

# Intelligent Architectures for Intelligent Machines

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Ontario Tech Distinguished Speaker Series Lecture

**SAFARI**

**ETH** zürich

**Carnegie Mellon**

Computing

is Bottlenecked by Data



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

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- 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

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## 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

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**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**

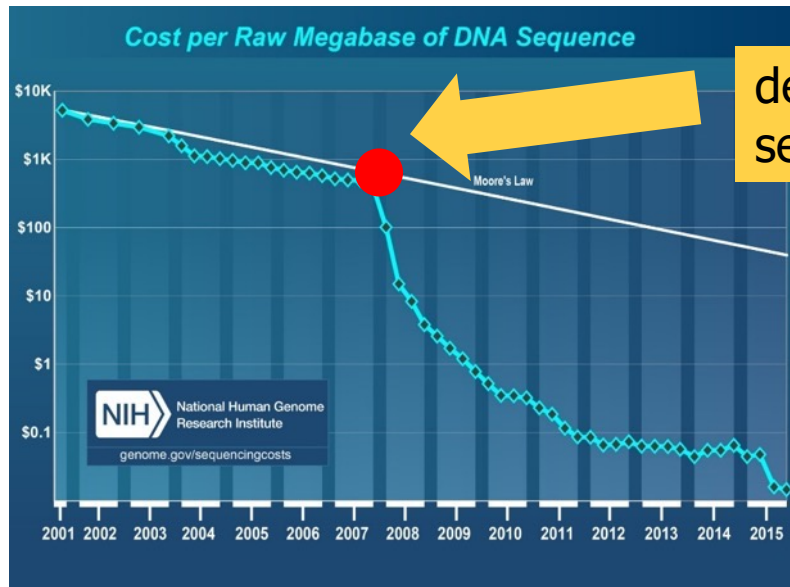
**VP9**



**Video Capture**

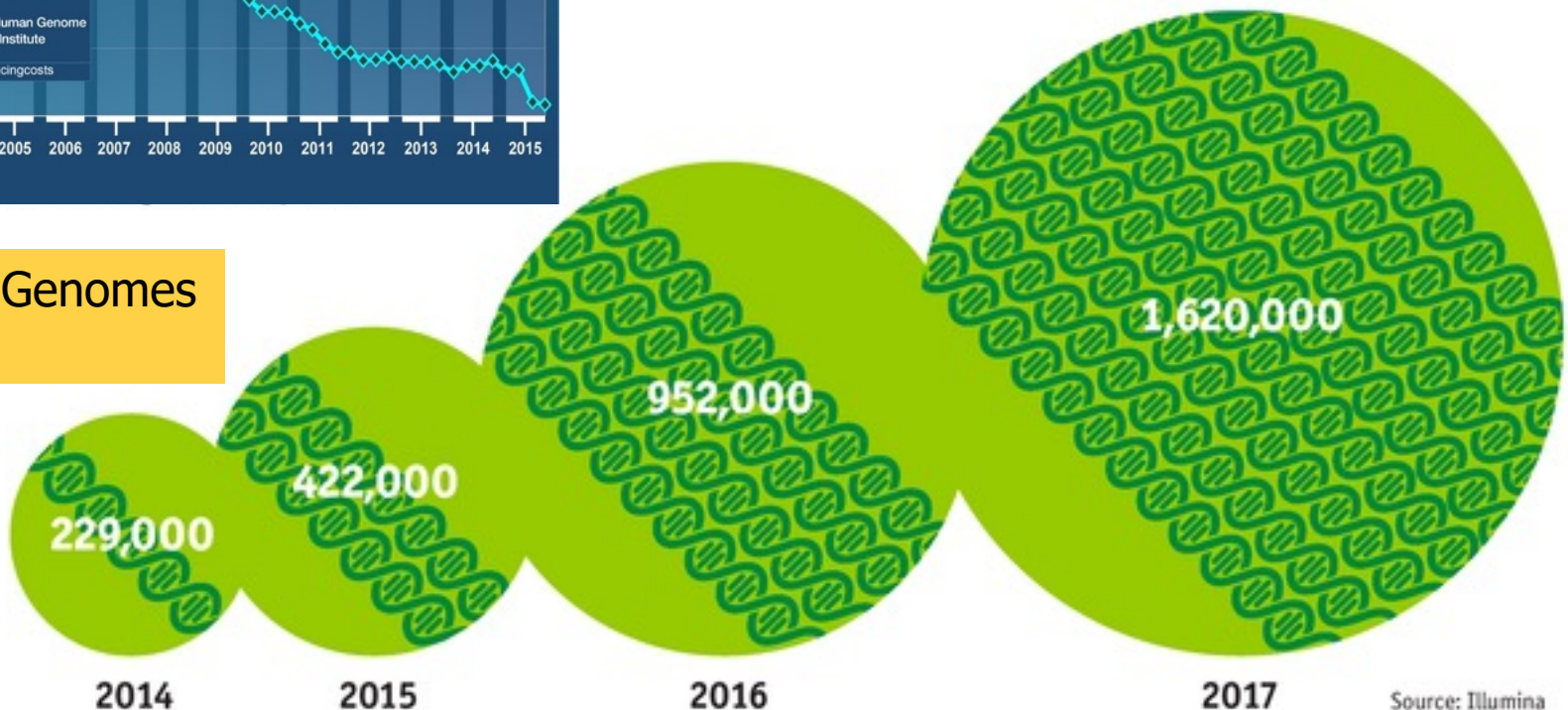
Google's **video codec**

# Data is Key for Future Workloads

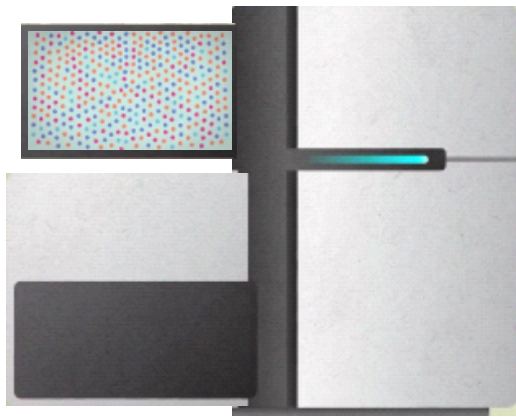


development of high-throughput sequencing (HTS) technologies

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

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## 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

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

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



Oxford Nanopore MinION

Data → performance & energy bottleneck

# 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

# 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

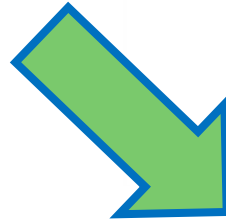
Damla Senol Cali<sup>†⌘</sup> Gurpreet S. Kalsi<sup>⌘</sup> Zülal Bingöl<sup>▽</sup> Can Firtina<sup>◇</sup> Lavanya Subramanian<sup>‡</sup> Jeremie S. Kim<sup>◇†</sup>  
Rachata Ausavarungnirun<sup>○</sup> Mohammed Alser<sup>◇</sup> Juan Gomez-Luna<sup>◇</sup> Amirali Boroumand<sup>†</sup> Anant Nori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

# Future of Genome Sequencing & Analysis

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MinION from ONT



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

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- **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>

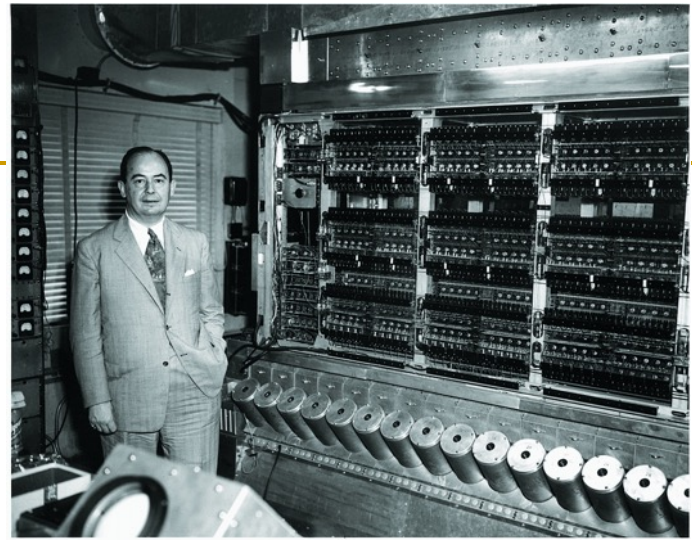
# Data Overwhelms Modern Machines ...

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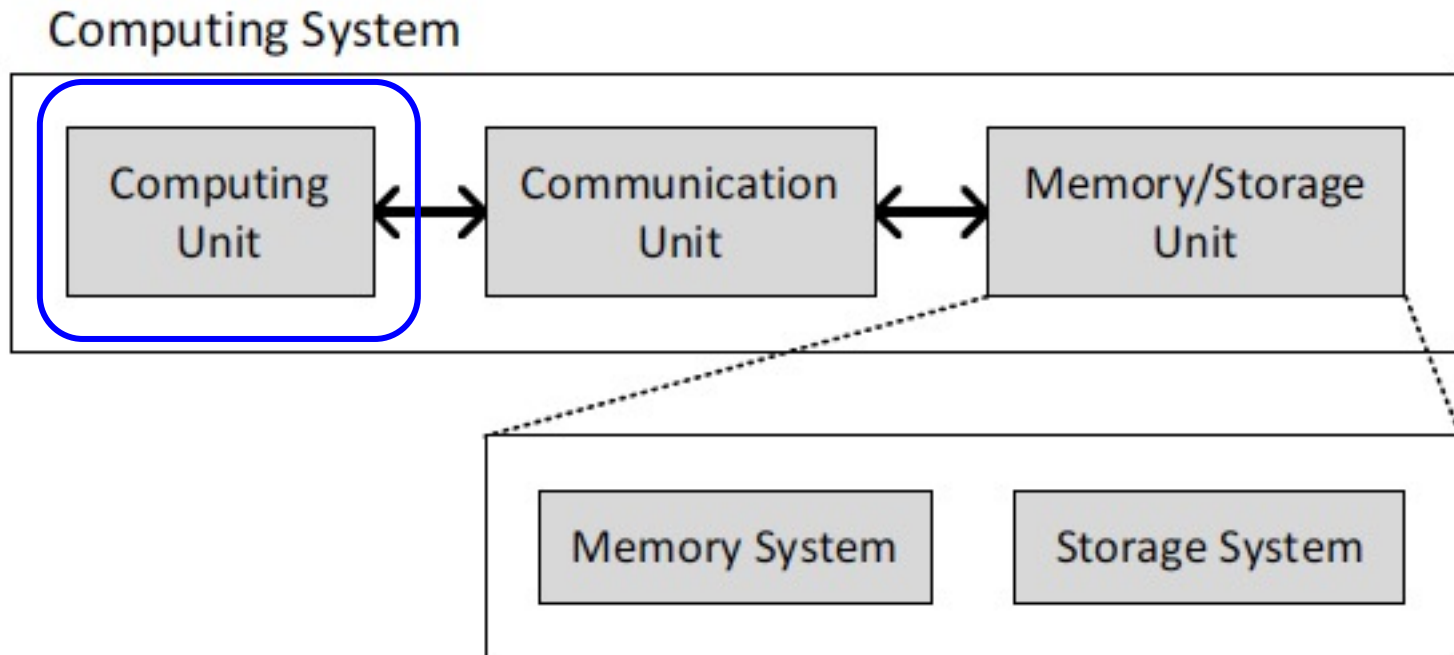
- Storage/memory capability
- Communication capability
- Computation capability
- Greatly impacts robustness, energy, performance, cost

# 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.







# 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 Boroumand<sup>1</sup>

Saugata Ghose<sup>1</sup>

Youngsok Kim<sup>2</sup>

Rachata Ausavarungnirun<sup>1</sup>

Eric Shiu<sup>3</sup>

Rahul Thakur<sup>3</sup>

Daehyun Kim<sup>4,3</sup>

Aki Kuusela<sup>3</sup>

Allan Knies<sup>3</sup>

Parthasarathy Ranganathan<sup>3</sup>

Onur Mutlu<sup>5,1</sup>

## An Intelligent Architecture Handles Data Well

# How to Handle Data Well

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- 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 ...

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- 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**

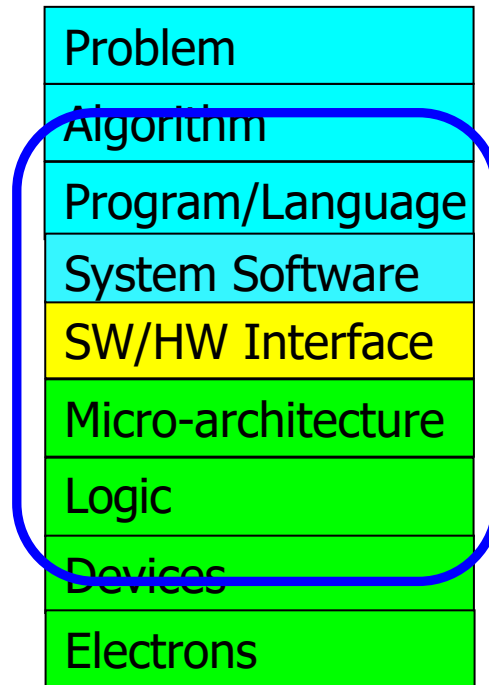
**Data-centric**

**Data-driven**

**Data-aware**

# We Need to Revisit the Entire Stack

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**We can get there step by step**



# Data-Centric (Memory-Centric) Architectures

# Data-Centric Architectures: Properties

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- **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

# Processing Data Where It Makes Sense

# Processing in/near Memory: An Old Idea

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- 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.

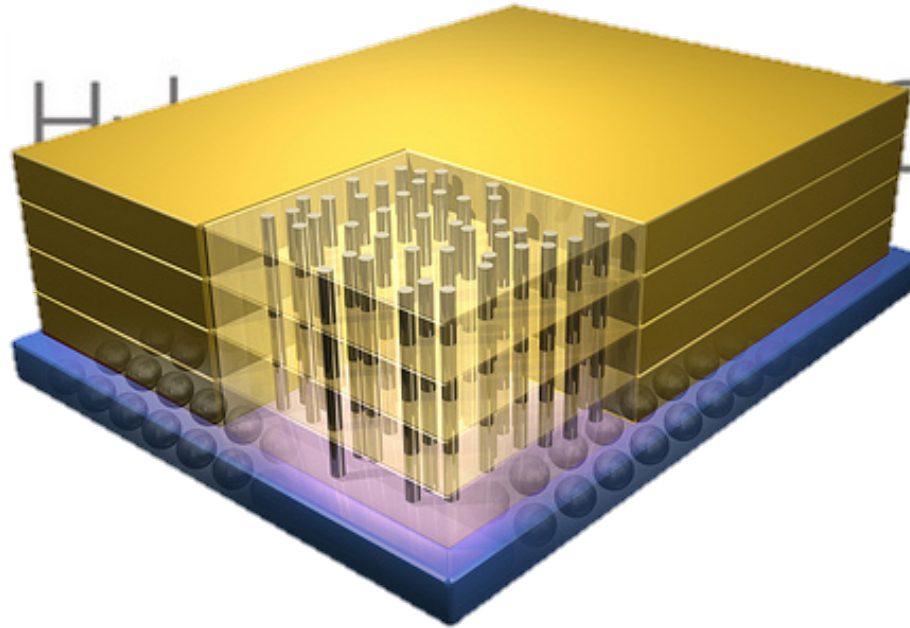
# Why In-Memory Computation Today?

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

# Why In-Memory Computation Today?

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# Memory Scaling Issues **Were** Real

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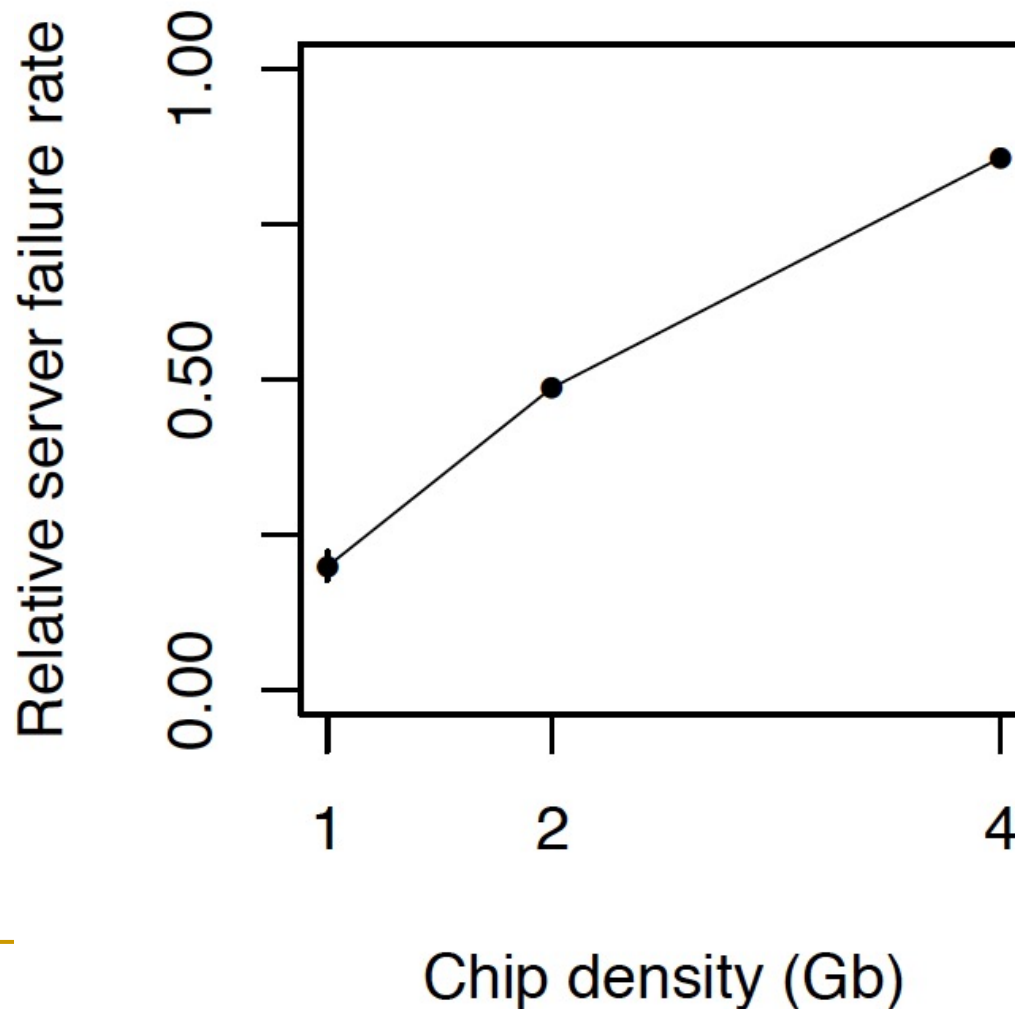
- Onur Mutlu,  
**"Memory Scaling: A Systems Architecture Perspective"**  
*Proceedings of the 5th International Memory Workshop (IMW)*, Monterey, CA, May 2013. Slides  
(pptx) (pdf)  
EETimes Reprint

## Memory Scaling: A Systems Architecture Perspective

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

# As Memory Scales, It Becomes Unreliable

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



*Intuition:  
quadratic  
increase  
in  
capacity*



# Large-Scale Failure Analysis of DRAM Chips

---

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

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

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

# Infrastructures to Understand Such Issues



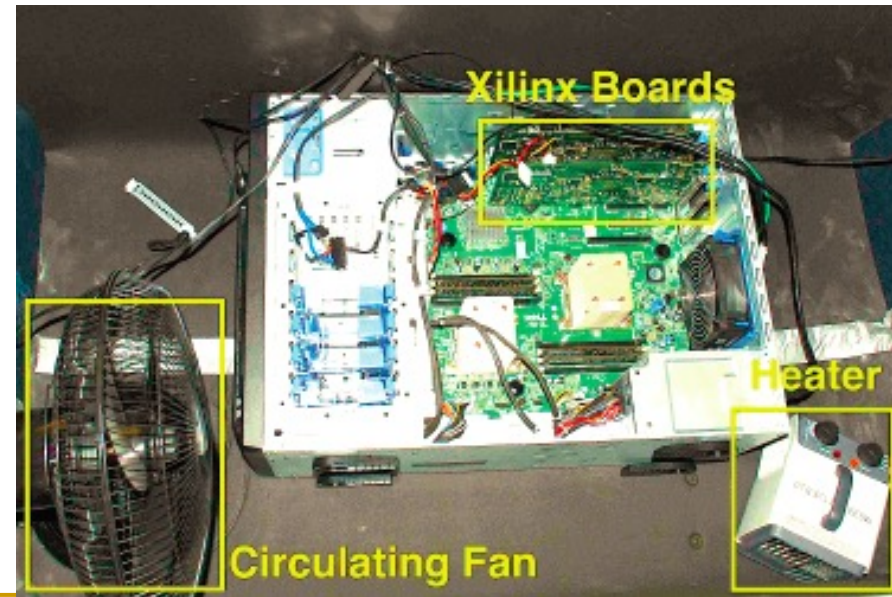
An Experimental Study of Data Retention Behavior in Modern DRAM Devices: Implications for Retention Time Profiling Mechanisms (Liu et al., ISCA 2013)

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

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

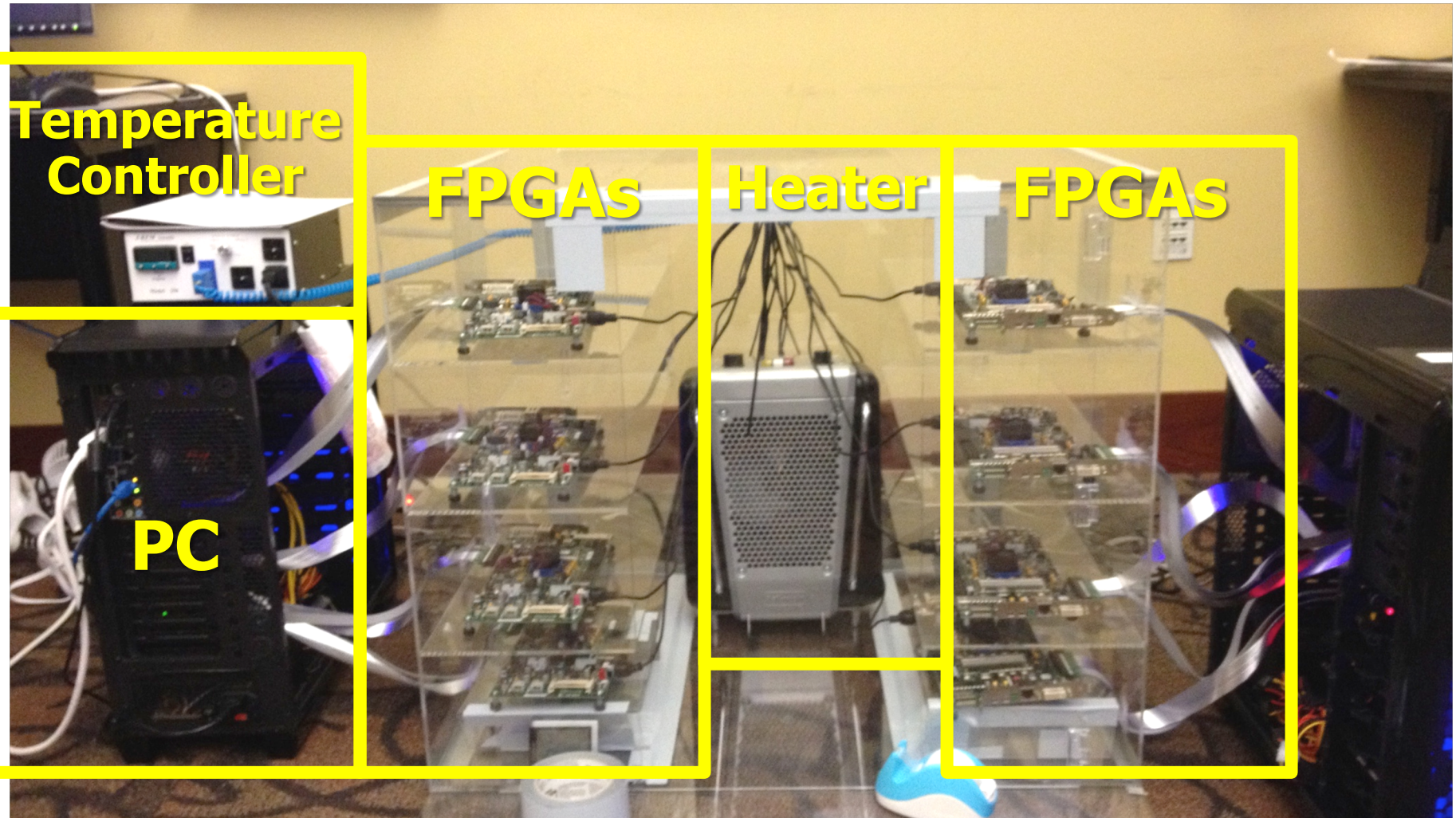
Adaptive-Latency DRAM: Optimizing DRAM Timing for the Common-Case (Lee et al., HPCA 2015)

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





# Infrastructures to Understand Such Issues



# SoftMC: Open Source DRAM Infrastructure

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





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

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

Hasan Hassan<sup>1,2,3</sup> Nandita Vijaykumar<sup>3</sup> Samira Khan<sup>4,3</sup> Saugata Ghose<sup>3</sup> Kevin Chang<sup>3</sup>  
Gennady Pekhimenko<sup>5,3</sup> Donghyuk Lee<sup>6,3</sup> Oguz Ergin<sup>2</sup> Onur Mutlu<sup>1,3</sup>

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

# A Curious Discovery [Kim et al., ISCA 2014]

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One can  
predictably induce errors  
in most DRAM memory chips

# The Story of RowHammer

- One can **predictably induce bit flips** in commodity DRAM chips
  - >80% of the tested DRAM chips are vulnerable
- First example of how a **simple hardware failure mechanism** can create a **widespread system security vulnerability**

**WIRED**

Forget Software—Now Hackers Are Exploiting Physics

BUSINESS	CULTURE	DESIGN	GEAR	SCIENCE
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ANDY GREENBERG SECURITY 08.31.16 7:00 AM

SHARE



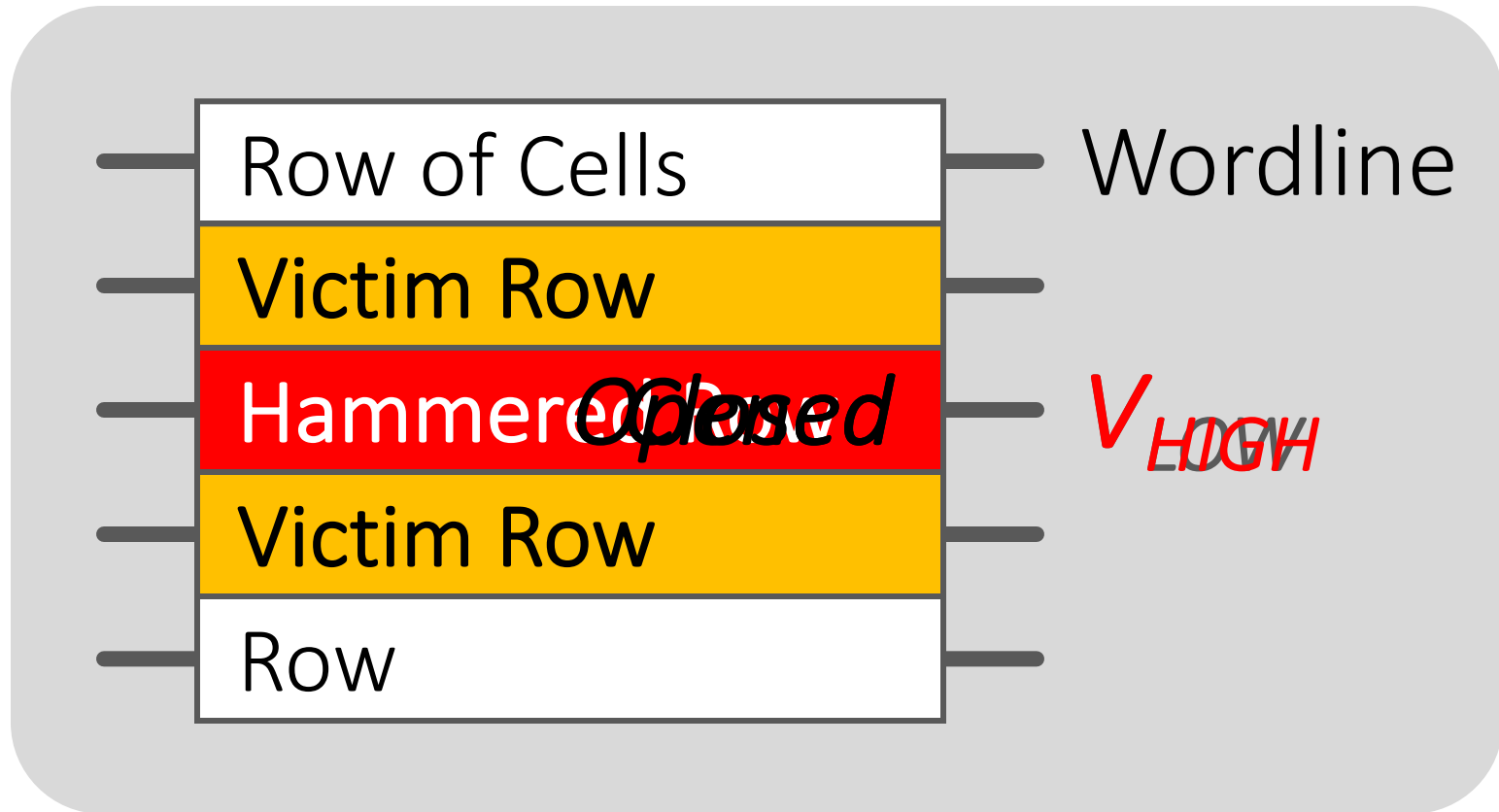
SHARE  
18276



TWEET

# FORGET SOFTWARE—NOW HACKERS ARE EXPLOITING PHYSICS

# Modern DRAM is Prone to Disturbance Errors

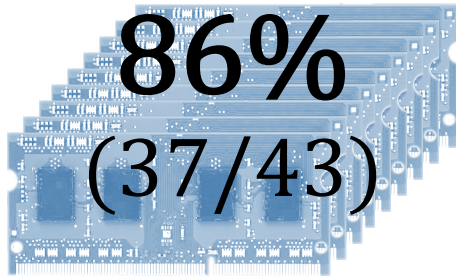


Repeatedly reading a row enough times (before memory gets refreshed) induces **disturbance errors** in adjacent rows in **most real DRAM chips you can buy today**



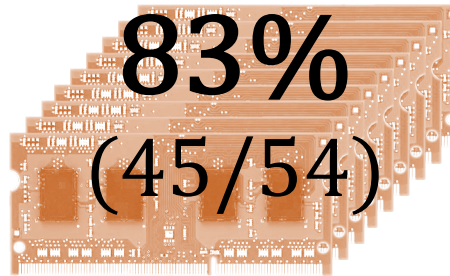
# Most DRAM Modules Are Vulnerable

A company



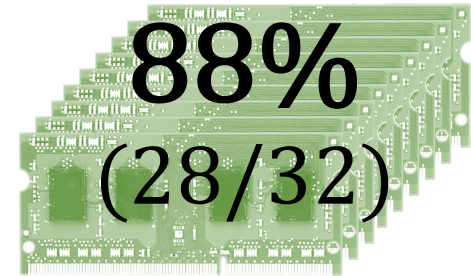
Up to  
 $1.0 \times 10^7$   
errors

B company



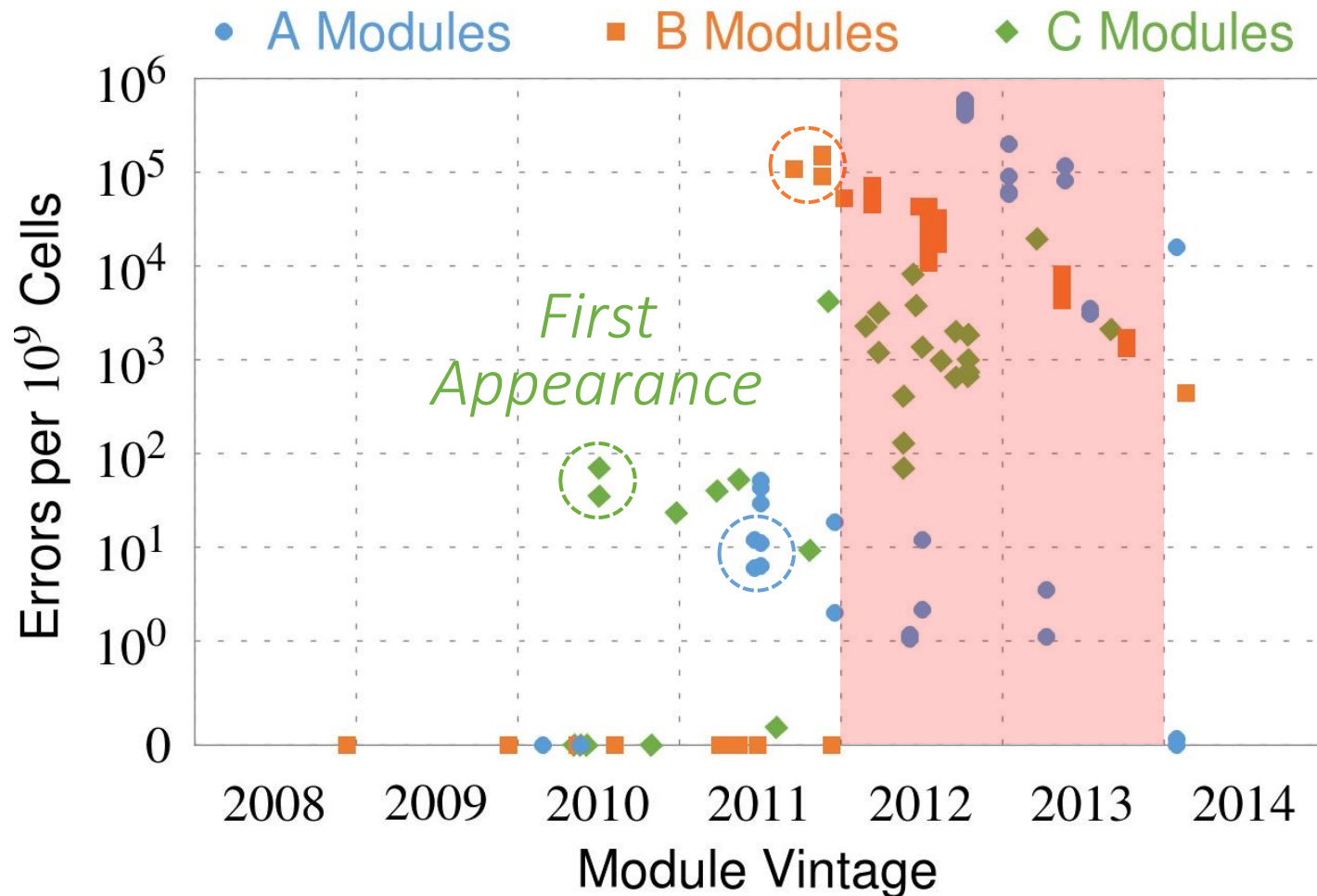
Up to  
 $2.7 \times 10^6$   
errors

C company



Up to  
 $3.3 \times 10^5$   
errors

# Recent DRAM Is More Vulnerable



*All modules from 2012-2013 are vulnerable*

# One Can Take Over an Otherwise-Secure System

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

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

# Project Zero

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

News and updates from the Project Zero team at Google

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

Monday, March 9, 2015

Exploiting the DRAM rowhammer bug to gain kernel privileges

# More Security Implications (I)

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

www.iaik.tugraz.at ■

Not there yet, but ...



ROOT privileges for web apps!

29

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



GATED  
COMMUNITIES

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

# More Security Implications (II)

**"Can gain control of a smart phone deterministically"**



Drammer: Deterministic Rowhammer  
Attacks on Mobile Platforms, CCS'16 <sup>47</sup>



# More Security Implications (VII)

---

## ■ USENIX Security 2019

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

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

*University of Maryland, College Park*

*<sup>†</sup>Vrije Universiteit Amsterdam*



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

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

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

[Read More](#)

# More Security Implications (VIII)

## ■ USENIX Security 2020

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

Fan Yao

*University of Central Florida*

*fan.yao@ucf.edu*

Adnan Siraj Rakin

*Arizona State University*

*asrakin@asu.edu*

Deliang Fan

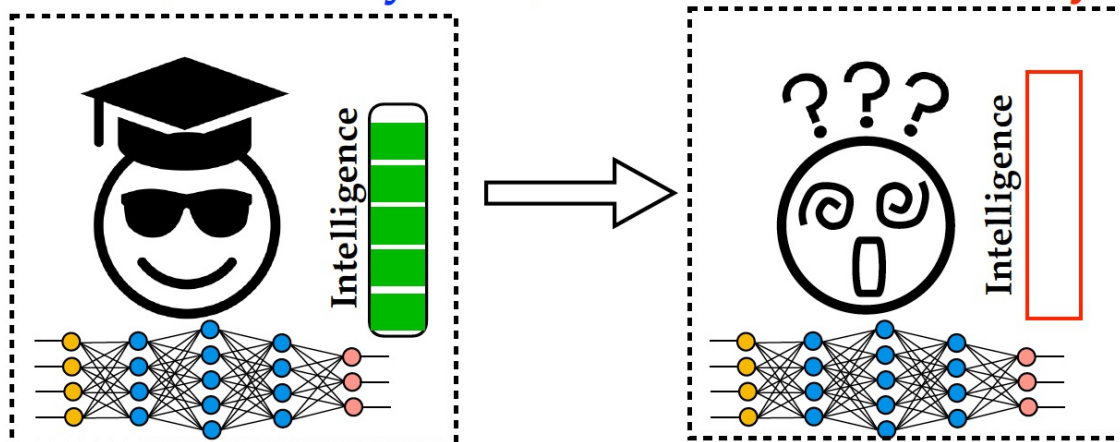
*Arizona State University*

*dfan@asu.edu*

Degrade the inference accuracy to the level of Random Guess

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

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



# 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](#)]

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

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

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



# 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]

## RowHammer: A Retrospective

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

## Main Memory Needs Intelligent Controllers

# RowHammer in 2020 (I)

---

- Jeremie S. Kim, Minesh Patel, A. Giray Yaglikci, Hasan Hassan, Roknoddin Azizi, Lois Orosa, and Onur Mutlu,  
**"Revisiting RowHammer: An Experimental Analysis of Modern Devices and Mitigation Techniques"**  
*Proceedings of the 47th International Symposium on Computer Architecture (ISCA)*, Valencia, Spain, June 2020.  
[[Slides \(pptx\)](#)] [[pdf](#)]  
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]  
[[Talk Video](#) (20 minutes)]  
[[Lightning Talk Video](#) (3 minutes)]

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

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

# Key Takeaways from 1580 Chips

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

# RowHammer in 2020 (II)

---

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

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

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

# RowHammer in 2020 (III)

---

- Lucian Cojocar, Jeremie Kim, Minesh Patel, Lillian Tsai, Stefan Saroiu, Alec Wolman, and Onur Mutlu,

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

*Proceedings of the 41st IEEE Symposium on Security and Privacy (S&P), San Francisco, CA, USA, May 2020.*

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

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

## Are We Susceptible to Rowhammer?

## An End-to-End Methodology for Cloud Providers

Lucian Cojocar, Jeremie Kim<sup>§†</sup>, Minesh Patel<sup>§</sup>, Lillian Tsai<sup>‡</sup>,  
Stefan Saroiu, Alec Wolman, and Onur Mutlu<sup>§†</sup>  
Microsoft Research, <sup>§</sup>ETH Zürich, <sup>†</sup>CMU, <sup>‡</sup>MIT

# BlockHammer Solution in 2021

---

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

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

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

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

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

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

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

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

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

<sup>1</sup>ETH Zürich

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

# Detailed Lectures on RowHammer

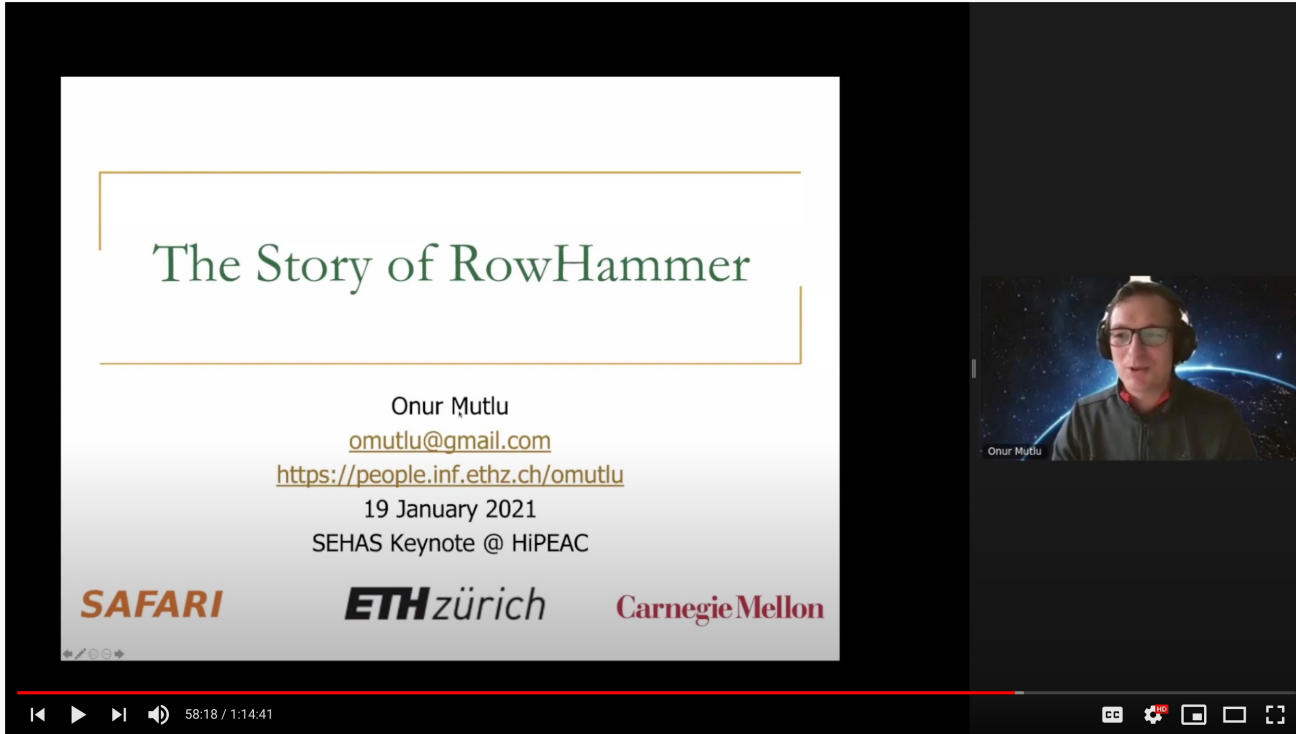
---

- **Computer Architecture, Fall 2020, Lecture 4b**
  - RowHammer (ETH Zürich, Fall 2020)
  - <https://www.youtube.com/watch?v=KDy632z23UE&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=8>
- **Computer Architecture, Fall 2020, Lecture 5a**
  - RowHammer in 2020: TRRespass (ETH Zürich, Fall 2020)
  - [https://www.youtube.com/watch?v=pwRw7QqK\\_qA&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=9](https://www.youtube.com/watch?v=pwRw7QqK_qA&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=9)
- **Computer Architecture, Fall 2020, Lecture 5b**
  - RowHammer in 2020: Revisiting RowHammer (ETH Zürich, Fall 2020)
  - <https://www.youtube.com/watch?v=gR7XR-Eepcg&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=10>
- **Computer Architecture, Fall 2020, Lecture 5c**
  - Secure and Reliable Memory (ETH Zürich, Fall 2020)
  - <https://www.youtube.com/watch?v=HvswnsfG3oQ&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=11>



# 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](mailto: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.

The Story of Rowhammer - Secure Hardware, Architectures, and Operating Systems Keynote - Onur Mutlu

1,293 views • Premiered Feb 2, 2021

64 0 SHARE SAVE ...

Onur Mutlu Lectures  
13.9K subscribers

<https://www.youtube.com/watch?v=sqd7PHQQ1AI>

ANALYTICS EDIT VIDEO



Rowhammer

# How Reliable/Secure/Safe is This Bridge?

---



# Collapse of the “Galloping Gertie” (1940)

---





# Another Example (1994)





# Yet Another Example (2007)

---



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



# A More Recent Example (2018)

---



# How Safe & Secure Is This Platform?

---



**Security is about preventing unforeseen consequences**



# How Safe & Secure Is **This** Platform?

---



## Fundamentally Secure, Reliable, Safe Computing Architectures

# Solution Direction: Principled Designs

---

Design fundamentally secure  
computing architectures

Predict and prevent  
safety & security issues

Computing Systems  
Need

Intelligent Memories

In-Field Patch-ability  
(Intelligent Memory)  
Can Avoid Many Failures

# 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

# The Problem

---

Data access is the major performance and energy bottleneck

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

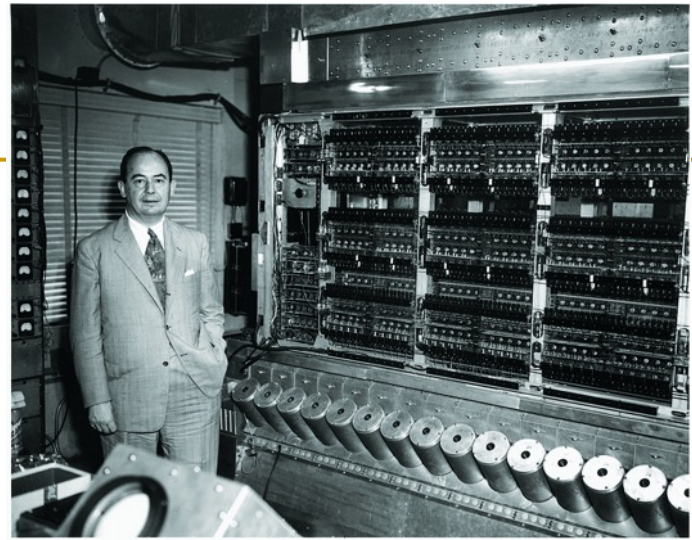
# The Problem

---

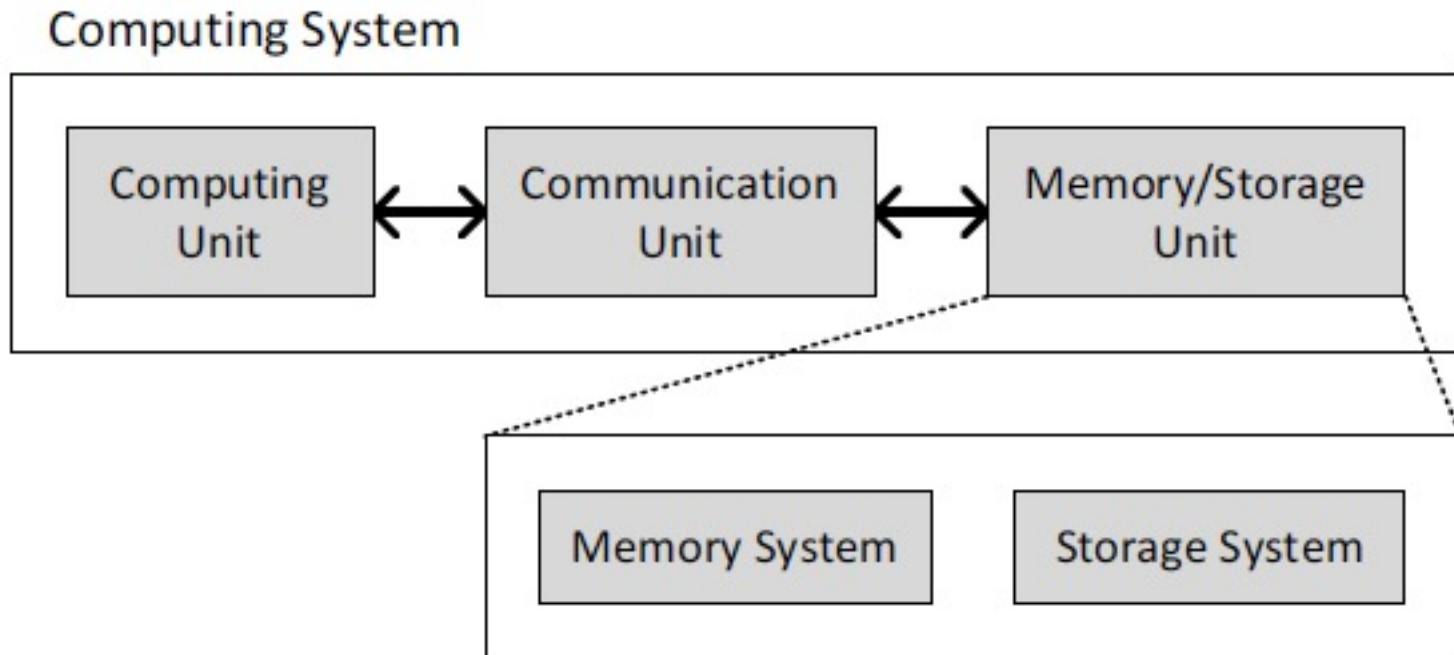
Processing of data  
is performed  
far away from the data

# A Computing System

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



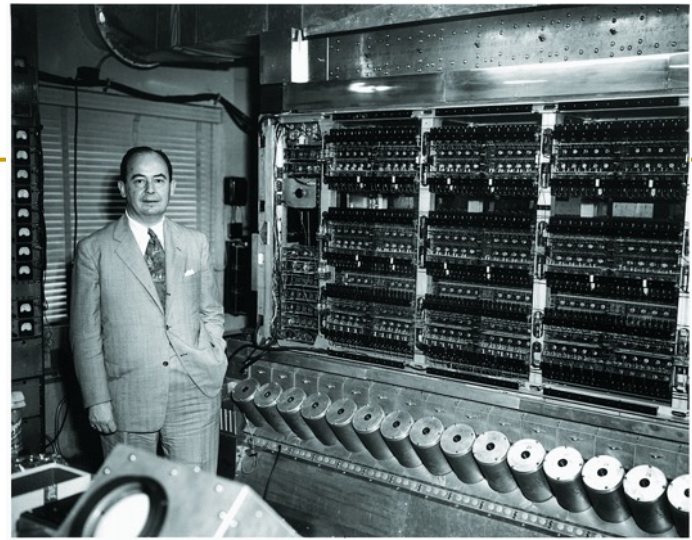
Burks, Goldstein, von Neumann, "Preliminary discussion of the logical design of an electronic computing instrument," 1946.





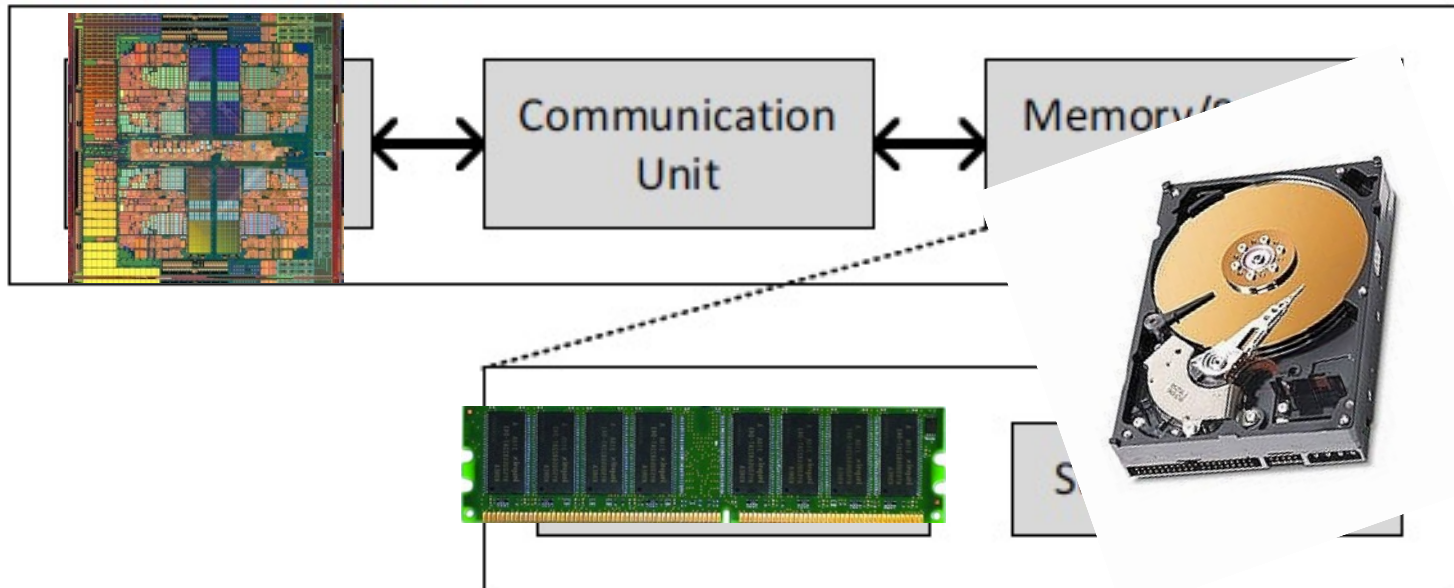
# A Computing System

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



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

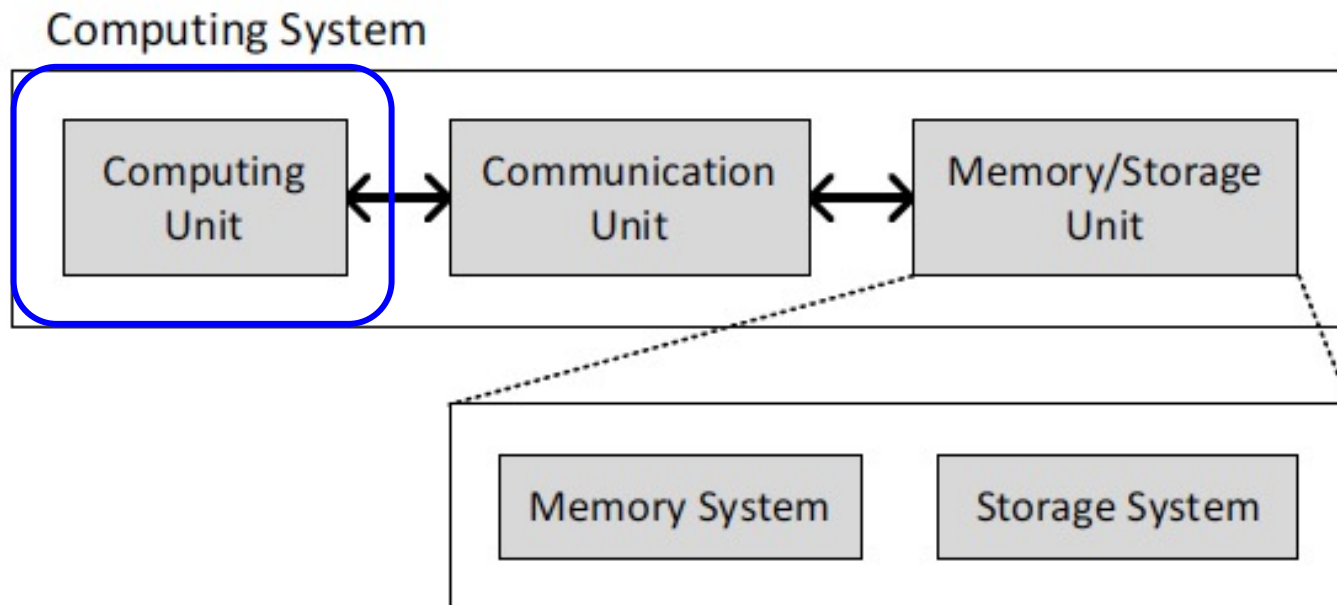
## Computing System



# Today's Computing Systems

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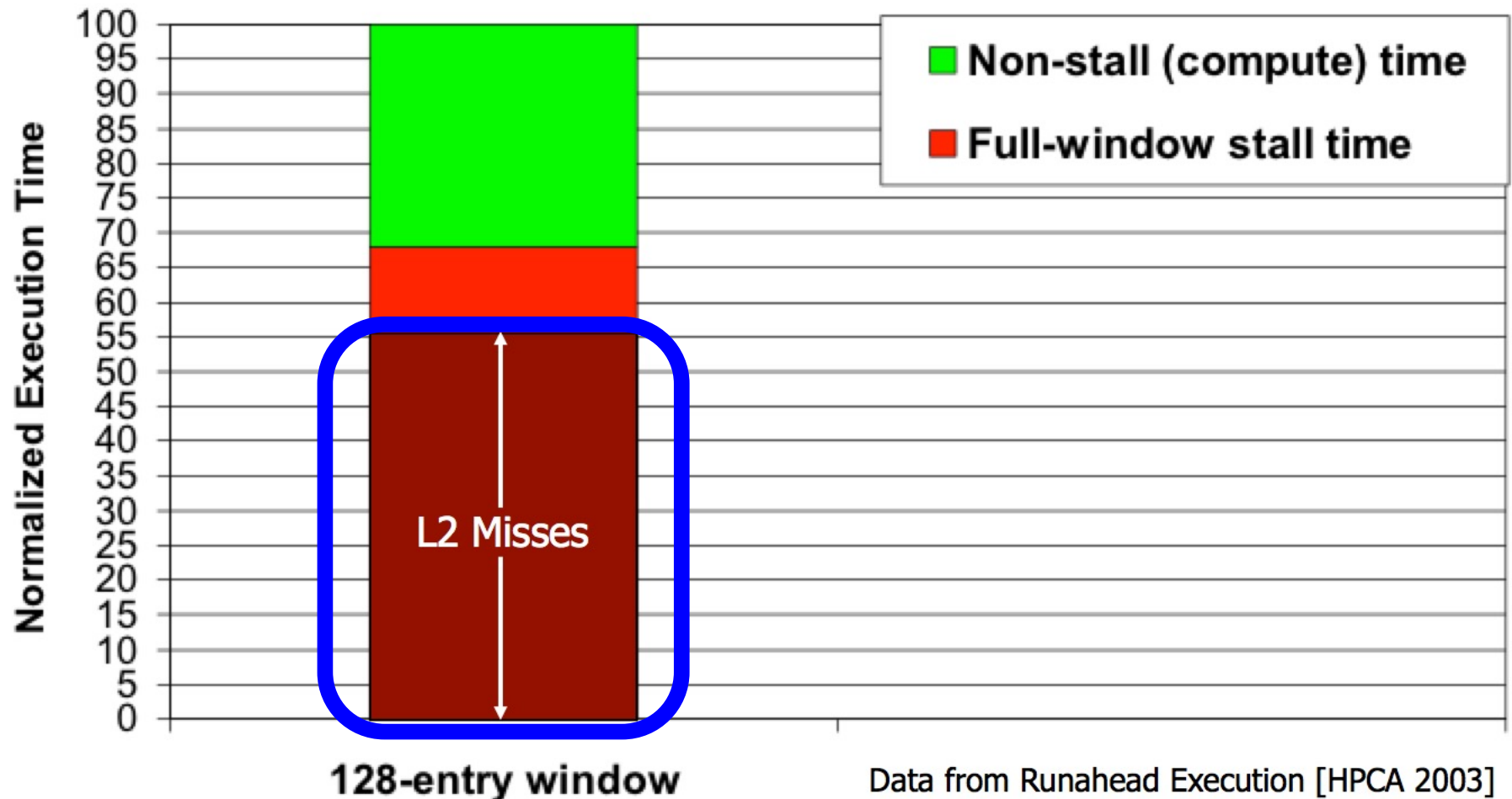
- Are overwhelmingly processor centric
- All data processed in the processor → at great system cost
- Processor is heavily optimized and is considered the master
- Data storage units are dumb and are largely unoptimized (except for some that are on the processor die)



# 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 §

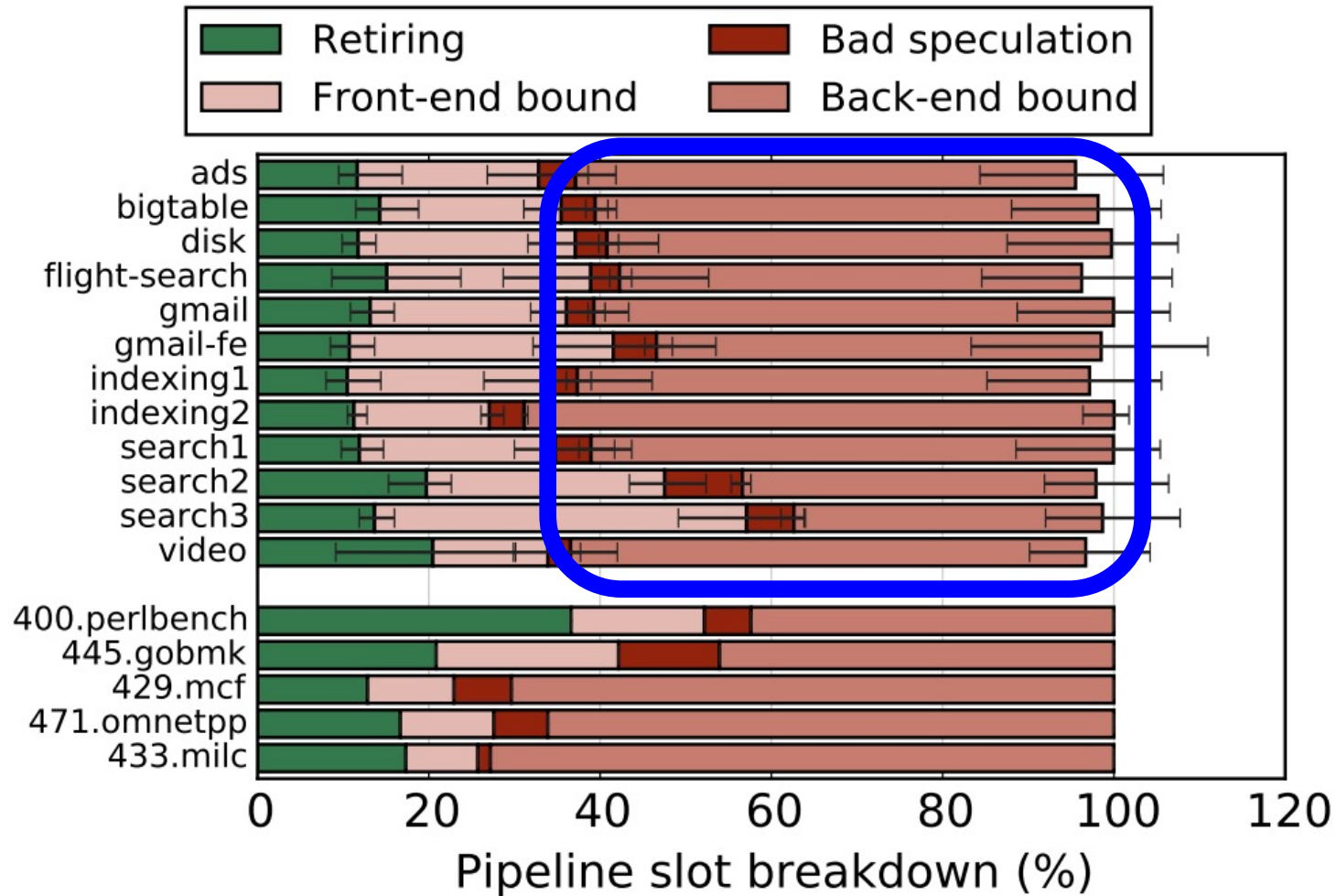
§ECE Department  
The University of Texas at Austin  
{onur,patt}@ece.utexas.edu

†Microprocessor Research  
Intel Labs  
jared.w.stark@intel.com

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

# The Performance Perspective (Today)

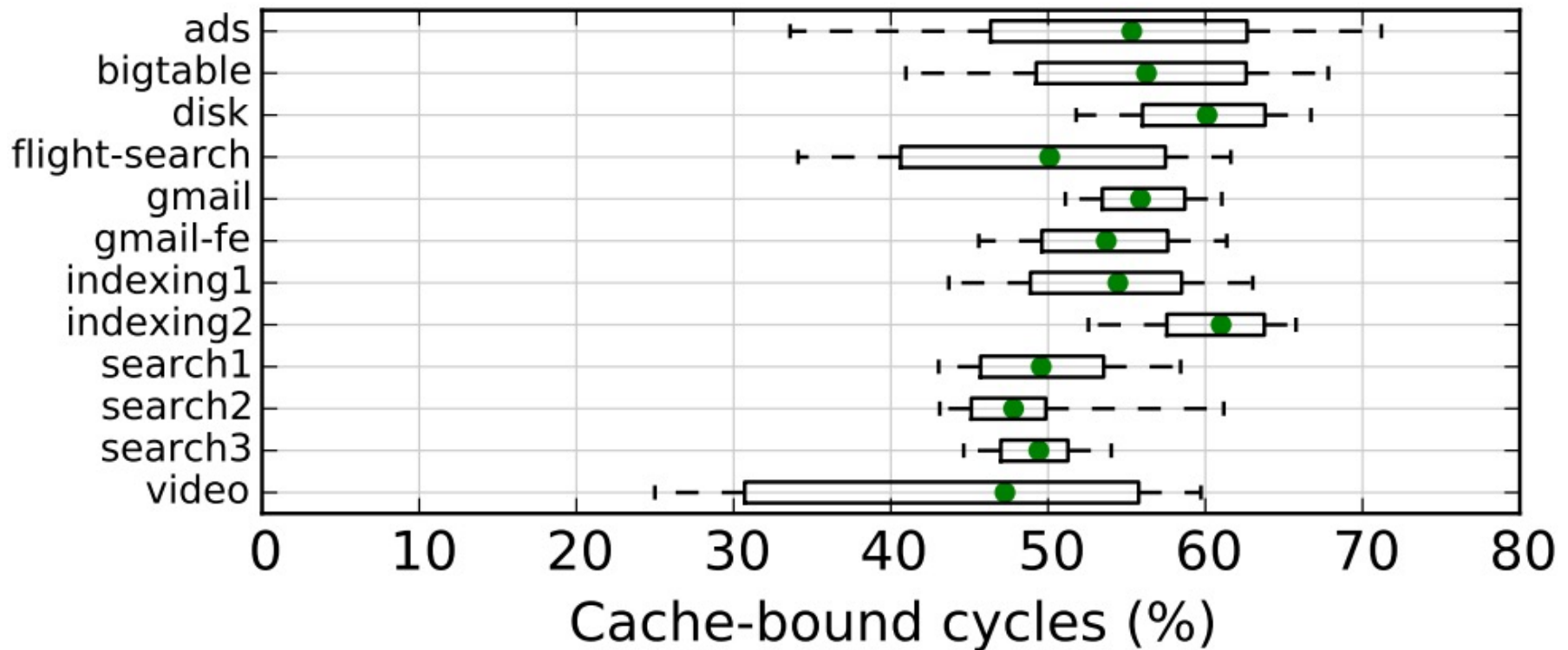
- All of Google's Data Center Workloads (2015):





# The Performance Perspective (Today)

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



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

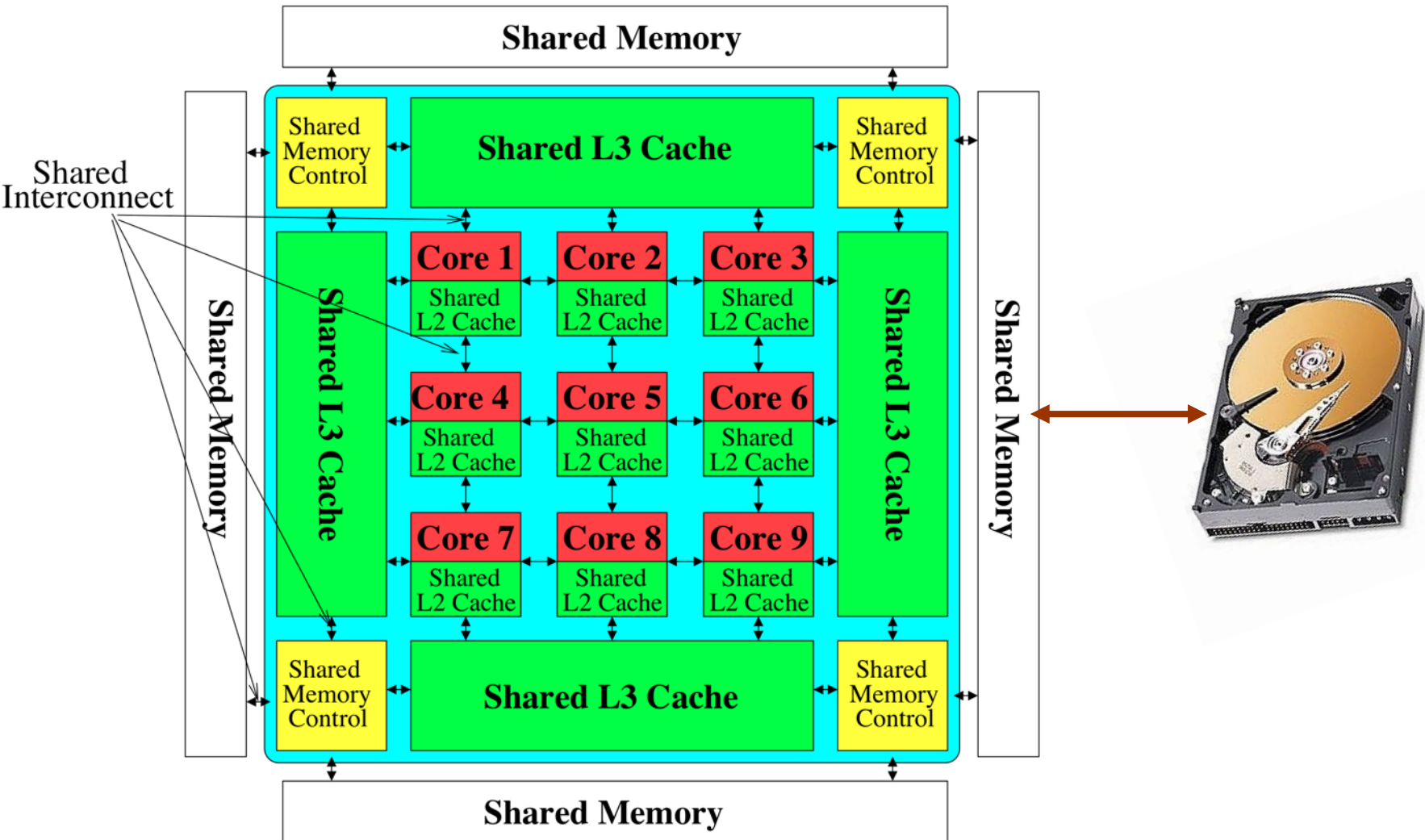


# Perils of Processor-Centric Design

---

- **Grossly-imbalanced systems**
  - ❑ Processing done only in **one place**
  - ❑ Everything 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

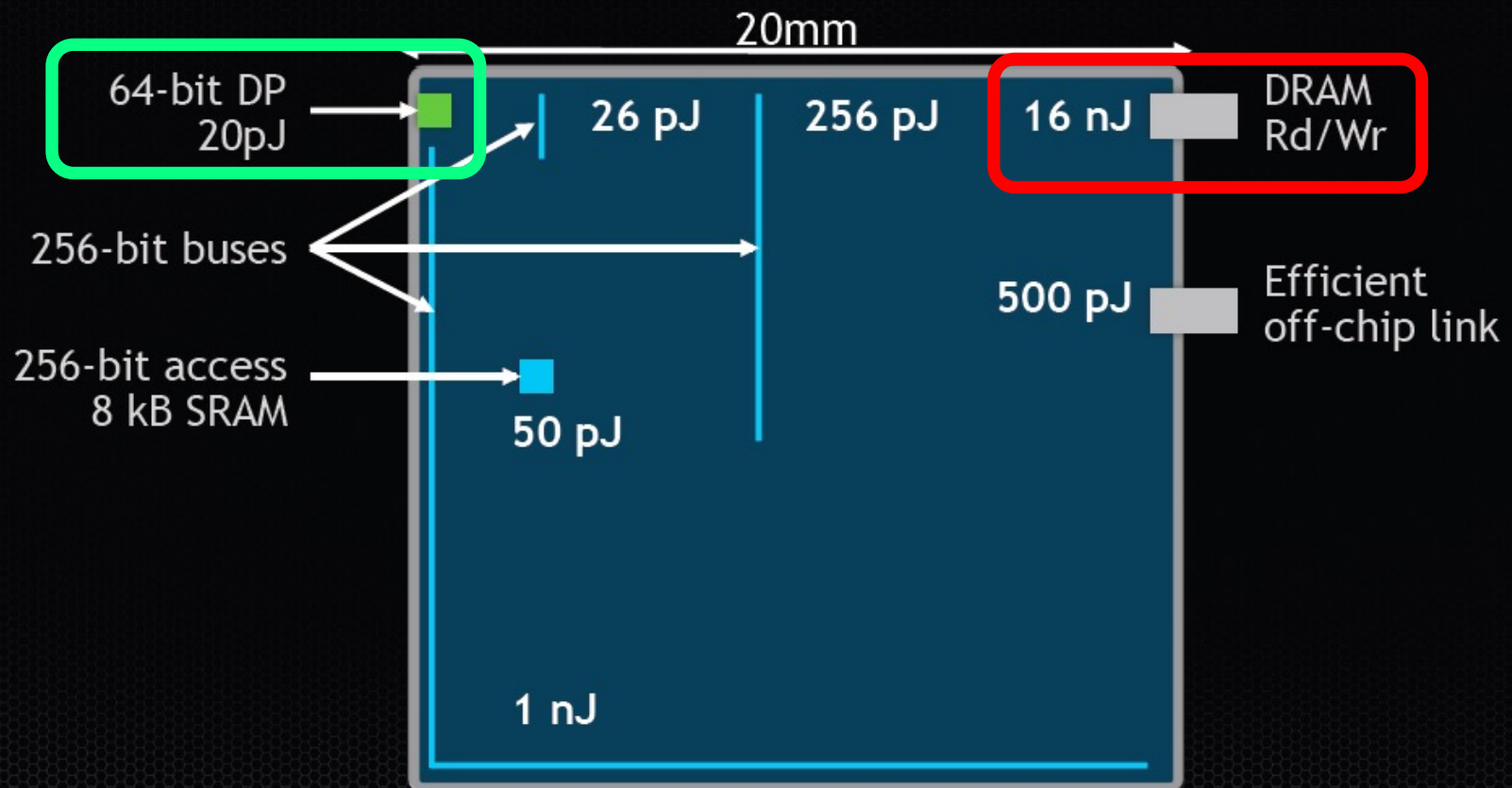


**Most of the system is dedicated to storing and moving data**

# The Energy Perspective

## Communication Dominates Arithmetic

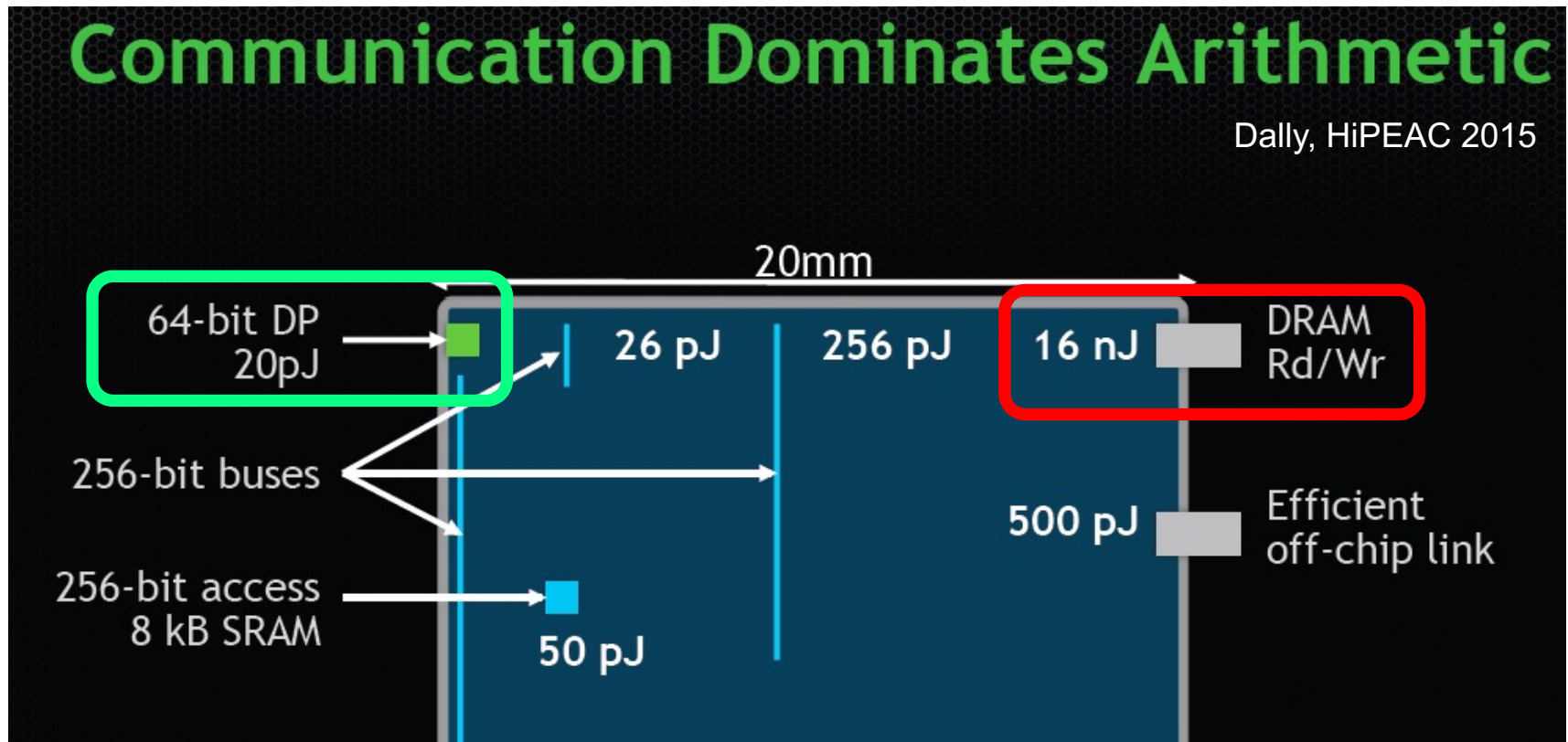
Dally, HiPEAC 2015



# Data Movement vs. Computation Energy

## Communication Dominates Arithmetic

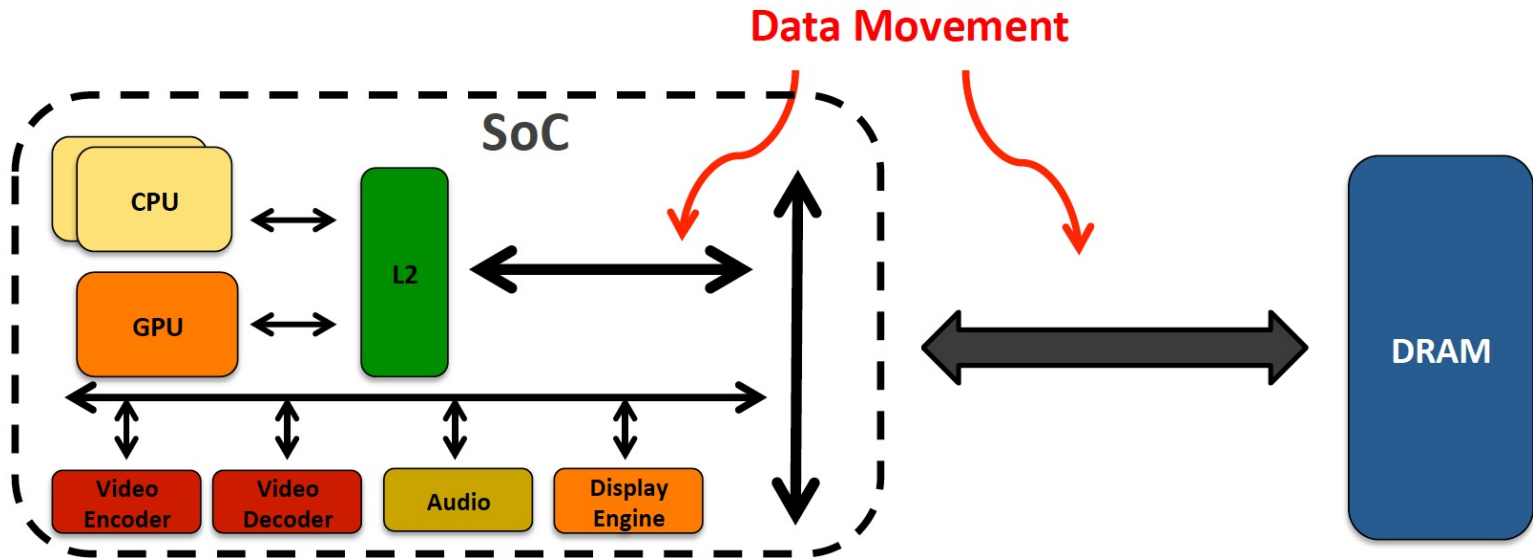
Dally, HiPEAC 2015



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

# Data Movement vs. Computation Energy

- **Data movement** is a major system energy bottleneck
  - ❑ Comprises 41% of mobile system energy during web browsing [2]
  - ❑ Costs  $\sim 115$  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 Boroumand<sup>1</sup>

Saugata Ghose<sup>1</sup>

Youngsok Kim<sup>2</sup>

Rachata Ausavarungnirun<sup>1</sup>

Eric Shiu<sup>3</sup>

Rahul Thakur<sup>3</sup>

Daehyun Kim<sup>4,3</sup>

Aki Kuusela<sup>3</sup>

Allan Knies<sup>3</sup>

Parthasarathy Ranganathan<sup>3</sup>

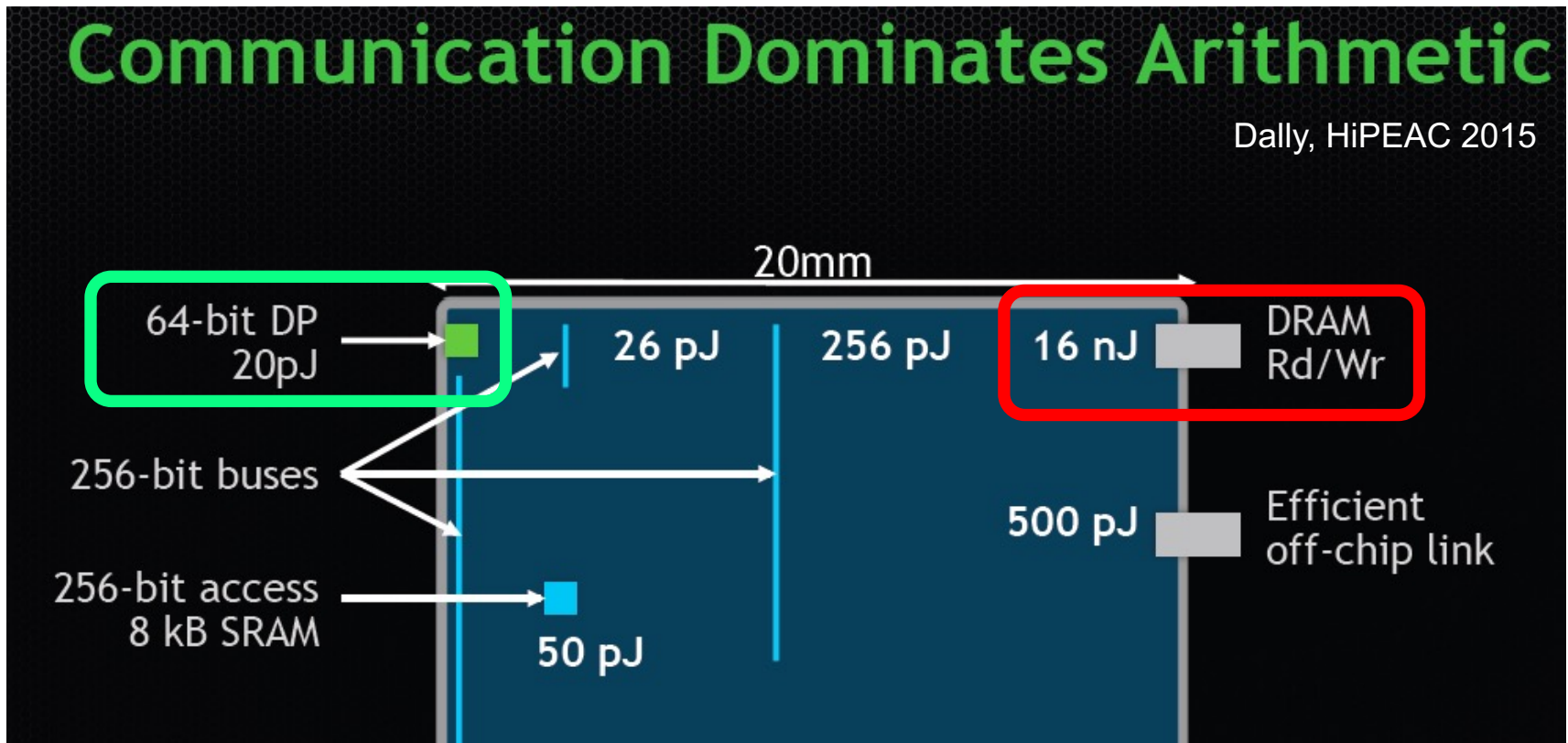
Onur Mutlu<sup>5,1</sup>



# We Do Not Want to Move Data!

## Communication Dominates Arithmetic

Dally, HiPEAC 2015



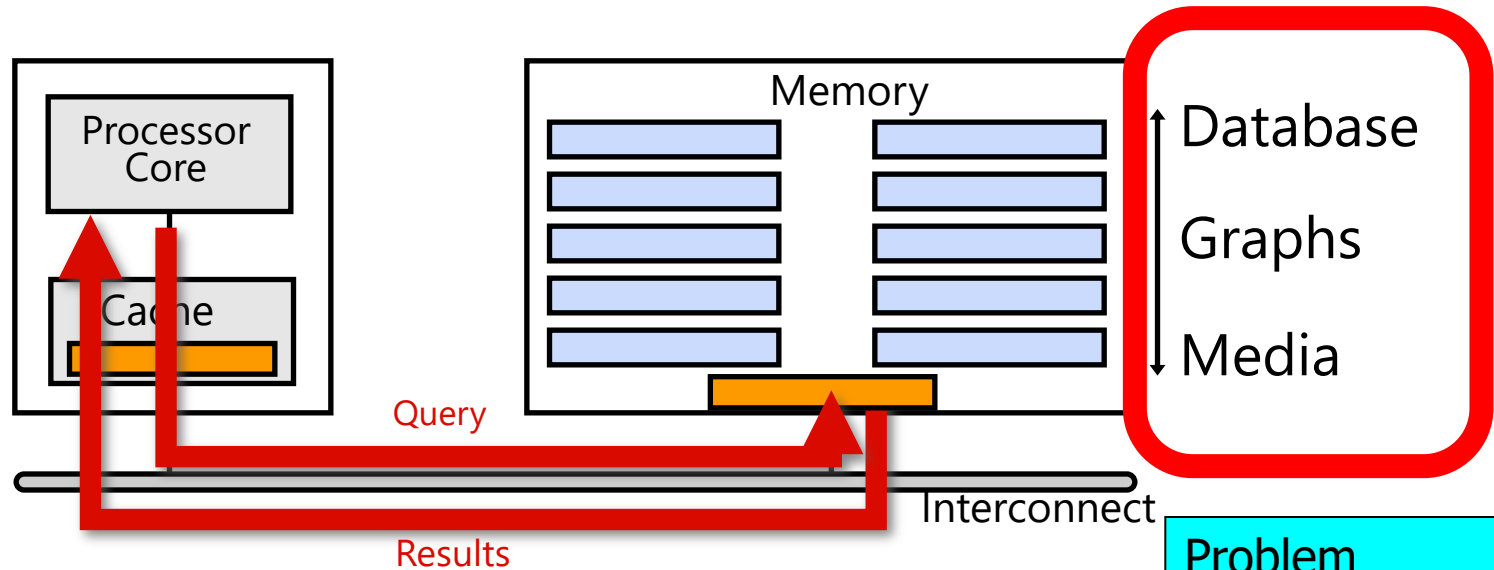
A memory access consumes  $\sim 100$ - $1000\times$  the energy of a complex addition

# 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?
  - ❑ processor chip and in-memory units?
  - ❑ software and hardware interfaces?
  - ❑ system software, compilers, languages?
  - ❑ algorithms and theoretical foundations?

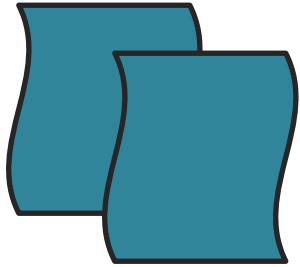
Problem
Algorithm
Program/Language
System Software
SW/HW Interface
Micro-architecture
Logic
Devices
Electrons

# Processing in Memory: Two Approaches

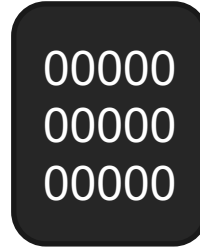
1. Processing using Memory
2. Processing near Memory

# Starting Simple: Data Copy and Initialization

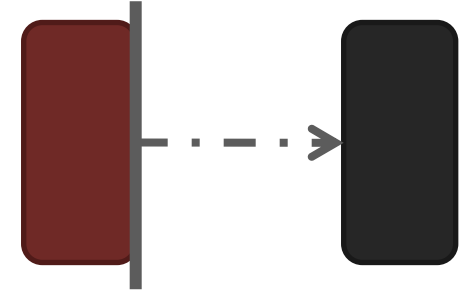
*memmove & memcpy: 5% cycles in Google's datacenter [Kanev+ ISCA'15]*



**Forking**



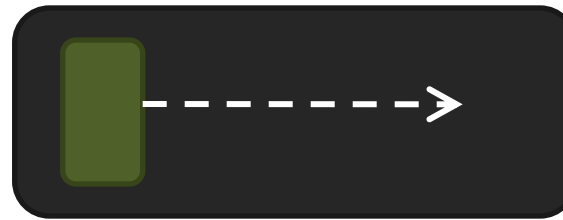
**Zero initialization  
(e.g., security)**



**Checkpointing**



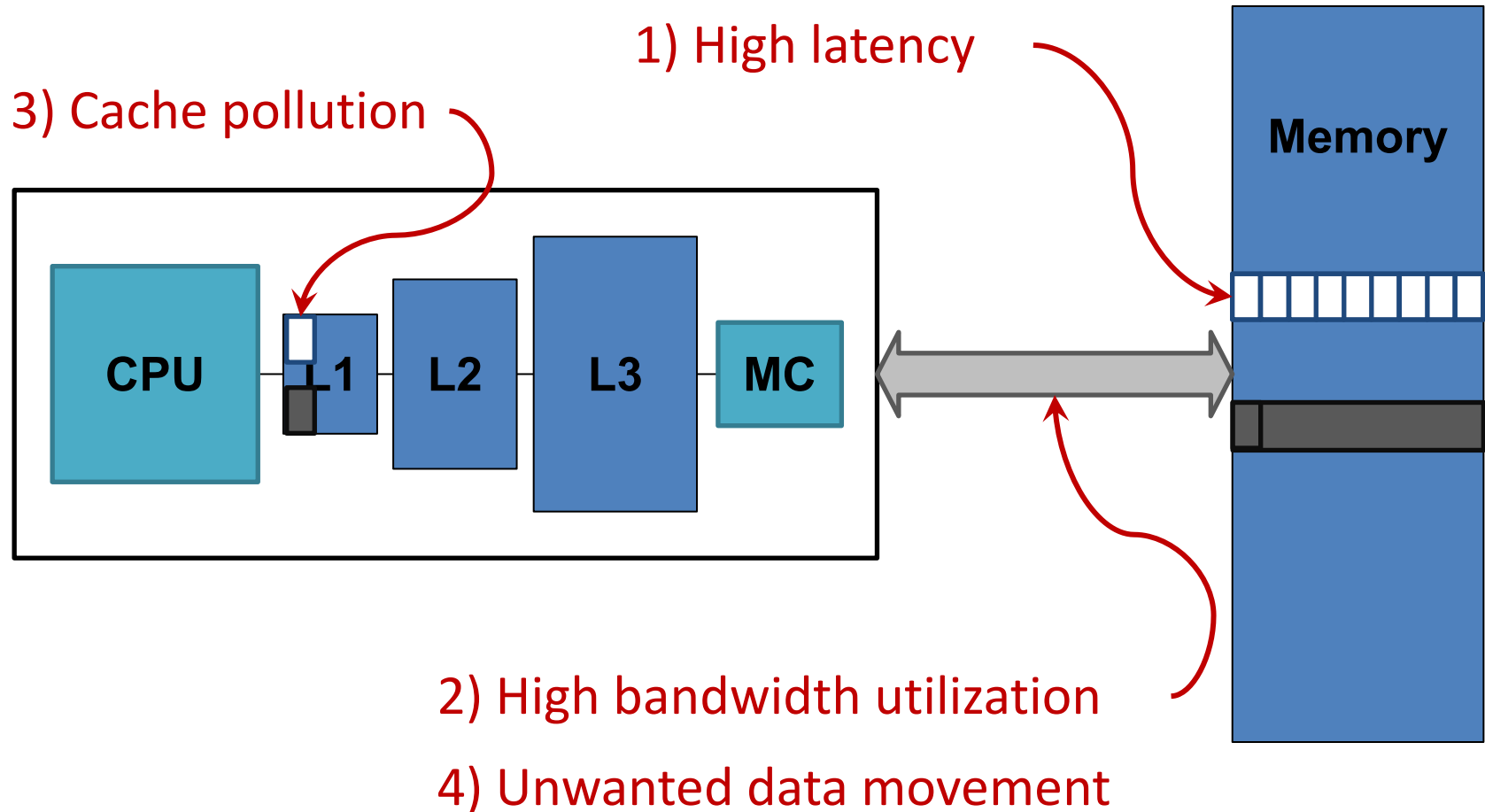
**VM Cloning  
Deduplication**



**Page Migration**

...  
Many more

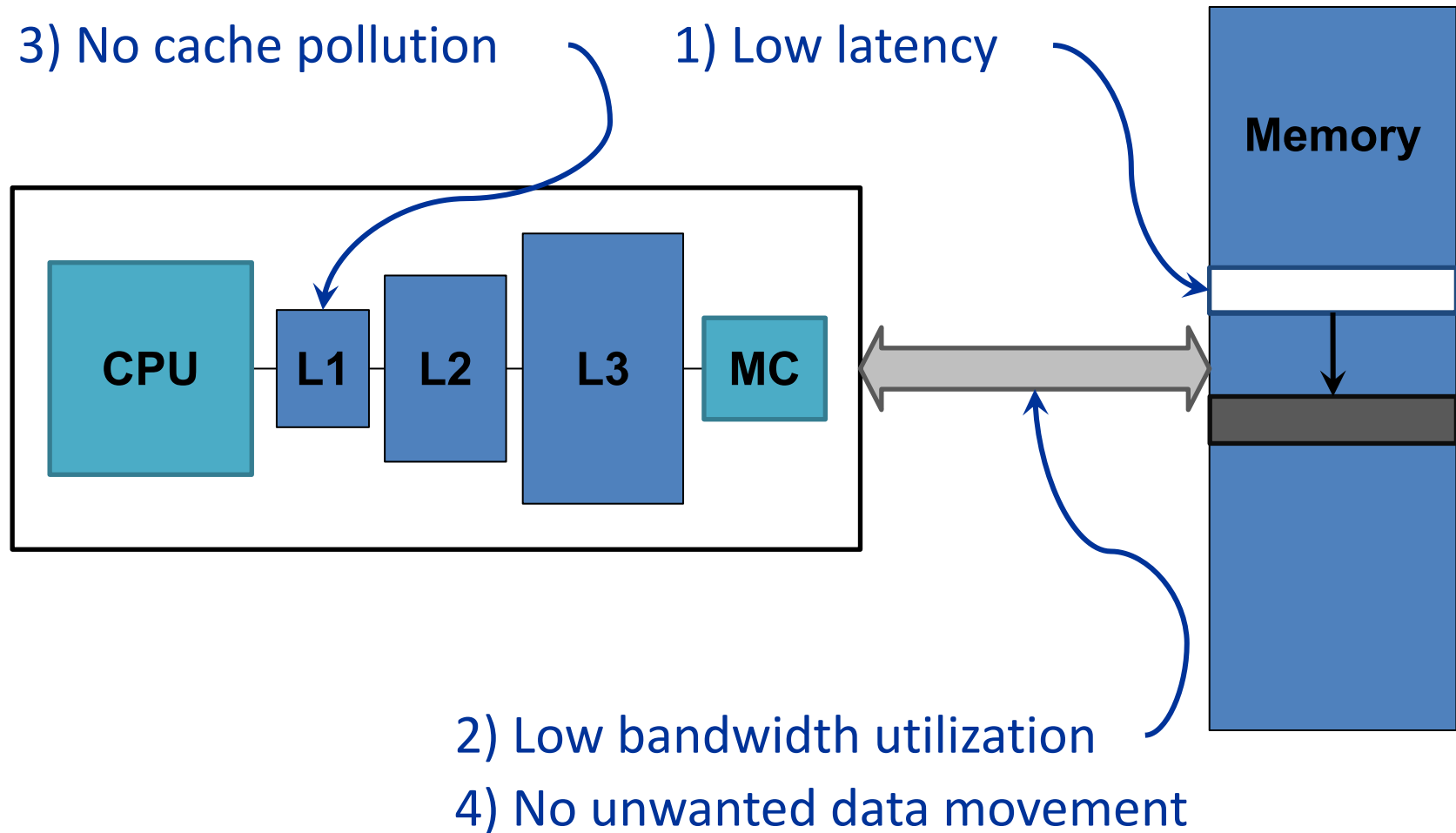
# Today's Systems: Bulk Data Copy



1046ns, 3.6uJ (for 4KB page copy via DMA)



# Future Systems: In-Memory Copy

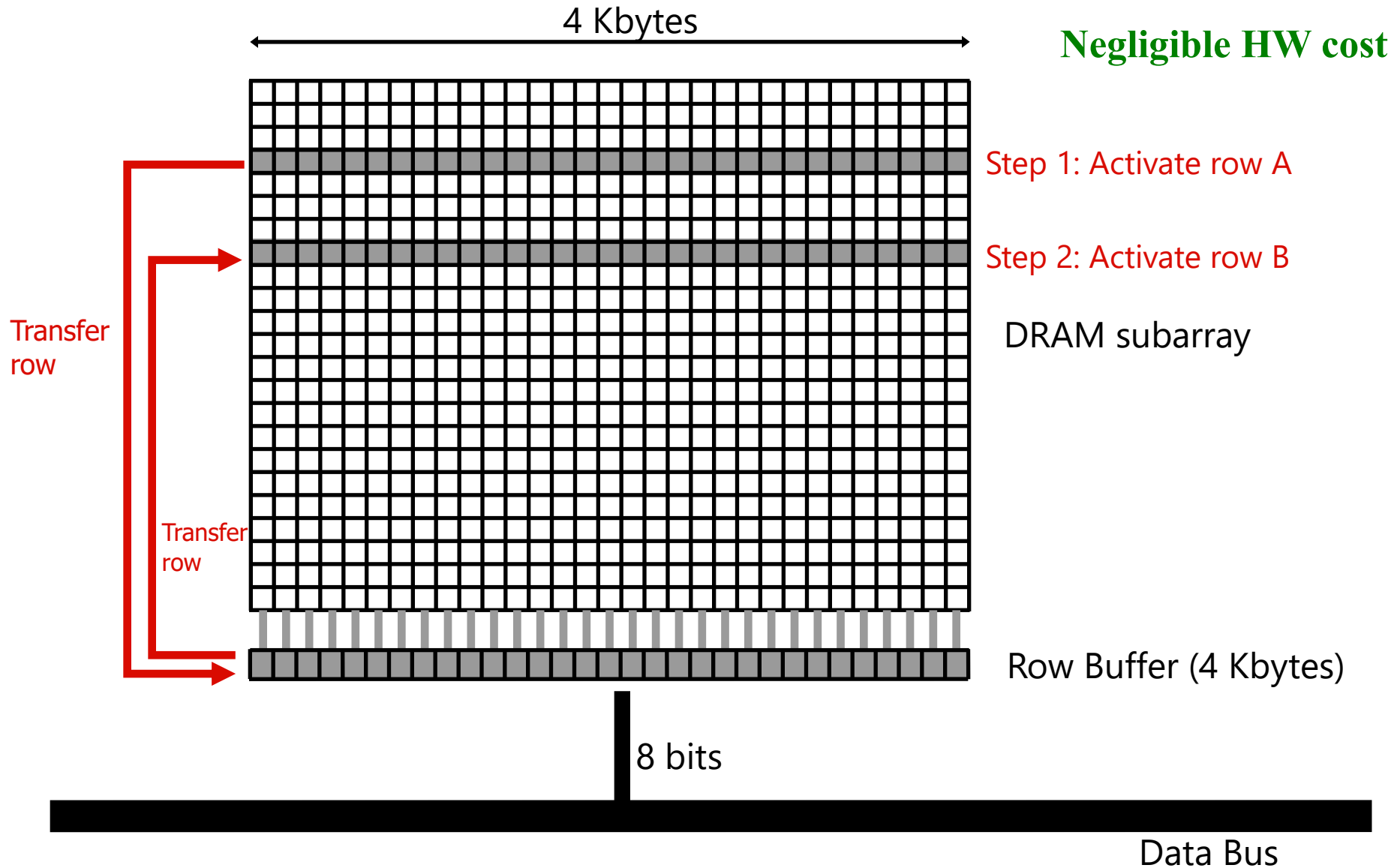


1046ns, 3.6uJ → 90ns, 0.04uJ

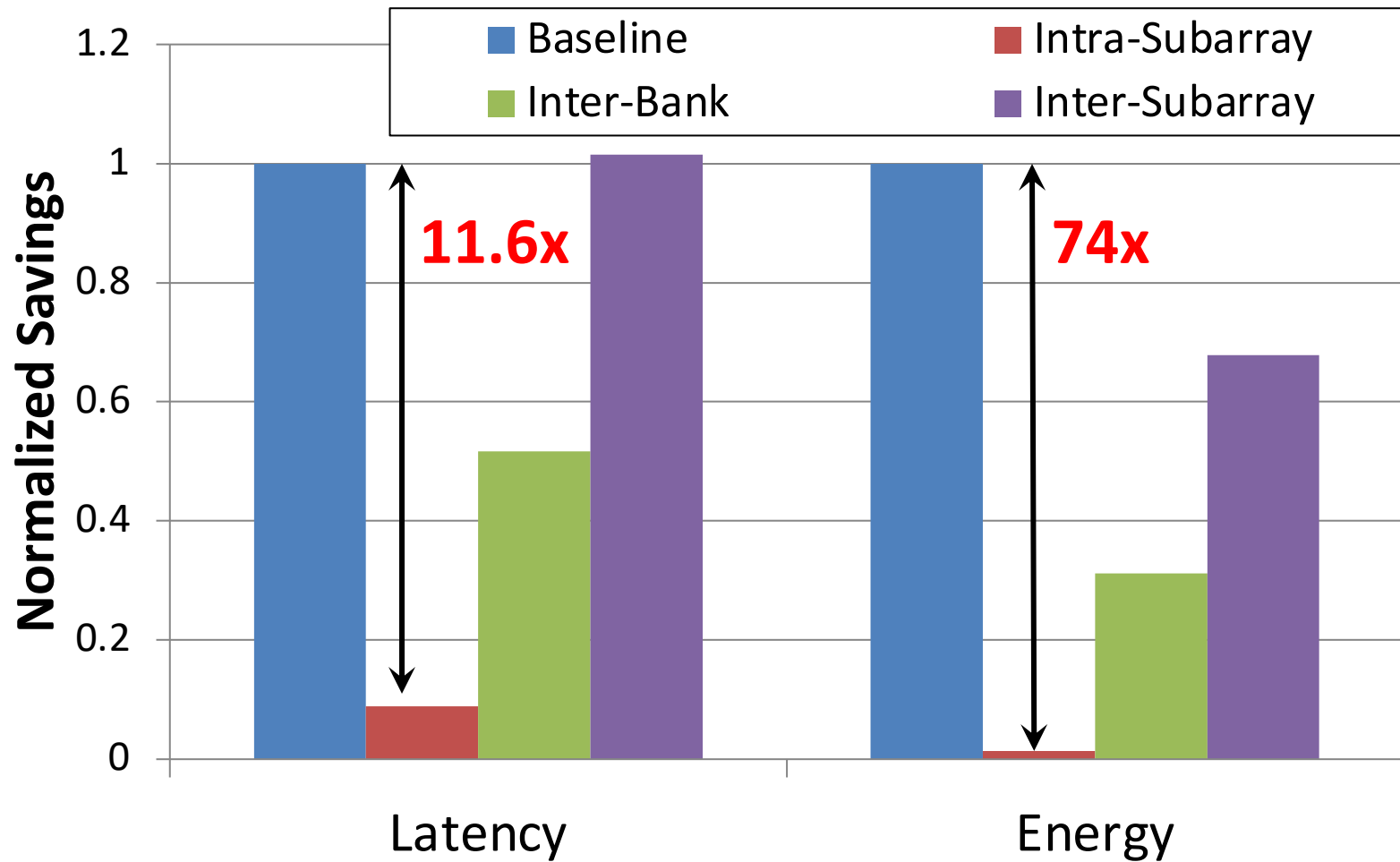
# RowClone: In-DRAM Row Copy

**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

Rachata Ausavarungnirun      Gennady Pekhimenko      Yixin Luo  
rachata@cmu.edu      gpekhime@cs.cmu.edu    yixinluo@andrew.cmu.edu

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

# RowClone Extensions and Follow-Up Work

---

- Can we do faster inter-subarray copy?
  - Yes, see LISA [Chang et al., HPCA 2016]
- Can we enable data movement at smaller granularities within a bank?
  - Yes, see FIGARO [Wang et al., MICRO 2020]
- Can we do better inter-bank copy?
  - Yes, see Network-on-Memory [CAL 2020]
- Can similar ideas and DRAM properties be used to perform computation on data?
  - Yes, see Ambit [Seshadri et al., CAL 2015, MICRO 2017]

# LISA: Increasing Connectivity in DRAM

---

- Kevin K. Chang, Prashant J. Nair, Saugata Ghose, Donghyuk Lee, Moinuddin K. Qureshi, and Onur Mutlu,  
**"Low-Cost Inter-Linked Subarrays (LISA): Enabling Fast Inter-Subarray Data Movement in DRAM"**  
*Proceedings of the 22nd International Symposium on High-Performance Computer Architecture (HPCA)*, Barcelona, Spain, March 2016.  
[[Slides \(pptx\)](#)] [[pdf](#)]  
[[Source Code](#)]

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

Kevin K. Chang<sup>†</sup>, Prashant J. Nair<sup>\*</sup>, Donghyuk Lee<sup>†</sup>, Saugata Ghose<sup>†</sup>, Moinuddin K. Qureshi<sup>\*</sup>, and Onur Mutlu<sup>†</sup>

<sup>†</sup>Carnegie Mellon University    <sup>\*</sup>Georgia Institute of Technology



# FIGARO: Fine-Grained In-DRAM Copy

---

- Yaohua Wang, Lois Orosa, Xiangjun Peng, Yang Guo, Saugata Ghose, Minesh Patel, Jeremie S. Kim, Juan Gómez Luna, Mohammad Sadrosadati, Nika Mansouri Ghiasi, and Onur Mutlu,  
**"FIGARO: Improving System Performance via Fine-Grained In-DRAM Data Relocation and Caching"**  
*Proceedings of the 53rd International Symposium on Microarchitecture (MICRO), Virtual, October 2020.*

## FIGARO: Improving System Performance via Fine-Grained In-DRAM Data Relocation and Caching

Yaohua Wang<sup>\*</sup> Lois Orosa<sup>†</sup> Xiangjun Peng<sup>⊙\*</sup> Yang Guo<sup>\*</sup> Saugata Ghose<sup>◇‡</sup> Minesh Patel<sup>†</sup>  
Jeremie S. Kim<sup>†</sup> Juan Gómez Luna<sup>†</sup> Mohammad Sadrosadati<sup>§</sup> Nika Mansouri Ghiasi<sup>†</sup> Onur Mutlu<sup>†‡</sup>

<sup>\*</sup>National University of Defense Technology <sup>†</sup>ETH Zürich <sup>⊙</sup>Chinese University of Hong Kong

<sup>◇</sup>University of Illinois at Urbana–Champaign <sup>‡</sup>Carnegie Mellon University <sup>§</sup>Institute of Research in Fundamental Sciences

# Network-On-Memory: Fast Inter-Bank Copy

---

- Seyyed Hossein SeyyedAghaei Rezaei, Mehdi Modarressi, Rachata Ausavarungnirun, Mohammad Sadrosadati, Onur Mutlu, and Masoud Daneshtalab,  
**"NoM: Network-on-Memory for Inter-Bank Data Transfer in Highly-Banked Memories"**  
*IEEE Computer Architecture Letters* (**CAL**), to appear in 2020.

## **NOm: NETWORK-ON-MEMORY FOR INTER-BANK DATA TRANSFER IN HIGHLY-BANKED MEMORIES**

Seyyed Hossein SeyyedAghaei Rezaei<sup>1</sup>  
Mohammad Sadrosadati<sup>3</sup>

Mehdi Modarressi<sup>1,3</sup>  
Onur Mutlu<sup>4</sup>

Rachata Ausavarungnirun<sup>2</sup>  
Masoud Daneshtalab<sup>5</sup>

<sup>1</sup>University of Tehran

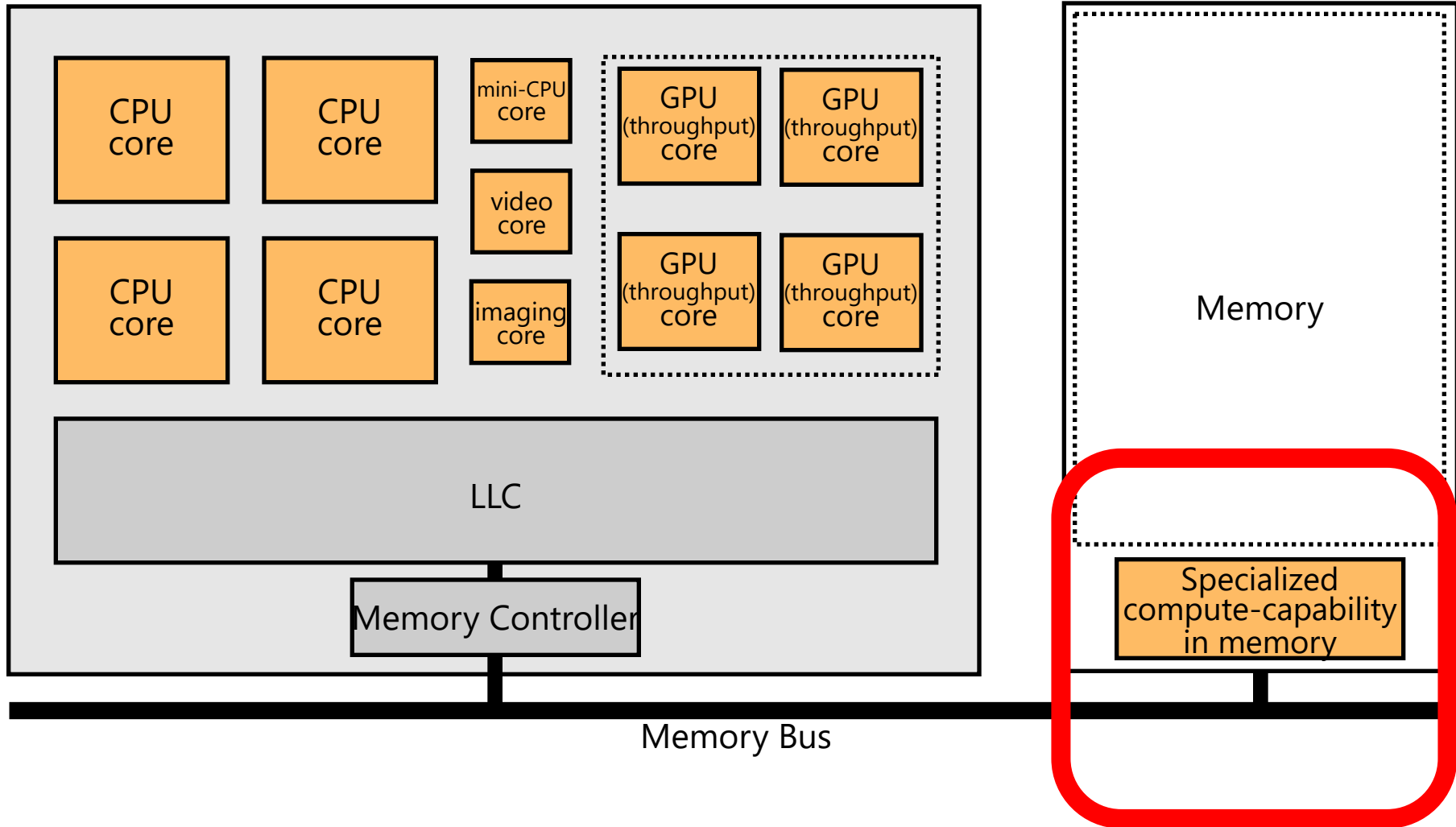
<sup>2</sup>King Mongkut's University of Technology North Bangkok

<sup>3</sup>Institute for Research in Fundamental Sciences

<sup>4</sup>ETH Zürich

<sup>5</sup>Mälardalens University

# Memory as an Accelerator



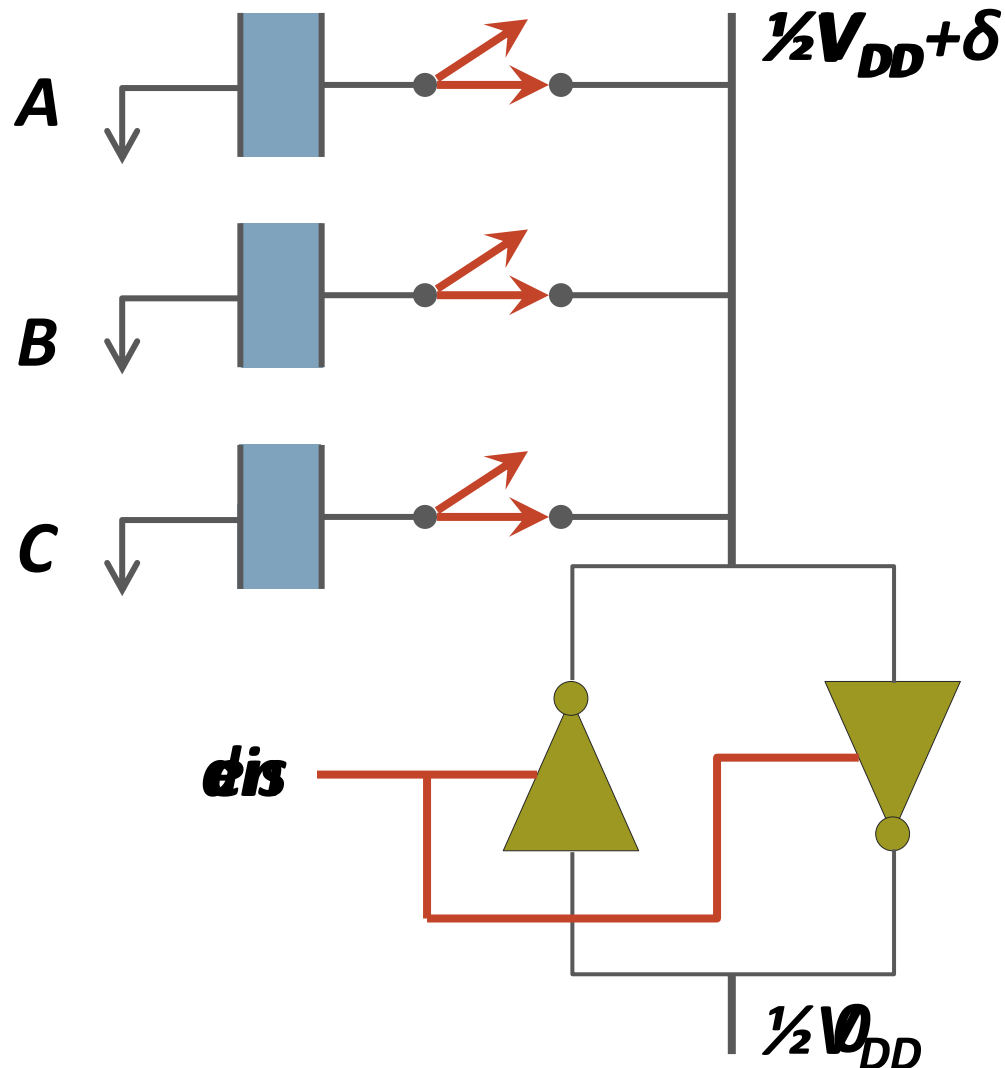
**Memory similar to a "conventional" accelerator**

# (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

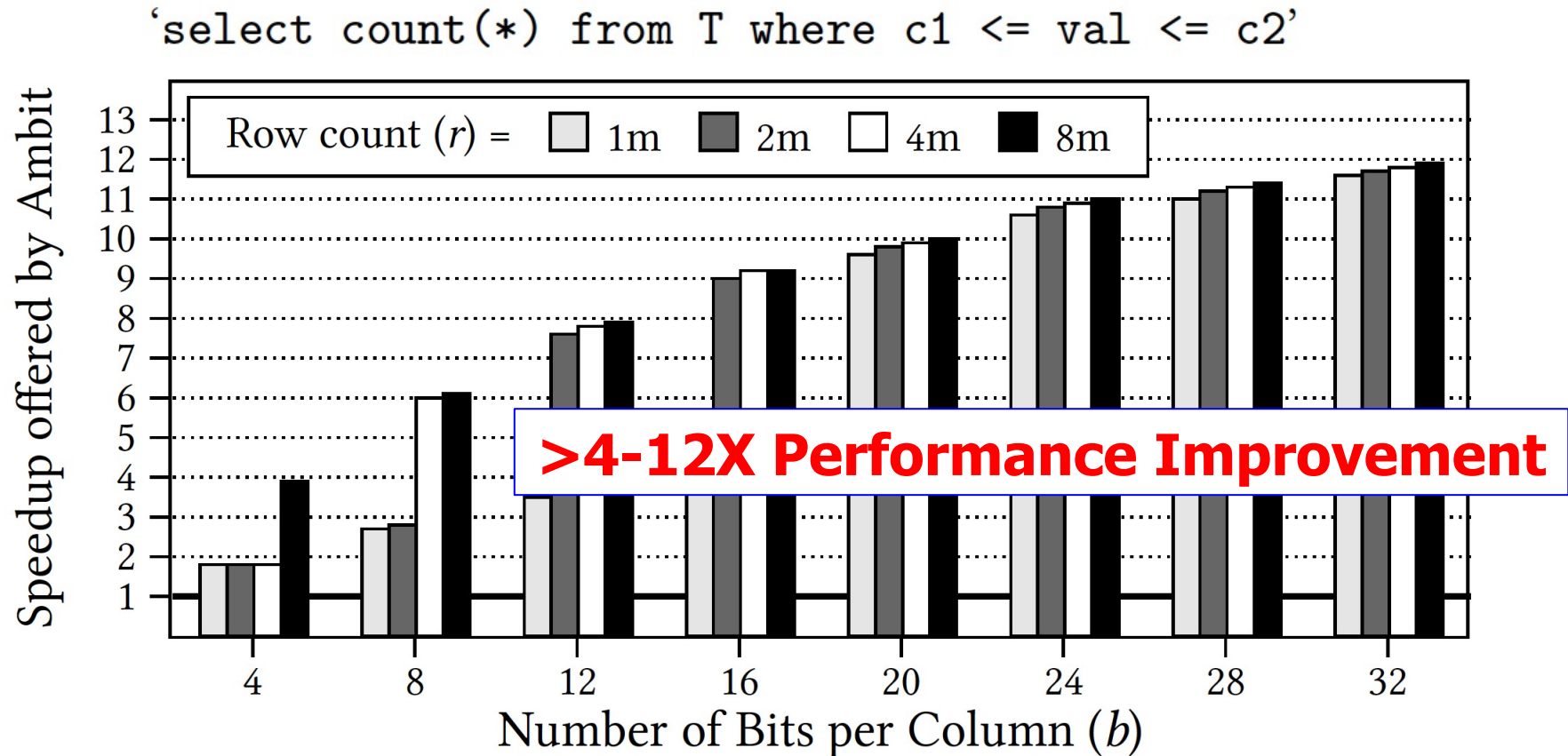
# In-DRAM AND/OR: Triple Row Activation



**Final State**  
 **$AB + BC + AC$**

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

# 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<sup>1,5</sup> Donghyuk Lee<sup>2,5</sup> Thomas Mullins<sup>3,5</sup> Hasan Hassan<sup>4</sup> Amirali Boroumand<sup>5</sup>  
Jeremie Kim<sup>4,5</sup> Michael A. Kozuch<sup>3</sup> Onur Mutlu<sup>4,5</sup> Phillip B. Gibbons<sup>5</sup> Todd C. Mowry<sup>5</sup>

<sup>1</sup>Microsoft Research India   <sup>2</sup>NVIDIA Research   <sup>3</sup>Intel   <sup>4</sup>ETH Zürich   <sup>5</sup>Carnegie 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

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- 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 <sup>1,2</sup>	*Geraldo F. Oliveira <sup>1</sup>	Sven Gregorio <sup>1</sup>	João Dinis Ferreira <sup>1</sup>
Nika Mansouri Ghiasi <sup>1</sup>	Minesh Patel <sup>1</sup>	Mohammed Alser <sup>1</sup>	Saugata Ghose <sup>3</sup>
	Juan Gómez-Luna <sup>1</sup>	Onur Mutlu <sup>1</sup>	

<sup>1</sup>ETH Zürich

<sup>2</sup>Simon Fraser University

<sup>3</sup>University 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<sup>†§</sup>

Minesh Patel<sup>§</sup>

Hasan Hassan<sup>§</sup>

Onur Mutlu<sup>§†</sup>

<sup>†</sup>Carnegie Mellon University

<sup>§</sup>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<sup>‡§</sup>

Minesh Patel<sup>§</sup>

Hasan Hassan<sup>§</sup>

Lois Orosa<sup>§</sup>

Onur Mutlu<sup>§‡</sup>

<sup>‡</sup>Carnegie Mellon University

<sup>§</sup>ETH Zürich

# Processing in Memory: Two Approaches

1. Processing using Memory
2. Processing near Memory



# Another Example: In-Memory Graph Processing

- Large graphs are everywhere (circa 2015)



36 Million  
Wikipedia Pages



1.4 Billion  
Facebook Users

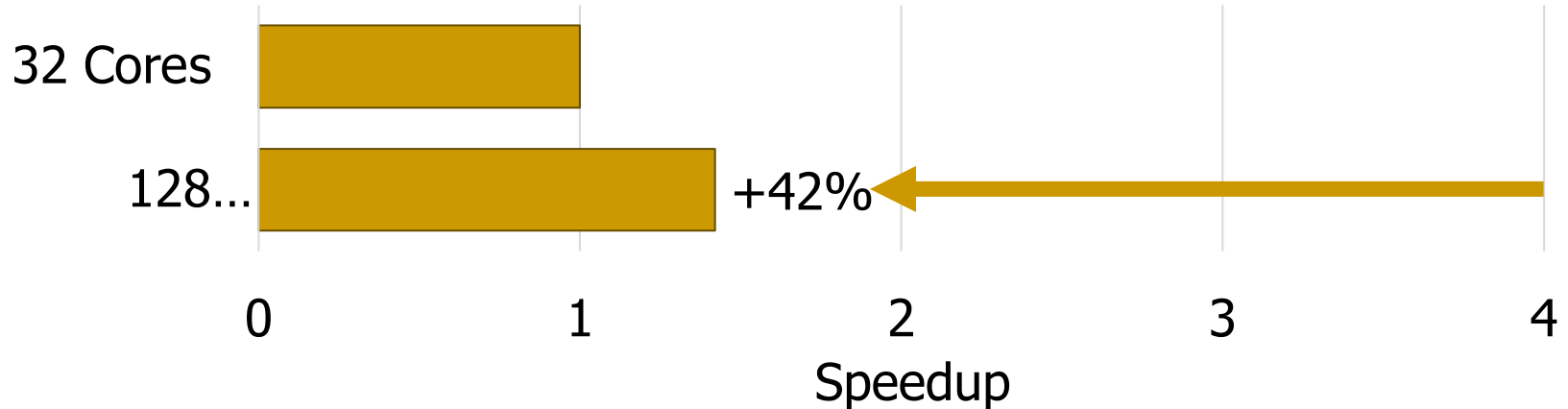


300 Million  
Twitter Users



30 Billion  
Instagram Photos

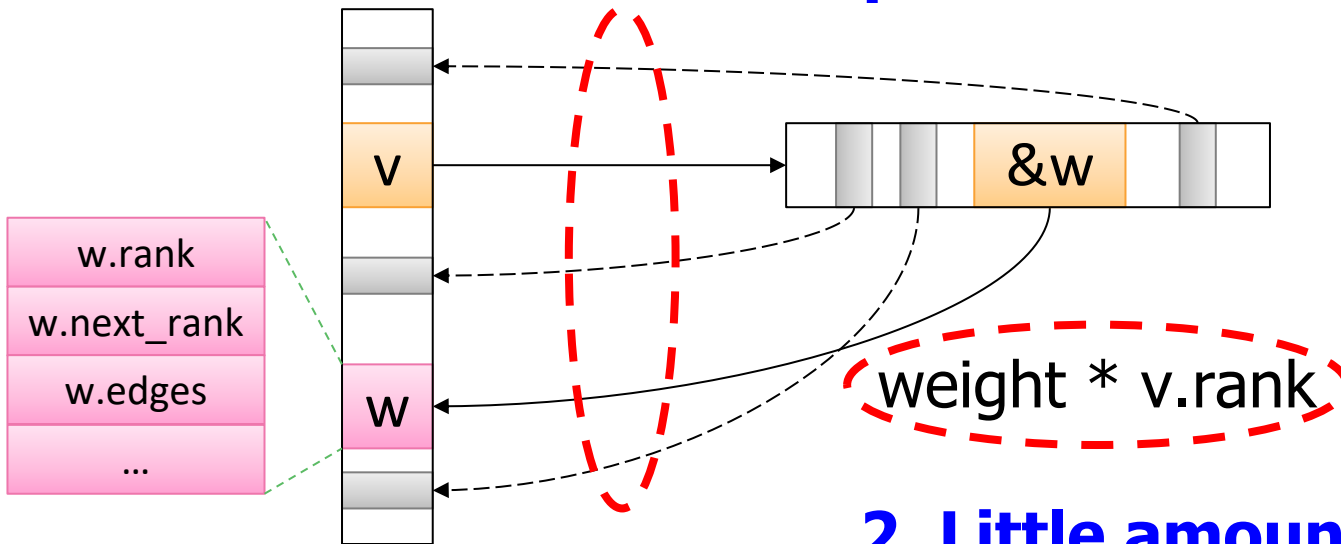
- Scalable large-scale graph processing is challenging



# Key Bottlenecks in Graph Processing

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

**1. Frequent random memory accesses**



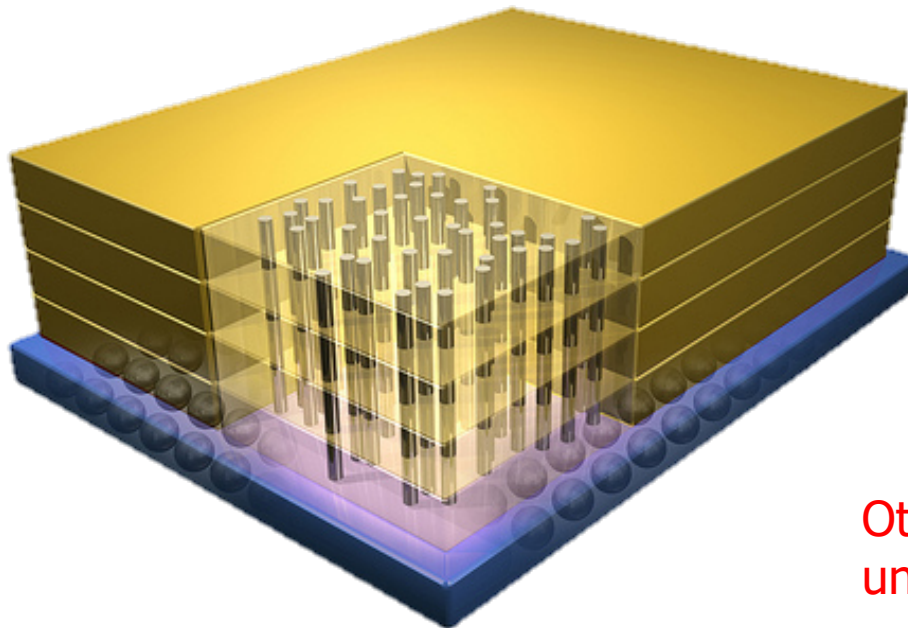
**2. Little amount of computation**

# Opportunity: 3D-Stacked Logic+Memory

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



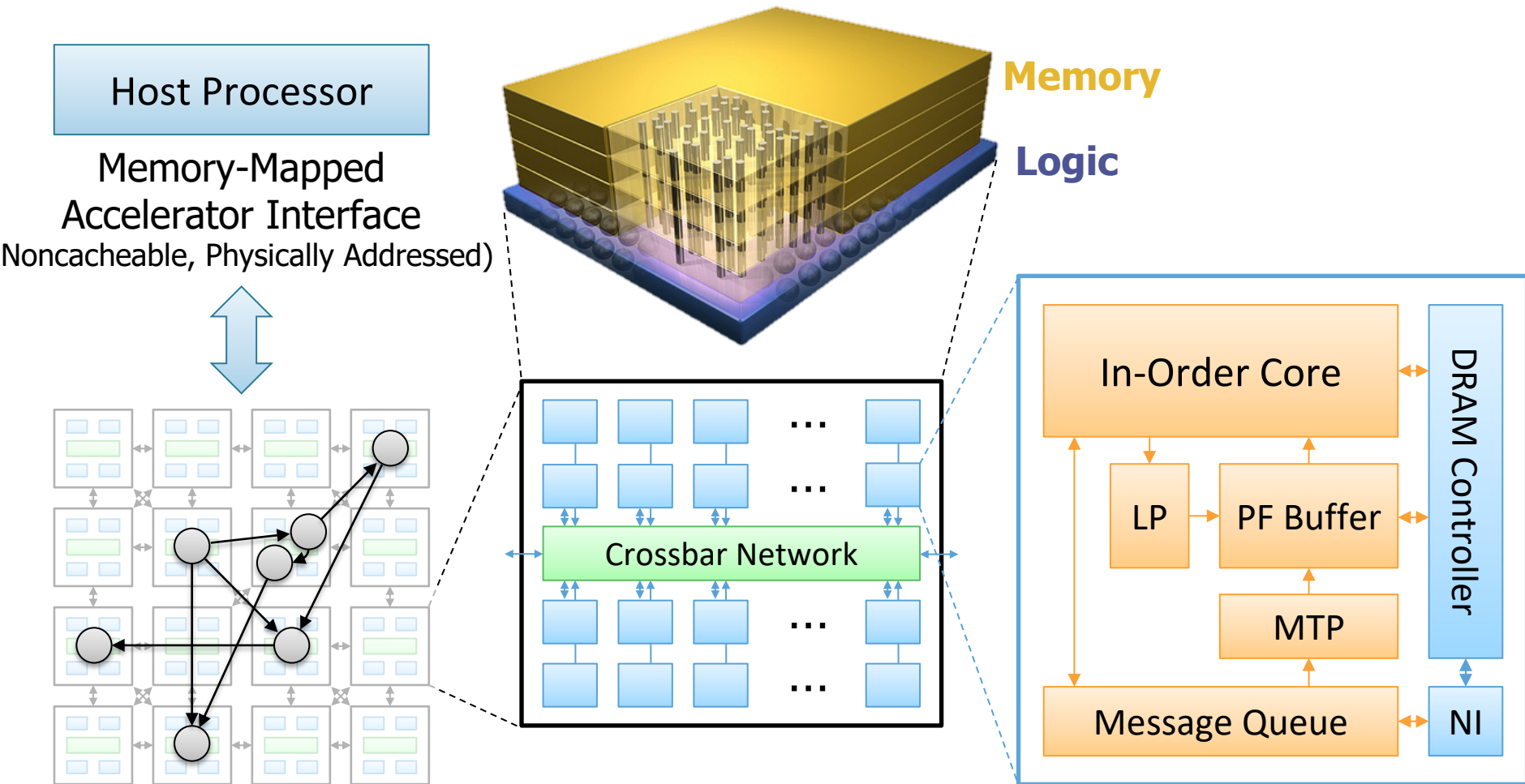
Memory

Logic

Other "True 3D" technologies  
under development

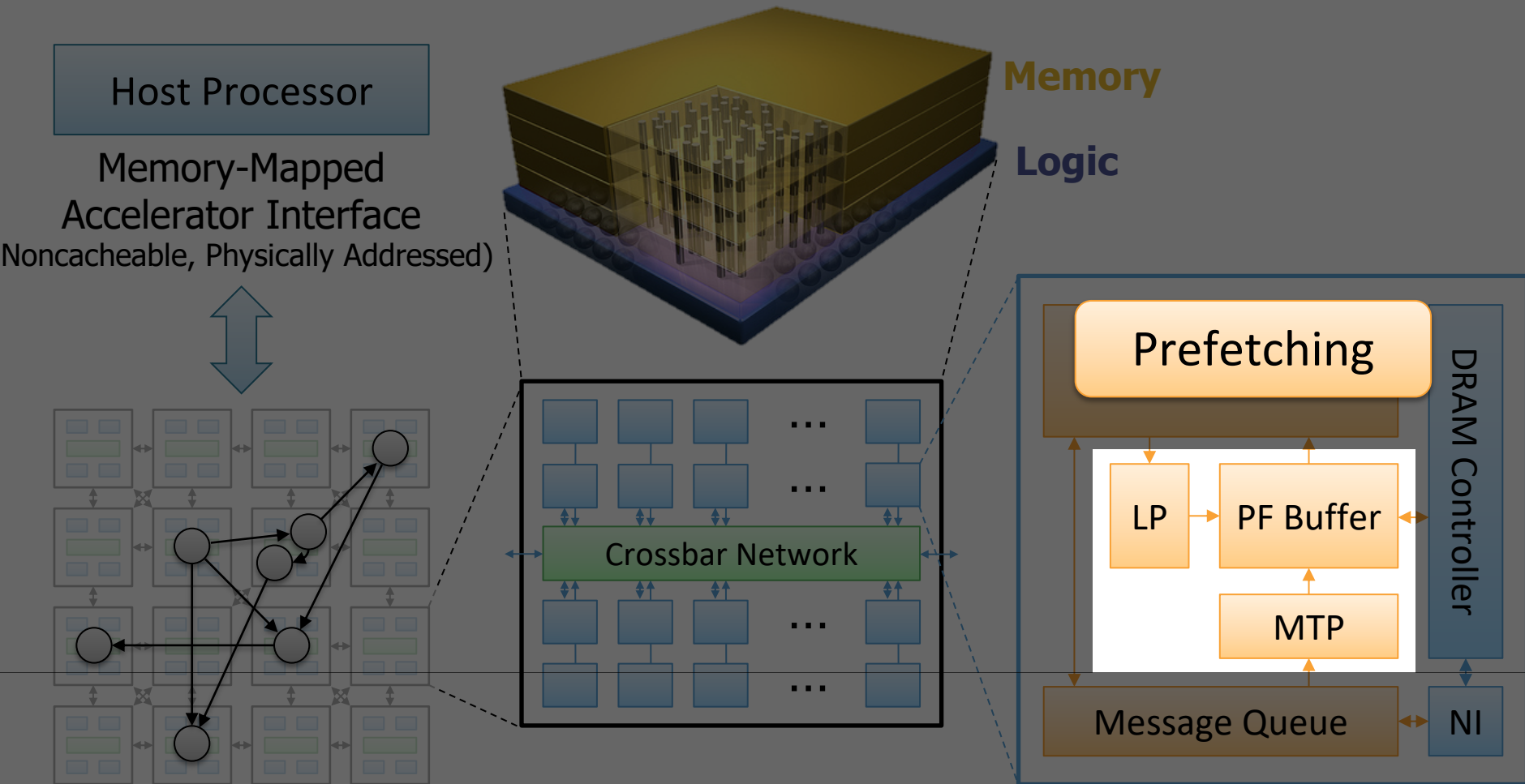
# Tesseract System for Graph Processing

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





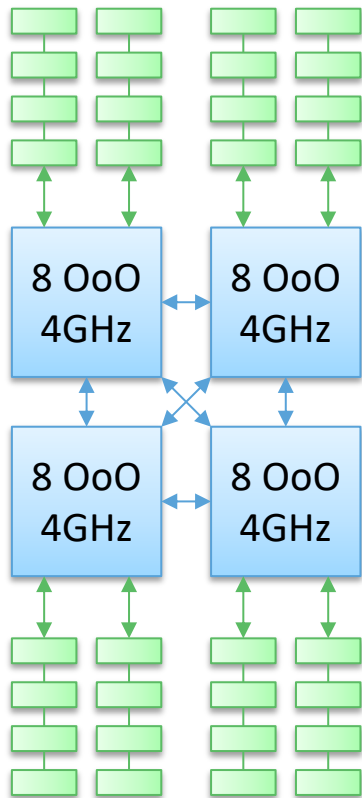
# Tesseract System for Graph Processing





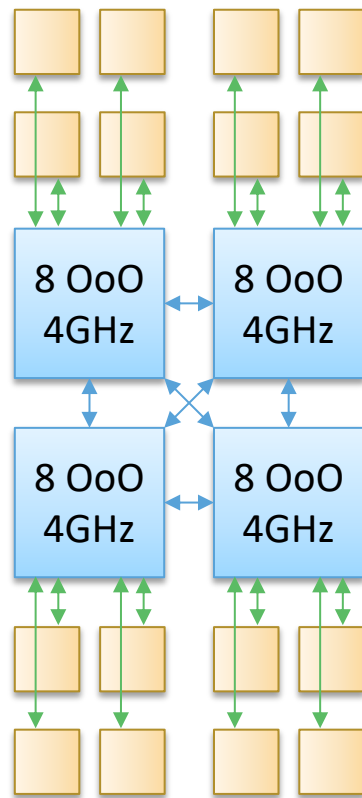
# Evaluated Systems

DDR3-OoO



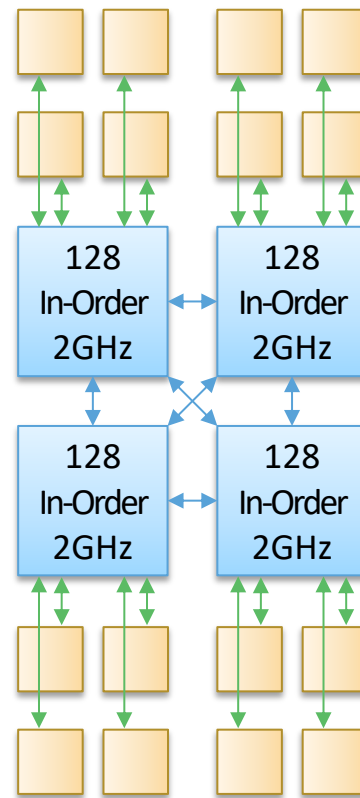
102.4GB/s

HMC-OoO



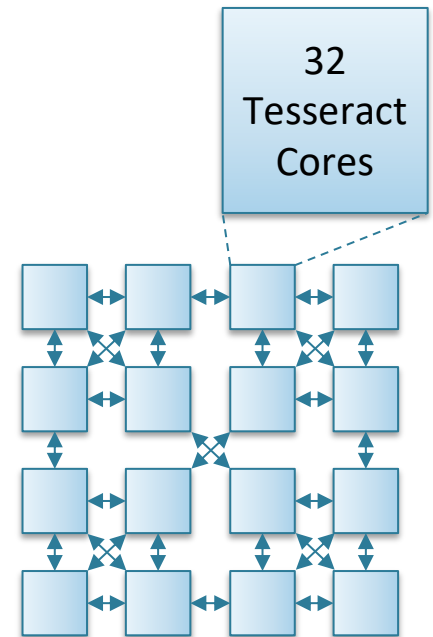
640GB/s

HMC-MC



640GB/s

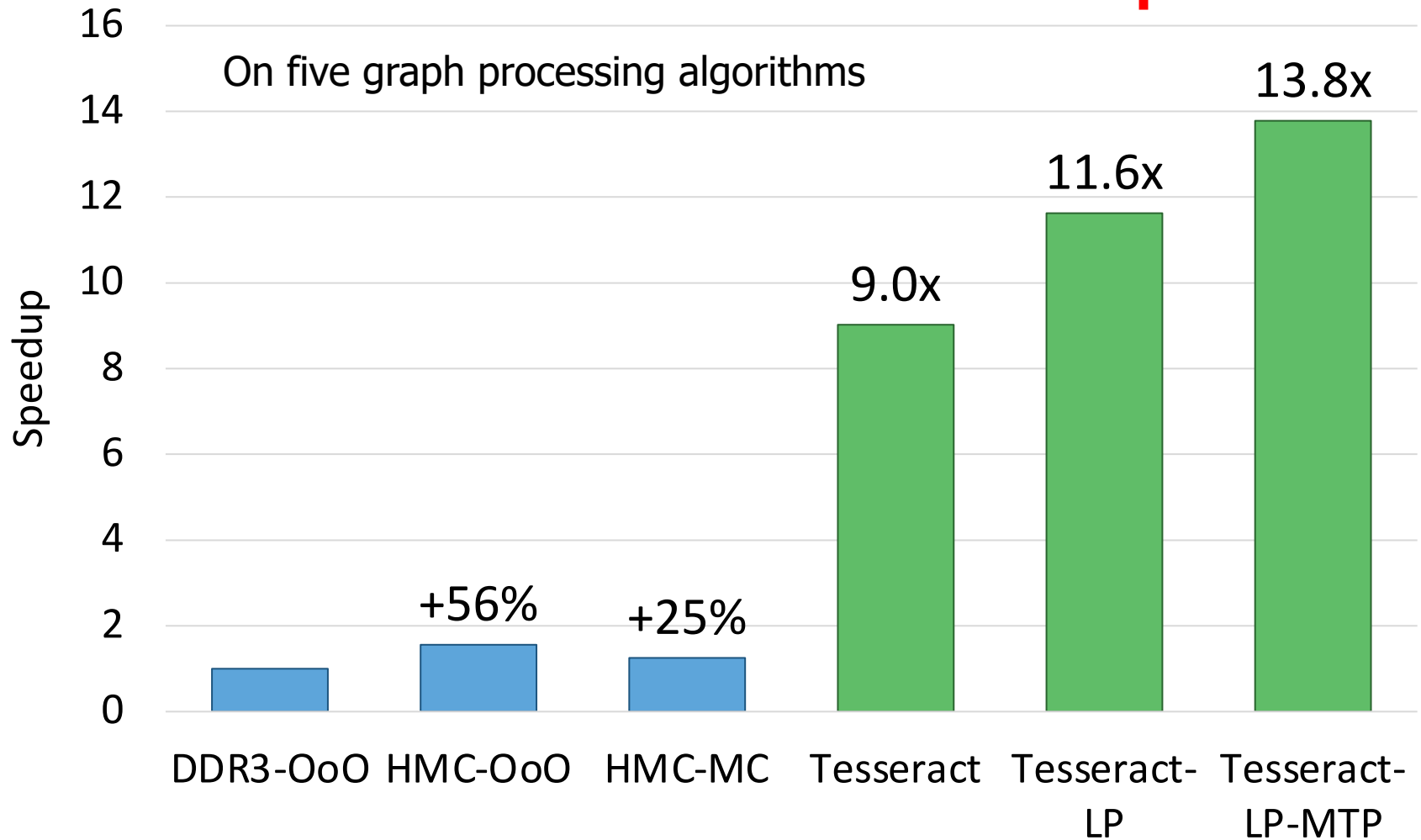
**Tesseract**



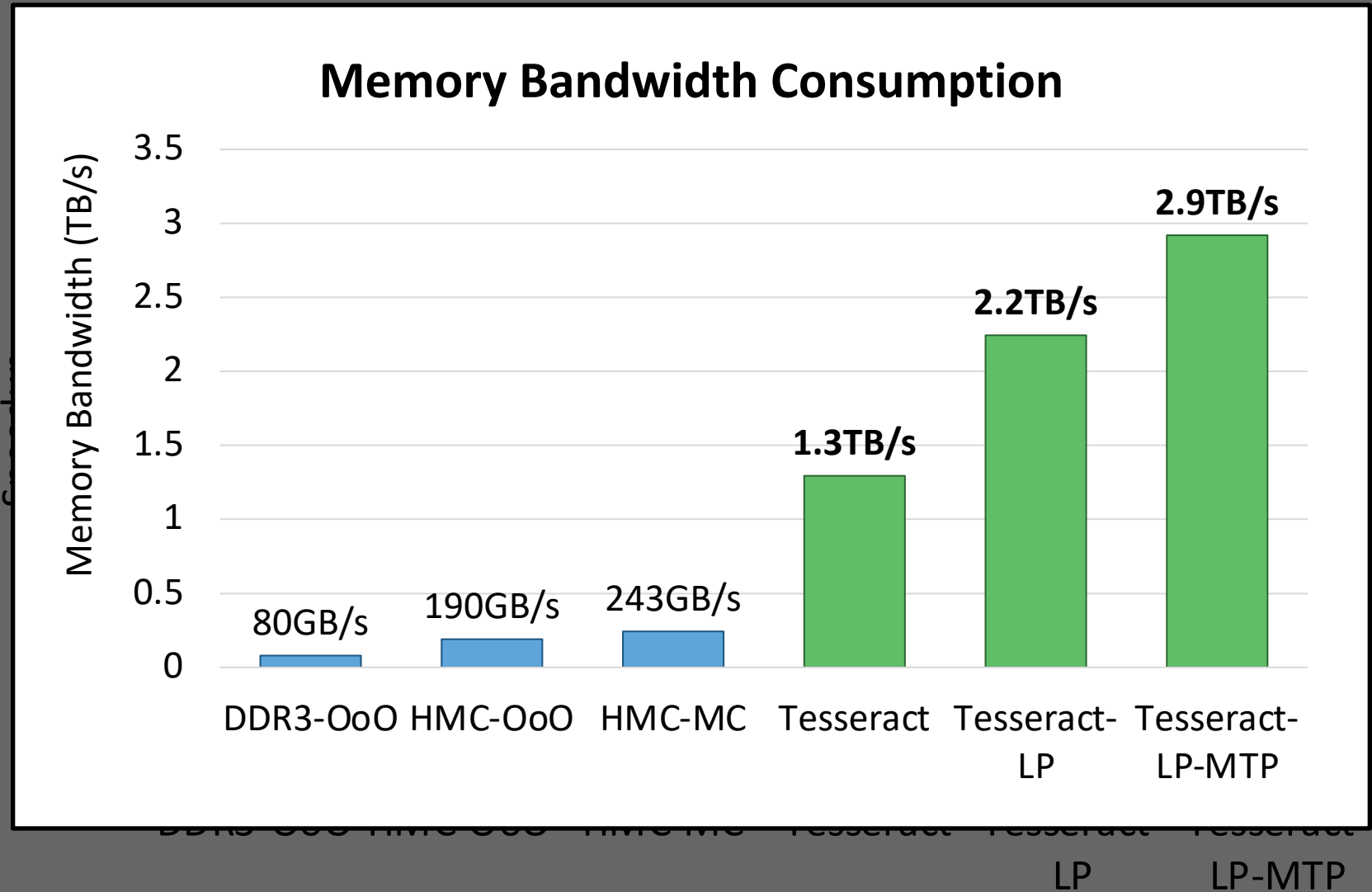
**8TB/s**

# Tesseract Graph Processing Performance

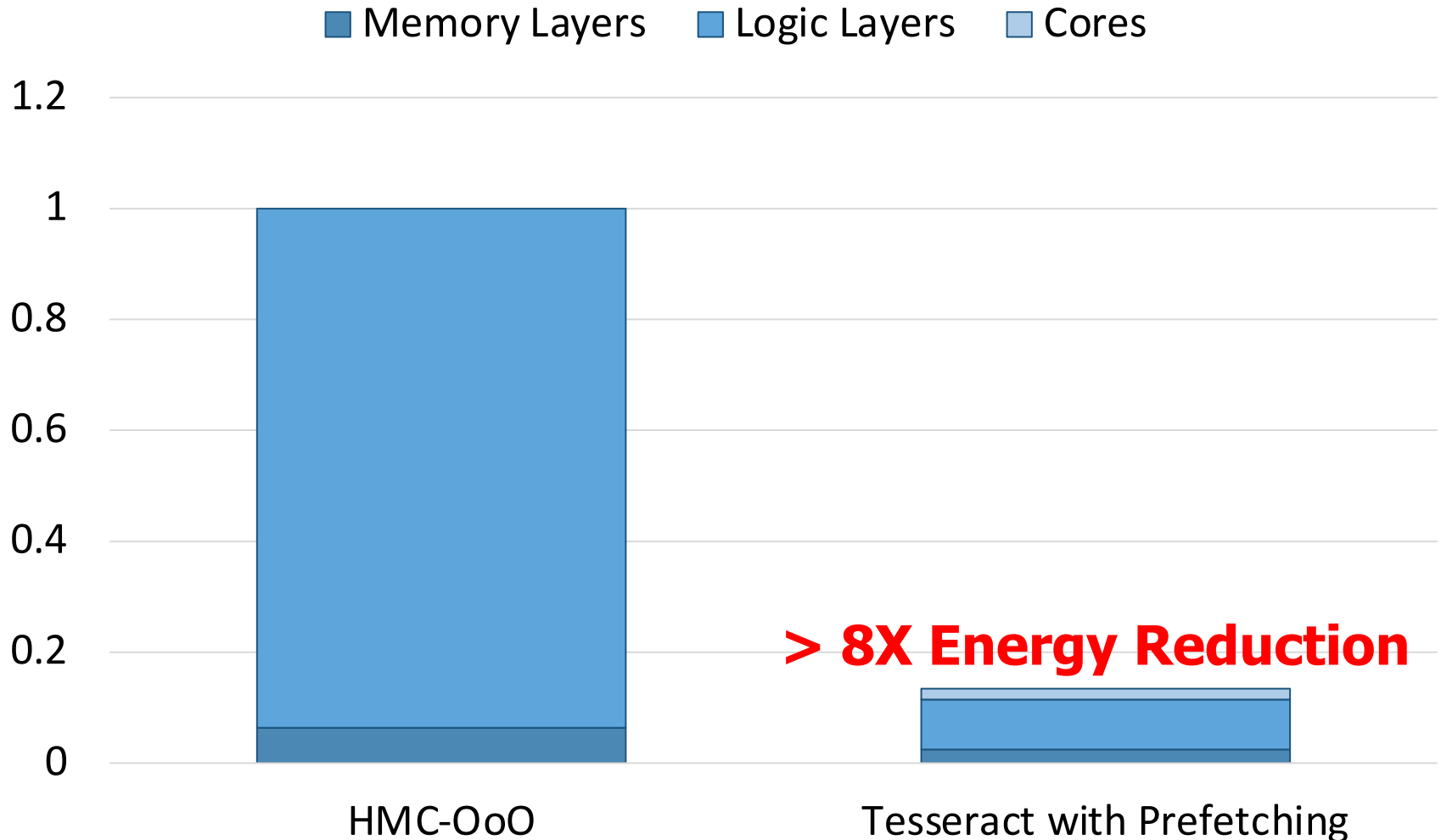
**>13X Performance Improvement**



# Tesseract Graph Processing Performance



# Tesseract Graph Processing System Energy



# More on Tesseract

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- Junwhan Ahn, Sungpack Hong, Sungjoo Yoo, Onur Mutlu, and Kiyoungh 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<sup>§</sup>   Sungjoo Yoo   Onur Mutlu<sup>†</sup>   Kiyoungh Choi

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

Seoul National University

<sup>§</sup>Oracle Labs

<sup>†</sup>Carnegie Mellon University

# 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**

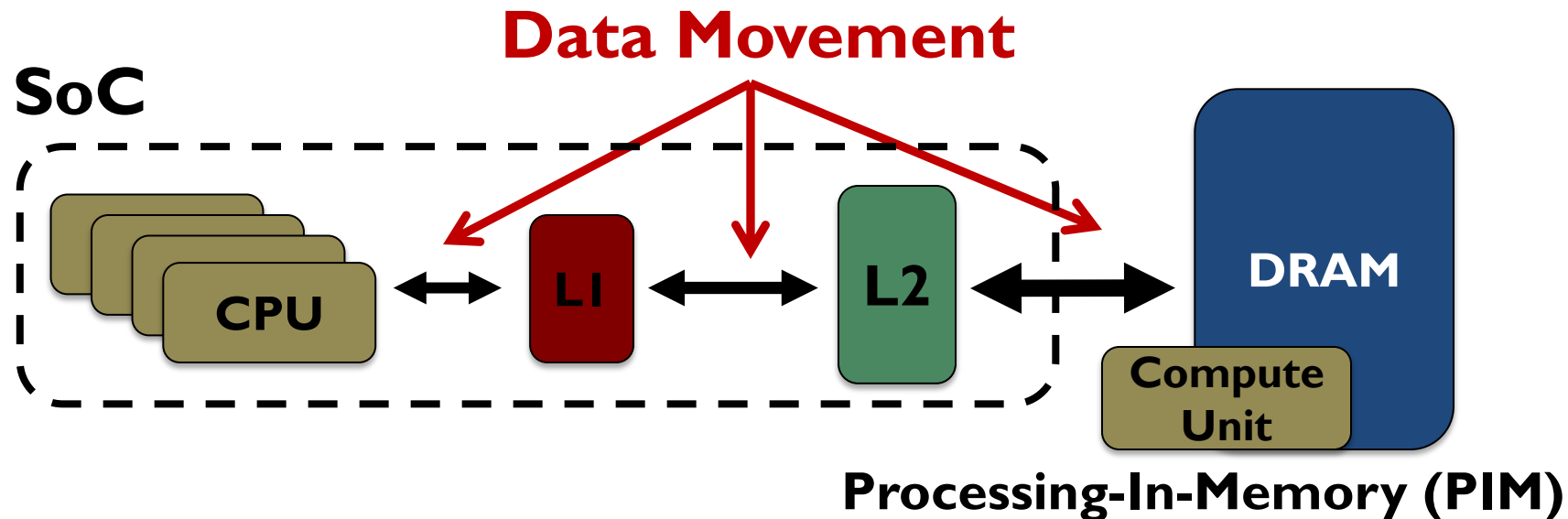


**Video Capture**

Google's **video codec**

# Energy Cost of Data Movement

**1<sup>st</sup> 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

**2<sup>nd</sup> 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**

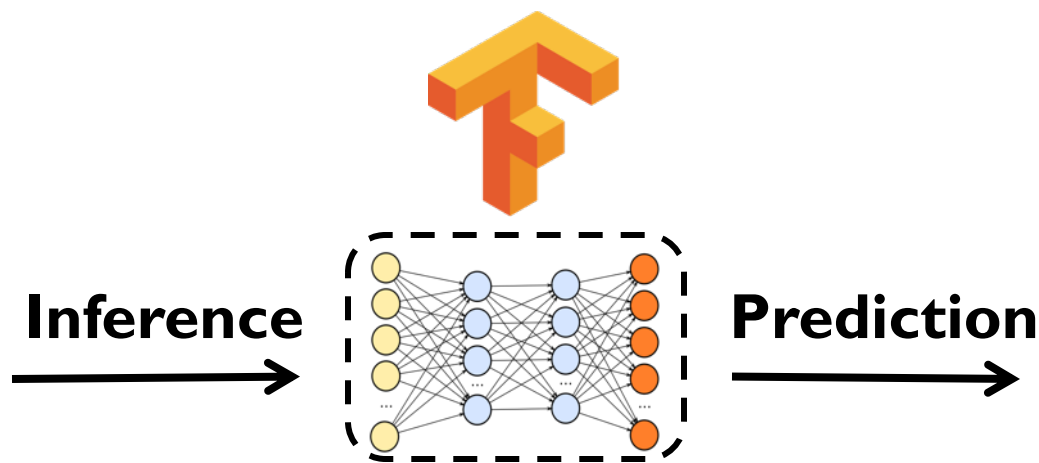
Google's **video codec**



**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

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- 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 Boroumand<sup>1</sup>

Saugata Ghose<sup>1</sup>

Youngsok Kim<sup>2</sup>

Rachata Ausavarungnirun<sup>1</sup>

Eric Shiu<sup>3</sup>

Rahul Thakur<sup>3</sup>

Daehyun Kim<sup>4,3</sup>

Aki Kuusela<sup>3</sup>

Allan Knies<sup>3</sup>

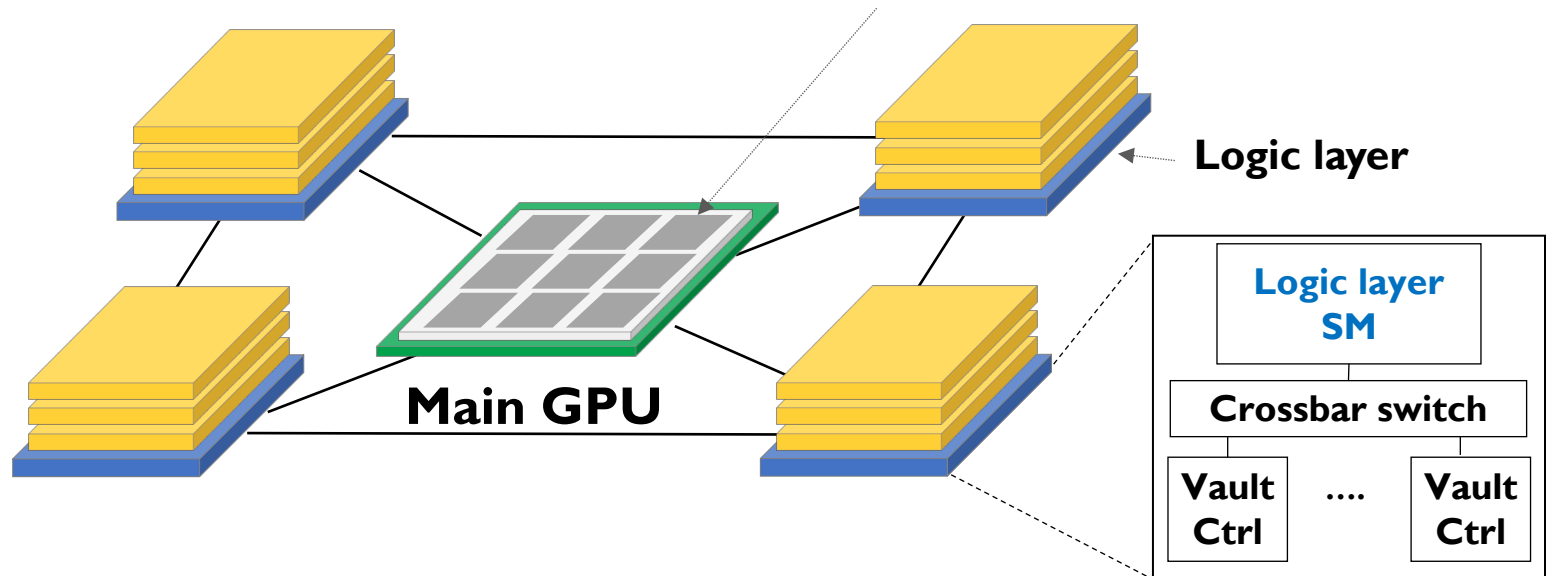
Parthasarathy Ranganathan<sup>3</sup>

Onur Mutlu<sup>5,1</sup>

# 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<sup>‡</sup> Eiman Ebrahimi<sup>†</sup> Gwangsun Kim\* Niladrish Chatterjee<sup>†</sup> Mike O'Connor<sup>†</sup>  
Nandita Vijaykumar<sup>‡</sup> Onur Mutlu<sup>§‡</sup> Stephen W. Keckler<sup>†</sup>

<sup>‡</sup>Carnegie Mellon University <sup>†</sup>NVIDIA <sup>\*</sup>KAIST <sup>§</sup>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 Pattnaik<sup>1</sup>    Xulong Tang<sup>1</sup>    Adwait Jog<sup>2</sup>    Onur Kayiran<sup>3</sup>  
Asit K. Mishra<sup>4</sup>    Mahmut T. Kandemir<sup>1</sup>    Onur Mutlu<sup>5,6</sup>    Chita R. Das<sup>1</sup>

<sup>1</sup>Pennsylvania State University    <sup>2</sup>College of William and Mary  
<sup>3</sup>Advanced Micro Devices, Inc.    <sup>4</sup>Intel Labs    <sup>5</sup>ETH Zürich    <sup>6</sup>Carnegie 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<sup>†</sup> Samira Khan<sup>‡</sup> Nandita Vijaykumar<sup>†</sup>  
Kevin K. Chang<sup>†</sup> Amirali Boroumand<sup>†</sup> Saugata Ghose<sup>†</sup> Onur Mutlu<sup>§†</sup>  
<sup>†</sup>*Carnegie Mellon University*   <sup>‡</sup>*University of Virginia*   <sup>§</sup>*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<sup>†</sup>, Eiman Ebrahimi<sup>‡</sup>, Onur Mutlu<sup>§</sup>, Yale N. Patt\*

*\*The University of Texas at Austin    <sup>†</sup>Apple    <sup>‡</sup>NVIDIA    <sup>§</sup>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<sup>§</sup>, Yale N. Patt\*

\**The University of Texas at Austin*    <sup>§</sup>*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<sup>a,b,c</sup>    Dionysios Diamantopoulos<sup>c</sup>    Christoph Hagleitner<sup>c</sup>    Juan Gómez-Luna<sup>b</sup>  
Sander Stuijk<sup>a</sup>    Onur Mutlu<sup>b</sup>    Henk Corporaal<sup>a</sup>  
<sup>a</sup>Eindhoven University of Technology    <sup>b</sup>ETH Zürich    <sup>c</sup>IBM 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.*  
[[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<sup>†⌘</sup> Gurpreet S. Kalsi<sup>⌘</sup> Zülal Bingöl<sup>▽</sup> Can Firtina<sup>◇</sup> Lavanya Subramanian<sup>‡</sup> Jeremie S. Kim<sup>◇†</sup>  
Rachata Ausavarungnirun<sup>○</sup> Mohammed Alser<sup>◇</sup> Juan Gomez-Luna<sup>◇</sup> Amirali Boroumand<sup>†</sup> Anant Nori<sup>⌘</sup>  
Allison Scibisz<sup>†</sup> Sreenivas Subramoney<sup>⌘</sup> Can Alkan<sup>▽</sup> Saugata Ghose<sup>\*†</sup> Onur Mutlu<sup>◇†▽</sup>  
<sup>†</sup>Carnegie Mellon University   <sup>⌘</sup>Processor Architecture Research Lab, Intel Labs   <sup>▽</sup>Bilkent University   <sup>◇</sup>ETH Zürich  
<sup>‡</sup>Facebook   <sup>○</sup>King Mongkut's University of Technology North Bangkok   <sup>\*</sup>University of Illinois at Urbana-Champaign

# Accelerating Time Series Analysis

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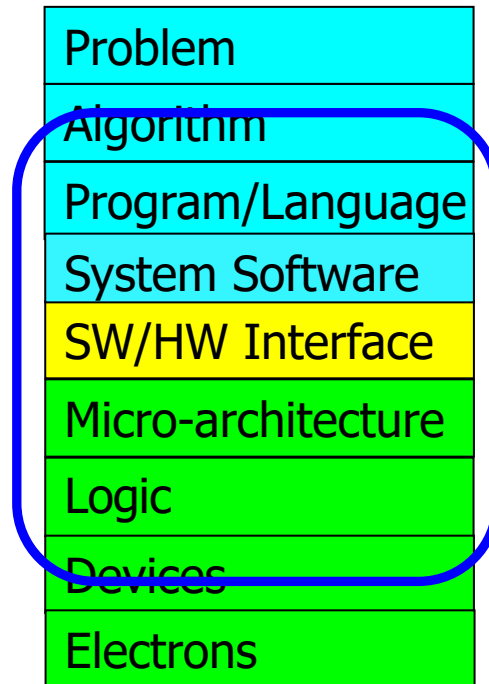
- Ivan Fernandez, Ricardo Quisiant, Christina Giannoula, Mohammed Alser, Juan Gómez-Luna, Eladio Gutiérrez, Oscar Plata, and Onur Mutlu,  
**"NATSA: A Near-Data Processing Accelerator for Time Series Analysis"**  
*Proceedings of the 38th IEEE International Conference on Computer Design (ICCD)*, Virtual,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

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

Ivan Fernandez <sup>§</sup>	Ricardo Quisiant <sup>§</sup>	Christina Giannoula <sup>†</sup>	Mohammed Alser <sup>‡</sup>
Juan Gómez-Luna <sup>‡</sup>	Eladio Gutiérrez <sup>§</sup>	Oscar Plata <sup>§</sup>	Onur Mutlu <sup>‡</sup>
<sup>§</sup> <i>University of Malaga</i>	<sup>†</sup> <i>National Technical University of Athens</i>	<sup>‡</sup> <i>ETH Zürich</i>	

# 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<sup>a,b</sup>, Saugata Ghose<sup>b,c</sup>, Juan Gómez-Luna<sup>a</sup>, Rachata Ausavarungnirun<sup>d</sup>

*SAFARI Research Group*

<sup>a</sup>*ETH Zürich*

<sup>b</sup>*Carnegie Mellon University*

<sup>c</sup>*University of Illinois at Urbana-Champaign*

<sup>d</sup>*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)

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

Saugata Ghose<sup>†</sup>   Amirali Boroumand<sup>†</sup>   Jeremie S. Kim<sup>†§</sup>   Juan Gómez-Luna<sup>§</sup>   Onur Mutlu<sup>§†</sup>

<sup>†</sup>*Carnegie Mellon University*

<sup>§</sup>*ETH Zürich*

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

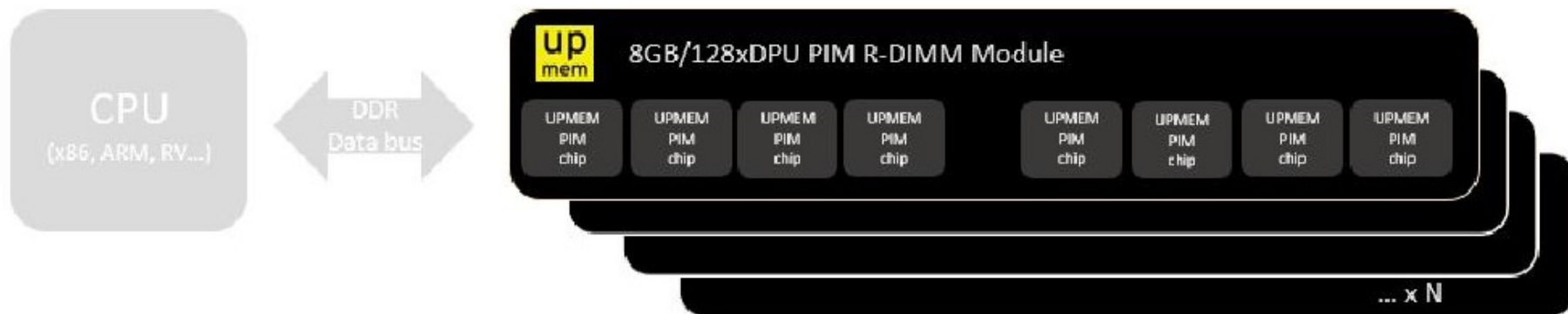
**"Processing-in-Memory: A Workload-Driven Perspective"**

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

[Preliminary arXiv version]

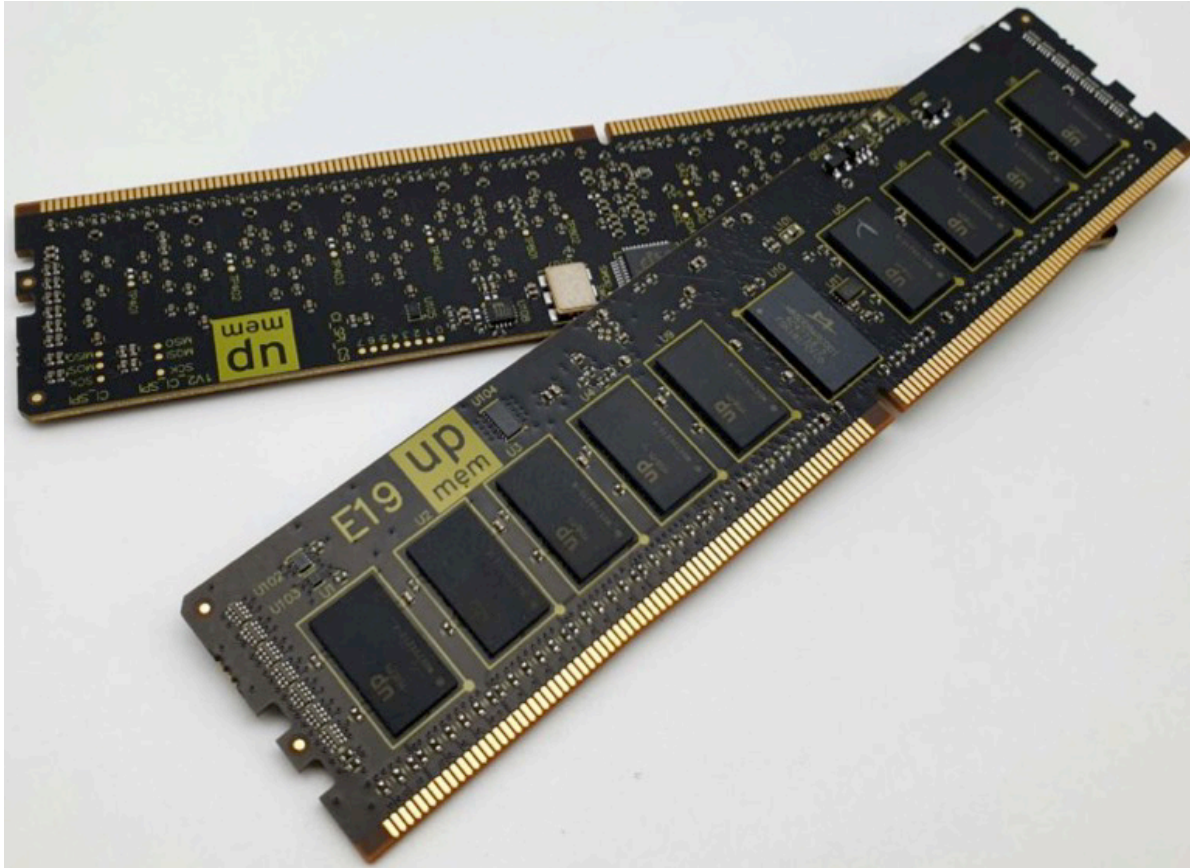
# UPMEM Processing-in-DRAM Engine (2019)

- **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

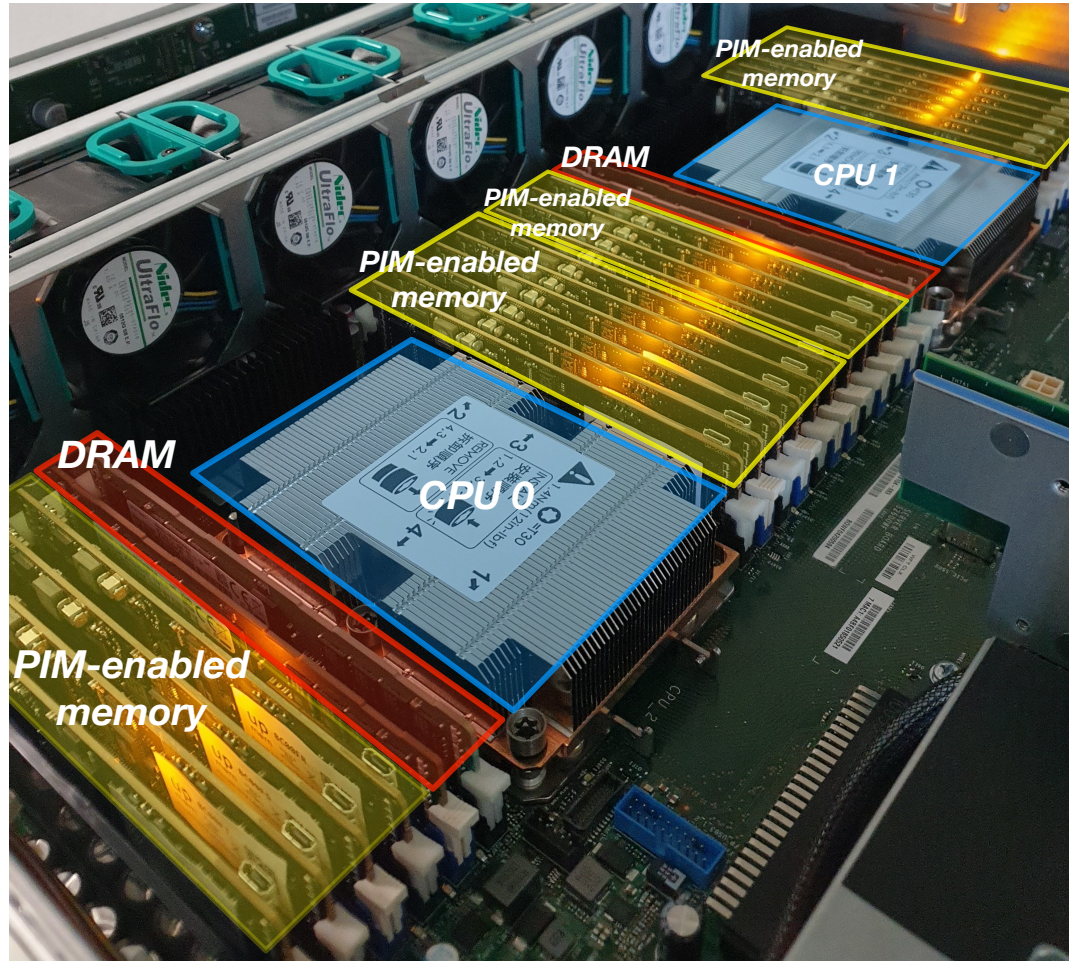
- E19: 8 chips DIMM (1 rank). DPUs @ 267 MHz
- P21: 16 chips DIMM (2 ranks). DPUs @ 350 MHz



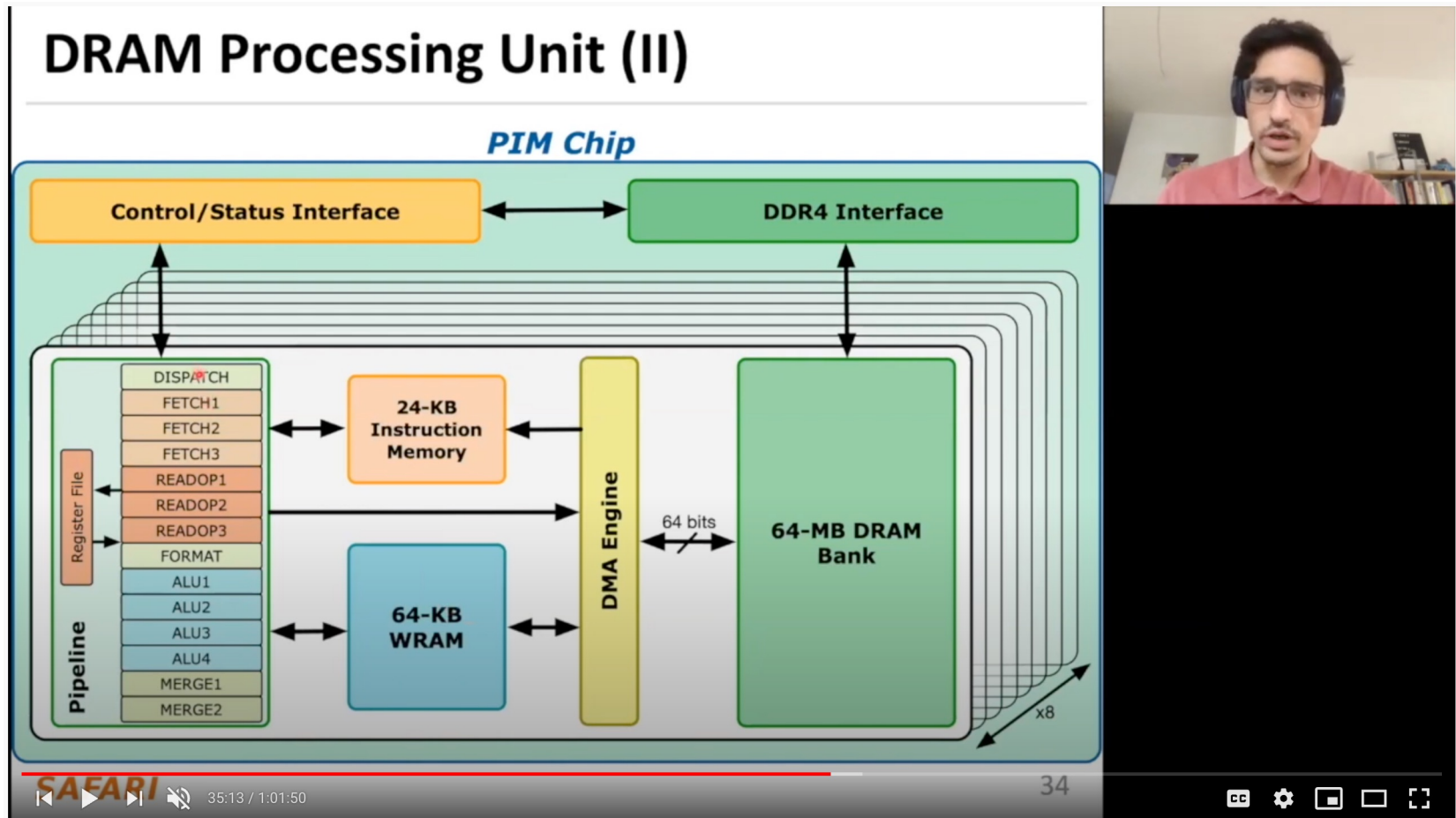


# PIM System Organization

- UPMEM-based PIM system with 20 UPMEM memory modules of 16 chips each (40 ranks) → 2560 DPUs



# 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  
16.7K subscribers

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).

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.

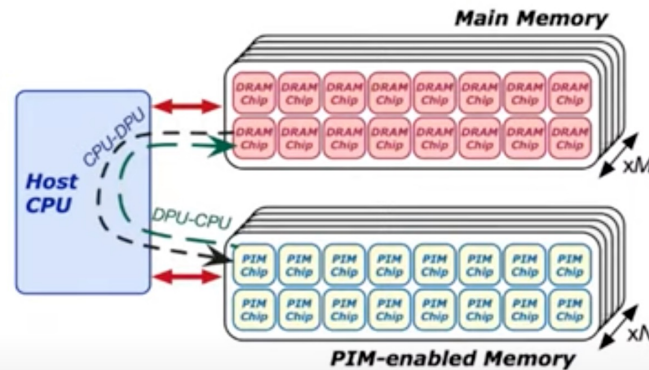
This paper provides the first comprehensive analysis of the first publicly-available real-world PIM architecture. We make two key contributions. First, we conduct an experimental characterization of the UPMEM-based PIM system using microbenchmarks to assess various architecture limits such as compute 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 2,556 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.



# 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



SAFARI Live Seminar: Understanding a Modern Processing-in-Memory Architecture

1,868 views • Streamed live on Jul 12, 2021

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Onur Mutlu Lectures  
17.6K subscribers

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

ANALYTICS

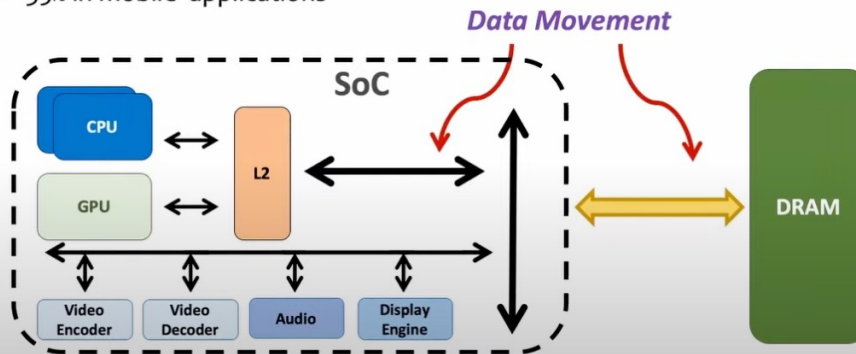
EDIT VIDEO

[https://www.youtube.com/watch?v=D8Hjy2IU9l4&list=PL5Q2soXY2Zi\\_tOTAYm--dYByNPL7JhwR9](https://www.youtube.com/watch?v=D8Hjy2IU9l4&list=PL5Q2soXY2Zi_tOTAYm--dYByNPL7JhwR9)

# 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

SAFARI

3

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

3,482 views • Premiered Jul 25, 2021

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Onur Mutlu Lectures

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[https://www.youtube.com/watch?v=Pp9jSU2b9oM&list=PL5Q2soXY2Zi8\\_VVChACnON4sfh2bJ5IrD&index=159](https://www.youtube.com/watch?v=Pp9jSU2b9oM&list=PL5Q2soXY2Zi8_VVChACnON4sfh2bJ5IrD&index=159)

# 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<sup>◇</sup> Mohammed Alser<sup>◇</sup> Damla Senol Cali<sup>✕</sup>

Dionysios Diamantopoulos<sup>▽</sup> Juan Gómez-Luna<sup>◇</sup>

Henk Corporaal<sup>\*</sup> Onur Mutlu<sup>◇✕</sup>

<sup>◇</sup>*ETH Zürich*    <sup>✕</sup>*Carnegie Mellon University*

<sup>\*</sup>*Eindhoven University of Technology*    <sup>▽</sup>*IBM Research Europe*

# Samsung Function-in-Memory DRAM (2021)



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

Korea on February 17, 2021

Audio



Share



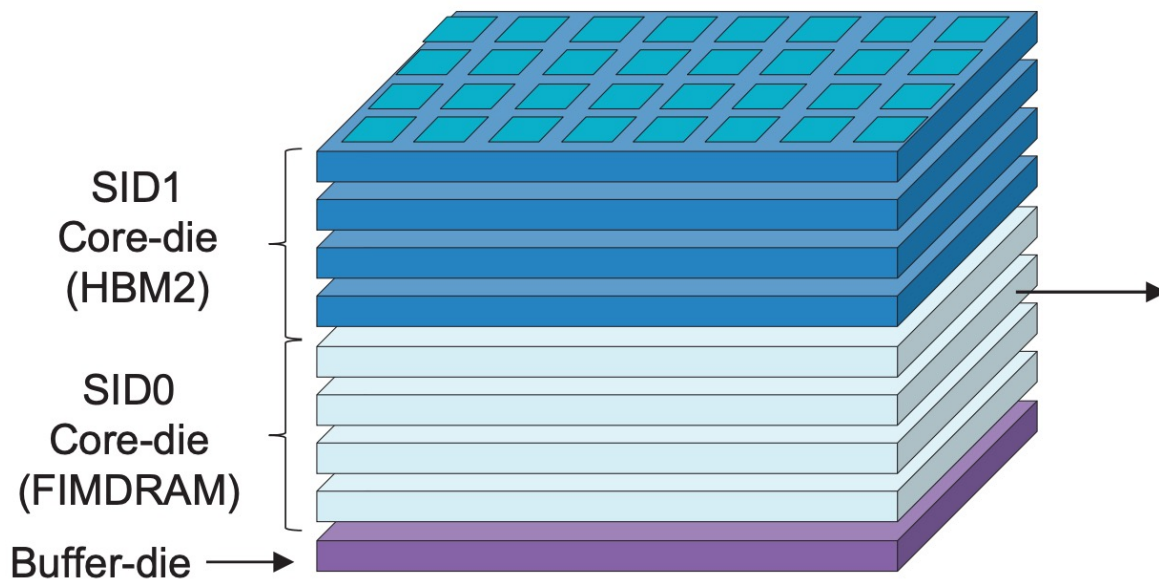
*The new architecture will deliver over twice the system performance and reduce energy consumption by more than 70%*

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 Kwon<sup>1</sup>, Suk Han Lee<sup>1</sup>, Jaehoon Lee<sup>1</sup>, Sang-Hyuk Kwon<sup>1</sup>, Je Min Ryu<sup>1</sup>, Jong-Pil Son<sup>1</sup>, Seongil O<sup>1</sup>, Hak-Soo Yu<sup>1</sup>, Haesuk Lee<sup>1</sup>, Soo Young Kim<sup>1</sup>, Youngmin Cho<sup>1</sup>, Jin Guk Kim<sup>1</sup>, Jongyoon Choi<sup>1</sup>, Hyun-Sung Shin<sup>1</sup>, Jin Kim<sup>1</sup>, BengSeng Phuah<sup>1</sup>, HyoungMin Kim<sup>1</sup>, Myeong Jun Song<sup>1</sup>, Ahn Choi<sup>1</sup>, Daeho Kim<sup>1</sup>, SooYoung Kim<sup>1</sup>, Eun-Bong Kim<sup>1</sup>, David Wang<sup>2</sup>, Shinhaeng Kang<sup>1</sup>, Yuhwan Ro<sup>3</sup>, Seungwoo Seo<sup>3</sup>, JoonHo Song<sup>3</sup>, Jaeyoun Youn<sup>1</sup>, Kyomin Sohn<sup>1</sup>, Nam Sung Kim<sup>1</sup>

<sup>1</sup>Samsung Electronics, Hwaseong, Korea

<sup>2</sup>Samsung Electronics, San Jose, CA

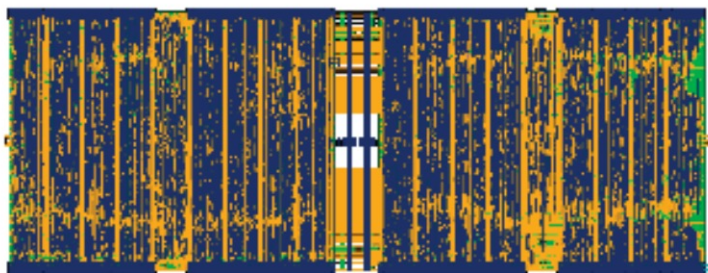
<sup>3</sup>Samsung Electronics, Suwon, Korea



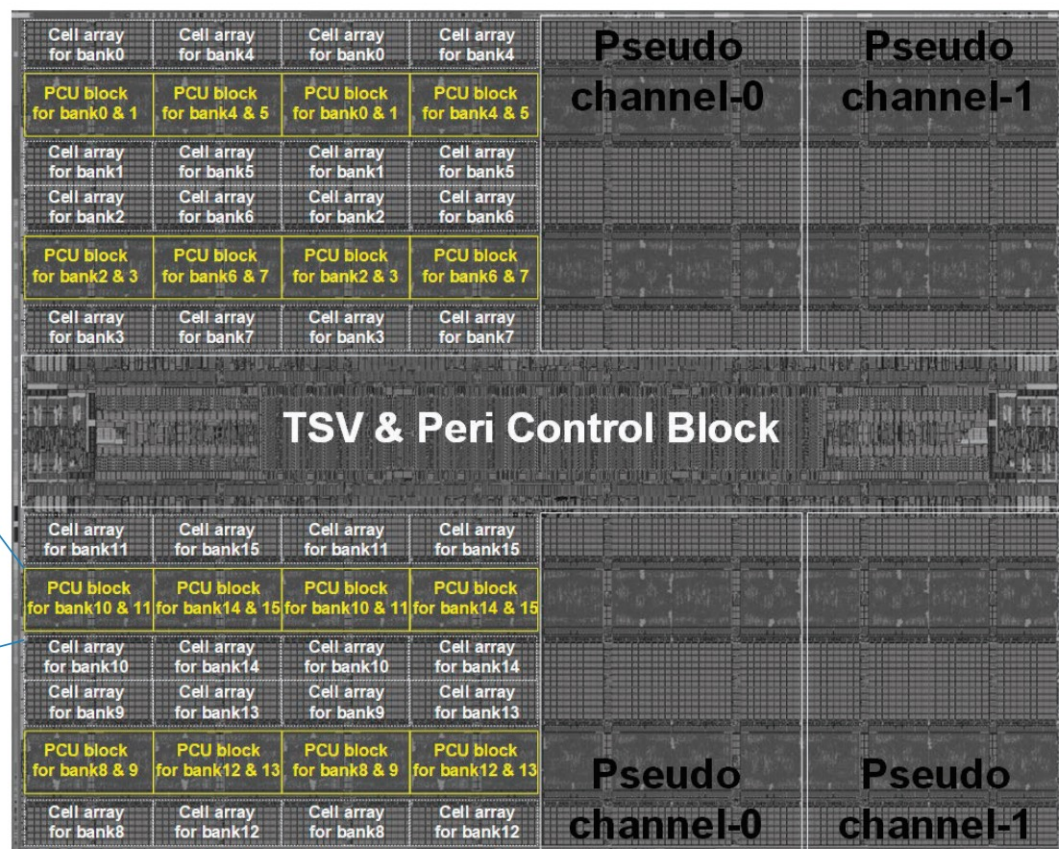
# Samsung Function-in-Memory DRAM (2021)

## Chip Implementation

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



[Digital RTL design for PCU block]



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 Kwon<sup>1</sup>, Suk Han Lee<sup>1</sup>, Jaehoon Lee<sup>1</sup>, Sang-Hyuk Kwon<sup>1</sup>, Je Min Ryu<sup>1</sup>, Jong-Pil Son<sup>1</sup>, Seongil O<sup>1</sup>, Hak-Soo Yu<sup>1</sup>, Haesuk Lee<sup>1</sup>, Soo Young Kim<sup>1</sup>, Youngmin Cho<sup>1</sup>, Jin Guk Kim<sup>1</sup>, Jongyeon Choi<sup>1</sup>, Hyun-Sung Shim<sup>1</sup>, Jin Kim<sup>1</sup>, BengSeng Phuah<sup>1</sup>, HyounMin Kim<sup>1</sup>, Myeong Jun Song<sup>1</sup>, Ahn Chai<sup>1</sup>, Daeho Kim<sup>1</sup>, SooYoung Kim<sup>1</sup>, Eun-Bong Kim<sup>1</sup>, David Wang<sup>2</sup>, Shinhaeng Kang<sup>3</sup>, Yulwan Ro<sup>3</sup>, Seungwoo Seo<sup>3</sup>, JoonHo Song<sup>3</sup>, Jaeyoun Yoon<sup>1</sup>, Kyomin Sohn<sup>1</sup>, Nam Sung Kim<sup>1</sup>

<sup>1</sup>Samsung Electronics, Hwaseong, Korea  
<sup>2</sup>Samsung Electronics, San Jose, CA  
<sup>3</sup>Samsung Electronics, Suwon, Korea



# 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](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>

# A Tutorial on PIM

---

- 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](mailto: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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<https://www.youtube.com/watch?v=H3sEaINPBOE>

ANALYTICS

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

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

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



# Computing Architectures with Minimal Data Movement

## How to Enable Adoption of Processing in Memory

# Potential Barriers to Adoption of PIM

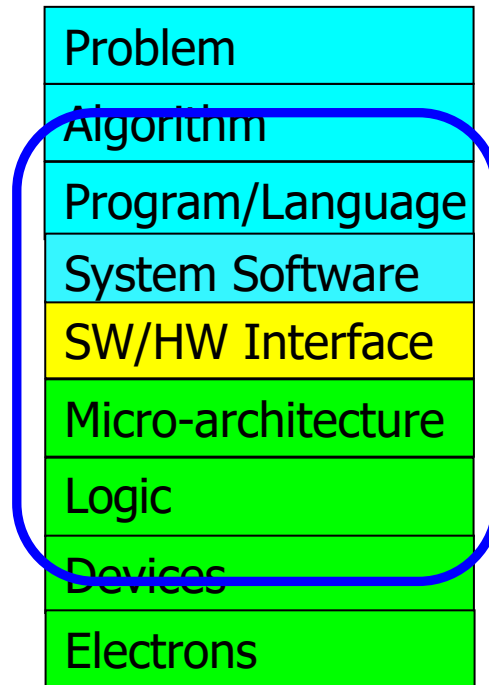
---

1. **Functionality** and **applications & software** for PIM
2. Ease of **programming** (interfaces and compiler/HW support)
3. **System** support: coherence, synchronization, virtual memory
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**

# 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

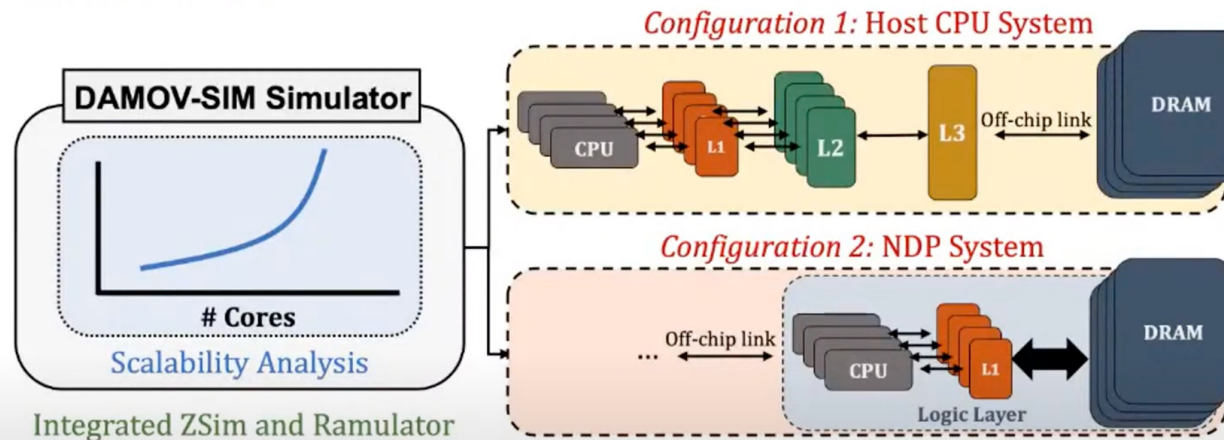
Data movement between the CPU and main memory is a first-order obstacle against improving performance, scalability, and energy efficiency in modern systems. Computer systems employ a range of techniques to reduce overheads tied to data movement, spanning from traditional mechanisms (e.g., deep multi-level 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>.

# 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

352 views • Streamed live on Jul 22, 2021

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Onur Mutlu Lectures  
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[https://www.youtube.com/watch?v=GWideVyo0nM&list=PL5Q2soXY2Zi\\_tOTAYm--dYByNPL7JhwR9&index=3](https://www.youtube.com/watch?v=GWideVyo0nM&list=PL5Q2soXY2Zi_tOTAYm--dYByNPL7JhwR9&index=3)



# PIM Can Enable New Medical 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.

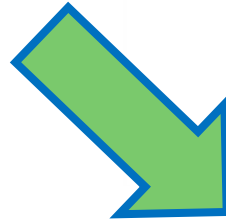
[[Preliminary arxiv.org version](#)]

# Future of Genome Sequencing & Analysis

---



MinION from ONT



SmidgION from ONT

# Accelerating Genome Analysis: Overview

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- 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

# 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

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Onur Mutlu Lectures  
15.9K subscribers

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

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# 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>

What We Have  
Less Time For



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

## **Data-Aware (Expressive)**

## **Computing Architectures**

# More Info in This 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](mailto: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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<https://www.youtube.com/watch?v=H3sEaINPBOE>

ANALYTICS

EDIT VIDEO

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

# 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

---

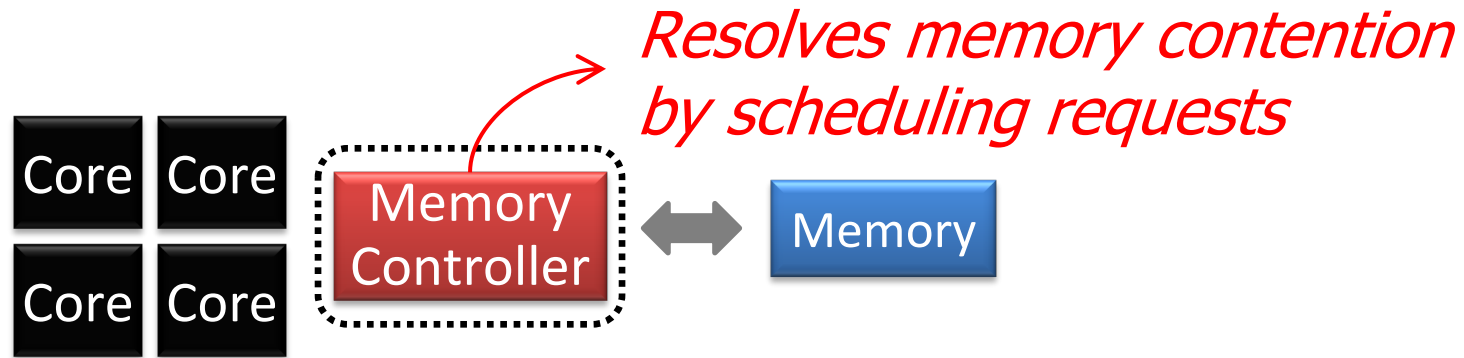
- Data-driven
  - Machine learns the “best” policies (how to do things)
- Sophisticated, workload-driven, changing, far-sighted policies
- Automatic data-driven policy learning
- All controllers are intelligent data-driven agents

**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.

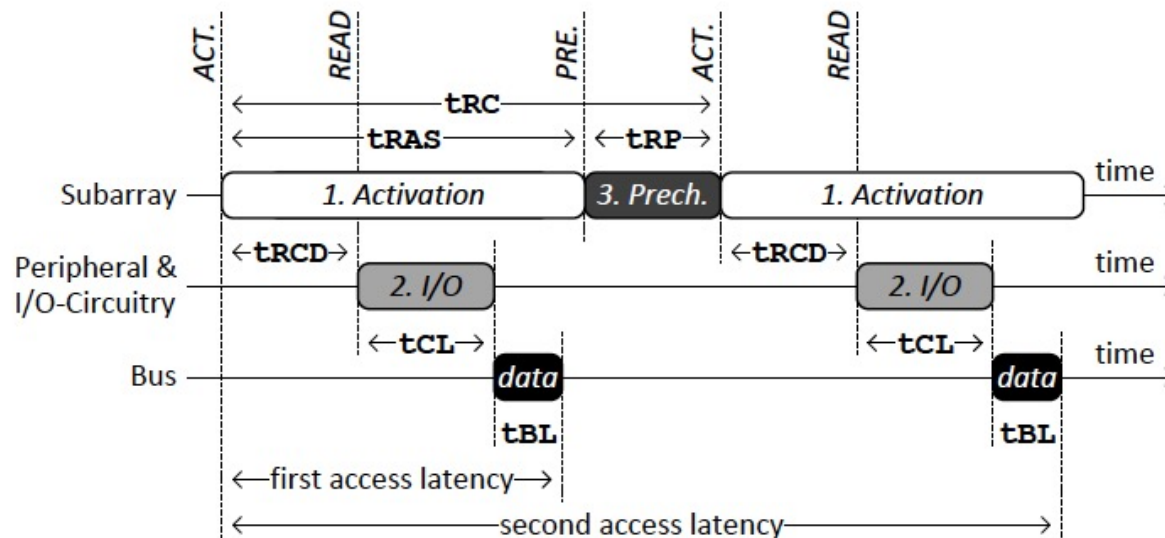
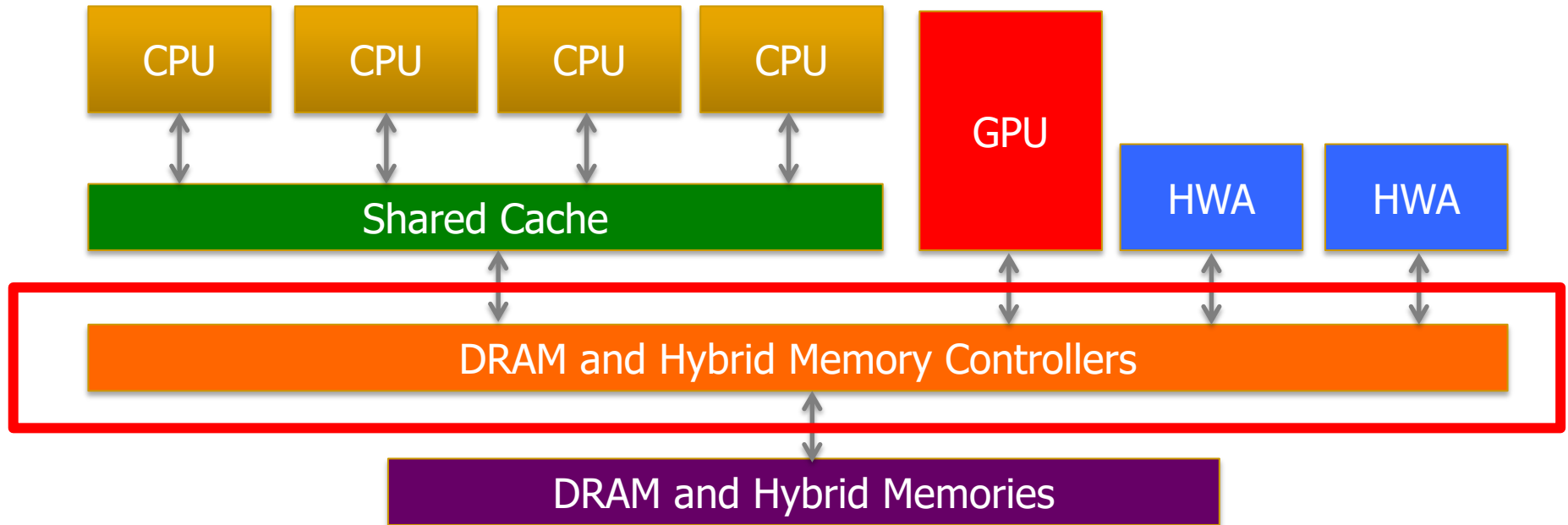


Figure 5. Three Phases of DRAM Access

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

Phase	Commands	Name	Value
1	ACT → READ	tRCD	15ns
	ACT → WRITE		
	ACT → PRE	tRAS	37.5ns
2	READ → data	tCL	15ns
	WRITE → data	tCWL	11.25ns
	data burst	tBL	7.5ns
3	PRE → ACT	tRP	15ns
1 & 3	ACT → ACT	tRC (tRAS+tRP)	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?

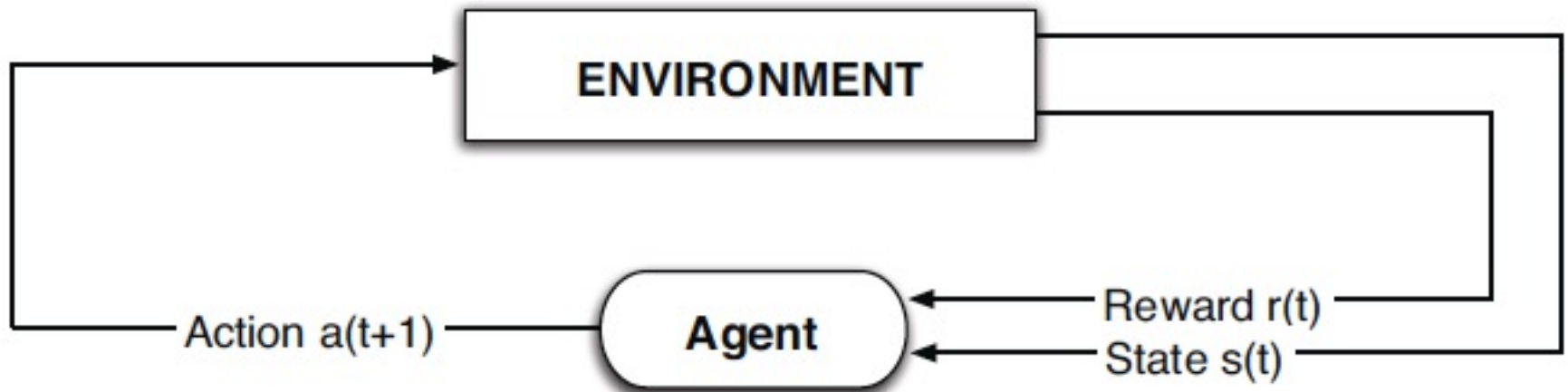
# Self-Optimizing DRAM Controllers

---

- 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

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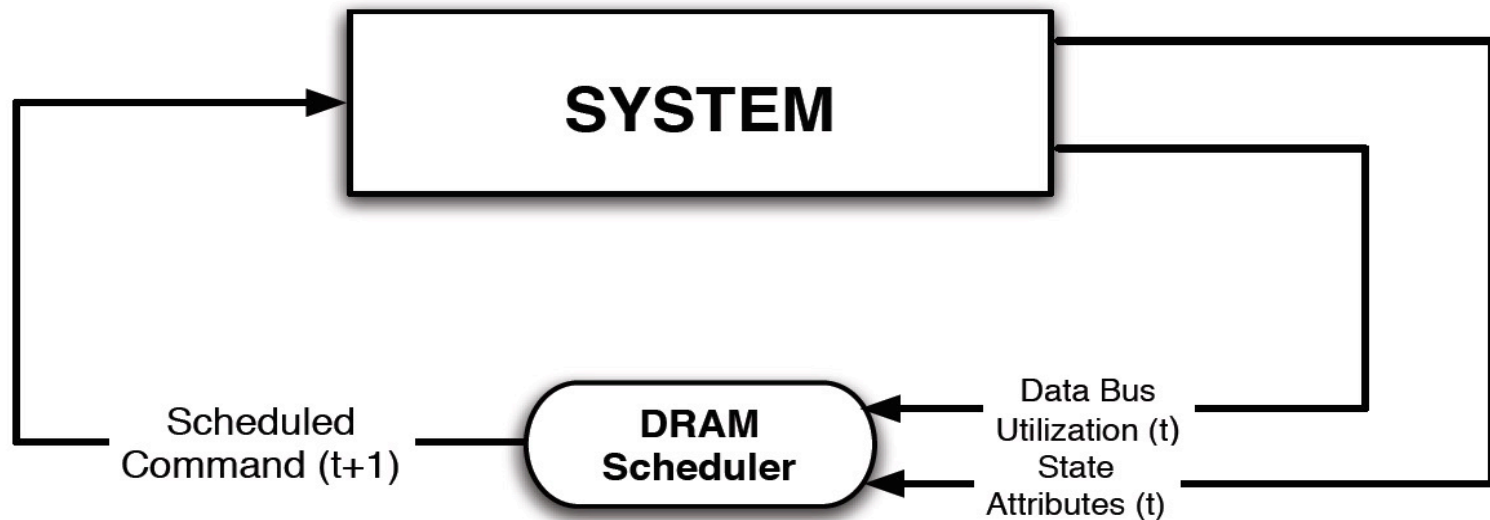
Goal: Learn to choose actions to maximize  $r_0 + \gamma r_1 + \gamma^2 r_2 + \dots$  ( $0 \leq \gamma < 1$ )

**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.*

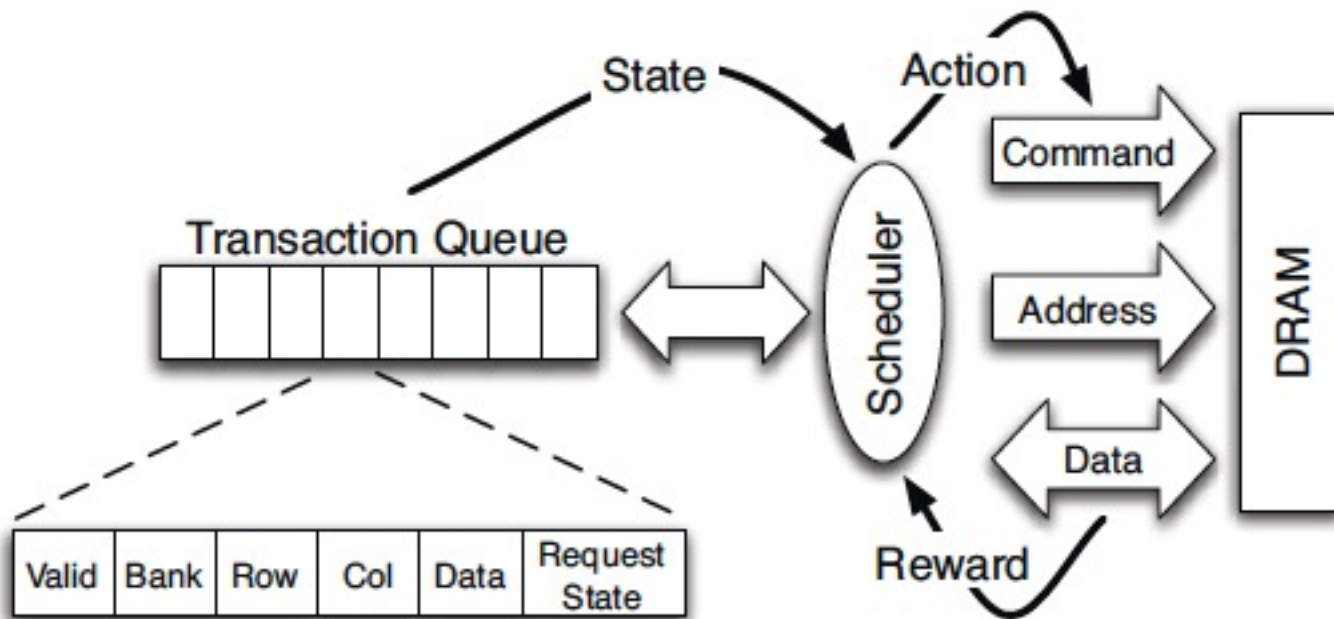


Figure 4: High-level overview of an RL-based scheduler.

# 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

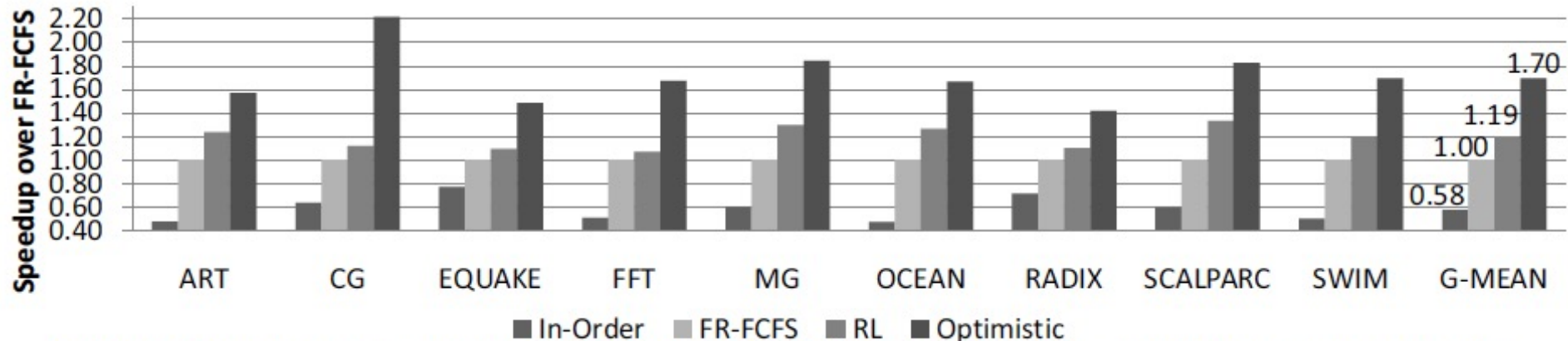


Figure 7: Performance comparison of in-order, FR-FCFS, RL-based, and optimistic memory controllers

**Large, robust performance improvements over many human-designed policies**

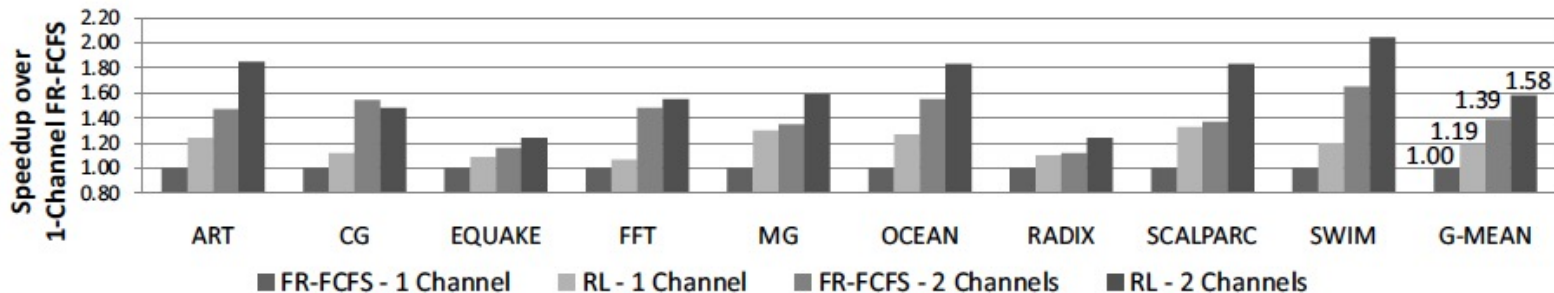


Figure 15: Performance comparison of FR-FCFS and RL-based memory controllers on systems with 6.4GB/s and 12.8GB/s peak DRAM bandwidth

# 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<sup>1,2</sup>   Onur Mutlu<sup>2</sup>   José F. Martínez<sup>1</sup>   Rich Caruana<sup>1</sup>

<sup>1</sup>Cornell University, Ithaca, NY 14850 USA

<sup>2</sup>Microsoft Research, Redmond, WA 98052 USA



# 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**

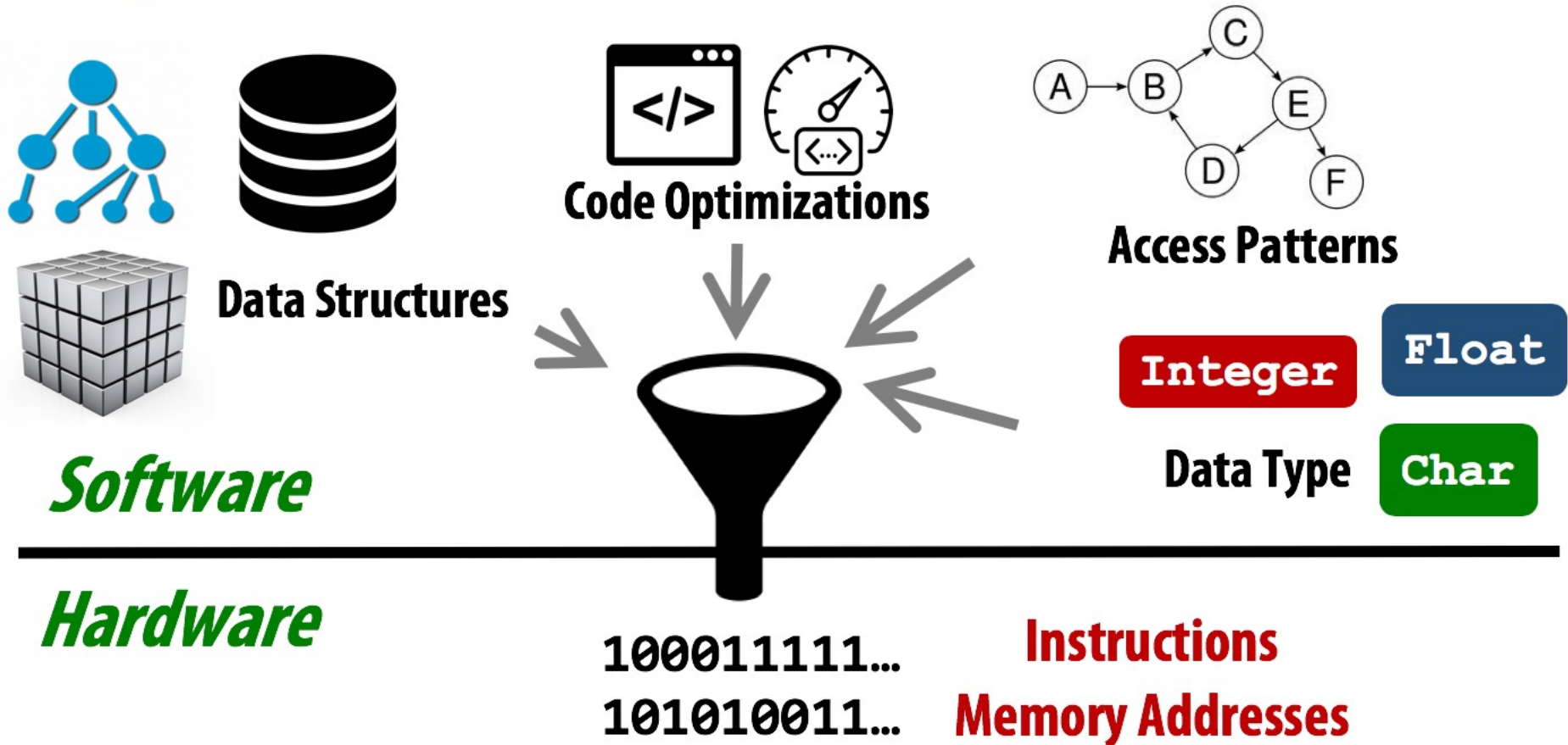
# Data-Aware Architectures

---

- 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

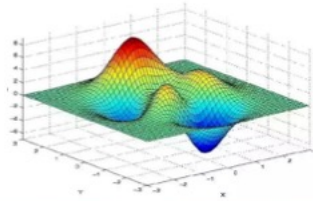




# A Solution: More Expressive Interfaces

**Performance**

**Software**



**Functionality**



**ISA  
Virtual Memory**

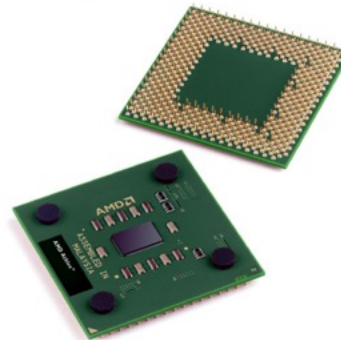
**Higher-level  
Program  
Semantics**

**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](#)]  
[[Lightning Talk Video](#)]

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

Nandita Vijaykumar<sup>†§</sup> Abhilasha Jain<sup>†</sup> Diptesh Majumdar<sup>†</sup> Kevin Hsieh<sup>†</sup> Gennady Pekhimenko<sup>‡</sup>  
Eiman Ebrahimi<sup>⌘</sup> Nastaran Hajinazar<sup>†</sup> Phillip B. Gibbons<sup>†</sup> Onur Mutlu<sup>§†</sup>

<sup>†</sup>Carnegie Mellon University

<sup>‡</sup>University of Toronto

<sup>⌘</sup>NVIDIA

<sup>†</sup>Simon Fraser University

<sup>§</sup>ETH Zürich

# X-MeM Aids 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 for GPUs

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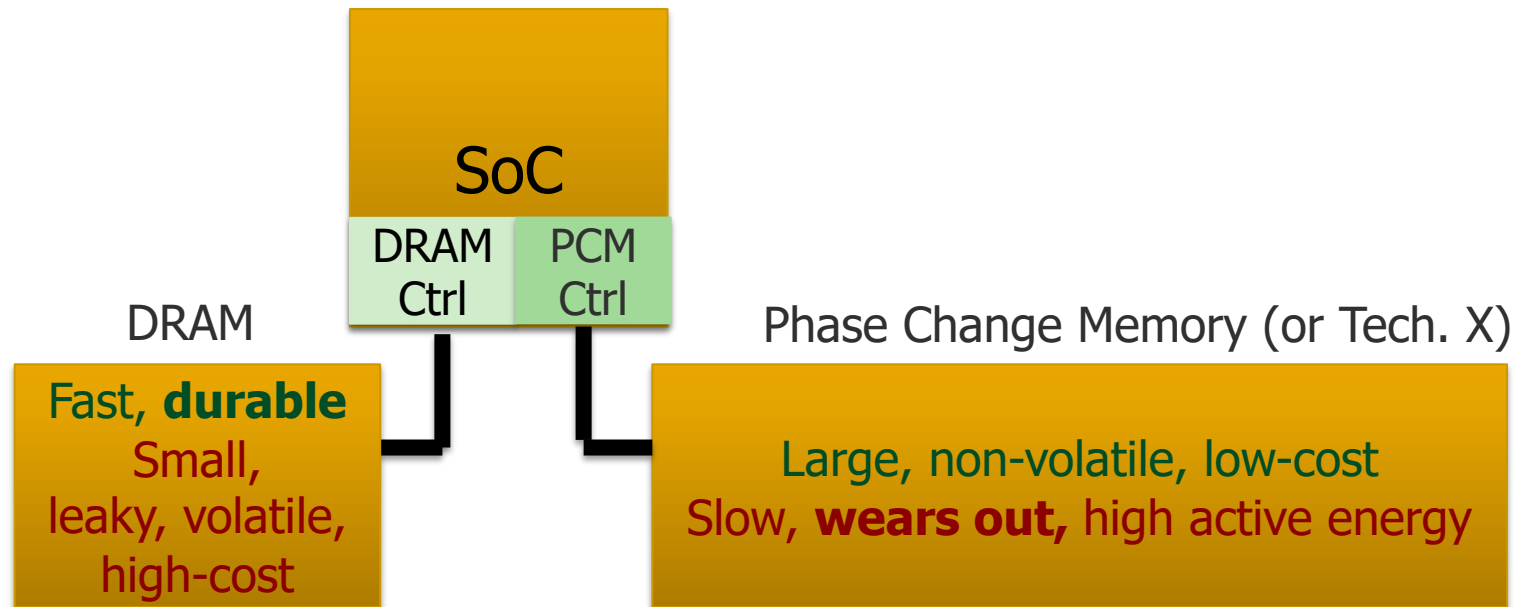
- Nandita Vijaykumar, Eiman Ebrahimi, Kevin Hsieh, Phillip B. Gibbons and Onur Mutlu, **"The Locality Descriptor: A Holistic Cross-Layer Abstraction to Express Data Locality in GPUs"**  
*Proceedings of the 45th International Symposium on Computer Architecture (ISCA)*, Los Angeles, CA, USA, June 2018.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

Nandita Vijaykumar <sup>†§</sup>	Eiman Ebrahimi <sup>‡</sup>	Kevin Hsieh <sup>†</sup>
Phillip B. Gibbons <sup>†</sup>	Onur Mutlu <sup>§†</sup>	
<sup>†</sup> Carnegie Mellon University	<sup>‡</sup> NVIDIA	<sup>§</sup> ETH Zürich

# 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](#)]

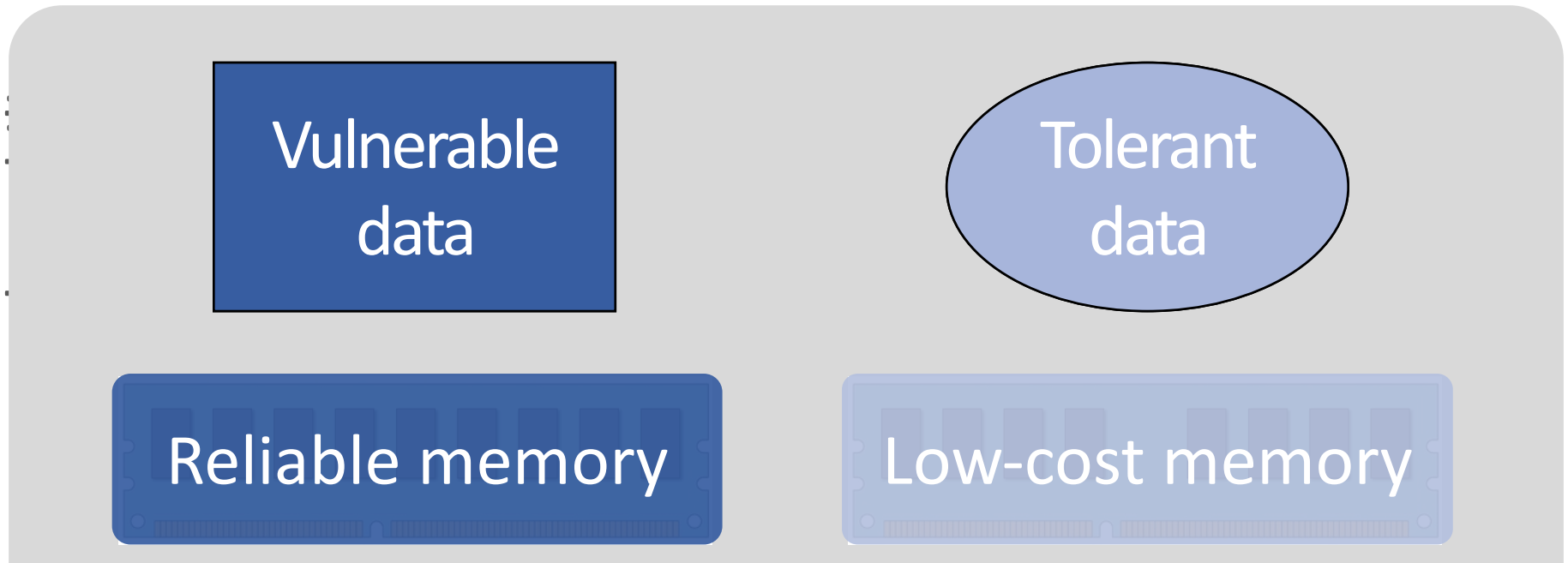
## Characterizing Application Memory Error Vulnerability to Optimize Datacenter Cost via Heterogeneous-Reliability Memory

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

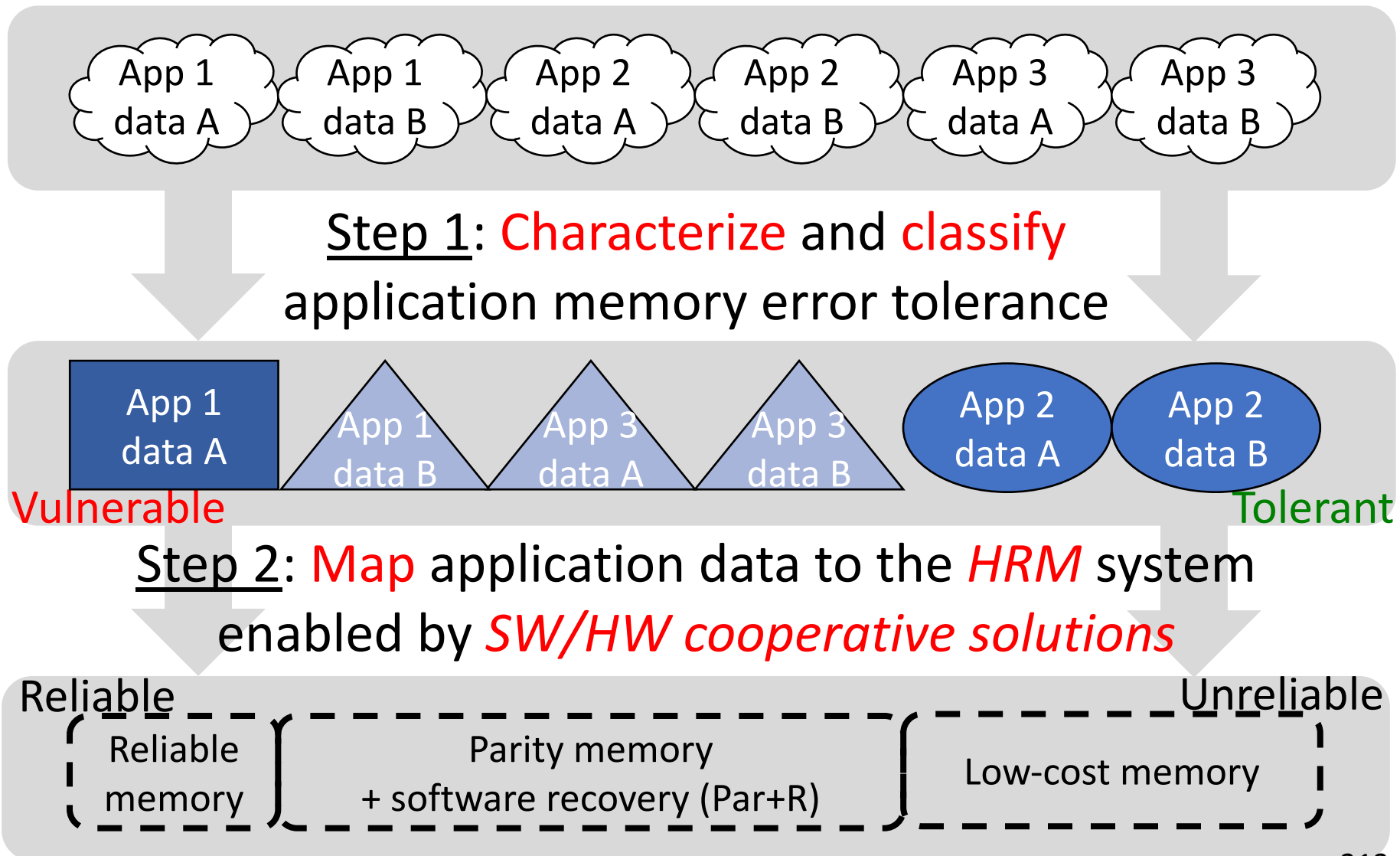
Reduces server hardware **cost** by **4.7 %**

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

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



# Heterogeneous-Reliability Memory



# More on Heterogeneous-Reliability Memory

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- 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](#)]  
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## Characterizing Application Memory Error Vulnerability to Optimize Datacenter Cost via Heterogeneous-Reliability Memory

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

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

# Another Example: EDEN for DNNs

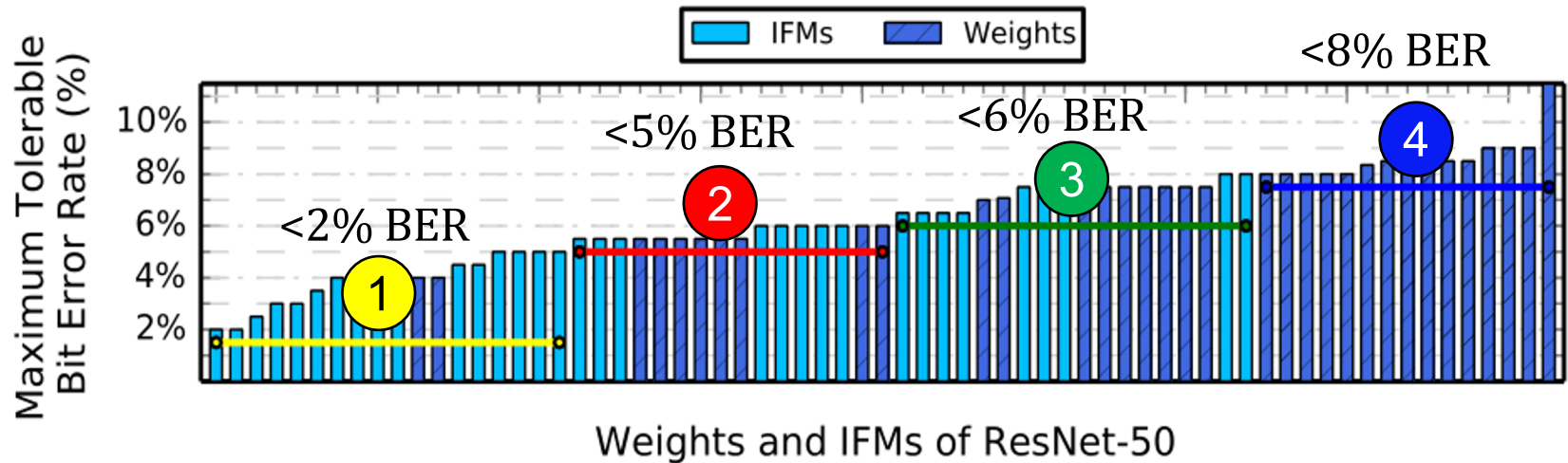
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- Deep Neural Network evaluation is very DRAM-intensive (especially for large networks)
1. Some data and layers in DNNs are very tolerant to errors
  2. Reduce DRAM latency and voltage on such data and layers
  3. While still achieving a user-specified 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: 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 Kanellopoulos<sup>1</sup> Nandita Vijaykumar<sup>2,1</sup> Christina Giannoula<sup>1,3</sup> Roknoddin Azizi<sup>1</sup>  
Skanda Koppula<sup>1</sup> Nika Mansouri Ghiasi<sup>1</sup> Taha Shahroodi<sup>1</sup> Juan Gomez Luna<sup>1</sup> Onur Mutlu<sup>1,2</sup>

<sup>1</sup>ETH Zürich

<sup>2</sup>Carnegie Mellon University

<sup>3</sup>National 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<sup>\*†</sup> Pratyush Patel<sup>✉</sup> Minesh Patel<sup>\*</sup> Konstantinos Kanellopoulos<sup>\*</sup> Saugata Ghose<sup>‡</sup>  
Rachata Ausavarungnirun<sup>⊙</sup> Geraldo F. Oliveira<sup>\*</sup> Jonathan Appavoo<sup>◇</sup> Vivek Seshadri<sup>▽</sup> Onur Mutlu<sup>\*‡</sup>

<sup>\*</sup>ETH Zürich <sup>†</sup>Simon Fraser University <sup>✉</sup>University of Washington <sup>‡</sup>Carnegie Mellon University

<sup>⊙</sup>King Mongkut's University of Technology North Bangkok <sup>◇</sup>Boston University <sup>▽</sup>Microsoft Research India

## **Data-Aware (Expressive)**

## **Computing Architectures**

# Concluding Remarks

# Recap: 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
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- 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**

# Concluding Remarks

---

- It is time to design **principled system architectures** to solve the **data handling** (i.e., memory/storage) problem
- Design complete 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**
  - ...

**Data-centric**

**Data-driven**

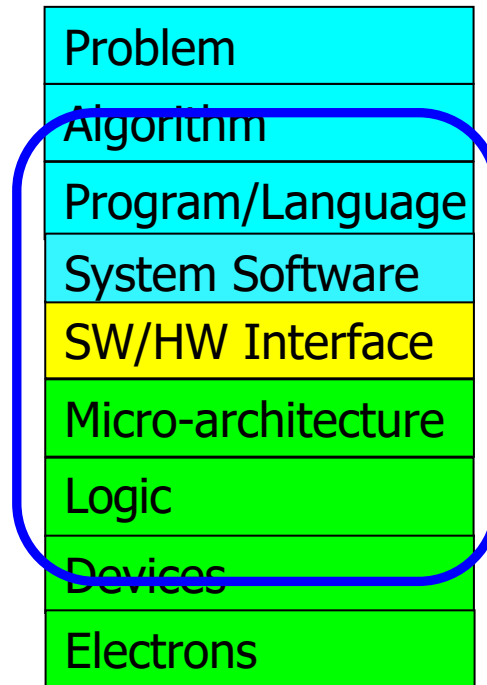
**Data-aware**





# 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**

# PIM Review and Open Problems

---

## A Modern Primer on Processing in Memory

Onur Mutlu<sup>a,b</sup>, Saugata Ghose<sup>b,c</sup>, Juan Gómez-Luna<sup>a</sup>, Rachata Ausavarungnirun<sup>d</sup>

*SAFARI Research Group*

<sup>a</sup>*ETH Zürich*

<sup>b</sup>*Carnegie Mellon University*

<sup>c</sup>*University of Illinois at Urbana-Champaign*

<sup>d</sup>*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<sup>†</sup>   Amirali Boroumand<sup>†</sup>   Jeremie S. Kim<sup>†§</sup>   Juan Gómez-Luna<sup>§</sup>   Onur Mutlu<sup>§†</sup>

<sup>†</sup>*Carnegie Mellon University*

<sup>§</sup>*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]

# A Longer Version of This Talk

---

- 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](mailto: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

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

ANALYTICS

EDIT VIDEO

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



# Funding Acknowledgments

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

# Acknowledgments

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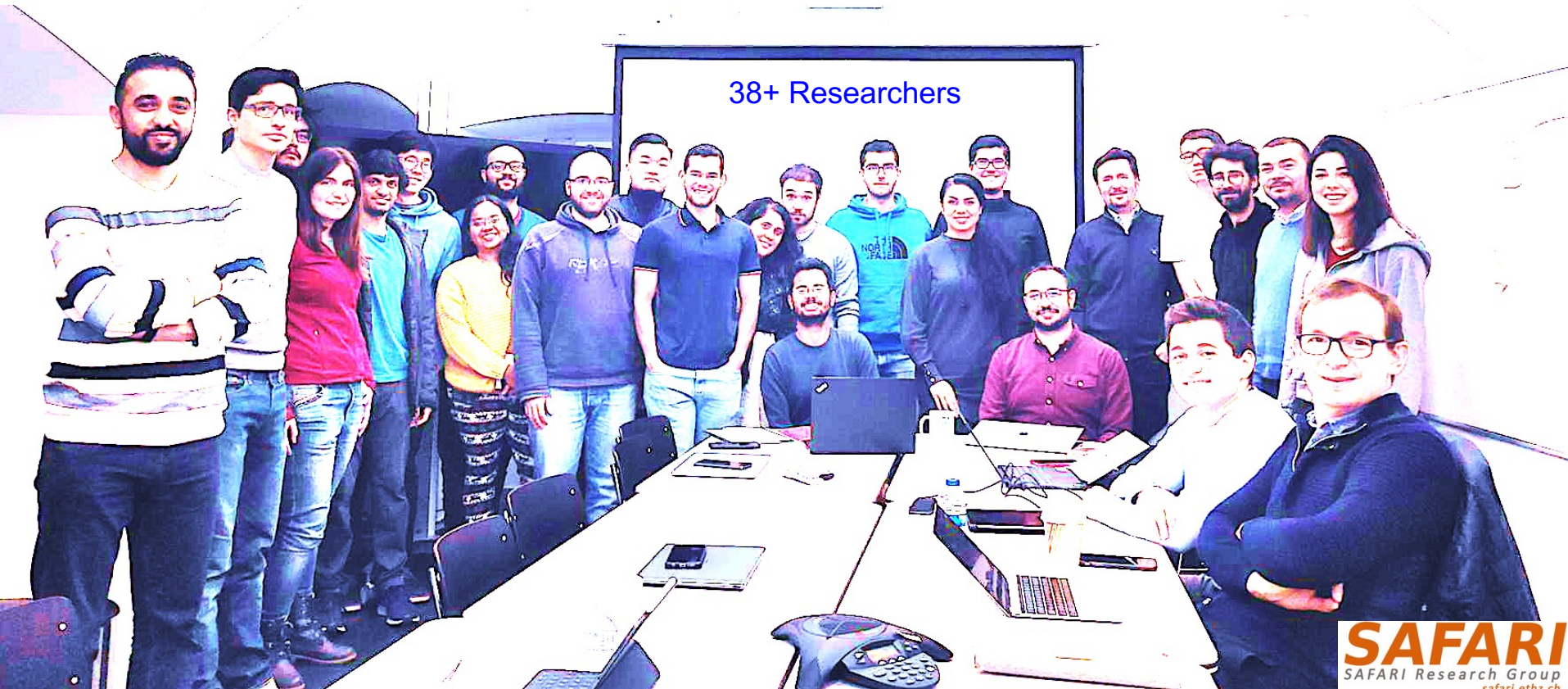
<https://safari.ethz.ch>

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# 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 April 2020 Edition

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- <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

# 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/>

# Intelligent Architectures for Intelligent Machines

Onur Mutlu

[omutlu@gmail.com](mailto:omutlu@gmail.com)

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

19 October 2021

Ontario Tech Distinguished Speaker Series Lecture

**SAFARI**

**ETH** zürich

**Carnegie Mellon**

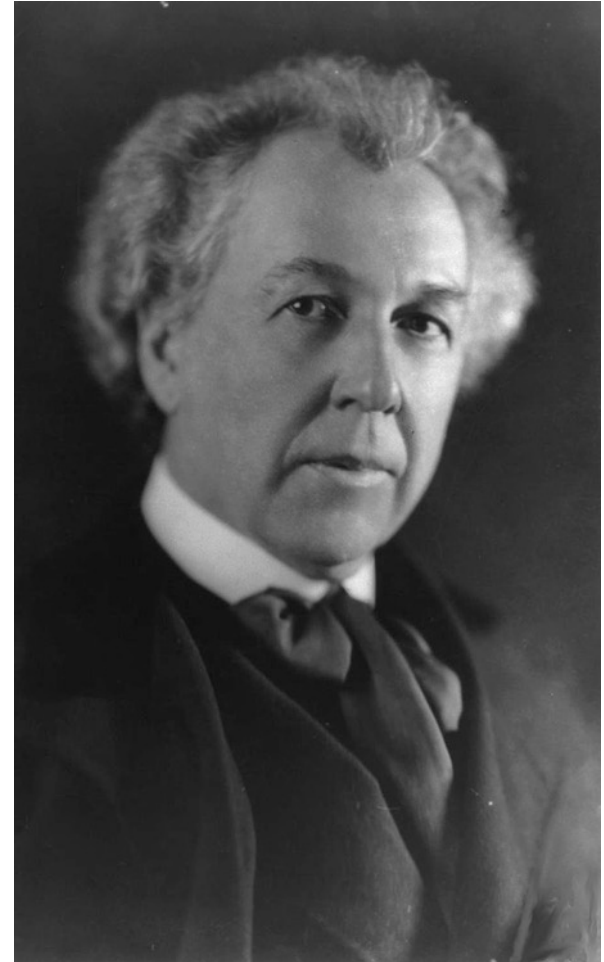


# Backup Slides

# A Quote from A Famous Architect

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



# Precedent-Based Design?

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





# Principled Design

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







# The Overarching Principle

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## Organic architecture

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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

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# Principled Design





# Another Principled Design



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

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

# Another Principled Design

---





# Principle Applied to Another Structure



Source: By 準建築人手札網站 Forgemind ArchiMedia - Flickr: IMG\_2489.JPG, CC BY 2.0

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

# The Overarching Principle

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## Zoomorphic architecture

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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."<sup>[1]</sup>

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.<sup>[3]</sup>



# Overarching Principles for Computing?

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# Readings, Videos, Reference Materials

# More on My Research & Teaching

# Brief Self Introduction

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## ■ 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](mailto:omutlu@gmail.com) (Best way to reach me)
- ❑ <https://people.inf.ethz.ch/omutlu/projects.htm>

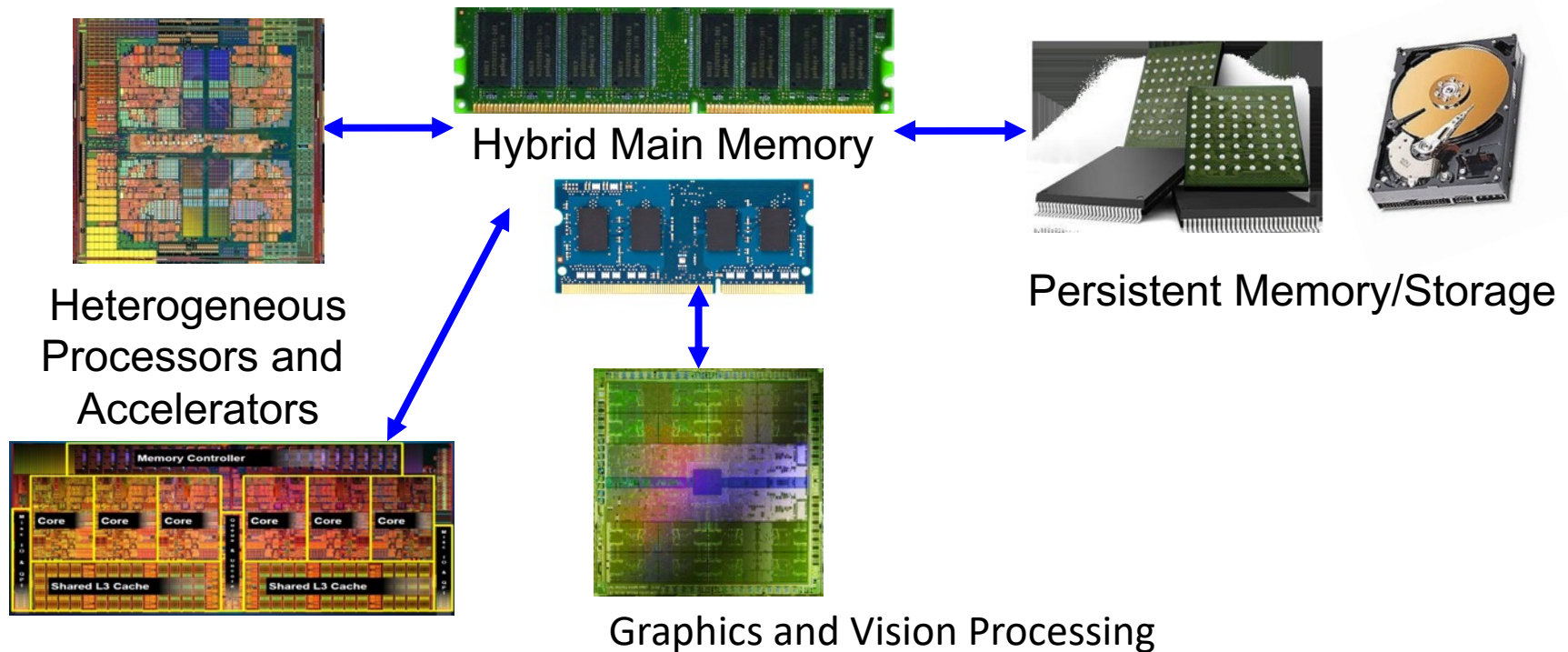
## ■ Research and Teaching in:

- ❑ 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

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



**Build fundamentally better architectures**

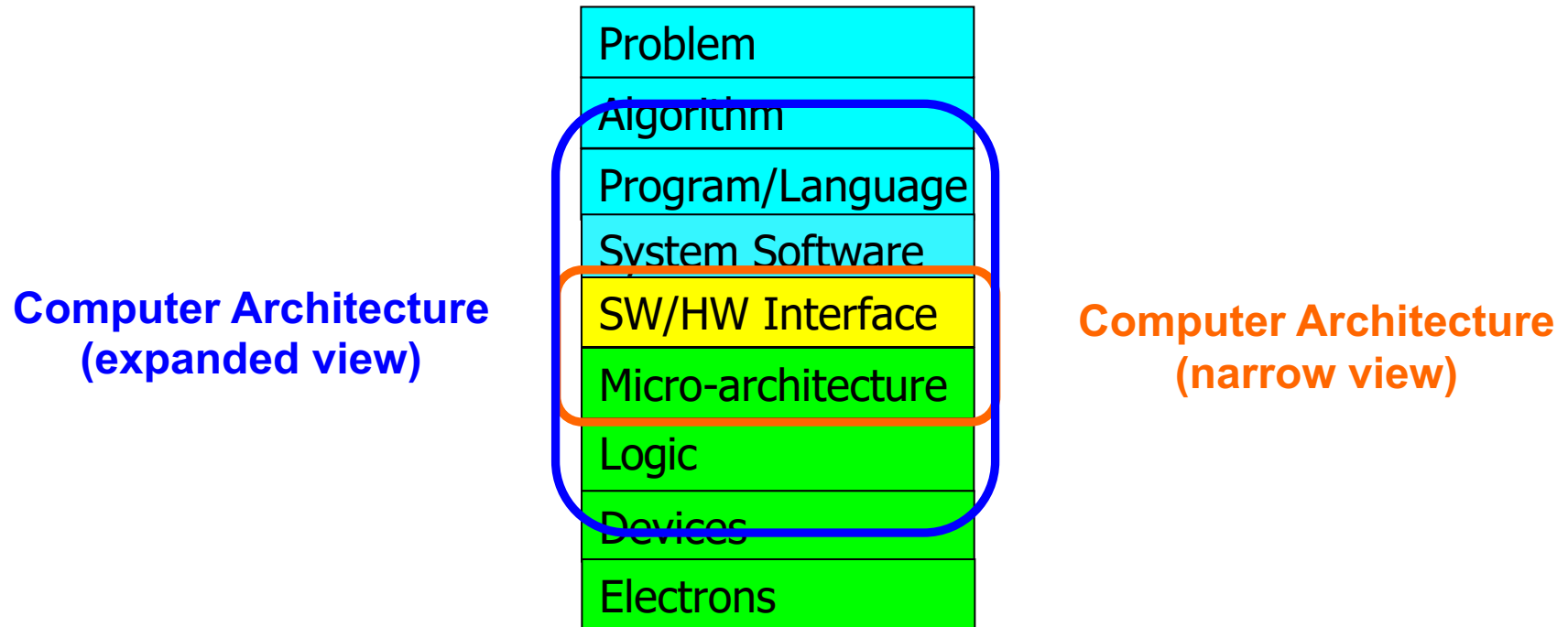
# Four Key Current Directions

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- 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

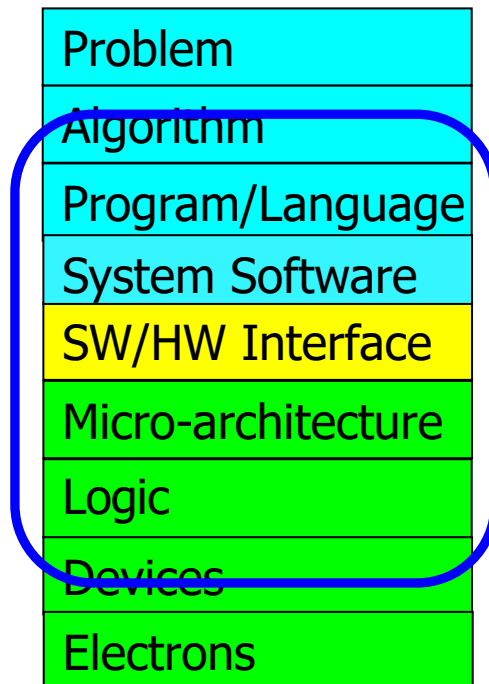
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To achieve the highest **energy efficiency** and **performance**:

**we must take the expanded view**  
of computer architecture

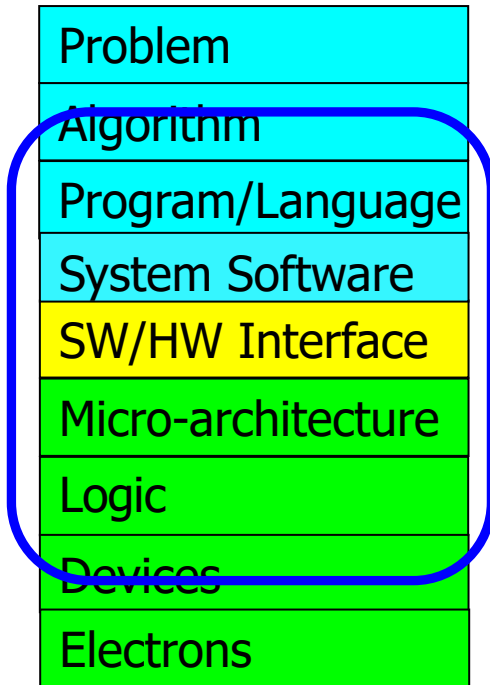


**Co-design across the hierarchy:**  
**Algorithms to devices**

**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

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



**SAFARI**  
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Newsletter  
January 2021

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Dear SAFARI friends,

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# SAFARI PhD and Post-Doc Alumni

---

- <https://safari.ethz.ch/safari-alumni/>
- Nastaran Hajinazar (ETH Zurich)
- Gagandeep Singh (ETH Zurich)
- Amirali Boroumand (Stanford Univ)
- Jeremie Kim (ETH Zurich)
- Nandita Vijaykumar (Univ. of Toronto, Assistant Professor)
- Kevin Hsieh (Microsoft Research, Senior Researcher)
- Justin Meza (Facebook)
- Mohammed Alser (ETH Zurich)
- Yixin Luo (Google)
- Kevin Chang (Facebook)
- Rachata Ausavarungrun (KMUNTB, Assistant Professor)
- Gennady Pekhimenko (Univ. of Toronto, Assistant Professor)
- Vivek Seshadri (Microsoft Research)
- Donghyuk Lee (NVIDIA Research, Senior Researcher)
- Yoongu Kim (Google)
- Lavanya Subramanian (Intel Labs → Facebook)
  
- Samira Khan (Univ. of Virginia, Assistant Professor)
- Saugata Ghose (Univ. of Illinois, Assistant Professor)



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

## ■ **Advanced Computer Architecture Course**

- ❑ Computer Architecture
- ❑ Fall 2020 Edition:  
<https://www.youtube.com/watch?v=c3mPdZA-Fmc&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN>



Onur Mutlu Lectures

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1:33:25

Digital Design & Computer Architecture: Lecture 1: Introduction and Basics

49K views • 1 year ago

Computer Architecture - Lecture 1: Introduction and Basics

36K views • 3 years ago

Computer Architecture - Lecture 1: Introduction and Basics

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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

Onur Mutlu Lectures

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Design of Digital Circuits - ETH Zurich - 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 Architecture

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### Advanced Computer Architecture Courses 2020-2012

Computer Architecture - ETH Zurich - Fall 2020

Onur Mutlu Lectures

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Computer Architecture - ETH Zurich - Fall 2019

Onur Mutlu Lectures

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Computer Architecture - ETH Zurich - Fall 2018

Onur Mutlu Lectures

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Computer Architecture - ETH Zurich - Fall 2017

Onur Mutlu Lectures

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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

Onur Mutlu Lectures

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Champéry Winter School 2020 - Memory Systems and Memory

Onur Mutlu Lectures

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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

Onur Mutlu Lectures

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Research Talks

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

SAFARI

# DDCA (Spring 2021)



Trace: · schedule

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Announcements

Materials

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

Resources

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

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

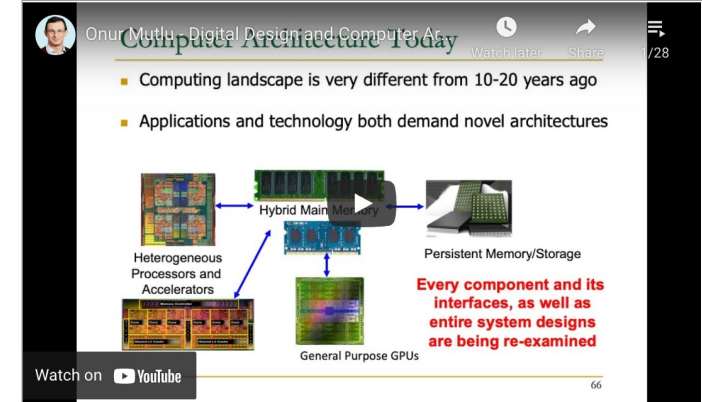
[https://www.youtube.com/watch?v=LbC0EZY8yw4&list=PL5Q2soXY2Zi\\_uej3aY39YB5pfW4SJ7LIN](https://www.youtube.com/watch?v=LbC0EZY8yw4&list=PL5Q2soXY2Zi_uej3aY39YB5pfW4SJ7LIN)

## Bachelor's course

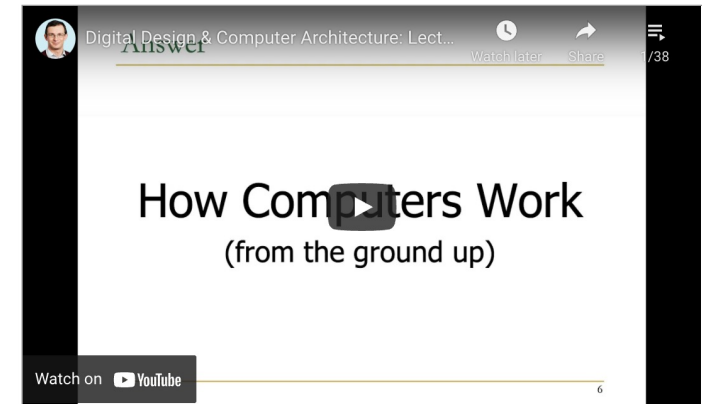
- ❑ 2<sup>nd</sup> semester at ETH Zurich
- ❑ Rigorous introduction into "How Computers Work"
- ❑ Digital Design/Logic
- ❑ Computer Architecture
- ❑ 10 FPGA Lab Assignments

## 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

Computer Architecture - Fall 2020

Recent ChangesMedia ManagerSitemap

Trace: start · schedule

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- Lecture Buzzwords
- Readings
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- Labs
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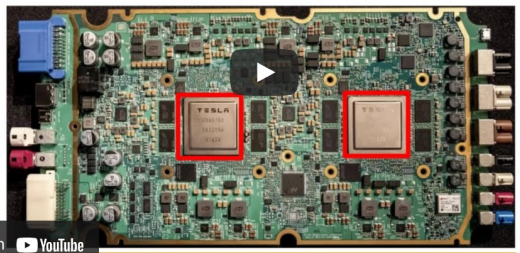
- Computer Architecture FS19: Course Webpage
- Computer Architecture FS19: Lecture Videos
- Digitaltechnik SS20: Course Webpage
- Digitaltechnik SS20: Lecture Videos
- Moodle
- Piazza (Q&A)
- HotCRP
- Verilog Practice Website (HDLBits)

Lecture Video Playlist on YouTube

Lecture Playlist

Computer Architecture - Lecture: Introduction

- ML accelerator: 260 mm<sup>2</sup>, 6 billion transistors, 600 GFLOPS GPU, 12 ARM 2.2 GHz CPUs.
- Two redundant chips for better safety.



Watch on YouTube

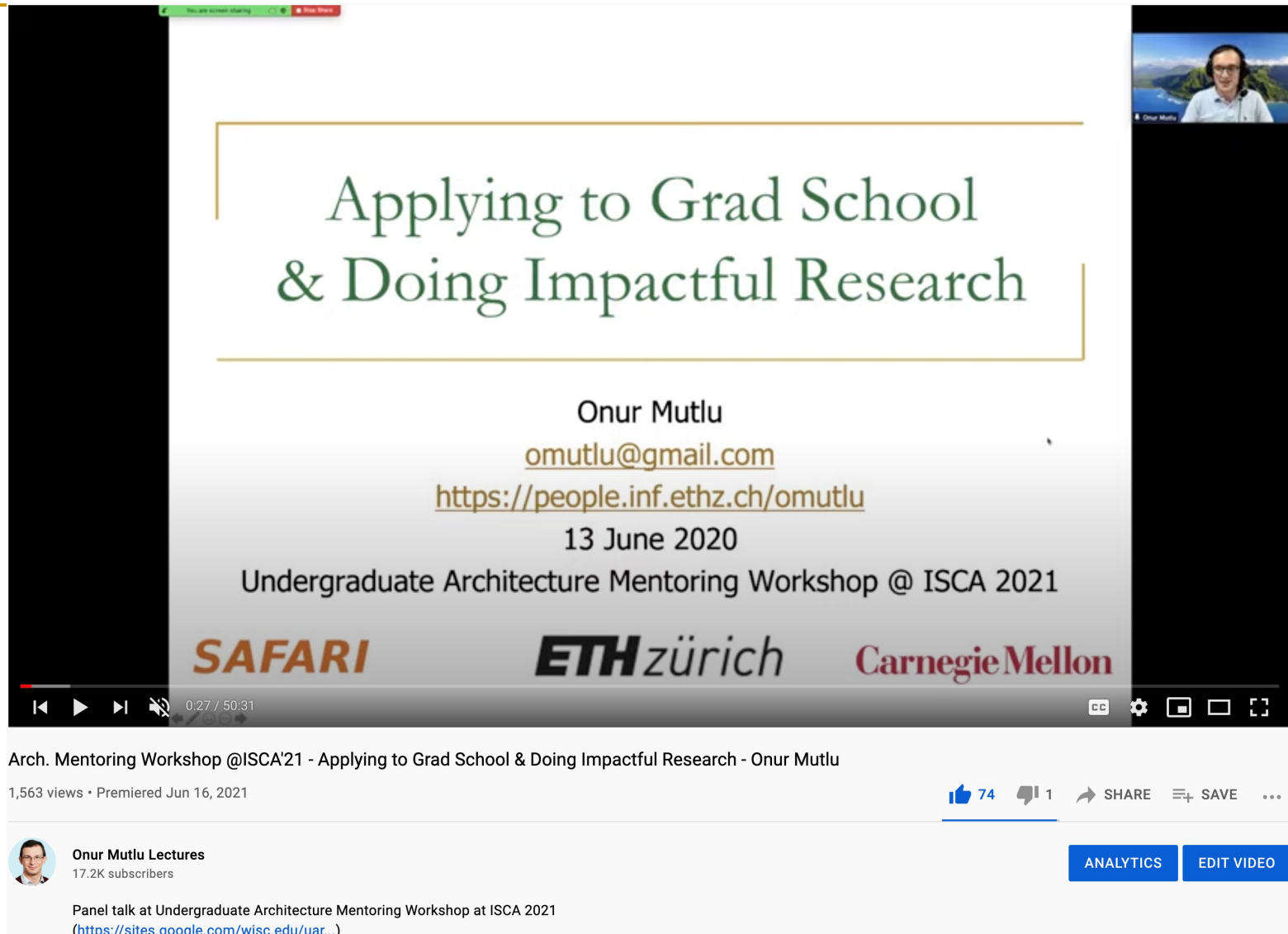
<https://www.youtube.com/watch?v=c3mPdZA-Fmc&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN>

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## Fall 2020 Lectures & Schedule

Week	Date	Lecture	Readings	Lab	HW
W1	17.09 Thu.	<b>L1: Introduction and Basics</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>	Described Suggested		HW 0 Out
		<b>L2a: Memory Performance Attacks</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>	Described Suggested	Lab 1 Out	
	18.09 Fri.	<b>L2b: Data Retention and Memory Refresh</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>	Described Suggested		
		<b>L2c: Course Logistics</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>			
W2	24.09 Thu.	<b>L3a: Introduction to Genome Sequence Analysis</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>	Described Suggested		HW 1 Out
		<b>L3b: Memory Systems: Challenges and Opportunities</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>	Described Suggested		
	25.09 Fri.	<b>L4a: Memory Systems: Solution Directions</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>	Described Suggested		
		<b>L4b: RowHammer</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>	Described Suggested		
W3	01.10 Thu.	<b>L5a: RowHammer in 2020: TRRespass</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>	Described Suggested		
		<b>L5b: RowHammer in 2020: Revisiting RowHammer</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>	Described Suggested		
		<b>L5c: Secure and Reliable Memory</b> <a href="#">CORA (PDF)</a> <a href="#">PPT</a> <a href="#">YouTube</a> <a href="#">Video</a>	Described		

# A Talk on Impactful Research & Teaching



The video player shows a presentation slide with the title "Applying to Grad School & Doing Impactful Research" in a green serif font, enclosed in a thin gold border. Below the title, the speaker's name "Onur Mutlu" is listed, followed by his email "omutlu@gmail.com" and a URL "https://people.inf.ethz.ch/omutlu". The date "13 June 2020" and the event "Undergraduate Architecture Mentoring Workshop @ ISCA 2021" are also displayed. At the bottom of the slide, the logos for "SAFARI", "ETH zürich", and "Carnegie Mellon" are shown. The video player interface includes a progress bar at 0:27 / 50:31, a small video thumbnail of the speaker in the top right, and a bottom bar with engagement metrics (74 likes, 1 comment), share, save, and analytics/edit options.

Applying to Grad School  
& Doing Impactful Research

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

SAFARI ETH zürich Carnegie Mellon

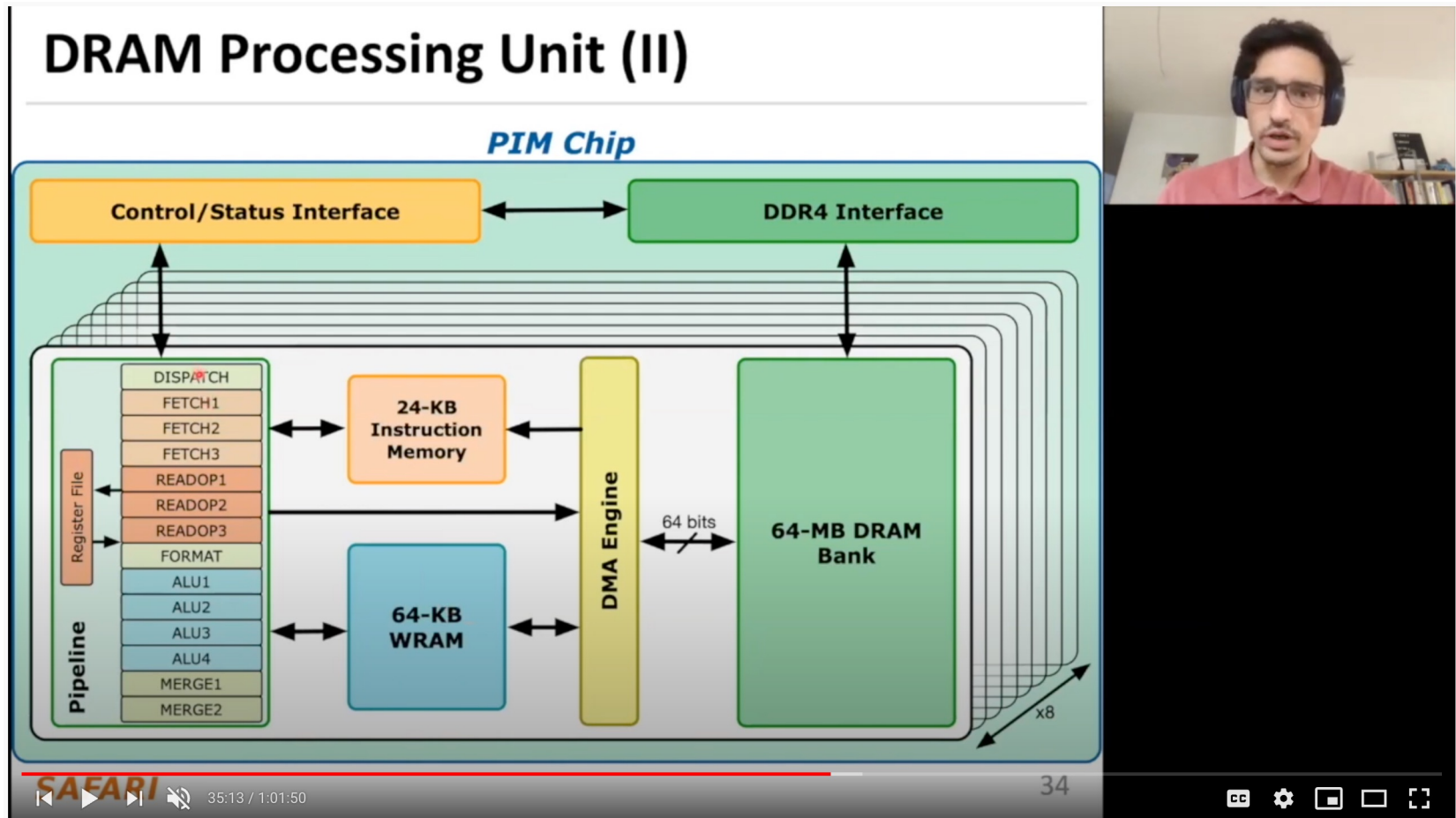
Arch. Mentoring Workshop @ISCA'21 - Applying to Grad School & Doing Impactful Research - Onur Mutlu  
1,563 views • Premiered Jun 16, 2021

Onur Mutlu Lectures  
17.2K subscribers

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



# 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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ANALYTICS

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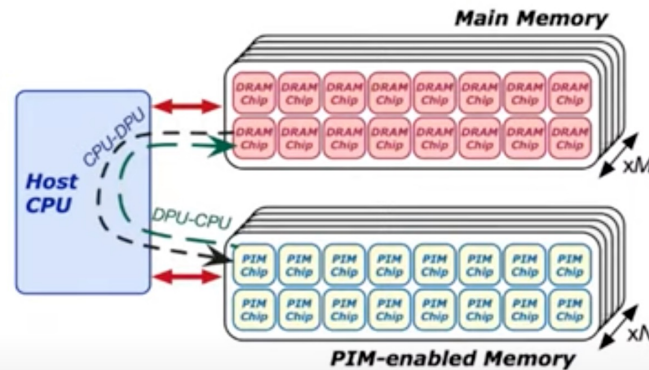
<https://www.youtube.com/watch?v=Sscy1Wrr22A&list=PL5Q2soXY2Zi9xidyIgBxUz7xRPS-wisBN&index=26>



# 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



SAFARI Live Seminar: Understanding a Modern Processing-in-Memory Architecture

1,868 views • Streamed live on Jul 12, 2021

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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

ANALYTICS

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[https://www.youtube.com/watch?v=D8Hjy2IU9l4&list=PL5Q2soXY2Zi\\_tOTAYm--dYByNPL7JhwR9](https://www.youtube.com/watch?v=D8Hjy2IU9l4&list=PL5Q2soXY2Zi_tOTAYm--dYByNPL7JhwR9)

# An Interview on Research and Education

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- Computing Research and Education (@ ISCA 2019)
  - [https://www.youtube.com/watch?v=8ffSEKZhmvo&list=PL5Q2soXY2Zi\\_4oP9LdL3cc8G6NIjD2Ydz](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](https://www.youtube.com/watch?v=tcQ3zZ3JpuA&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJI&index=15)

# More Thoughts and Suggestions

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- 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 \(pptx\) \(pdf\)](#)]

# Papers, Talks, Videos, Artifacts

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- 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/>

# End of Backup Slides