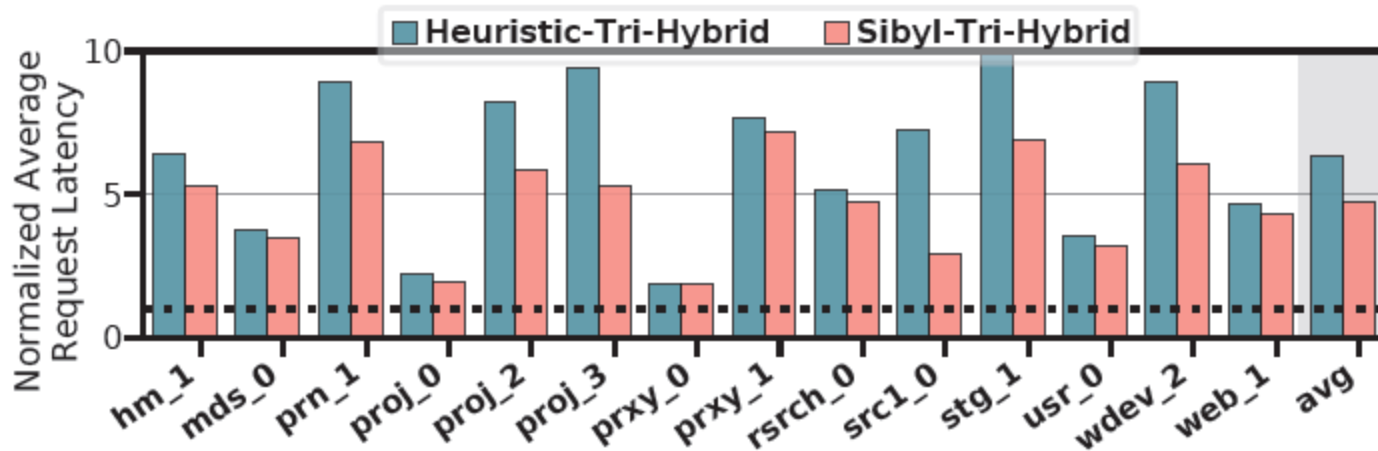
(a) Performance-optimized
(H&M)



(b) Cost-optimized
(H&L)

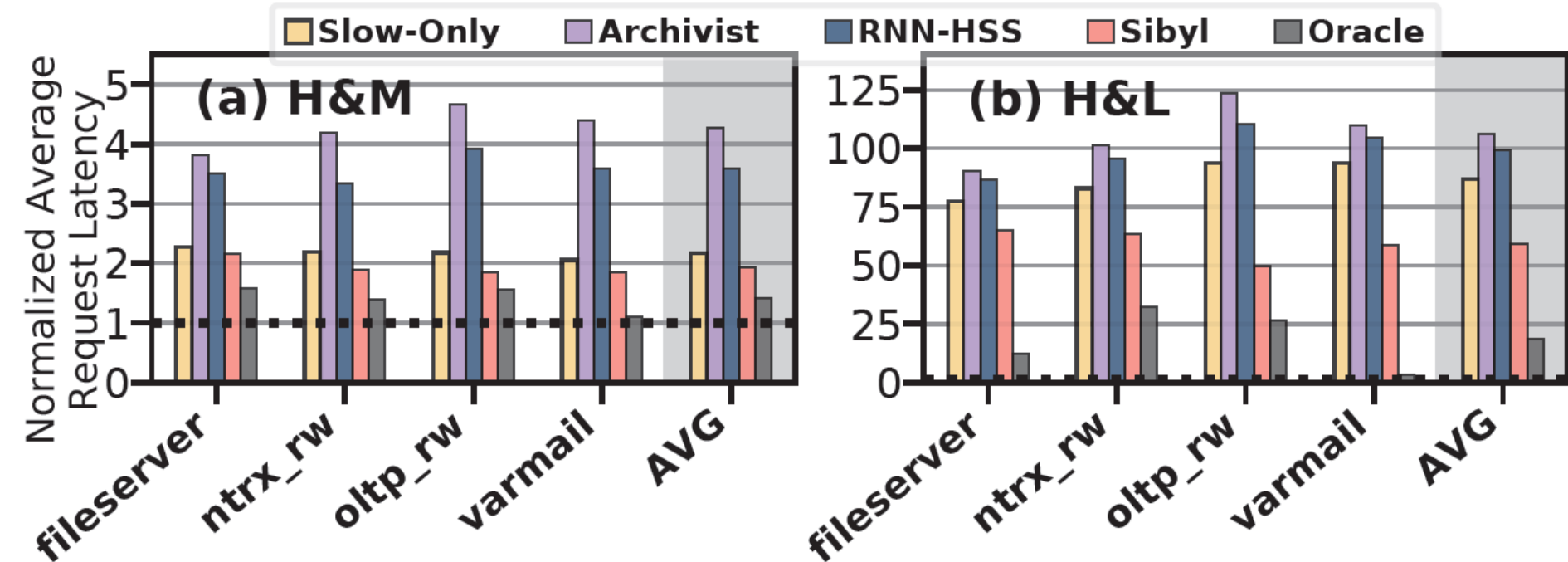
Configuration	CDE	HPS	Archivist	RNN-HSS
H&M	32.6%	21.9%	54.2%	22.7%
H&L	22.8%	49.1%	86.9%	41.9%

Latency in Tri-Hybrid System



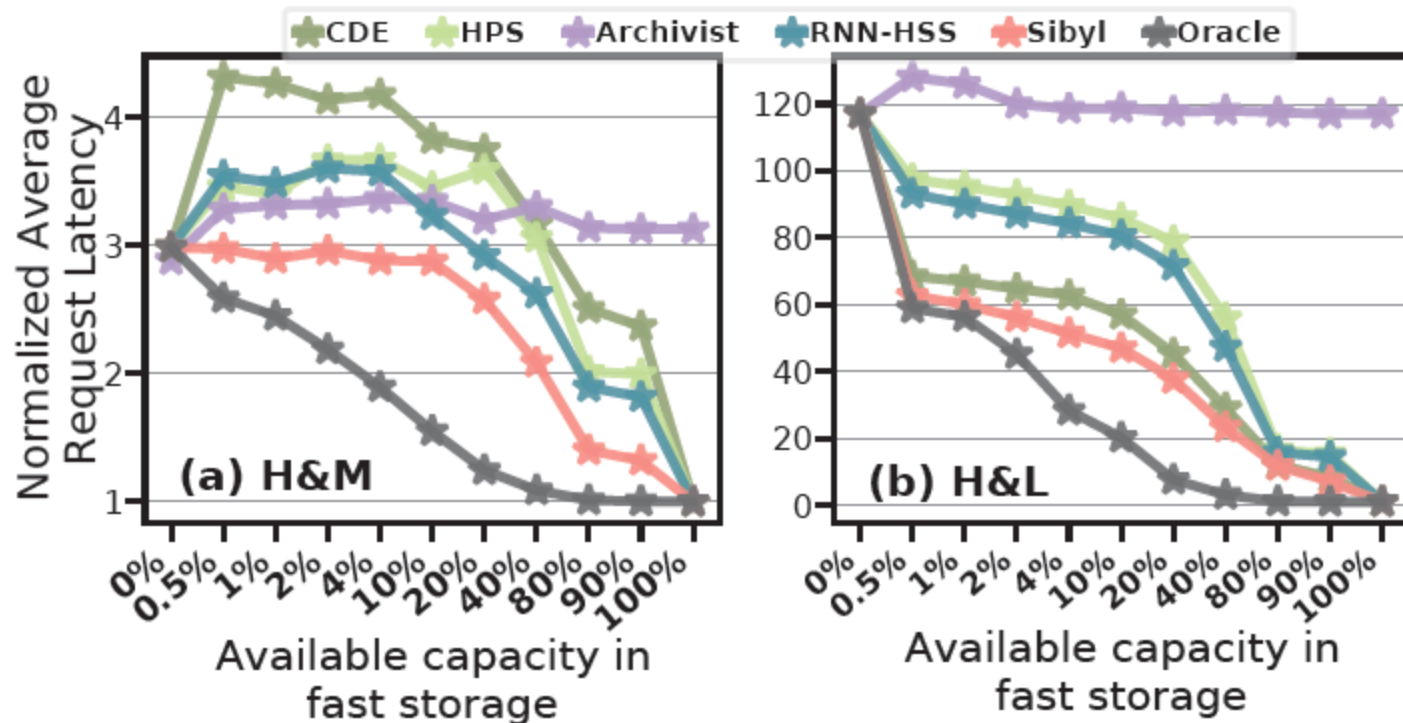
Sibyl outperforms the heuristic-based data placement policy for tri-hybrid system by 48.2% on average across all workloads

Latency for Unseen Workloads

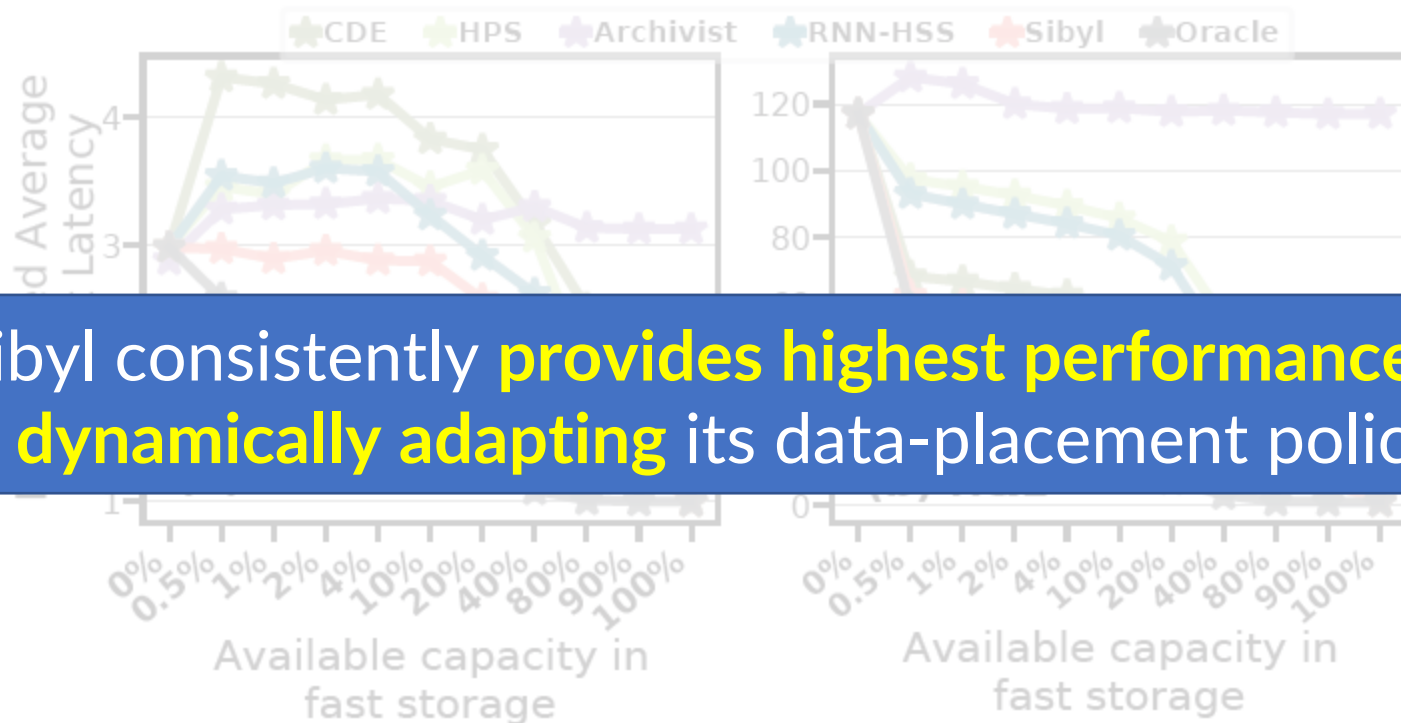


In H&M (H&L) configurations, Sibyl outperforms RNN-HSS and Archivist by 46.1% (54.6%) and 8.5% (44.1%) respectively

Sensitivity to Fast Storage Capacity



Sensitivity to Fast Storage Capacity



Sibyl consistently **provides highest performance** by **dynamically adapting** its data-placement policy

Overhead Analysis

- **Performance Overhead**
 - **~10ns** for every inference on the evaluated system; this is several orders of magnitude less than I/O latency of high-end SSD
- **Implementation Overhead**
 - **124.4 KiB** of implementation overhead
- **Metadata overhead**
 - 0.1% of the total storage capacity when using a 4 KiB data placement granularity
 - **40-bit** metadata overhead per data placement unit

For More on Sybil

- To appear in ISCA 2022

Sibyl: Adaptive and Extensible Data Placement in Hybrid Storage Systems Using Online Reinforcement Learning

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<https://arxiv.org/pdf/2205.07394.pdf>

An Intelligent Architecture

- Data-driven
 - Machine learns the “best” policies (how to do things)
- Sophisticated, workload-driven, changing, far-sighted policies
- Automatic data-driven policy learning
- All controllers are intelligent data-driven agents

**We need to rethink design
(of all controllers)**

Data-Driven **(Self-Optimizing)** **Computing Architectures**

Data-Aware Architectures

Corollaries: Architectures Today ...

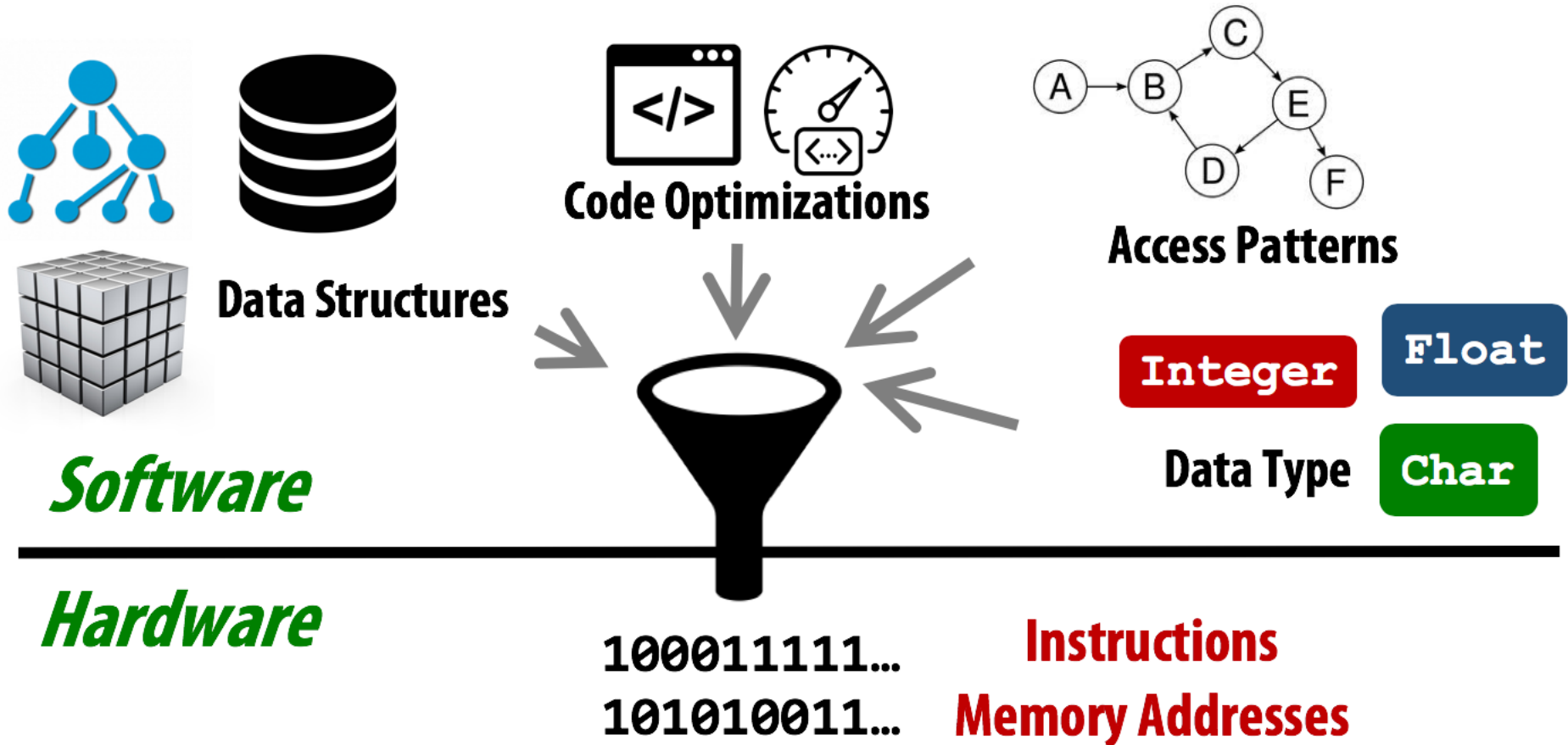
- Architectures are **terrible at dealing with data**
 - ❑ Designed to mainly store and move data vs. to compute
 - ❑ They are **processor-centric** as opposed to **data-centric**
- Architectures are **terrible at taking advantage of vast amounts of data** (and metadata) available to them
 - ❑ Designed to make simple decisions, ignoring lots of data
 - ❑ They make **human-driven decisions** vs. **data-driven** decisions
- Architectures are **terrible at knowing and exploiting different properties of application data**
 - ❑ Designed to treat all data as the same
 - ❑ They make **component-aware decisions** vs. **data-aware**

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 Expressiveness

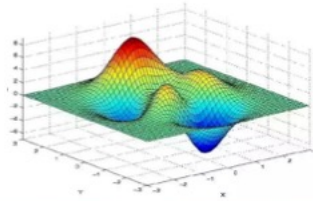
Higher-level information is not visible to HW



A Solution: More Expressive Interfaces

Performance

Software



Functionality



**ISA
Virtual Memory**

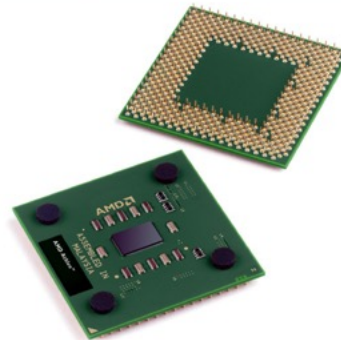
**Higher-level
Program
Semantics**

**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](#)]
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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^{§†}

[†]Carnegie Mellon University

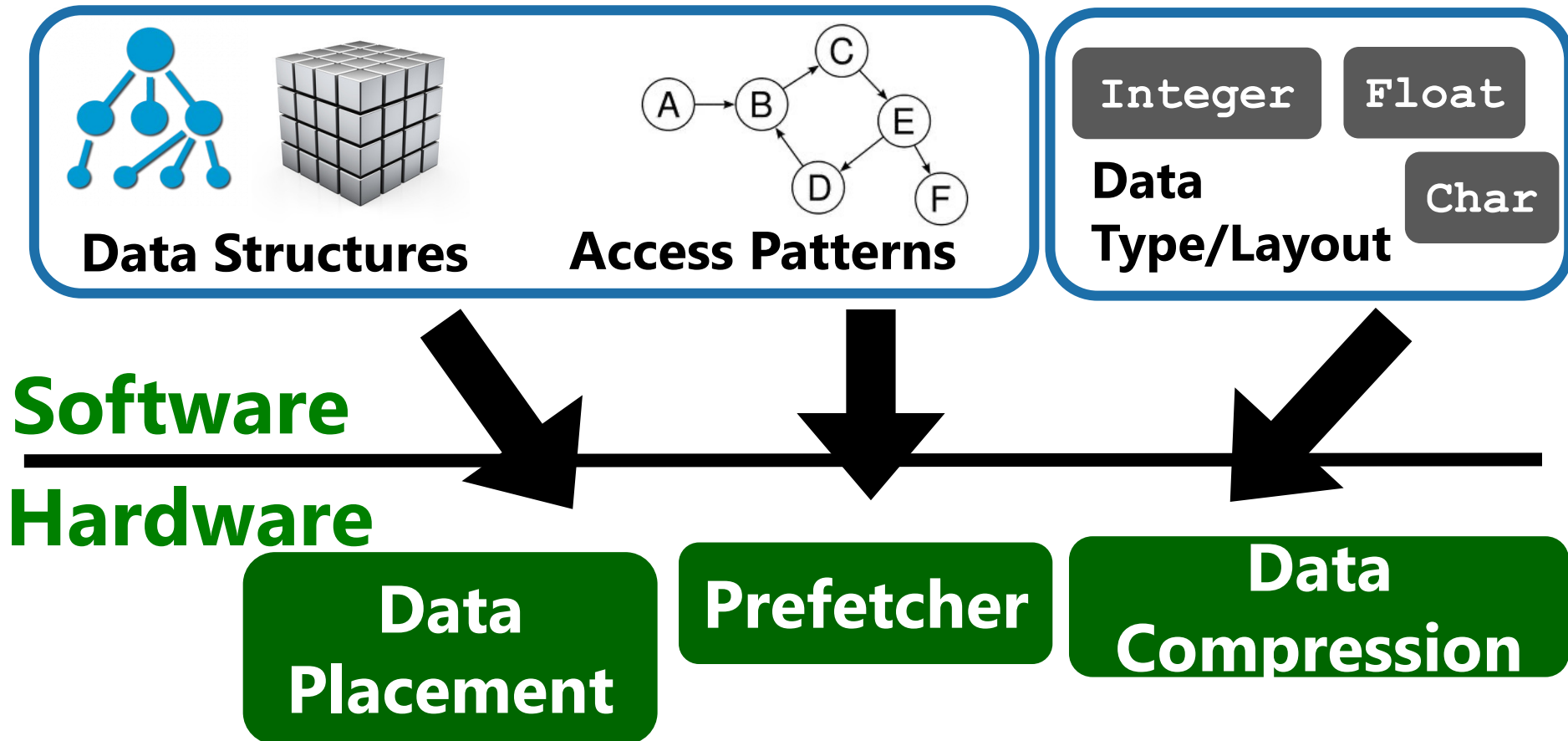
[‡]University of Toronto

[⌘]NVIDIA

[†]Simon Fraser University

[§]ETH Zürich

SW provides key program information to HW



Broader goal: Enable many cross-layer optimizations

Express:

Data structures

Access semantics

Data types

Working set

Reuse

Access frequency

...

Optimizations:

Cache Management

Data Placement in DRAM

Data Compression

Approximation

DRAM Cache Management

NVM Management

NUCA/NUMA

Optimizations

...

Benefits:

More efficient HW:

✓ **Performance**

**Reduced SW
burden:**

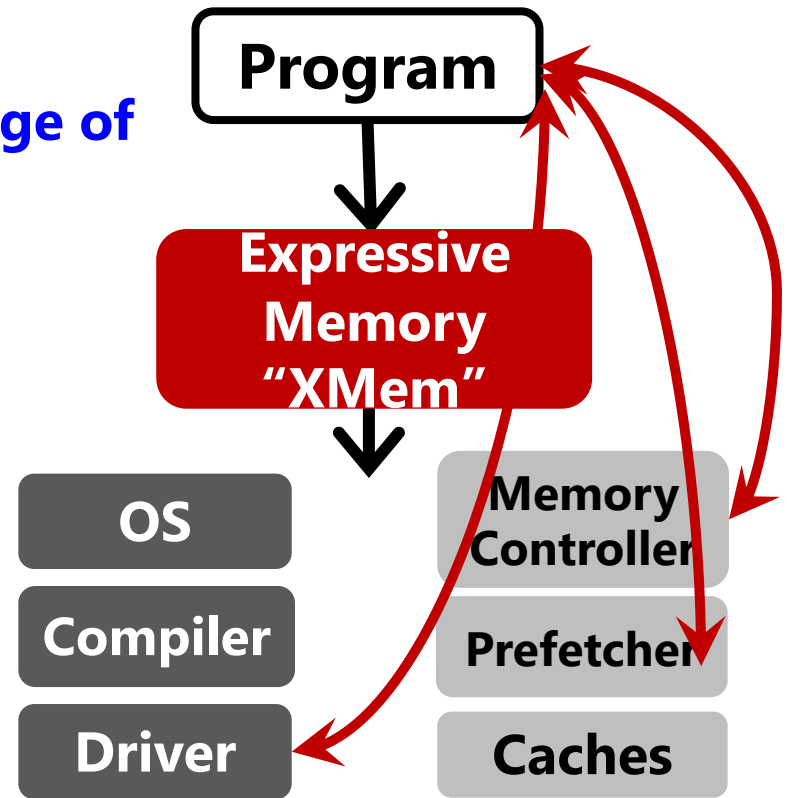
✓ **Programmability**

✓ **Portability**

Our approach: Rich cross-layer abstractions

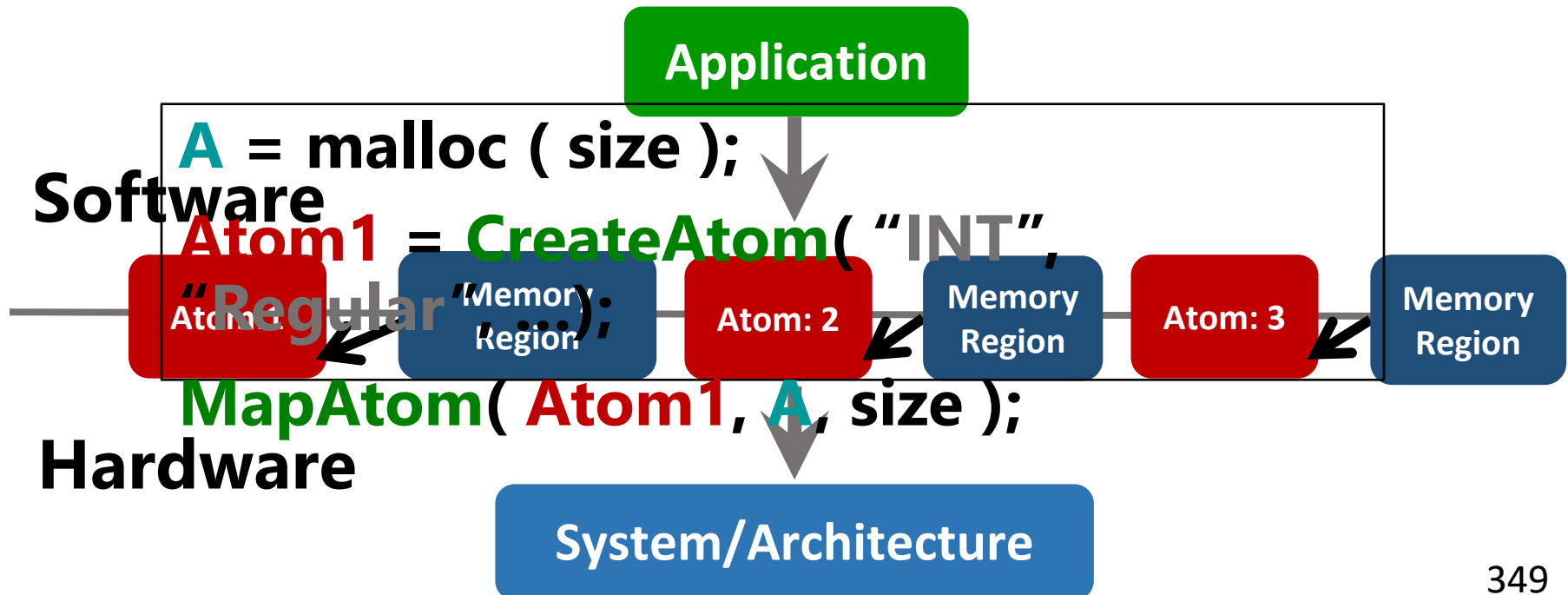
1. **Generality:** Enable a wide range of cross-layer approaches
2. **Minimize programmer effort**
3. **Overhead**

Approach: Flexibly associate specific semantic information with any **data & code**



Example: XMem

- **Goal:** convey data semantics to the hardware enables more intelligent management of resources.
- **XMem:** introduces a new HW/SW abstraction, called *Atom*, for conveying data semantics



XMem Aids/Enables Many Optimizations

Table 1: Summary of the example memory optimizations that XMem aids.

Memory optimization	Example semantics provided by XMem (described in §3.3)	Example Benefits of XMem
Cache management	(i) Distinguishing between data structures or pools of similar data; (ii) Working set size; (iii) Data reuse	Enables: (i) applying different caching policies to different data structures or pools of data; (ii) avoiding cache thrashing by <i>knowing</i> the active working set size; (iii) bypassing/prioritizing data that has no/high reuse. (§5)
Page placement in DRAM e.g., [23, 24]	(i) Distinguishing between data structures; (ii) Access pattern; (iii) Access intensity	Enables page placement at the <i>data structure</i> granularity to (i) isolate data structures that have high row buffer locality and (ii) spread out concurrently-accessed irregular data structures across banks and channels to improve parallelism. (§6)
Cache/memory compression e.g., [25–32]	(i) Data type: integer, float, char; (ii) Data properties: sparse, pointer, data index	Enables using a <i>different compression algorithm</i> for each data structure based on data type and data properties, e.g., sparse data encodings, FP-specific compression, delta-based compression for pointers [27].
Data prefetching e.g., [33–36]	(i) Access pattern: strided, irregular, irregular but repeated (e.g., graphs), access stride; (ii) Data type: index, pointer	Enables (i) <i>highly accurate</i> software-driven prefetching while leveraging the benefits of hardware prefetching (e.g., by being memory bandwidth-aware, avoiding cache thrashing); (ii) using different prefetcher <i>types</i> for different data structures: e.g., stride [33], tile-based [20], pattern-based [34–37], data-based for indices/pointers [38, 39], etc.
DRAM cache management e.g., [40–46]	(i) Access intensity; (ii) Data reuse; (iii) Working set size	(i) Helps avoid cache thrashing by knowing working set size [44]; (ii) Better DRAM cache management via reuse behavior and access intensity information.
Approximation in memory e.g., [47–53]	(i) Distinguishing between pools of similar data; (ii) Data properties: tolerance towards approximation	Enables (i) each memory component to track how approximable data is (at a fine granularity) to inform approximation techniques; (ii) data placement in heterogeneous reliability memories [54].
Data placement: NUMA systems e.g., [55, 56]	(i) Data partitioning across threads (i.e., relating data to threads that access it); (ii) Read-Write properties	Reduces the need for profiling or data migration (i) to co-locate data with threads that access it and (ii) to identify Read-Only data, thereby enabling techniques such as replication.
Data placement: hybrid memories e.g., [16, 57, 58]	(i) Read-Write properties (Read-Only/Read-Write); (ii) Access intensity; (iii) Data structure size; (iv) Access pattern	Avoids the need for profiling/migration of data in hybrid memories to (i) effectively manage the asymmetric read-write properties in NVM (e.g., placing Read-Only data in the NVM) [16, 57]; (ii) make tradeoffs between data structure "hotness" and size to allocate fast/high bandwidth memory [14]; and (iii) leverage row-buffer locality in placement based on access pattern [45].
Managing NUCA systems e.g., [15, 59]	(i) Distinguishing pools of similar data; (ii) Access intensity; (iii) Read-Write or Private-Shared properties	(i) Enables using different cache policies for different data pools (similar to [15]); (ii) Reduces the need for reactive mechanisms that detect sharing and read-write characteristics to inform cache policies.

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"**
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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^{§†}
[†]Carnegie Mellon University [‡]NVIDIA [§]ETH Zürich

Locality Descriptor: Executive Summary

Exploiting data locality in GPUs is a challenging task

Flexible,
architecture-
agnostic interface

Application

Access to
program
semantics

Software

Locality
Descriptor

Hardware

Data
Placement

Cache
Management

CTA
Scheduling

Data
Prefetching

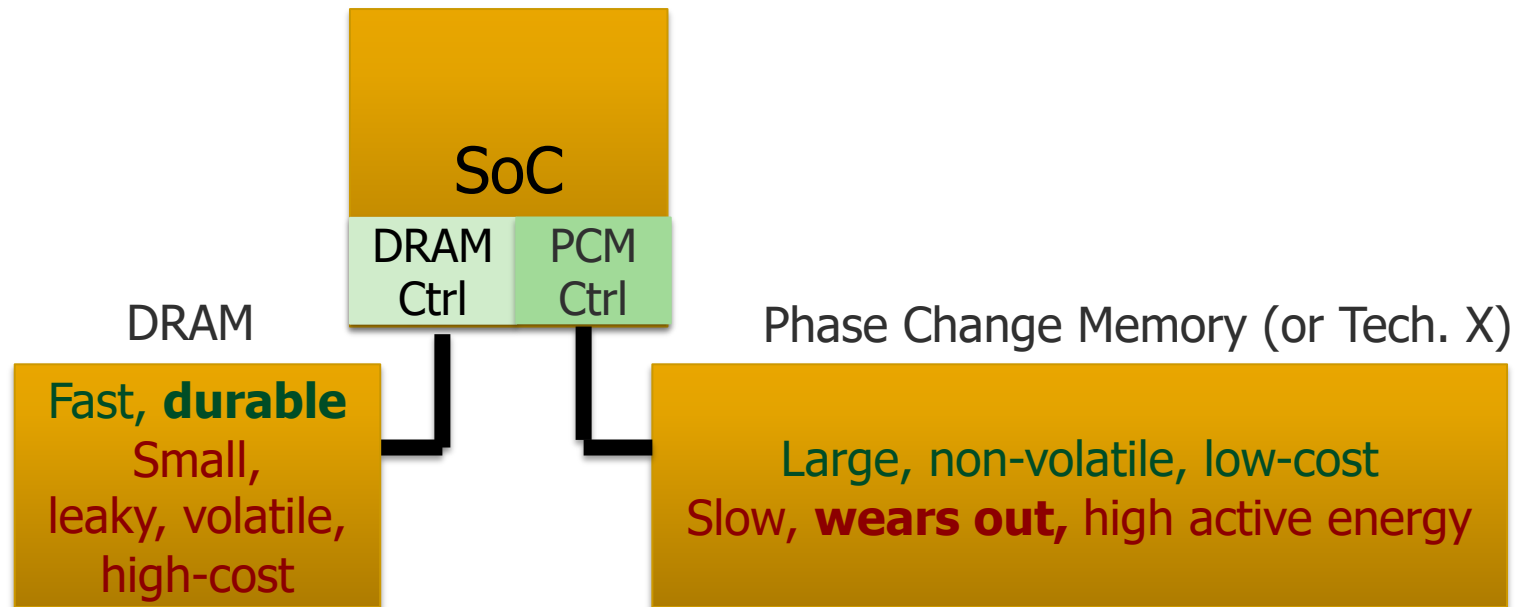
...

Performance Benefits:

26.6% (up to 46.6%) from cache locality

53.7% (up to 2.8x) from NUMA locality

An Example: Hybrid Memory Management



Hardware/software manage data allocation and movement
to achieve the best of multiple technologies

Meza+, "[Enabling Efficient and Scalable Hybrid Memories](#)," IEEE Comp. Arch. Letters, 2012.

Yoon+, "[Row Buffer Locality Aware Caching Policies for Hybrid Memories](#)," ICCD 2012 Best Paper Award.

An Example: Heterogeneous-Reliability Memory

- Yixin Luo, Sriram Govindan, Bikash Sharma, Mark Santaniello, Justin Meza, Aman Kansal, Jie Liu, Badriddine Khessib, Kushagra Vaid, and Onur Mutlu,
"Characterizing Application Memory Error Vulnerability to Optimize Data Center Cost via Heterogeneous-Reliability Memory"
Proceedings of the 44th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Atlanta, GA, June 2014. [[Summary](#)]
[[Slides \(pptx\)](#)] [[pdf](#)] [[Coverage on ZDNet](#)]

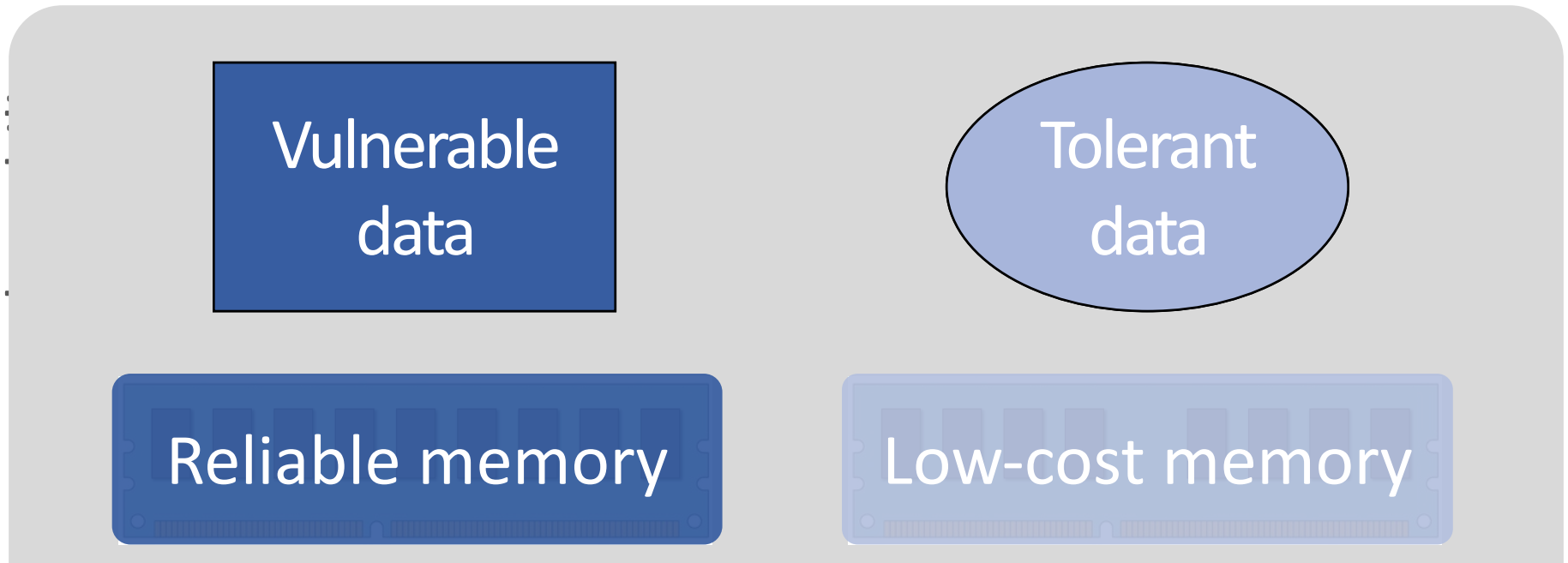
Characterizing Application Memory Error Vulnerability to Optimize Datacenter Cost via Heterogeneous-Reliability Memory

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

Carnegie Mellon University, yixinluo@cs.cmu.edu, {meza, onur}@cmu.edu

*Microsoft Corporation, {srgovin, bsharma, marksan, kansal, jie.liu, bknessib, kvaid}@microsoft.com

Exploiting Memory Error Tolerance with Hybrid Memory Systems



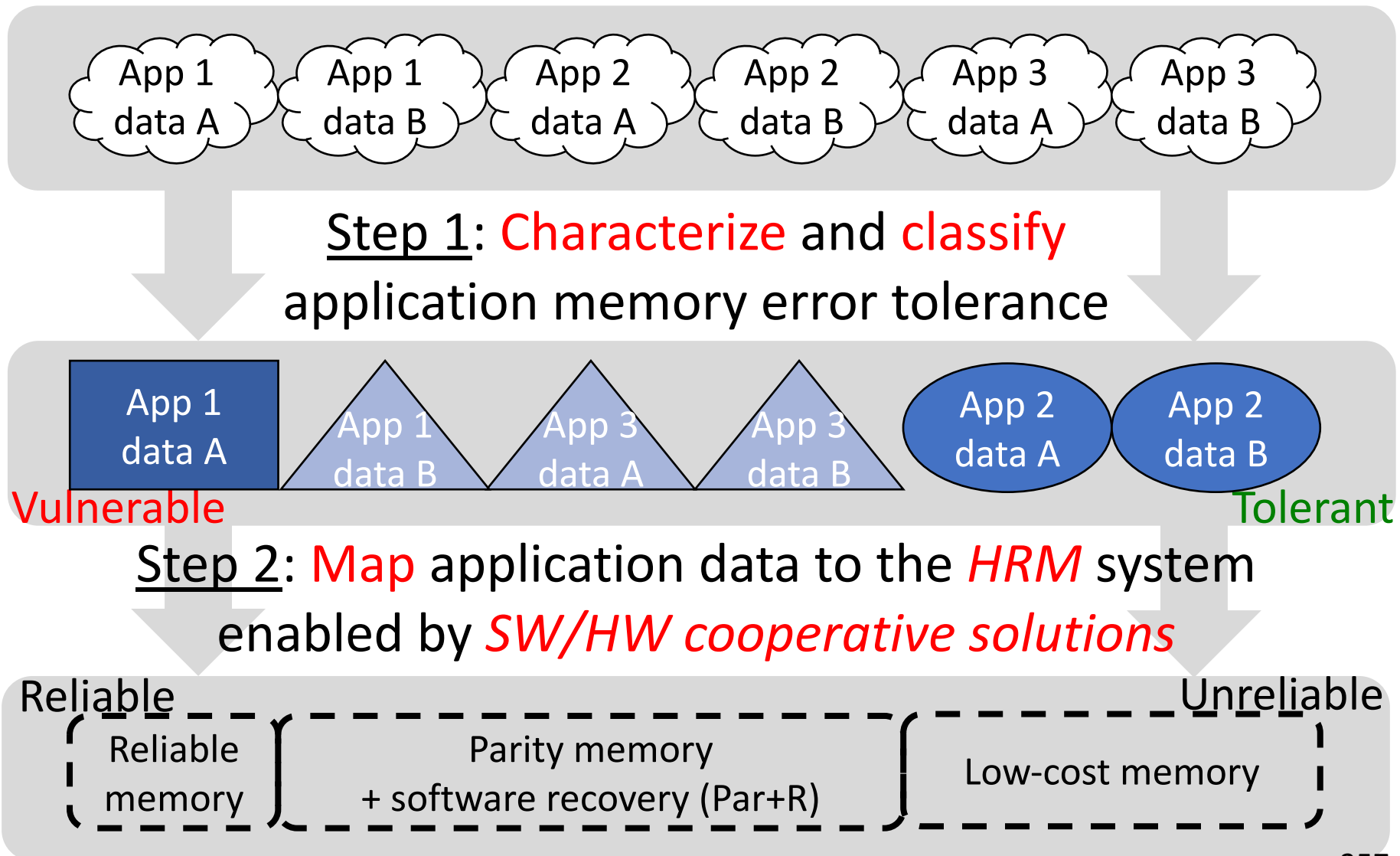
On Microsoft's Web Search workload

Reduces server hardware **cost** by **4.7 %**

Achieves single server **availability** target of **99.90 %**

Heterogeneous-Reliability Memory [DSN 2014]

Heterogeneous-Reliability Memory



More on Heterogeneous-Reliability Memory

- Yixin Luo, Sriram Govindan, Bikash Sharma, Mark Santaniello, Justin Meza, Aman Kansal, Jie Liu, Badriddine Khessib, Kushagra Vaid, and Onur Mutlu,
"Characterizing Application Memory Error Vulnerability to Optimize Data Center Cost via Heterogeneous-Reliability Memory"
Proceedings of the 44th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Atlanta, GA, June 2014. [[Summary](#)]
[[Slides \(pptx\)](#)] [[pdf](#)] [[Coverage on ZDNet](#)]

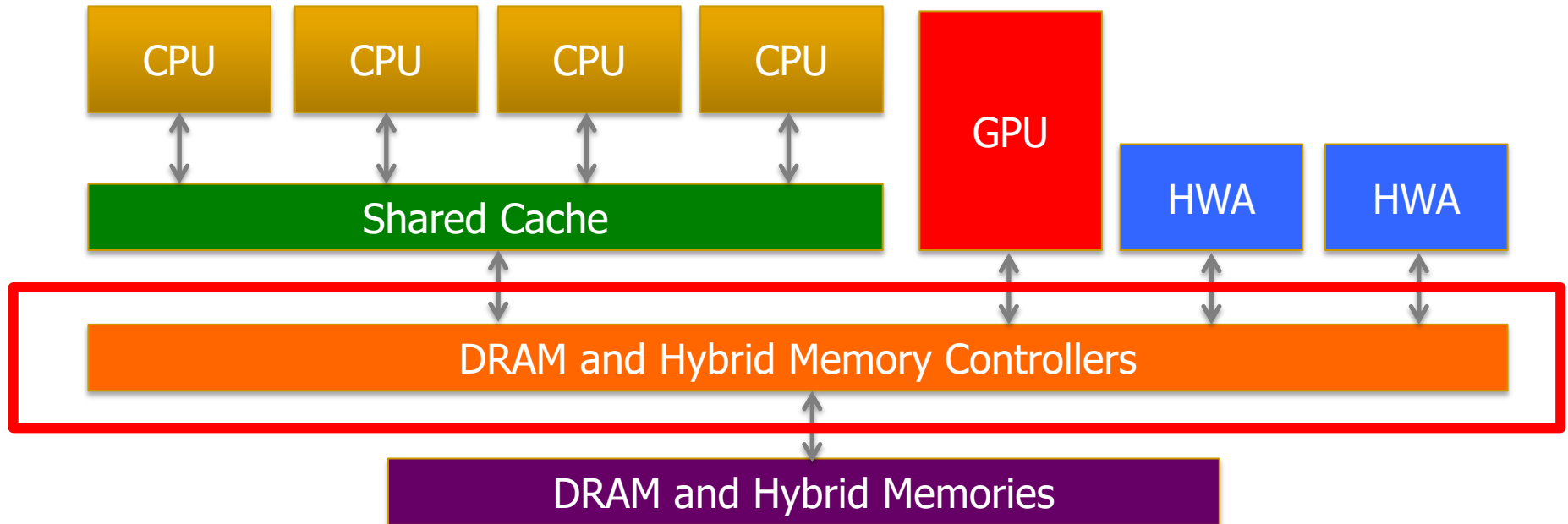
Characterizing Application Memory Error Vulnerability to Optimize Datacenter Cost via Heterogeneous-Reliability Memory

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

Carnegie Mellon University, yixinluo@cs.cmu.edu, {meza, onur}@cmu.edu

*Microsoft Corporation, {srgovin, bsharma, marksan, kansal, jie.liu, bknessib, kvaid}@microsoft.com

Data-Aware Cross-Layer Hybrid System Management



- Heterogeneous agents: CPUs, GPUs, and HWAs
- Main memory interference between CPUs, GPUs, HWAs
- Many timing constraints for various memory types
- Many goals at the same time: performance, fairness, QoS, energy efficiency, ...

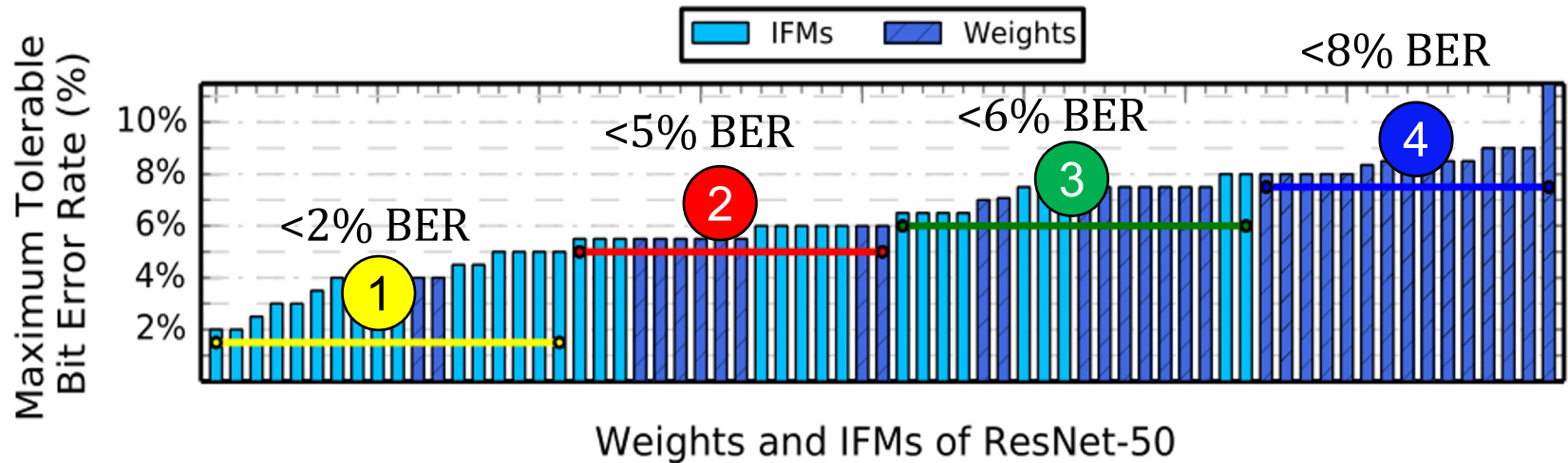
Another Example: EDEN for DNNs

- Deep Neural Network evaluation is very DRAM-intensive (especially for large networks)
1. Some data and layers in DNNs are very tolerant to errors
 2. Reduce DRAM latency and voltage on such data and layers
 3. While still achieving a user-specified DNN accuracy target by making training DRAM-error-aware

**Data-aware management of DRAM latency and voltage
for Deep Neural Network Inference**

Example DNN Data Type to DRAM Mapping

Mapping example of ResNet-50:



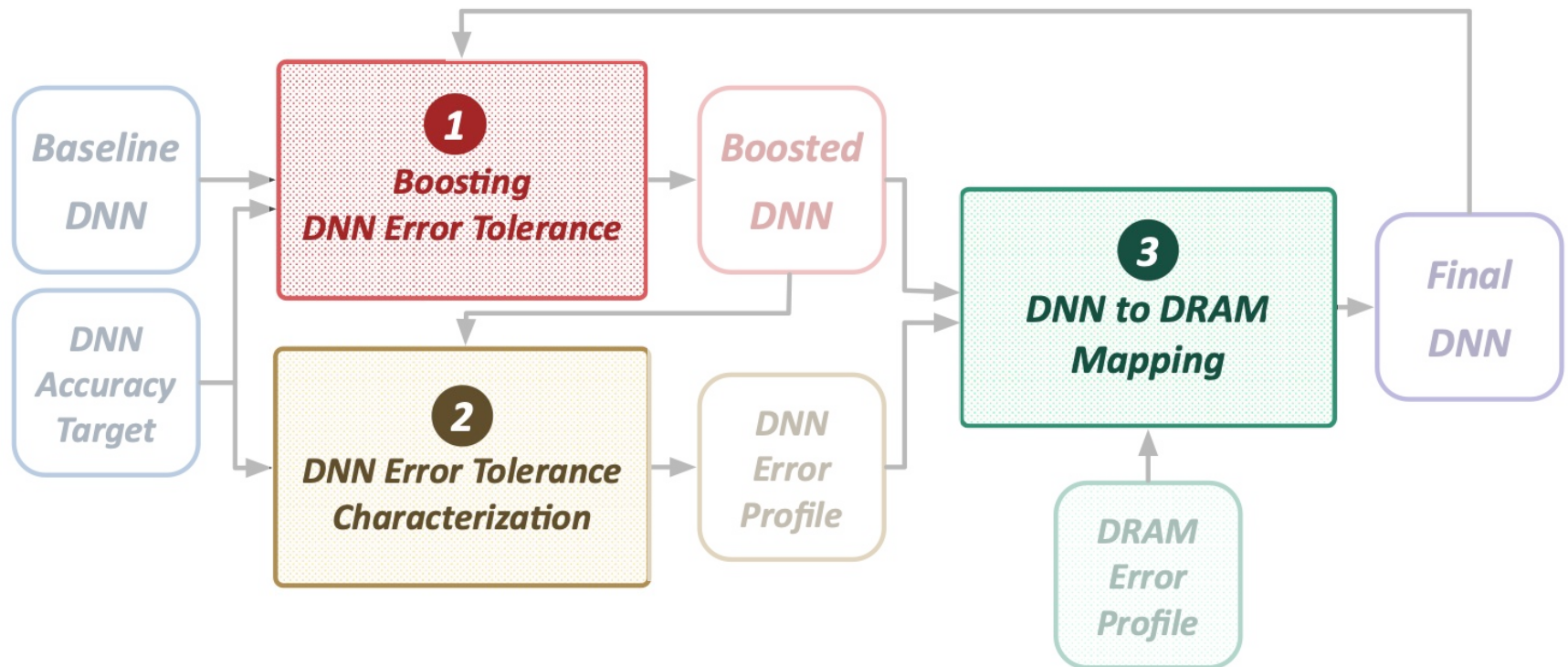
Map more error-tolerant DNN layers
to DRAM partitions with lower voltage/latency

4 DRAM partitions with different error rates

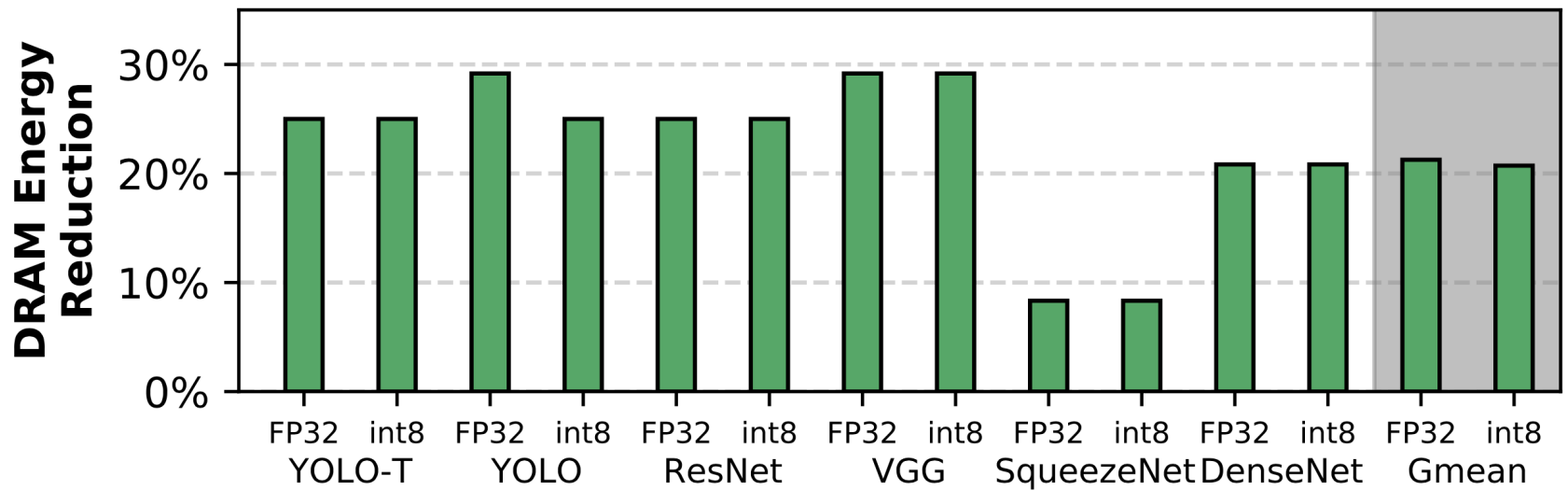
EDEN: Overview

Key idea: Enable **accurate, efficient** DNN inference using **approximate DRAM**

EDEN is an **iterative** process that has **3 key steps**

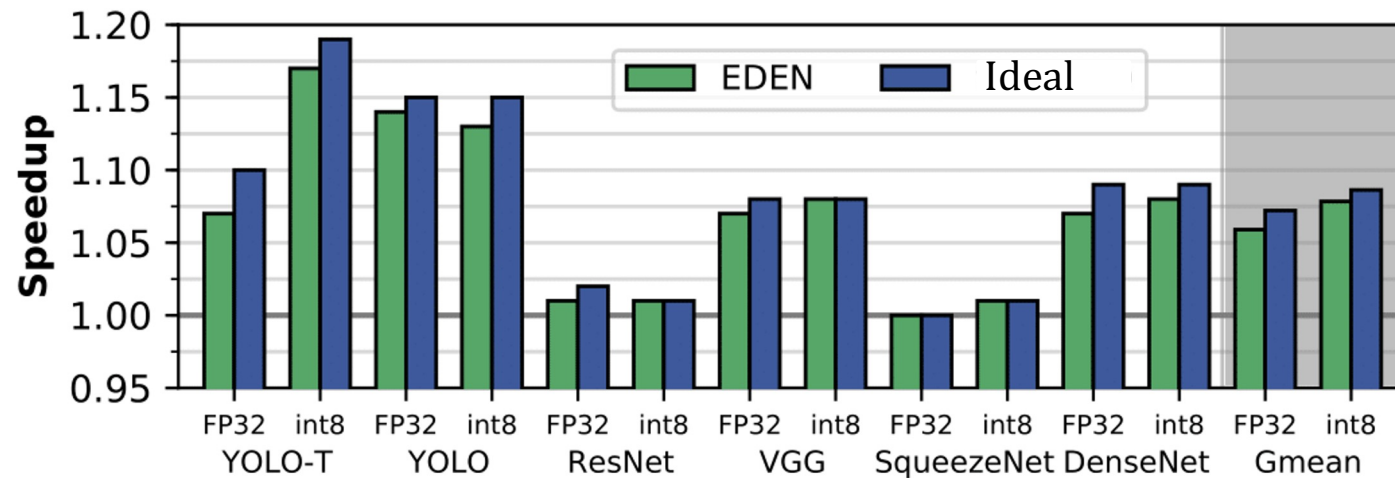


CPU: DRAM Energy Evaluation



Average 21% DRAM energy reduction
maintaining accuracy within 1% of original

CPU: Performance Evaluation



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

EDEN achieves **close to the ideal** speedup
possible via tRCD scaling

GPU, Eyeriss, and TPU: Energy Evaluation

- GPU: average **37% energy reduction**
- Eyeriss: average **31% energy reduction**
- TPU: average **32% energy reduction**

EDEN: Data-Aware Efficient DNN Inference

- Skanda Koppula, Lois Orosa, A. Giray Yaglikci, Roknoddin Azizi, Taha Shahroodi, Konstantinos Kanellopoulos, and Onur Mutlu,
"EDEN: Enabling Energy-Efficient, High-Performance Deep Neural Network Inference Using Approximate DRAM"
Proceedings of the 52nd International Symposium on Microarchitecture (MICRO), Columbus, OH, USA, October 2019.
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Video](#) (90 seconds)]

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

Skanda Koppula Lois Orosa A. Giray Yağlıkçı
Roknoddin Azizi Taha Shahroodi Konstantinos Kanellopoulos Onur Mutlu
ETH Zürich

SMASH: SW/HW Indexing Acceleration

- Konstantinos Kanellopoulos, Nandita Vijaykumar, Christina Giannoula, Roknoddin Azizi, Skanda Koppula, Nika Mansouri Ghiasi, Taha Shahroodi, Juan Gomez-Luna, and Onur Mutlu,

"SMASH: Co-designing Software Compression and Hardware-Accelerated Indexing for Efficient Sparse Matrix Operations"

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

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

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

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

[[Lightning Talk Video](#) (90 seconds)]

[[Full Talk Lecture](#) (30 minutes)]

SMASH: Co-designing Software Compression and Hardware-Accelerated Indexing for Efficient Sparse Matrix Operations

Konstantinos Kanellopoulos¹ Nandita Vijaykumar^{2,1} Christina Giannoula^{1,3} Roknoddin Azizi¹
Skanda Koppula¹ Nika Mansouri Ghiasi¹ Taha Shahroodi¹ Juan Gomez Luna¹ Onur Mutlu^{1,2}

¹ETH Zürich

²Carnegie Mellon University

³National Technical University of Athens

Data-Aware Virtual Memory Framework

Nastaran Hajinazar, Pratyush Patel, Minesh Patel, Konstantinos Kanellopoulos, Saugata Ghose, Rachata Ausavarungnirun, Geraldo Francisco de Oliveira Jr., Jonathan Appavoo, Vivek Seshadri, and Onur Mutlu, **"The Virtual Block Interface: A Flexible Alternative to the Conventional Virtual Memory Framework"**

Proceedings of the 47th International Symposium on Computer Architecture (ISCA), Virtual, June 2020.

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

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

[[ARM Research Summit Poster \(pptx\)](#) ([pdf](#))]

[[Talk Video](#) (26 minutes)]

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

[[Lecture Video](#) (43 minutes)]

The Virtual Block Interface: A Flexible Alternative to the Conventional Virtual Memory Framework

Nastaran Hajinazar^{*†} Pratyush Patel[⌘] Minesh Patel^{*} Konstantinos Kanellopoulos^{*} Saugata Ghose[‡]
Rachata Ausavarungnirun[⊙] Geraldo F. Oliveira^{*} Jonathan Appavoo[◇] Vivek Seshadri[▽] Onur Mutlu^{*‡}

^{*}ETH Zürich [†]Simon Fraser University [⌘]University of Washington [‡]Carnegie Mellon University

[⊙]King Mongkut's University of Technology North Bangkok [◇]Boston University [▽]Microsoft Research India

SW/HW Climate Modeling Accelerator

- Gagandeep Singh, Dionysios Diamantopoulos, Christoph Hagleitner, Juan Gómez-Luna, Sander Stuijk, Onur Mutlu, and Henk Corporaal,
"NERO: A Near High-Bandwidth Memory Stencil Accelerator for Weather Prediction Modeling"
Proceedings of the 30th International Conference on Field-Programmable Logic and Applications (FPL), Gothenburg, Sweden, September 2020.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (23 minutes)]
Nominated for the Stamatis Vassiliadis Memorial Award.

NERO: A Near High-Bandwidth Memory Stencil Accelerator for Weather Prediction Modeling

Gagandeep Singh^{a,b,c} Dionysios Diamantopoulos^c Christoph Hagleitner^c Juan Gómez-Luna^b
Sander Stuijk^a Onur Mutlu^b Henk Corporaal^a
^aEindhoven University of Technology ^bETH Zürich ^cIBM Research Europe, Zurich

HW/SW Time Series Analysis Accelerator

- Ivan Fernandez, Ricardo Quisiant, Christina Giannoula, Mohammed Alser, Juan Gómez-Luna, Eladio Gutiérrez, Oscar Plata, and Onur Mutlu,
"NATSA: A Near-Data Processing Accelerator for Time Series Analysis"
Proceedings of the 38th IEEE International Conference on Computer Design (ICCD), Virtual, October 2020.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (10 minutes)]
[[Source Code](#)]

NATSA: A Near-Data Processing Accelerator for Time Series Analysis

Ivan Fernandez[§]

Ricardo Quisiant[§]

Christina Giannoula[†]

Mohammed Alser[‡]

Juan Gómez-Luna[‡]

Eladio Gutiérrez[§]

Oscar Plata[§]

Onur Mutlu[‡]

[§]*University of Malaga*

[†]*National Technical University of Athens*

[‡]*ETH Zürich*

FPGA-based Processing Near Memory

- Gagandeep Singh, Mohammed Alser, Damla Senol Cali, Dionysios Diamantopoulos, Juan Gómez-Luna, Henk Corporaal, and Onur Mutlu, ["FPGA-based Near-Memory Acceleration of Modern Data-Intensive Applications"](#) *IEEE Micro* (**IEEE MICRO**), 2021.

FPGA-based Near-Memory Acceleration of Modern Data-Intensive Applications

Gagandeep Singh[◇] Mohammed Alser[◇] Damla Senol Cali[✕]

Dionysios Diamantopoulos[▽] Juan Gómez-Luna[◇]

Henk Corporaal^{*} Onur Mutlu^{◇✕}

[◇]*ETH Zürich* [✕]*Carnegie Mellon University*

^{*}*Eindhoven University of Technology* [▽]*IBM Research Europe*

Accelerating Linked Data Structures

- Kevin Hsieh, Samira Khan, Nandita Vijaykumar, Kevin K. Chang, Amirali Boroumand, Saugata Ghose, and Onur Mutlu,
["Accelerating Pointer Chasing in 3D-Stacked Memory: Challenges, Mechanisms, Evaluation"](#)
Proceedings of the 34th IEEE International Conference on Computer Design (ICCD), Phoenix, AZ, USA, October 2016.

Accelerating Pointer Chasing in 3D-Stacked Memory: Challenges, Mechanisms, Evaluation

Kevin Hsieh[†] Samira Khan[‡] Nandita Vijaykumar[†]
Kevin K. Chang[†] Amirali Boroumand[†] Saugata Ghose[†] Onur Mutlu^{§†}
[†]Carnegie Mellon University [‡]University of Virginia [§]ETH Zürich

Accelerating Approximate String Matching

- Damla Senol Cali, Gurpreet S. Kalsi, Zülal Bingöl, Can Firtina, Lavanya Subramanian, Jeremie S. Kim, Rachata Ausavarungnirun, Mohammed Alser, Juan Gomez-Luna, Amirali Boroumand, Anant Nori, Allison Scibisz, Sreenivas Subramoney, Can Alkan, Saugata Ghose, and Onur Mutlu, **"GenASM: A High-Performance, Low-Power Approximate String Matching Acceleration Framework for Genome Sequence Analysis"**
Proceedings of the 53rd International Symposium on Microarchitecture (MICRO), Virtual, October 2020.
[[Lightning Talk Video](#) (1.5 minutes)]
[[Lightning Talk Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (18 minutes)]
[[Slides \(pptx\)](#) ([pdf](#))]

GenASM: A High-Performance, Low-Power Approximate String Matching Acceleration Framework for Genome Sequence Analysis

Damla Senol Cali^{†⋈} Gurpreet S. Kalsi[⋈] Zülal Bingöl[▽] Can Firtina[◇] Lavanya Subramanian[‡] Jeremie S. Kim^{◇†}
Rachata Ausavarungnirun[⊙] Mohammed Alser[◇] Juan Gomez-Luna[◇] Amirali Boroumand[†] Anant Nori[⋈]
Allison Scibisz[†] Sreenivas Subramoney[⋈] Can Alkan[▽] Saugata Ghose^{*†} Onur Mutlu^{◇†▽}
[†]Carnegie Mellon University [⋈]Processor Architecture Research Lab, Intel Labs [▽]Bilkent University [◇]ETH Zürich
[‡]Facebook [⊙]King Mongkut's University of Technology North Bangkok ^{*}University of Illinois at Urbana-Champaign

Accelerating Genome Analysis [IEEE MICRO 2020]

- Mohammed Alser, Zülal Bingöl, Damla Senol Cali, Jeremie Kim, Saugata Ghose, Can Alkan, and Onur Mutlu,
["Accelerating Genome Analysis: A Primer on an Ongoing Journey"](#)
[IEEE Micro \(IEEE MICRO\)](#), Vol. 40, No. 5, pages 65-75, September/October 2020.
[[Slides \(pptx\)\(pdf\)](#)]
[[Talk Video \(1 hour 2 minutes\)](#)]

Accelerating Genome Analysis: A Primer on an Ongoing Journey

Mohammed Alser

ETH Zürich

Zülal Bingöl

Bilkent University

Damla Senol Cali

Carnegie Mellon University

Jeremie Kim

ETH Zurich and Carnegie Mellon University

Saugata Ghose

University of Illinois at Urbana–Champaign and
Carnegie Mellon University

Can Alkan

Bilkent University

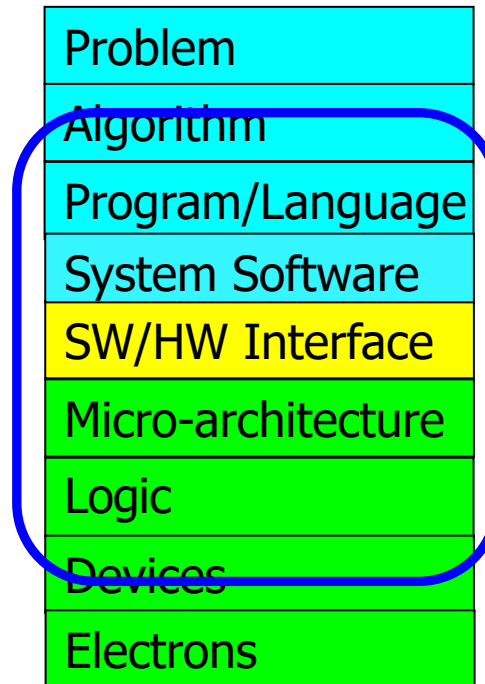
Onur Mutlu

ETH Zurich, Carnegie Mellon University, and
Bilkent University

Data-Aware (Expressive)

Computing Architectures

We Need to **Rethink** the Entire Stack

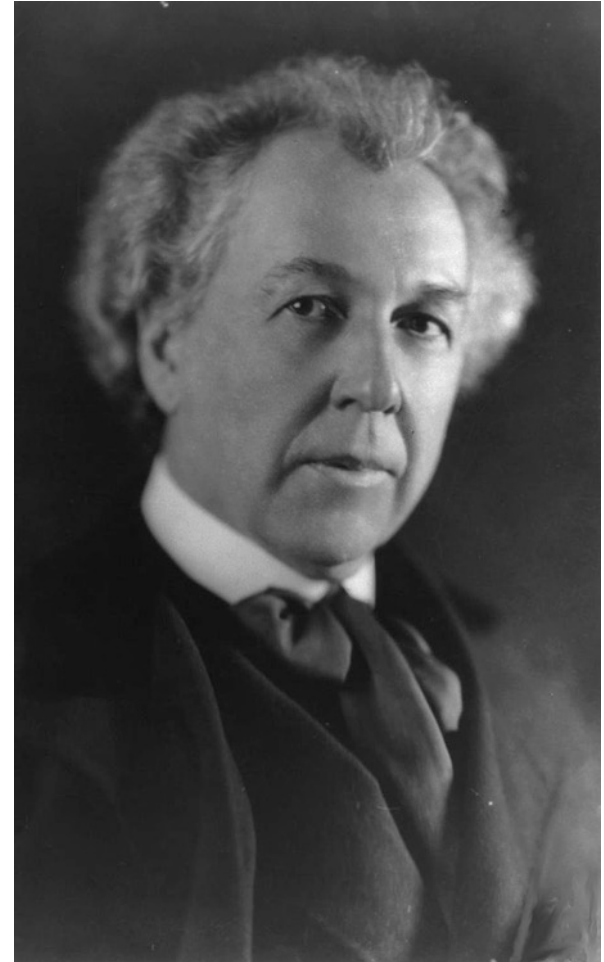


We can get there case by case

Principled Architectures & What They Can Enable

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



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 Principles for Computing?



Readings, Videos, Reference Materials

More on My Research & Teaching

Brief Self Introduction



■ Onur Mutlu

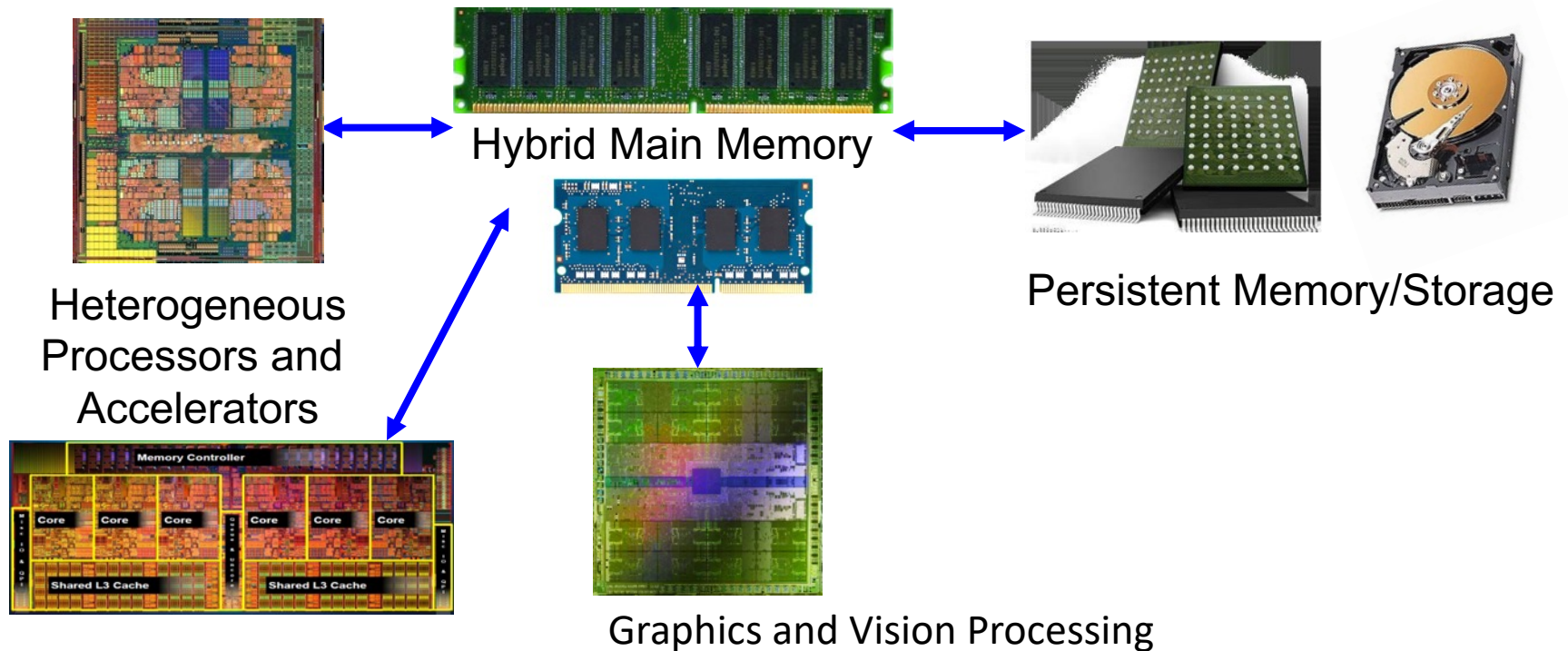
- ❑ Full Professor @ ETH Zurich ITET (INFK), since September 2015
- ❑ Strecker Professor @ Carnegie Mellon University ECE/CS, 2009-2016, 2016-...
- ❑ PhD from UT-Austin, worked at Google, VMware, Microsoft Research, Intel, AMD
- ❑ <https://people.inf.ethz.ch/omutlu/>
- ❑ omutlu@gmail.com (Best way to reach me)
- ❑ <https://people.inf.ethz.ch/omutlu/projects.htm>

■ Research and Teaching in:

- ❑ Computer architecture, computer systems, hardware security, bioinformatics
- ❑ Memory and storage systems
- ❑ Hardware security, safety, predictability
- ❑ Fault tolerance
- ❑ Hardware/software cooperation
- ❑ Architectures for bioinformatics, health, medicine
- ❑ ...

Current Research Mission

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

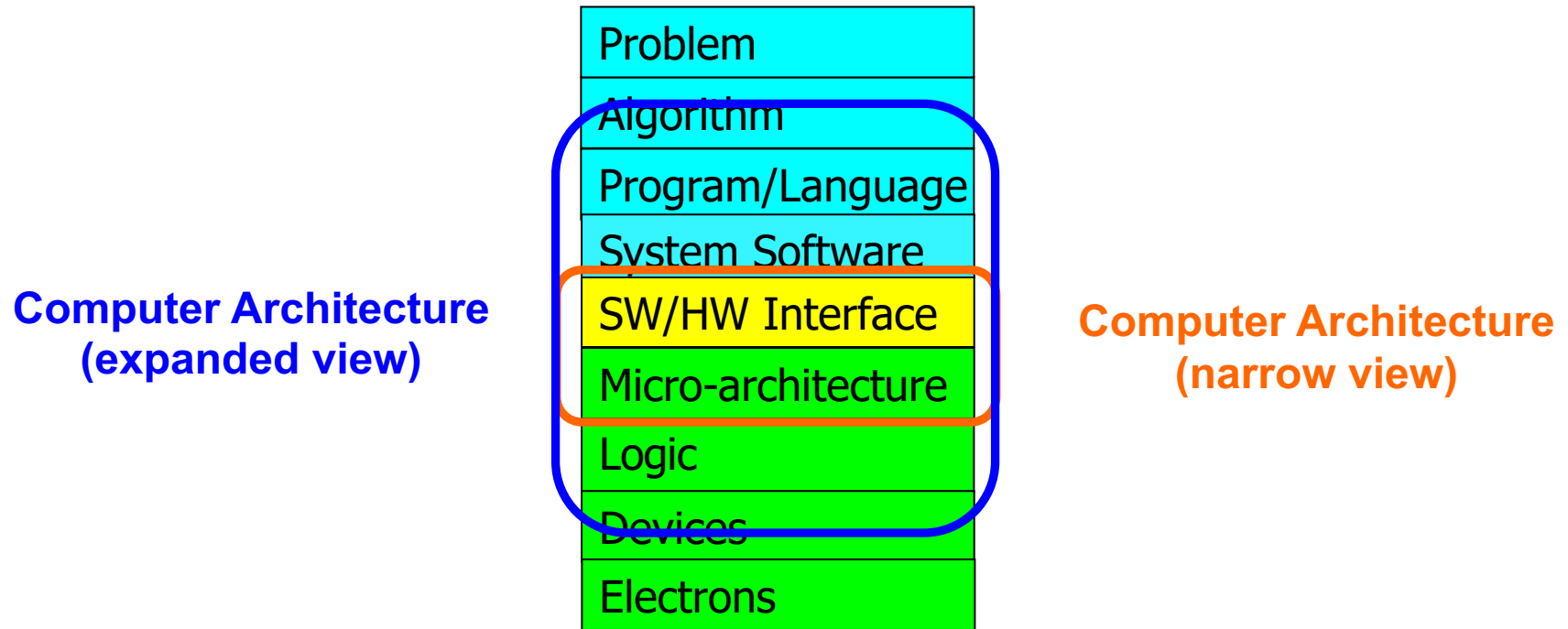


Build fundamentally better architectures

Four Key Current Directions

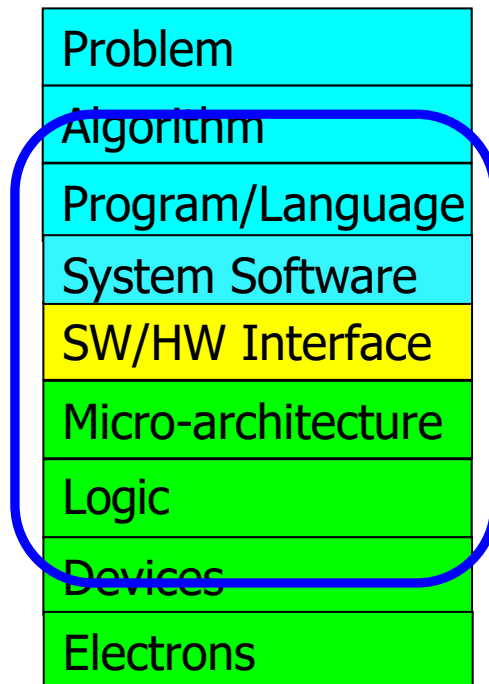
- Fundamentally Secure/Reliable/Safe Architectures
- Fundamentally Energy-Efficient Architectures
 - Memory-centric (Data-centric) Architectures
- Fundamentally Low-Latency and Predictable Architectures
- Architectures for AI/ML, Genomics, Medicine, Health

The Transformation Hierarchy



To achieve the highest **energy efficiency** and **performance**:

we must take the expanded view
of computer architecture

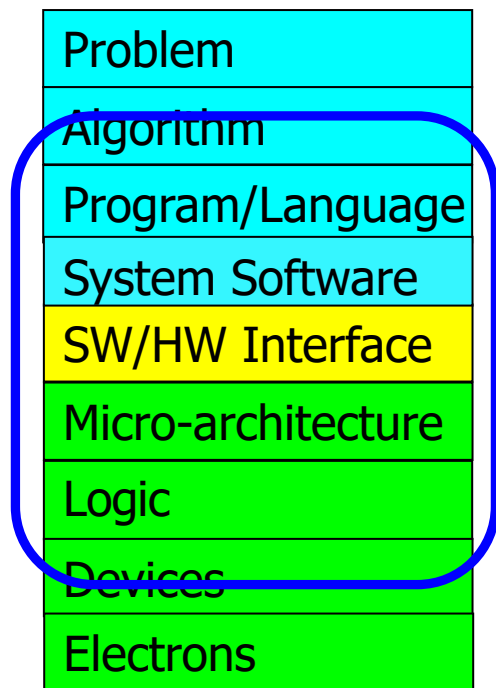


Co-design across the hierarchy:
Algorithms to devices

Specialize as much as possible
within the design goals

Current Research Mission & Major Topics

Build fundamentally better architectures



**Broad research
spanning apps, systems, logic
with architecture at the center**

- Data-centric arch. for low energy & high perf.
 - Proc. in Mem/DRAM, NVM, unified mem/storage
- Low-latency & predictable architectures
 - Low-latency, low-energy yet low-cost memory
 - QoS-aware and predictable memory systems
- Fundamentally secure/reliable/safe arch.
 - Tolerating all bit flips; patchable HW; secure mem
- Architectures for ML/AI/Genomics/Health/Med
 - Algorithm/arch./logic co-design; full heterogeneity
- Data-driven and data-aware architectures
 - ML/AI-driven architectural controllers and design
 - Expressive memory and expressive systems

Onur Mutlu's SAFARI Research Group

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

<https://safari.ethz.ch/safari-newsletter-april-2020/>



SAFARI
SAFARI Research Group
safari.ethz.ch

Think BIG, Aim HIGH!

SAFARI

<https://safari.ethz.ch>

SAFARI Newsletter April 2020 Edition

- <https://safari.ethz.ch/safari-newsletter-april-2020/>



[View in your browser](#)

Think Big, Aim High



Dear SAFARI friends,

2019 and the first three months of 2020 have been very positive eventful times for SAFARI.

SAFARI Newsletter January 2021 Edition

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



SAFARI
SAFARI Research Group

Newsletter
January 2021

*Think Big, Aim High, and
Have a Wonderful 2021!*



Dear SAFARI friends,

Happy New Year! We are excited to share our group highlights with you in this second edition of the SAFARI newsletter (You can find the first edition from April 2020 [here](#)). 2020 has

SAFARI Newsletter December 2021 Edition

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

SAFARI
SAFARI Research Group

Think Big, Aim High

ETH zürich



View in your browser
December 2021



Papers, Talks, Artifacts

- All are available at

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

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

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

Open Source Tools: SAFARI GitHub



SAFARI Research Group at ETH Zurich and Carnegie Mellon University

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

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

[🏠 Overview](#) [💻 Repositories 55](#) [📦 Packages](#) [👤 People 40](#) [👥 Teams 1](#) [📁 Projects](#) [⚙ Settings](#)

Pinned

Customize your pins

 **ramulator** Public ⋮

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

● C++ ☆ 250 🍴 130

 **prim-benchmarks** Public ⋮

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

● C ☆ 18 🍴 8

 **DAMOV** Public ⋮

DAMOV is a benchmark suite and a methodical framework targeting the study of data movement bottlenecks in modern applications. It is intended to study new architectures, such as near-data processin...

● C++ ☆ 12 🍴 1

📁 Repositories

Type ▾ Language ▾ Sort ▾ New

Pythia

A Customizable Hardware Prefetching Framework Using Online Reinforcement Learning.

● C++ ☆ 0 🍴 1 🔄 0 📄 0 Updated yesterday

BurstLink

☆ 0 🍴 0 🔄 0 📄 0 Updated 21 days ago

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

403

SAFARI PhD and Post-Doc Alumni

- <https://safari.ethz.ch/safari-alumni/>
- Minesh Patel (ETH Zurich), MICRO 2020 and DSN 2020 Best Paper Awards; ISCA Hall of Fame 2021
- Damla Senol Cali (Bionano Genomics), SRC TECHCON 2019 Best Student Presentation Award
- Nastaran Hajinazar (ETH Zurich)
- Gagandeep Singh (ETH Zurich), FPL 2020 Best Paper Award Finalist
- Amirali Boroumand (Stanford Univ → Google), SRC TECHCON 2018 Best Student Presentation Award
- Jeremie Kim (ETH Zurich), EDAA Outstanding Dissertation Award 2020; IEEE Micro Top Picks 2019; ISCA/MICRO HoF 2021
- Nandita Vijaykumar (Univ. of Toronto, Assistant Professor), ISCA Hall of Fame 2021
- Kevin Hsieh (Microsoft Research, Senior Researcher)
- Justin Meza (Facebook), HiPEAC 2015 Best Student Presentation Award; ICCD 2012 Best Paper Award
- Mohammed Alser (ETH Zurich), IEEE Turkey Best PhD Thesis Award 2018
- Yixin Luo (Google), HPCA 2015 Best Paper Session
- Kevin Chang (Facebook), SRC TECHCON 2016 Best Student Presentation Award
- Rachata Ausavarungrun (KMUNTB, Assistant Professor), NOCS 2015 and NOCS 2012 Best Paper Award Finalist
- Gennady Pekhimenko (Univ. of Toronto, Assistant Professor), ISCA Hall of Fame 2021; ASPLOS 2015 SRC Winner
- Vivek Seshadri (Microsoft Research)
- Donghyuk Lee (NVIDIA Research, Senior Researcher), HPCA Hall of Fame 2018
- Yoongu Kim (Software Robotics → Google), TCAD'19 Top Pick Award; IEEE Micro Top Picks'10; HPCA'10 Best Paper Session
- Lavanya Subramanian (Intel Labs → Facebook)
- Samira Khan (Univ. of Virginia, Assistant Professor), HPCA 2014 Best Paper Session
- Saugata Ghose (Univ. of Illinois, Assistant Professor), DFRWS-EU 2017 Best Paper Award
- Jawad Haj-Yahya (Huawei Research Zurich, Principal Researcher)

Principle: Teaching and Research

...

Teaching drives Research

Research drives Teaching

...

Principle: Learning and Scholarship

Focus on
learning and scholarship

Principle: Insight and Ideas

Focus on Insight

Encourage New Ideas

Principle: Learning and Scholarship

The quality of your work
defines your impact

Principle: Good Mindset, Goals & Focus

You can make a
good impact
on the world

Research & Teaching: Some Overview Talks

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

■ 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=njX_14584Jw&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBjI&index=16

■ Accelerating Genome Analysis

- https://www.youtube.com/watch?v=r7sn41IH-4A&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBjI&index=41

■ Rethinking Memory System Design

- https://www.youtube.com/watch?v=F7xZLNMIY1E&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBjI&index=3

■ Intelligent Architectures for Intelligent Machines

- https://www.youtube.com/watch?v=c6_LgzuNdkw&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBjI&index=25

■ The Story of RowHammer

- https://www.youtube.com/watch?v=sgd7PHQQ1AI&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBjI&index=39

Online Courses & Lectures

■ **First Computer Architecture & Digital Design Course**

- ❑ Digital Design and Computer Architecture
- ❑ **Spring 2021 Livestream** Edition:
https://www.youtube.com/watch?v=LbC0EZY8yw4&list=PL5Q2soXY2Zi_uej3aY39YB5pfW4SJ7LIN

■ **Advanced Computer Architecture Course**

- ❑ Computer Architecture
- ❑ **Fall 2021 Livestream** Edition:
<https://www.youtube.com/watch?v=c3mPdZA-Fmc&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN>
- ❑ **Fall 2020** Edition:
https://www.youtube.com/watch?v=4yfkM_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF



Onur Mutlu Lectures

16.9K subscribers

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How Computers Work (from the ground up)

1:33:25

Digital Design & Computer Architecture: Lecture 1: Introduction and Basics

49K views • 1 year ago

Computer Architecture - Lecture 1: Introduction and...

36K views • 3 years ago

Computer Architecture - Lecture 1: Introduction and...

31K views • 1 year ago

Computer Architecture - Lecture 1: Introduction and...

30K views • 8 months ago

Design of Digital Circuits - Lecture 1: Introduction and...

22K views • 2 years ago

Computer Architecture - Lecture 2: Fundamentals,...

17K views • 3 years ago

First Course in Computer Architecture & Digital Design 2021-2013

Livestream - Digital Design and Computer Architecture - ETH...

Onur Mutlu Lectures

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Digital Design & Computer Architecture - ETH Zürich...

Onur Mutlu Lectures

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Design of Digital Circuits - ETH Zürich - Spring 2019

Onur Mutlu Lectures

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Design of Digital Circuits - ETH Zürich - Spring 2018

Onur Mutlu Lectures

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Digital Circuits and Computer Architecture - ETH Zurich - ...

Onur Mutlu Lectures

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Spring 2015 -- Computer Architecture Lectures --...

Carnegie Mellon Computer Archite...

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Advanced Computer Architecture Courses 2020-2012

Computer Architecture - ETH Zürich - Fall 2020

Onur Mutlu Lectures

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Computer Architecture - ETH Zürich - Fall 2019

Onur Mutlu Lectures

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Computer Architecture - ETH Zürich - Fall 2018

Onur Mutlu Lectures

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Computer Architecture - ETH Zürich - Fall 2017

Onur Mutlu Lectures

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Fall 2015 - 740 Computer Architecture

Carnegie Mellon Computer Archite...

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Special Courses on Memory Systems

Memory Technology Lectures

Onur Mutlu Lectures

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Champéry Winter School 2020 - Memory Systems and Memory...

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Perugia NIPS Summer School 2019

Onur Mutlu Lectures

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SAMOS Tutorial 2019 - Memory Systems

Onur Mutlu Lectures

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TU Wien 2019 - Memory Systems and Memory-Centric...

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ACACES 2018 Lectures -- Memory Systems and Memory...

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Research Talks

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

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DDCA (Spring 2021)



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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

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

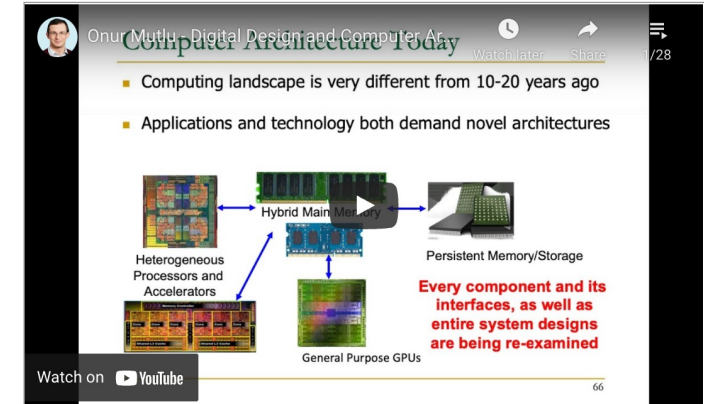
https://www.youtube.com/watch?v=LbC0EZY8yw4&list=PL5Q2soXY2Zi_uej3aY39YB5pfW4SJ7LIN

Bachelor's course

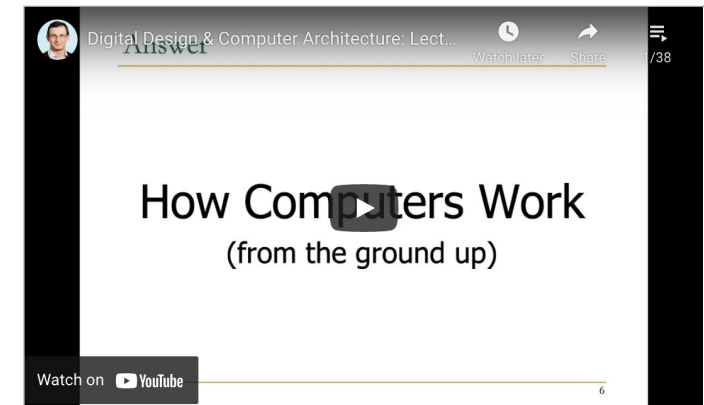
- ❑ 2nd semester at ETH Zurich
- ❑ Rigorous introduction into "How Computers Work"
- ❑ Digital Design/Logic
- ❑ Computer Architecture
- ❑ 10 FPGA Lab Assignments

Lecture Video Playlist on YouTube

Livestream Lecture Playlist



Recorded Lecture Playlist



Spring 2021 Lectures/Schedule

Week	Date	Livestream	Lecture	Readings	Lab	HW
W1	25.02 Thu.	YouTube Live	L1: Introduction and Basics 02:00 (PDF) 02:00 (PPT)	Required Suggested Mentioned		
	26.02 Fri.	YouTube Live	L2a: Tradeoffs, Metrics, Mindset 02:00 (PDF) 02:00 (PPT)	Required		
			L2b: Mysteries in Computer Architecture 02:00 (PDF) 02:00 (PPT)	Required Suggested Mentioned		
W2	04.03 Thu.	YouTube Live	L3a: Mysteries in Computer Architecture II 02:00 (PDF) 02:00 (PPT)	Required Suggested Mentioned		

Comp Arch (Fall 2020)

■ <https://safari.ethz.ch/architecture/fall2020/doku.php?id=schedule>

■ <https://www.youtube.com/watch?v=c3mPdZA-Fmc&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN>

- 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

SAFARI



Computer Architecture - Fall 2020

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Resources

- Computer Architecture FS19: Course Webpage
- Computer Architecture FS19: Lecture Videos
- Digitaltechnik SS20: Course Webpage
- Digitaltechnik SS20: Lecture Videos
- Moodle
- Piazza (Q&A)
- HotCRP
- Verilog Practice Website (HDLBits)

Lecture Video Playlist on YouTube

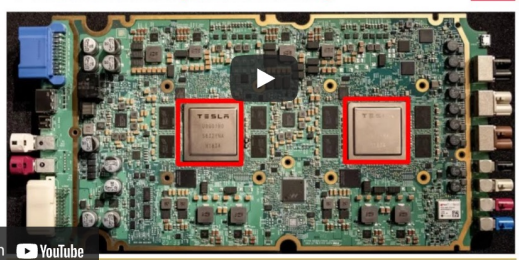
Lecture Playlist



Computer Architecture - Lecture: Introduction

■ ML accelerator: 260 mm², 6 billion transistors, 600 GFLOPS GPU, 12 ARM 2.2 GHz CPUs.

■ Two redundant chips for better safety.



Watch on YouTube

<https://www.youtube.com/watch?v=c3mPdZA-Fmc&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN>

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Fall 2020 Lectures & Schedule

Week	Date	Lecture	Readings	Lab	HW
W1	17.09 Thu.	L1: Introduction and Basics CORA (PDF) PPT YouTube Video	Described Suggested		HW 0 Out
		L2a: Memory Performance Attacks CORA (PDF) PPT YouTube Video	Described Suggested	Lab 1 Out	
	18.09 Fri.	L2b: Data Retention and Memory Refresh CORA (PDF) PPT YouTube Video	Described Suggested		
		L2c: Course Logistics CORA (PDF) PPT YouTube Video			
W2	24.09 Thu.	L3a: Introduction to Genome Sequence Analysis CORA (PDF) PPT YouTube Video	Described Suggested		HW 1 Out
		L3b: Memory Systems: Challenges and Opportunities CORA (PDF) PPT YouTube Video	Described Suggested		
	25.09 Fri.	L4a: Memory Systems: Solution Directions CORA (PDF) PPT YouTube Video	Described Suggested		
		L4b: RowHammer CORA (PDF) PPT YouTube Video	Described Suggested		
W3	01.10 Thu.	L5a: RowHammer in 2020: TRRespass CORA (PDF) PPT YouTube Video	Described Suggested		
		L5b: RowHammer in 2020: Revisiting RowHammer CORA (PDF) PPT YouTube Video	Described Suggested		
		L5c: Secure and Reliable Memory CORA (PDF) PPT YouTube Video	Described		

Comp Arch (Current)

■ <https://safari.ethz.ch/architecture/fall2021/doku.php?id=schedule>

■ **Youtube Livestream:**

❑ 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


Computer Architecture - Fall 2021

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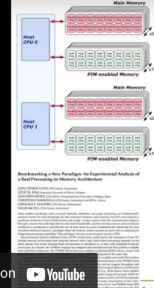
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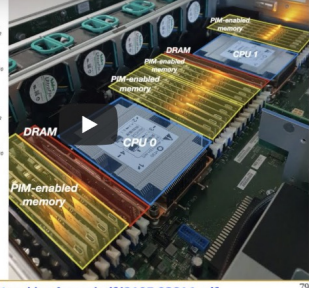
Resources

- Computer Architecture FS20: Course Webpage
- Computer Architecture FS20: Lecture Videos
- Digitaltechnik SS21: Course Webpage
- Digitaltechnik SS21: Lecture Videos
- Moodle
- HotCRP
- Verilog Practice Website (HDLBits)


Computer Architecture - Lecture Introduction

2.560 DRPU Processing in Memory System





Watch on

YouTube

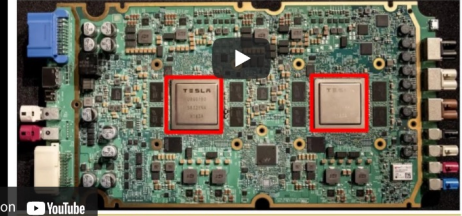
<https://arxiv.org/pdf/2105.03814.pdf>

Recorded Lecture Playlist


Computer Architecture - Lecture Introduction

TESLA Full Self-Driving Computer (2021)

- ML accelerator: 260 mm², 6 billion transistors, 600 GFLOPS GPU, 12 ARM 2.2 GHz CPUs.
- Two redundant chips for better safety.



Watch on

YouTube

<https://www.youtube.com/watch?v=Ucp0TTmvqOE?e=4236>

Fall 2021 Lectures & Schedule

Week	Date	Livestream	Lecture	Readings	Lab	HW
W1	30.09 Thu.	  Live	L1: Introduction and Basics (PDF) (PPT)	Required Mentioned	Lab 1 Out	HW 0 Out
	01.10 Fri.	  Live	L2: Trends, Tradeoffs and Design Fundamentals (PDF) (PPT)	Required Mentioned		
W2	07.10 Thu.	  Live	L3a: Memory Systems: Challenges and Opportunities (PDF) (PPT)	Described Suggested		HW 1 Out
			L3b: Course Info & Logistics (PDF) (PPT)			
			L3c: Memory Performance Attacks (PDF) (PPT)	Described Suggested		
	08.10 Fri.	  Live	L4a: Memory Performance Attacks (PDF) (PPT)	Described Suggested	Lab 2 Out	
			L4b: Data Retention and Memory Refresh (PDF) (PPT)	Described Suggested		
			L4c: RowHammer (PDF) (PPT)	Described Suggested		

Seminar (Spring'21)

■ https://safari.ethz.ch/architecture_seminar/spring2021/doku.php?id=schedule

■ https://www.youtube.com/watch?v=t3m93ZpLOyw&list=PL5Q2soXY2Zi_awYdjmWVIUegsbY7TPGW4

- Critical analysis course
 - Taken by Bachelor's/Masters/PhD students
 - Cutting-edge research topics + fundamentals in Computer Architecture
 - 20+ research papers, presentations, analyses



Seminar in Computer Architecture - Spring 2021

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- Fall 2020
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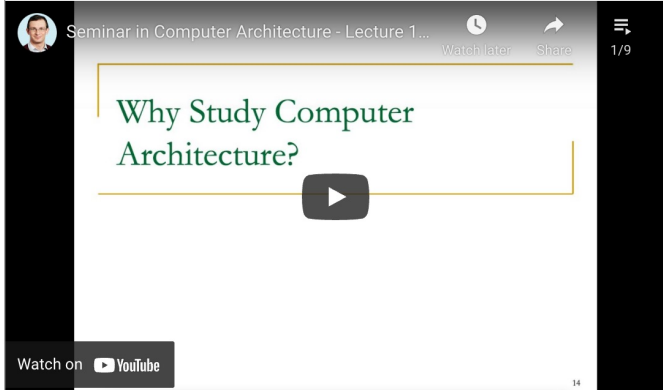
- Fall 2020
- Fall 2020: Lecture Videos
- Fall 2019
- Fall 2019: Lecture Videos
- Fall 2018
- Fall 2018: Lecture Videos

Digital Design and Computer Architecture

- Spring 2020
- Spring 2020: Lecture Videos
- Spring 2019
- Spring 2019: Lecture Videos

Lecture Video Playlist on YouTube

Lecture Playlist



Watch on YouTube

Spring 2021 Lectures/Schedule

Week	Date	Livestream	Lecture	Readings	Assignments
W1	25.02 Thu.	YouTube Live	L1a: Introduction and Basics PDF PPT	Suggested	
			Optional Lecture: Design Fundamentals PDF PPT		
			L1b: Course Logistics PDF PPT	Suggested	
W2	04.03 Thu.	YouTube Live	L2: Example Review: RowClone PDF PPT	Suggested	
W3	11.03 Thu.	YouTube Live	L3: Example Review: Memory Channel Partitioning PDF PPT	Suggested	
W4	18.03 Thu.	YouTube Live	L4: Example Review: GateKeeper PDF PPT	Suggested	
W5	25.03 Thu.		S1.1: Spectre Attacks: Exploiting Speculative Execution, S&P 2019 PPT PDF	Mentioned	
		YouTube Premiere	S1.2: BlockHammer: Preventing RowHammer at Low Cost by Blacklisting Rapidly-Accessed DRAM Rows, HPCA 2021 PPT PDF		
W6	01.04 Thu.		S2.1: D-RaNGe: Using Commodity DRAM Devices to Generate True Random Numbers with Low Latency and High Throughput, HPCA 2019 PPT PDF		
		YouTube Live	S2.2: ComputeDRAM: In-Memory Compute Using Off-the-Shelf DRAMs, MICRO 2019 PPT PDF	Mentioned	
W7	15.04 Thu.		S3.1: PIM-Enabled Instructions: A Low-Overhead, Locality-Aware Processing-in-Memory Architecture,	Mentioned	

Seminar (Current)

- https://safari.ethz.ch/architecture_seminar/fall2021/doku.php?id=schedule
- **Youtube Livestream:**
 - https://www.youtube.com/watch?v=4TcP297mdsI&list=PL5Q2soXY2Zi_7UBNmC9B8Yr5JSwTG9yH4
- Critical analysis course
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Seminar in Computer Architecture - Fall 2021

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- Fall 2018: Lecture Videos

Digital Design and Computer Architecture

- Spring 2021
- Spring 2021: Lecture Videos
- Spring 2020
- Spring 2020: Lecture Videos
- Spring 2019
- Spring 2019: Lecture Videos

Lecture Video Playlist on YouTube

Lecture Playlist



Watch on YouTube

Fall 2021 Lectures/Schedule

Week	Date	Livestream	Lecture	Readings	Assignments
W1	23.09 Thu.	YouTube Live	L1a: Course Logistics	Suggested	
			L1b: Introduction and Basics	Suggested	
			L1c: Architectural Design Fundamentals	Suggested	
W2	30.09 Thu.	YouTube Live	L2: GateKeeper	Suggested	
W3	07.10 Thu.	YouTube Live	L3: RowClone (Processing using DRAM)	Suggested	

Hands-On Projects & Seminars Courses

- https://safari.ethz.ch/projects_and_seminars/doku.php



SAFARI Project & Seminars Courses
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Projects

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- [Ramulator](#)
- [Accelerating Genomics](#)
- [Mobile Genomics](#)
- [Processing-in-Memory](#)
- [Heterogeneous Systems](#)
- [SSD Simulator](#)

[start](#)

SAFARI Projects & Seminars Courses (Spring 2021)

Welcome to the wiki for Project and Seminar courses SAFARI offers.

Courses we offer:

- Understanding and Improving Modern DRAM Performance, Reliability, and Security with Hands-On Experiments
- Designing and Evaluating Memory Systems and Modern Software Workloads with Ramulator
- Accelerating Genome Analysis with FPGAs, GPUs, and New Execution Paradigms
- Genome Sequencing on Mobile Devices
- Exploring the Processing-in-Memory Paradigm for Future Computing Systems
- Hands-on Acceleration on Heterogeneous Computing Systems
- Understanding and Designing Modern NAND Flash-Based Solid-State Drives (SSDs) by Building a Practical SSD Simulator

PIM Course (Current)

Fall 2021 Edition:

- https://safari.ethz.ch/projects_and_seminars/fall2021/doku.php?id=processing_in_memory

Youtube Livestream:

- https://www.youtube.com/watch?v=9e4Chnwdovo&list=PL5Q2soXY2Zi-841fUYYUK9EsXKhQKRPyX

Project course

- Taken by Bachelor's/Master's students
- Processing-in-Memory lectures
- Hands-on research exploration
- Many research readings

PIM Review and Open Problems
Processing in Memory Course: Meeting 1: Ex...

Watch later Share 1/10

A Modern Primer on Processing in Memory

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

SAFARI Research Group

^aETH Zürich
^bCarnegie Mellon University
^cUniversity of Illinois at Urbana-Champaign
^dKing Mongkut's University of Technology North Bangkok

Onur Mutlu, Saugata Ghose, Juan Gomez-Luna, and Rachata Ausavarungnirun, "A Modern Primer on Processing in Memory" Invited Book Chapter in *Emerging Computing: From Devices to Systems - Looking Beyond Moore and Von Neumann*, Springer, to be published in 2021.

Watch on YouTube

<https://arxiv.org/pdf/1903.03988.pdf> 108

Fall 2021 Meetings/Schedule

Week	Date	Livestream	Meeting	Learning Materials	Assignments
W1	05.10 Tue.	YouTube Live	M1: P&S PIM Course Presentation PDF (PDF) PPT (PPT)	Required Materials Recommended Materials	HW 0 Out
W2	12.10 Tue.	YouTube Live	M2: Real-World PIM Architectures PDF (PDF) PPT (PPT)		
W3	19.10 Tue.	YouTube Live	M3: Real-World PIM Architectures II PDF (PDF) PPT (PPT)		
W4	26.10 Tue.	YouTube Live	M4: Real-World PIM Architectures III PDF (PDF) PPT (PPT)		
W5	02.11 Tue.	YouTube Live	M5: Real-World PIM Architectures IV PDF (PDF) PPT (PPT)		
W6	09.11 Tue.	YouTube Live	M6: End-to-End Framework for Processing-using-Memory PDF (PDF) PPT (PPT)		
W7	16.11 Tue.	YouTube Live	M7: How to Evaluate Data Movement Bottlenecks PDF (PDF) PPT (PPT)		
W8	23.11 Tue.	YouTube Live	M8: Programming PIM Architectures PDF (PDF) PPT (PPT)		
W9	30.11 Tue.	YouTube Live	M9: Benchmarking and Workload Suitability on PIM PDF (PDF) PPT (PPT)		
W10	07.12 Tue.	YouTube Live	M10: Bit-Serial SIMD Processing using DRAM PDF (PDF) PPT (PPT)		

SAFARI Live Seminars (I)

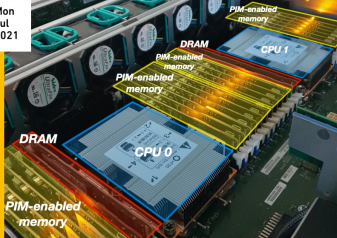
SAFARI Live Seminars in Computer Architecture

Dr. Juan Gómez Luna, ETH Zurich

Understanding a Modern Processing-in-Memory Architecture: Benchmarking and Experimental Characterization

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12 Mon Jul 2021

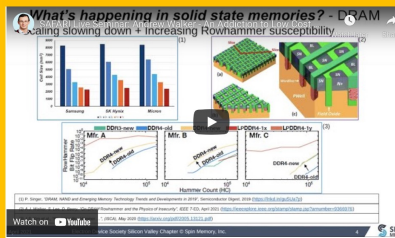
SAFARI Live Seminars in Computer Architecture

Dr. Andrew Walker, Schiltron Corporation & Nexgen Power Systems

An Addition to Low Cost Per Memory Bit – How to Recognize It and What to Do About It

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SAFARI Live Seminars in Computer Architecture

Geraldo F. Oliveira, ETH Zurich

DAMOV: A New Methodology and Benchmark Suite for Evaluating Data Movement Bottlenecks

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22 Do Jul 2021



Near-Data Processing (2/2)

UPMEM (2019) Samsung HBM-PIM

Near-DRAM-banks processing for general-purpose computing

0.9 TOPS compute throughput¹

Samsung FIMDRAM (2021)

Near-DRAM-banks processing for neural networks

1.2 TFLOPS compute throughput²

The goal of Near-Data Processing (NDP) is to mitigate data movement

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SAFARI Live Seminars in Computer Architecture

Gennady Pekhimenko, University of Toronto

Efficient DNN Training at Scale: from Algorithms to Hardware

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5 Do Aug 2021



DNN Training vs. Inference

Step 1 - Forward Pass (makes a prediction)

Step 2 - Backward Pass (calculates error gradients)

Generated in the forward pass

Used in the backward pass

DNN training requires stashing feature maps for the backward pass (not required in inference)

SAFARI Live Seminars in Computer Architecture

Jawad Haj-Yahya, Huawei Research Center Zurich

Power Management Mechanisms in Modern Microprocessors and Their Security Implications

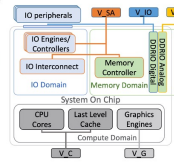
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16 Mo Aug 2021



Overview of a Modern SoC Architecture

- 3 domains in modern thermally-constrained mobile SoC: Compute, Memory, IO
- Several voltage sources exist, and some of them are shared between domains
- IO controllers and engines, IO interconnect, memory controller, and DDRIO typically each has an independent clock



SAFARI Live Seminars in Computer Architecture

Ataberk Olgun, TOBB & ETH Zurich

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

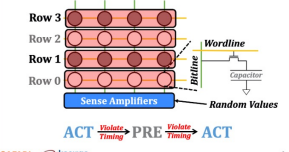
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15 Mi Sep 2021



Using QUAC to Generate Random Values

Use QUAC to activate DRAM rows that are initialized with conflicting data (e.g., two '1's and two '0's) to generate random values



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SAFARI Live Seminars in Computer Architecture

Minesh Patel, ETH Zurich

Enabling Effective Error Mitigation in Memory Chips That Use On-Die ECCs

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SAFARI Research Group

21 Tue Sep 2021



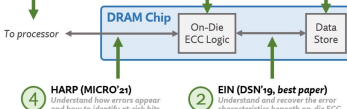
Position Paper (Ongoing) Arguing for increased transparency of DRAM reliability characteristics

REAPER (ISCA'17) Understand the basic properties of DRAM data-retention errors

BEER (MICRO'20, best paper) Determine exactly how on-die ECCs adjust error characteristics

HARP (MICRO'21) Understand how errors appear and how to identify at-risk bits

EIN (DSN'19, best paper) Understand and recover the error characteristics beneath on-die ECC



SAFARI Live Seminars in Computer Architecture

Christina Giannoula, National Technical University of Athens

Efficient Synchronization Support for Near-Data-Processing Architectures

SAFARI
SAFARI Research Group

27 Mo Sep 2021



NDP Synchronization Solution Space

Shared Memory

Message-passing

Hardware Cache Coherence

Remote Atomics

Specialized Hardware Support

Software-based Schemes

Specialized Hardware Support

NDP Systems: SynCron [HPCA'21]

SAFARI Live Seminars in Computer Architecture

Jawad Haj-Yahya, Huawei Research Center Zurich

Security Implications of Power Management Mechanisms in Modern Processors, Current Studies and Future Trends

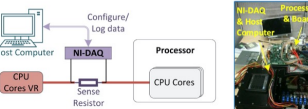
SAFARI
SAFARI Research Group

4 Mo Okt 2021



Experimental Methodology

- We experimentally study three modern Intel processors
 - Haswell, Coffee Lake, and Cannon Lake
- We measure voltage and current using a Data Acquisition card (NI-DAQ)



<https://safari.ethz.ch/safari-seminar-series/>

SAFARI Live Seminars (II)

SAFARI Live Seminars in Computer Architecture

Nastaran Hajinazar, ETH Zurich

Data-Centric and Data-Aware Frameworks for Fundamentally Efficient Data Handling in Modern Computing Systems

SAFARI
SAFARI Research Group

27 Wed Oct 2021

Overview of Our Approach

Data and the **efficient computation of data** should be the ultimate priority of the system

- **Data-Centric Architectures**
 - Enable computation with minimal data movement
 - Compute where data resides
- **Data-Aware Architectures**
 - Understand what they can do with and to each piece of data
 - Make use of different properties of data to improve performance, efficiency, etc.

SAFARI 15



SAFARI Live Seminar: Nastaran Hajinazar 27 Oct 2021

Posted on October 1, 2021 by ewent

Join us for our [SAFARI Live Seminar](#) with [Nastaran Hajinazar](#).

Wednesday, October 27 at 7:00 pm Zurich time (CEST)

SAFARI Live Seminars in Computer Architecture

Damla Senol Cali, Bionano Genomics

Accelerating Genome Sequence Analysis via Efficient Hardware/Algorithm Co-Design

SAFARI
SAFARI Research Group

7 Sun Nov 2021

Our Goal & Approach

- **Our Goal:**
Accelerating genome sequence analysis by **efficient hardware/algorithm co-design**
- **Our Approach:**
 - (1) Analyze the **multiple steps** and the **associated tools** in the genome sequence analysis pipeline,
 - (2) Expose the **tradeoffs** between accuracy, performance, memory usage and scalability, and
 - (3) Co-design **fast and efficient algorithms** along with **scalable and energy-efficient customized hardware accelerators** for the key bottleneck steps of the pipeline

Damla Senol Cali SAFARI 10



SAFARI Live Seminar: Damla Senol Cali 07 Nov 2021

Posted on October 18, 2021 by ewent

Join us for our [SAFARI Live Seminar](#) with [Damla Senol Cali](#).

Sunday, November 07 at 6:00 pm Zurich time (CEST)

SAFARI Live Seminars in Computer Architecture

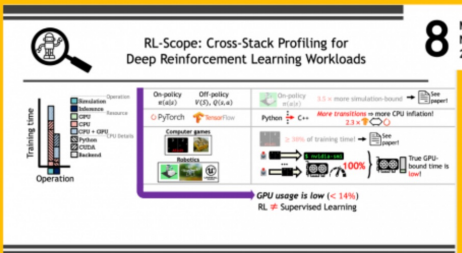
Gennady Pekhimenko, University of Toronto

Machine Learning Tools in Action

ETH zürich
SAFARI
SAFARI Research Group

8 Mo Nov 2021

RL-Scope: Cross-Stack Profiling for Deep Reinforcement Learning Workloads



SAFARI Live Seminar: Gennady Pekhimenko 08 Nov 2021

Posted on November 1, 2021 by ewent

Join us for our [SAFARI Live Seminar](#) with [Gennady Pekhimenko](#).

Monday, November 08 at 4:00 pm Zurich time (CET)

SAFARI Live Seminars in Computer Architecture

Serghei Mangul, Mangul Lab, USC

Opportunities and challenges of computational data-driven immunology

SAFARI
SAFARI Research Group
ETH zürich

11 Thu Nov 2021

Opportunities and challenges of computational data-driven immunology



Serghei Mangul, Ph.D
Assistant Professor,
University of Southern California
<https://mangul-lab.usc.edu/lab/>

SAFARI Live Seminar: Serghei Mangul 11 Nov 2021

Posted on November 5, 2021 by ewent

Join us for our [SAFARI Live Seminar](#) with [Serghei Mangul](#).

Thursday, November 11 at 11:00 am Zurich time (CET), ETH Zentrum ETZ K91

https://www.youtube.com/watch?v=D8Hjy2iU9l4&list=PL5Q2soXY2Zi_tOTAYm--dYByNPL7JhwR9&index=1

Open-Source Artifacts

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

Open Source Tools: SAFARI GitHub



SAFARI Research Group at ETH Zurich and Carnegie Mellon University

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

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

[🏠 Overview](#) [💻 Repositories 55](#) [📦 Packages](#) [👤 People 40](#) [👥 Teams 1](#) [📁 Projects](#) [⚙ Settings](#)

Pinned

Customize your pins

**ramulator** Public ⋮

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

● C++ ☆ 250 🍴 130

**prim-benchmarks** Public ⋮

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

● C ☆ 18 🍴 8

**DAMOV** Public ⋮

DAMOV is a benchmark suite and a methodical framework targeting the study of data movement bottlenecks in modern applications. It is intended to study new architectures, such as near-data processin...

● C++ ☆ 12 🍴 1

📁 Repositories

Type ▾ Language ▾ Sort ▾ New

Pythia

A Customizable Hardware Prefetching Framework Using Online Reinforcement Learning.

● C++ ☆ 0 🍴 1 🔄 0 📄 0 Updated yesterday

BurstLink

☆ 0 🍴 0 🔄 0 📄 0 Updated 21 days ago

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

423

Repositories 45 Packages People 12 Projects

Find a repository...

Type ▾

Language ▾

Sort ▾

COVIDHunter

COVIDHunter 🦠: An accurate and flexible COVID-19 outbreak simulation model that forecasts the strength of future mitigation measures and the numbers of cases, hospitalizations, and deaths for a given day, while considering the potential effect of environmental conditions. Described by Alser et al. (preliminary version at <https://arxiv.org/abs/2...>)

simulation epidemiology covid-19 covid-19-data covid-19-tracker
 reproduction-number covidhunter

Swift MIT 1 5 0 0 Updated 9 hours ago

SNP-Selective-Hiding

An optimization-based mechanism 🧠 to selectively hide the minimum number of overlapping SNPs among the family members 👥 who participated in the genomic studies (i.e. GWAS). Our goal is to distort the dependencies among the family members in the original database for achieving better privacy without significantly degrading the data utility.

gwas genomics data-privacy differential-privacy
 genomic-data-analysis laplace-distribution genomic-privacy

MATLAB 0 0 0 0 Updated 10 hours ago

SneakySnake

SneakySnake 🐍 is the first and the only pre-alignment filtering algorithm that works efficiently and fast on modern CPU, FPGA, and GPU architectures. It greatly (by more than two orders of magnitude) expedites sequence alignment calculation for both short and long reads. Described in the Bioinformatics (2020) by Alser et al. <https://arxiv.org/abs...>

fpga gpu smith-waterman needleman-wunsch
 sequence-alignment long-reads minimap2

VHDL GPL-3.0 6 31 0 1 Updated on May 12

ramulator

A Fast and Extensible DRAM Simulator, with built-in support for modeling many different DRAM technologies including DDRx, LPDDRx, GDDRx, WIOx, HBMx, and various academic proposals. Described in the IEEE CAL 2015 paper by Kim et al. at http://users.ece.cmu.edu/~omutlu/pub/ramulator_dram_simulator-ieee-cal15.pdf

C++ MIT 121 237 47 4 Updated on May 11

Top languages

C++ C C# AGS Script
 VHDL

Most used topics

dram reliability
 error-correcting-codes
 experimental-data
 pre-alignment-filtering

People

12 >



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

An Interview on Research and Education

- **Computing Research and Education (@ ISCA 2019)**
 - https://www.youtube.com/watch?v=8ffSEKZhmvo&list=PL5Q2soXY2Zi_4oP9LdL3cc8G6NIjD2Ydz

- **Maurice Wilkes Award Speech (10 minutes)**
 - https://www.youtube.com/watch?v=tcQ3zZ3JpuA&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJI&index=15

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"](#)
*[57th Design Automation Conference Early Career Workshop \(**DAC**\)](#), Virtual, 19 July 2020.*
[\[Slides \(pptx\) \(pdf\)\]](#)

More Thoughts and Suggestions (II)

- Onur Mutlu,
"Computer Architecture: Why Is It So Important and Exciting Today?"
Invited Lecture at *Izmir Institute of Technology (IYTE)*, Virtual, 16 October 2020.
[[Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (2 hours 12 minutes)]

- Onur Mutlu,
"Applying to Graduate School & Doing Impactful Research"
Invited Panel Talk at *the 3rd Undergraduate Mentoring Workshop, held with the 48th International Symposium on Computer Architecture (ISCA)*, Virtual, 18 June 2021.
[[Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (50 minutes)]

A Talk on Impactful Research & Teaching



The video player shows a presentation slide with the following content:

Applying to Grad School
& Doing Impactful Research

Onur Mutlu
omutlu@gmail.com
<https://people.inf.ethz.ch/omutlu>
13 June 2020
Undergraduate Architecture Mentoring Workshop @ ISCA 2021

Logos for SAFARI, ETH zürich, and Carnegie Mellon are displayed at the bottom of the slide.

Below the video player, the video title is "Arch. Mentoring Workshop @ISCA'21 - Applying to Grad School & Doing Impactful Research - Onur Mutlu". It has 1,563 views and premiered on Jun 16, 2021. The video has 74 likes and 1 comment. The channel is "Onur Mutlu Lectures" with 17.2K subscribers. The video description mentions a panel talk at the Undergraduate Architecture Mentoring Workshop at ISCA 2021, with a link to <https://sites.google.com/wisc.edu/uar...>. Buttons for "ANALYTICS" and "EDIT VIDEO" are visible.

An Interview on Computing Futures



Interview with Onur Mutlu @ ISCA 2019 on computing research & education (after Maurice Wilkes Award)

6,749 views • Oct 19, 2019

👍 195 🗨️ 0 ➦ SHARE ⚙️ ⌂ ...



Onur Mutlu Lectures
19.1K subscribers

ANALYTICS

EDIT VIDEO

Papers, Talks, Videos, Artifacts

- All are available at

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

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

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

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

Fundamental Thinking

Historical: Opportunities at the Bottom

There's Plenty of Room at the Bottom

From Wikipedia, the free encyclopedia

"There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics" was a lecture given by [physicist Richard Feynman](#) at the annual [American Physical Society](#) meeting at [Caltech](#) on December 29, 1959.^[1] Feynman considered the possibility of direct manipulation of individual atoms as a more powerful form of synthetic chemistry than those used at the time. Although versions of the talk were reprinted in a few popular magazines, it went largely unnoticed and did not inspire the conceptual beginnings of the field. Beginning in the 1980s, nanotechnology advocates cited it to establish the scientific credibility of their work.

Historical: Opportunities at the Bottom (II)

There's Plenty of Room at the Bottom

From Wikipedia, the free encyclopedia

Feynman considered some ramifications of a general ability to manipulate matter on an atomic scale. He was particularly interested in the possibilities of denser computer circuitry, and microscopes that could see things much smaller than is possible with scanning electron microscopes. These ideas were later realized by the use of the scanning tunneling microscope, the atomic force microscope and other examples of scanning probe microscopy and storage systems such as Millipede, created by researchers at IBM.

Feynman also suggested that it should be possible, in principle, to make nanoscale machines that "arrange the atoms the way we want", and do chemical synthesis by mechanical manipulation.

He also presented the possibility of "swallowing the doctor", an idea that he credited in the essay to his friend and graduate student Albert Hibbs. This concept involved building a tiny, swallowable surgical robot.

Historical: Opportunities at the Top

REVIEW

There's plenty of room at the Top: What will drive computer performance after Moore's law?

 Charles E. Leiserson¹,  Neil C. Thompson^{1,2,*},  Joel S. Emer^{1,3},  Bradley C. Kuszmaul^{1,†}, Butler W. Lampson^{1,4},  ...

+ See all authors and affiliations

Science 05 Jun 2020:
Vol. 368, Issue 6495, eaam9744
DOI: 10.1126/science.aam9744

Much of the improvement in computer performance comes from decades of miniaturization of computer components, a trend that was foreseen by the Nobel Prize-winning physicist Richard Feynman in his 1959 address, “There’s Plenty of Room at the Bottom,” to the American Physical Society. In 1975, Intel founder Gordon Moore predicted the regularity of this miniaturization trend, now called Moore’s law, which, until recently, doubled the number of transistors on computer chips every 2 years.

Unfortunately, semiconductor miniaturization is running out of steam as a viable way to grow computer performance—there isn’t much more room at the “Bottom.” If growth in computing power stalls, practically all industries will face challenges to their productivity. Nevertheless, opportunities for growth in computing performance will still be available, especially at the “Top” of the computing-technology stack: software, algorithms, and hardware architecture.

Axiom, Revisited

There **is** plenty of room both at the top and at the bottom

but **much more so**

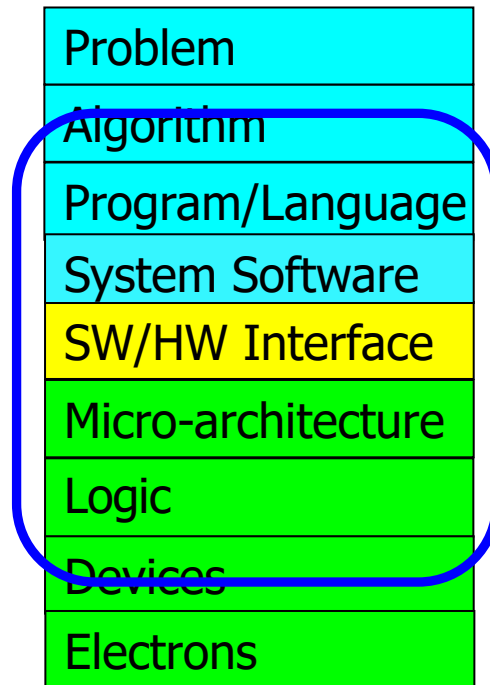
when you

communicate well between and optimize across

the top and the bottom

Hence the Expanded View

**Computer Architecture
(expanded view)**



Data-centric

Data-driven

Data-aware

End of Backup Slides