

# Computer Architecture

## Lecture 12a: Simulation II (with a Focus on Memory)

Prof. Onur Mutlu

ETH Zürich

Fall 2022

4 November 2022

# Simulation: The Field of Dreams

# Some General Issues in Architectural Simulation

# An Example Simulator

# Ramulator: A **Fast** and **Extensible** DRAM Simulator

[IEEE Comp Arch Letters'15]

# Ramulator Motivation

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

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

Table 1. Landscape of DRAM-based memory

# Ramulator

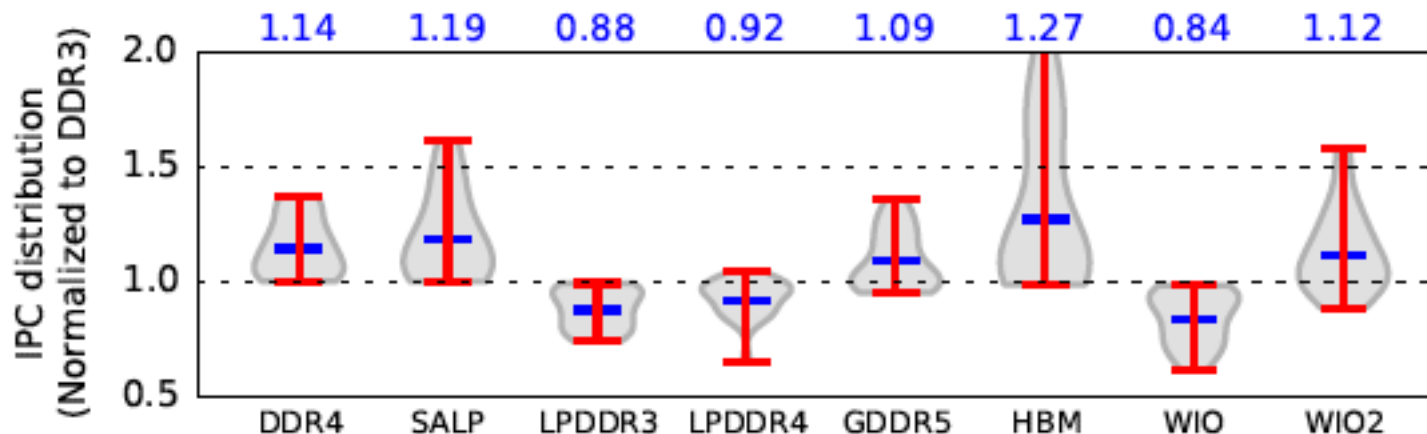
- Provides out-of-the box support for many DRAM standards:
  - DDR3/4, LPDDR3/4, GDDR5, WIO1/2, HBM, plus new proposals (SALP, AL-DRAM, TLDRAM, RowClone, and SARP)
- ~2.5X faster than fastest open-source simulator
- Modular and extensible to different standards

<i>Simulator</i> (clang -O3)	<i>Cycles (10<sup>6</sup>)</i>		<i>Runtime (sec.)</i>		<i>Req/sec (10<sup>3</sup>)</i>		<i>Memory</i> (MB)
	<i>Random</i>	<i>Stream</i>	<i>Random</i>	<i>Stream</i>	<i>Random</i>	<i>Stream</i>	
Ramulator	652	411	752	249	133	402	2.1
DRAMSim2	645	413	2,030	876	49	114	1.2
USIMM	661	409	1,880	750	53	133	4.5
DrSim	647	406	18,109	12,984	6	8	1.6
NVMain	666	413	6,881	5,023	15	20	4,230.0

Table 3. Comparison of five simulators using two traces

# Case Study: Comparison of DRAM Standards

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



Across 22 workloads, simple CPU model

Figure 2. Performance comparison of DRAM standards



# Ramulator Paper and Source Code

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

## Ramulator: A Fast and Extensible DRAM Simulator

Yoongu Kim<sup>1</sup>      Weikun Yang<sup>1,2</sup>      Onur Mutlu<sup>1</sup>  
<sup>1</sup>Carnegie Mellon University      <sup>2</sup>Peking University

# Ramulator: Free & Open Source

☰ README.md

## Ramulator: A DRAM Simulator

Ramulator is a fast and cycle-accurate DRAM simulator [1, 2] that supports a wide array of commercial, as well as academic, DRAM standards:

- DDR3 (2007), DDR4 (2012)
- LPDDR3 (2012), LPDDR4 (2014)
- GDDR5 (2009)
- WIO (2011), WIO2 (2014)
- HBM (2013)
- SALP [3]
- TL-DRAM [4]
- RowClone [5]
- DSARP [6]

The initial release of Ramulator is described in the following paper:

Y. Kim, W. Yang, O. Mutlu. "[Ramulator: A Fast and Extensible DRAM Simulator](#)". In *IEEE Computer Architecture Letters*, March 2015.

For information on new features, along with an extensive memory characterization using Ramulator, please read:

S. Ghose, T. Li, N. Hajinazar, D. Senol Cali, O. Mutlu. "[Demystifying Complex Workload-DRAM Interactions: An Experimental Study](#)". In *Proceedings of the ACM International Conference on Measurement and Modeling of Computer Systems (SIGMETRICS)*, June 2019 ([slides](#)). In *Proceedings of the ACM on Measurement and Analysis of Computing Systems (POMACS)*, 2019.

[1] Kim et al. *Ramulator: A Fast and Extensible DRAM Simulator*. IEEE CAL 2015.

[2] Ghose et al. *Demystifying Complex Workload-DRAM Interactions: An Experimental Study*. SIGMETRICS 2019.

[3] Kim et al. *A Case for Exploiting Subarray-Level Parallelism (SALP) in DRAM*. ISCA 2012.

[4] Lee et al. *Tiered-Latency DRAM: A Low Latency and Low Cost DRAM Architecture*. HPCA 2013.

[5] Seshadri et al. *RowClone: Fast and Energy-Efficient In-DRAM Bulk Data Copy and Initialization*. MICRO 2013.

[6] Chang et al. *Improving DRAM Performance by Parallelizing Refreshes with Accesses*. HPCA 2014.

## Usage

Ramulator supports three different usage modes.

1. **Memory Trace Driven:** Ramulator directly reads memory traces from a file, and simulates only the DRAM subsystem. Each line in the trace file represents a memory request, with the hexadecimal address followed by 'R' or 'W' for read or write.

- 0x12345680 R

- 0x4cbd56c0 W

- ...

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

# Ramulator: Integration with Other Simulators

☰ README.md

## Usage

Ramulator supports three different usage modes.

1. **Memory Trace Driven:** Ramulator directly reads memory traces from a file, and simulates only the DRAM subsystem. Each line in the trace file represents a memory request, with the hexadecimal address followed by 'R' or 'W' for read or write.

- 0x12345680 R
- 0x4cbd56c0 W
- ...

2. **CPU Trace Driven:** Ramulator directly reads instruction traces from a file, and simulates a simplified model of a "core" that generates memory requests to the DRAM subsystem. Each line in the trace file represents a memory request, and can have one of the following two formats.

- `<num-cpuinst> <addr-read>` : For a line with two tokens, the first token represents the number of CPU (i.e., non-memory) instructions before the memory request, and the second token is the decimal address of a *read*.
- `<num-cpuinst> <addr-read> <addr-writeback>` : For a line with three tokens, the third token is the decimal address of the *writeback* request, which is the dirty cache-line eviction caused by the read request before it.

3. **gem5 Driven:** Ramulator runs as part of a full-system simulator (gem5 [7]), from which it receives memory request as they are generated.

For some of the DRAM standards, Ramulator is also capable of reporting power consumption by relying on either VAMPIRE [8] or DRAMPower [9] as the backend.

[7] The gem5 Simulator System.

[8] Ghose et al. *What Your DRAM Power Models Are Not Telling You: Lessons from a Detailed Experimental Study*. SIGMETRICS 2018.

[9] Chandrasekar et al. *DRAMPower: Open-Source DRAM Power & Energy Estimation Tool*. IEEE CAL 2015.

## Getting Started

Ramulator requires a C++11 compiler (e.g., `clang++`, `g++-5`).

1. **Memory Trace Driven**

```
$ cd ramulator
$ make -j
$ ./ramulator configs/DDR3-config.cfg --mode=dram dram.trace
Simulation done. Statistics written to DDR3.stats
# NOTE: dram.trace is a very short trace file provided only as an example.
$ ./ramulator configs/DDR3-config.cfg --mode=dram --stats my_output.txt dram.trace
Simulation done. Statistics written to my_output.txt
# NOTE: optional --stats flag changes the statistics output filename
```

2. **CPU Trace Driven**

# Ramulator: Reproducibility

## Reproducing Results from Paper (Kim et al. [1])

### Debugging & Verification (Section 4.1)

For debugging and verification purposes, Ramulator can print the trace of every DRAM command it issues along with their address and timing information. To do so, please turn on the `print_cmd_trace` variable in the configuration file.

### Comparison Against Other Simulators (Section 4.2)

For comparing Ramulator against other DRAM simulators, we provide a script that automates the process: `test_ddr3.py`. Before you run this script, however, you must specify the location of their executables and configuration files at designated lines in the script's source code:

- Ramulator
- DRAMSim2 (<https://wiki.umd.edu/DRAMSim2>): `test_ddr3.py` lines 39-40
- USIMM (<http://www.cs.utah.edu/~rajeew/jwac12>): `test_ddr3.py` lines 54-55
- DrSim (<http://ph.ece.utexas.edu/public/Main/DrSim>): `test_ddr3.py` lines 66-67
- NVMain (<http://wiki.nvmain.org>): `test_ddr3.py` lines 78-79

Please refer to their respective websites to download, build, and set-up the other simulators. The simulators must be executed in saturation mode (always filling up the request queues when possible).

All five simulators were configured using the same parameters:

- DDR3-1600K (11-11-11), 1 Channel, 1 Rank, 2Gb x8 chips
- FR-FCFS Scheduling
- Open-Row Policy
- 32/32 Entry Read/Write Queues
- High/Low Watermarks for Write Queue: 28/16

Finally, execute `test_ddr3.py <num-requests>` to start off the simulation. Please make sure that there are no other active processes during simulation to yield accurate measurements of memory usage and CPU time.

### Cross-Sectional Study of DRAM Standards (Section 4.3)

Please use the CPU traces (SPEC 2006) provided in the `cputraces` folder to run CPU trace driven simulations.

## Other Tips

### Power Estimation

For estimating power consumption, Ramulator can record the trace of every DRAM command it issues to a file in DRAMPower [8] format. To do so, please turn on the `record_cmd_trace` variable in the configuration file. The resulting DRAM command trace (e.g., `cmd-trace-chan-N-rank-M.cmdtrace`) should be fed into a compatible DRAM energy simulator such as VAMPIRE [8] or DRAMPower [9] with the correct configuration (standard/speed/organization) to estimate energy/power usage for a single rank (a current limitation of both VAMPIRE and DRAMPower).

# Ramulator Project Course

## Exploration of Emerging Memory Systems (Spring/Fall 2022)

### Fall 2022 Edition:

- ❑ [https://safari.ethz.ch/projects\\_and\\_seminars/fall2022/doku.php?id=ramulator](https://safari.ethz.ch/projects_and_seminars/fall2022/doku.php?id=ramulator)

### Spring 2022 Edition:

- ❑ [https://safari.ethz.ch/projects\\_and\\_seminars/spring2022/doku.php?id=ramulator](https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=ramulator)

### Youtube Livestream (Spring 2022):

- ❑ [https://www.youtube.com/watch?v=aM-lIXRQd3s&list=PL5Q2soXY2Zi\\_TlmlGw\\_Z8hBo2925ZApgV](https://www.youtube.com/watch?v=aM-lIXRQd3s&list=PL5Q2soXY2Zi_TlmlGw_Z8hBo2925ZApgV)

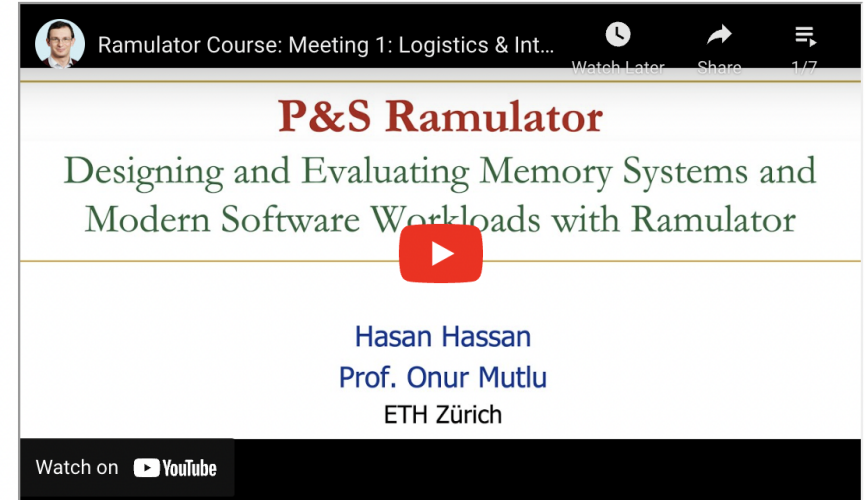
### Bachelor's course

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

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

### Lecture Video Playlist on YouTube

Lecture Playlist



### 2022 Meetings/Schedule (Tentative)

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

# Bonus Assignment as Part of Next HW

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- Review the Ramulator paper
  - Same points as any other BONUS review in the next HW

# Example Studies using Ramulator

# An Example Study using Ramulator (I)

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- Saugata Ghose, Tianshi Li, Nastaran Hajinazar, Damla Senol Cali, and Onur Mutlu, **"Demystifying Workload–DRAM Interactions: An Experimental Study"**  
*Proceedings of the ACM International Conference on Measurement and Modeling of Computer Systems (**SIGMETRICS**), Phoenix, AZ, USA, June 2019.*  
[[Preliminary arXiv Version](#)]  
[[Abstract](#)]  
[[Slides \(pptx\)](#) ([pdf](#))]  
[[MemBen Benchmark Suite](#)]  
[[Source Code for GPGPUSim-Ramulator](#)]

## Demystifying Complex Workload–DRAM Interactions: An Experimental Study

Saugata Ghose<sup>†</sup>

Tianshi Li<sup>†</sup>

Nastaran Hajinazar<sup>‡†</sup>

Damla Senol Cali<sup>†</sup>

Onur Mutlu<sup>§†</sup>

<sup>†</sup>Carnegie Mellon University

<sup>‡</sup>Simon Fraser University

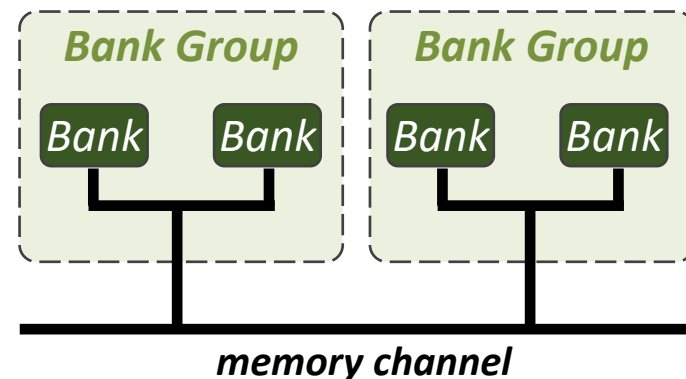
<sup>§</sup>ETH Zürich



- Manufacturers are developing many new types of DRAM
  - **DRAM limits performance, energy improvements:**  
new types may overcome some limitations
  - Memory systems now serve a **very diverse set of applications:**  
can no longer take a one-size-fits-all approach
- **So which DRAM type works best with which application?**
  - Difficult to understand intuitively due to the complexity of the interaction
  - Can't be tested methodically on real systems: new type needs a new CPU
- We perform a **wide-ranging experimental study to uncover the combined behavior** of workloads and DRAM types
  - **115 prevalent/emerging applications and multiprogrammed workloads**
  - **9 modern DRAM types:** DDR3, DDR4, GDDR5, HBM, HMC, LPDDR3, LPDDR4, Wide I/O, Wide I/O 2

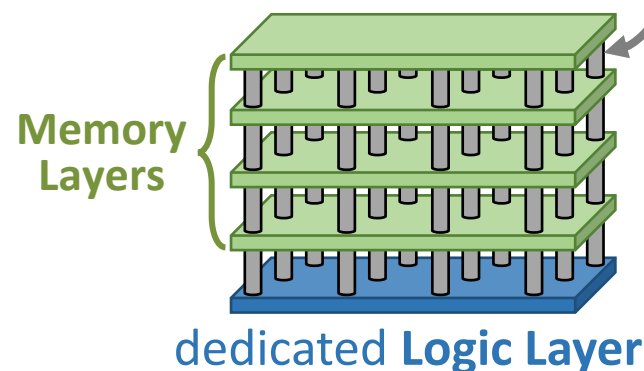
DRAM Type	Banks per Rank	Bank Groups	3D-Stacked	Low-Power
DDR3	8			
DDR4	16	✓	increased latency	
GDDR5	16	✓	increased area/power	
HBM High-Bandwidth Memory	16		✓	
HMC Hybrid Memory Cube	256	narrower rows, higher latency	✓	
Wide I/O	4		✓	✓
Wide I/O 2	8		✓	✓
LPDDR3	8			✓
LPDDR4	16			✓

## ■ Bank groups



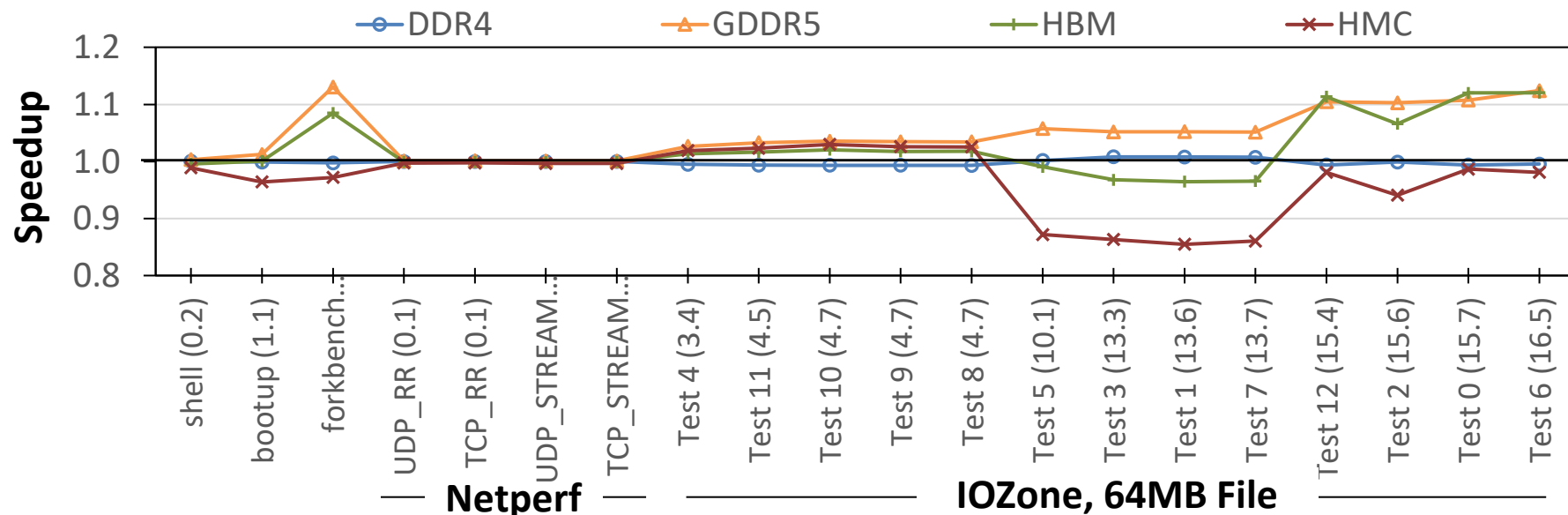
## ■ 3D-stacked DRAM

high bandwidth with  
Through-Silicon  
Vias (TSVs)



## 4. Need for Lower Access Latency: Performance

- New DRAM types often increase access latency in order to provide more banks, higher throughput
- Many applications can't make up for the increased latency
  - Especially true of common OS routines (e.g., file I/O, process forking)



- A variety of desktop/scientific, server/cloud, GPGPU applications

Several applications don't benefit from more parallelism

1. DRAM latency remains a critical bottleneck for many applications
2. Bank parallelism is not fully utilized by a wide variety of our applications
3. Spatial locality continues to provide significant performance benefits if it is exploited by the memory subsystem
4. For some classes of applications, low-power memory can provide energy savings without sacrificing significant performance

- Manufacturers are developing many new types of DRAM
  - **DRAM limits performance, energy improvements:**  
new types may overcome some limitations
  - Memory systems now serve a **very diverse set of applications:**  
can no longer take a one-size-fits-all approach
  - Difficult to intuitively determine which DRAM–workload pair works best
- We perform a **wide-ranging experimental study to uncover the combined behavior** of workloads, DRAM types
  - 115 prevalent/emerging applications and multiprogrammed workloads
  - 9 modern DRAM types
- 12 key observations on DRAM–workload behavior

Open-source tools: <https://github.com/CMU-SAFARI/ramulator>

Full paper: <https://arxiv.org/pdf/1902.07609>

# For More Information...

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- Saugata Ghose, Tianshi Li, Nastaran Hajinazar, Damla Senol Cali, and Onur Mutlu, **"Demystifying Workload–DRAM Interactions: An Experimental Study"**  
*Proceedings of the ACM International Conference on Measurement and Modeling of Computer Systems (**SIGMETRICS**), Phoenix, AZ, USA, June 2019.*  
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## Demystifying Complex Workload–DRAM Interactions: An Experimental Study

Saugata Ghose<sup>†</sup>

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# BlockHammer Study in 2021

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

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

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

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

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

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

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

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

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

[[BlockHammer Source Code](#)]

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

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

A. Giray 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

# Summary: BlockHammer

- BlockHammer is **the first work to practically enable throttling-based RowHammer mitigation**
- BlockHammer is implemented in **the memory controller** (*no proprietary information of / no modifications to DRAM chips*)
- BlockHammer is *both* **scalable with worsening RowHammer** and **compatible with commodity DRAM chips**
- BlockHammer is **open-source** along with **six state-of-the-art mechanisms**: <https://github.com/CMU-SAFARI/BlockHammer>





# BlockHammer: Free & Open Source

☰ README.md

## BlockHammer

Aggressive memory density scaling causes modern DRAM devices to suffer from [RowHammer](#), a phenomenon where rapidly activating a DRAM row can cause bit-flips in physically-nearby rows. Recent studies [1, 2, 3] demonstrate that modern DRAM chips, including chips previously marketed as RowHammer-safe, are even more vulnerable to RowHammer than older chips. Many works show that attackers can exploit RowHammer bit-flips to reliably mount system-level attacks to escalate privilege and leak private data. Therefore, it is critical to ensure RowHammer-safe operation on all DRAM-based systems.

Unfortunately, state-of-the-art RowHammer mitigation mechanisms face two major challenges. First, they incur increasingly higher performance and/or area overheads when applied to more vulnerable DRAM chips. Second, they require either proprietary information about or modifications to the DRAM chip design. In this paper, we show that it is possible to efficiently and scalably prevent RowHammer bit-flips without knowledge of or modification to DRAM internals.

We introduce BlockHammer, a low-cost, effective, and easy-to-adopt RowHammer mitigation mechanism that overcomes the two key challenges by selectively throttling memory accesses that could otherwise cause RowHammer bit-flips. The key idea of BlockHammer is to (1) track row activation rates using area-efficient Bloom filters and (2) use the tracking data to ensure that no row is ever activated rapidly enough to induce RowHammer bit-flips. By doing so, BlockHammer (1) makes it impossible for a RowHammer bit-flip to occur and (2) greatly reduces a RowHammer attack's impact on the performance of co-running benign applications.

Compared to state-of-the-art RowHammer mitigation mechanisms, BlockHammer provides competitive performance and energy when the system is not under a RowHammer attack and significantly better performance and energy when the system is under attack.

The full paper is published in [HPCA 2021](#) and the pdf is available online: [arXiv:2102.05981 \[cs.CR\]](#)

## Citation

Please cite our full HPCA 2021 paper if you find this repository useful.

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.

## Getting Started

This repository has two subdirectories. Please refer to each subdirectory on reproducing results.

- [Ramulator Model](#): This subdirectory includes an extended version of [Ramulator](#) with a RowHammerDefense class, which implements BlockHammer along with six state-of-the-art RowHammer mitigation mechanisms:

Mechanism	Reference
PARA	Y. Kim, et al., "Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors," in ISCA, 2014.
CBT	S. M. Seyedzadeh et al., "Mitigating Wordline Crosstalk Using Adaptive Trees of Counters," in ISCA, 2018.
ProHIT	M. Son et al., "Making DRAM Stronger Against Row Hammering," in DAC, 2017.
MrLoc	J. M. You et al., "MRLoc: Mitigating Row-Hammering Based on Memory Locality," in DAC, 2019.
TWiCe	E. Lee et al., "TWiCe: Preventing Row-hammering by Exploiting Time Window Counters" in ISCA, 2019.
Graphene	Y. Park et al., "Graphene: Strong yet Lightweight Row Hammer Protection," in MICRO, 2020.

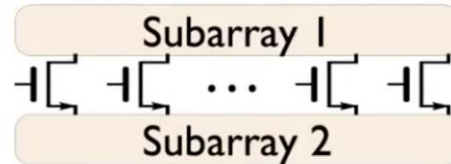
- [RTL Model](#): This subdirectory includes RTL implementation of the counters and buffers used in BlockHammer.

# Many Other Ideas Evaluated w/ Ramulator

## Key Idea and Applications

- **Low-cost Inter-linked subarrays (LISA)**

- Fast bulk data movement between subarrays
- Wide datapath via isolation transistors: 0.8% DRAM chip area



- LISA is a **versatile substrate** → new applications

**Fast bulk data copy:** Copy latency 1.363ms → 0.148ms (9.2x)

→ 66% speedup, -55% DRAM energy

**In-DRAM caching:** Hot data access latency 48.7ns → 21.5ns (2.2x)

→ 5% speedup

**Fast precharge:** Precharge latency 13.1ns → 5.0ns (2.6x)

→ 8% speedup



zoom

Computer Architecture - Lecture 9: Memory Latency & Memory Controllers (Fall 2022)



Onur Mutlu Lectures  
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711 views Streamed live on Oct 27, 2022

Computer Architecture, ETH Zürich, Fall 2022 (<https://safari.ethz.ch/architecture/f...>)

# Ramulator for Processing in Memory

# Simulation Infrastructure for PIM

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- **Ramulator** extended for PIM
  - Flexible and extensible DRAM simulator
  - Can model many different memory standards and proposals
  - Kim+, “**Ramulator: A Flexible and Extensible DRAM Simulator**”, IEEE CAL 2015.
  - <https://github.com/CMU-SAFARI/ramulator-pim>
  - <https://github.com/CMU-SAFARI/ramulator>
  - [[Source Code for Ramulator-PIM](#)]

## Ramulator: A Fast and Extensible DRAM Simulator

Yoongu Kim<sup>1</sup>    Weikun Yang<sup>1,2</sup>    Onur Mutlu<sup>1</sup>  
<sup>1</sup>Carnegie Mellon University    <sup>2</sup>Peking University

# Ramulator for PIM

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- Gagandeep Singh, Juan Gomez-Luna, Giovanni Mariani, Geraldo F. Oliveira, Stefano Corda, Sander Stujik, Onur Mutlu, and Henk Corporaal, **"NAPEL: Near-Memory Computing Application Performance Prediction via Ensemble Learning"**  
*Proceedings of the 56th Design Automation Conference (DAC)*, Las Vegas, NV, USA, June 2019.  
[[Slides \(pptx\)](#)] [[pdf](#)]  
[[Poster \(pptx\)](#)] [[pdf](#)]  
[[Source Code for Ramulator-PIM](#)]

## NAPEL: Near-Memory Computing Application Performance Prediction via Ensemble Learning

Gagandeep Singh <sup>a,c</sup>	Juan Gómez-Luna <sup>b</sup>	Giovanni Mariani <sup>c</sup>	Geraldo F. Oliveira <sup>b</sup>
Stefano Corda <sup>a,c</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 - Zurich

# Ramulator Project Course

## Exploration of Emerging Memory Systems (Spring/Fall 2022)

### Fall 2022 Edition:

- ❑ [https://safari.ethz.ch/projects\\_and\\_seminars/fall2022/doku.php?id=ramulator](https://safari.ethz.ch/projects_and_seminars/fall2022/doku.php?id=ramulator)

### Spring 2022 Edition:

- ❑ [https://safari.ethz.ch/projects\\_and\\_seminars/spring2022/doku.php?id=ramulator](https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=ramulator)

### Youtube Livestream (Spring 2022):

- ❑ [https://www.youtube.com/watch?v=aM-lIXRQd3s&list=PL5Q2soXY2Zi\\_TlmlGw\\_Z8hBo2925ZApgV](https://www.youtube.com/watch?v=aM-lIXRQd3s&list=PL5Q2soXY2Zi_TlmlGw_Z8hBo2925ZApgV)

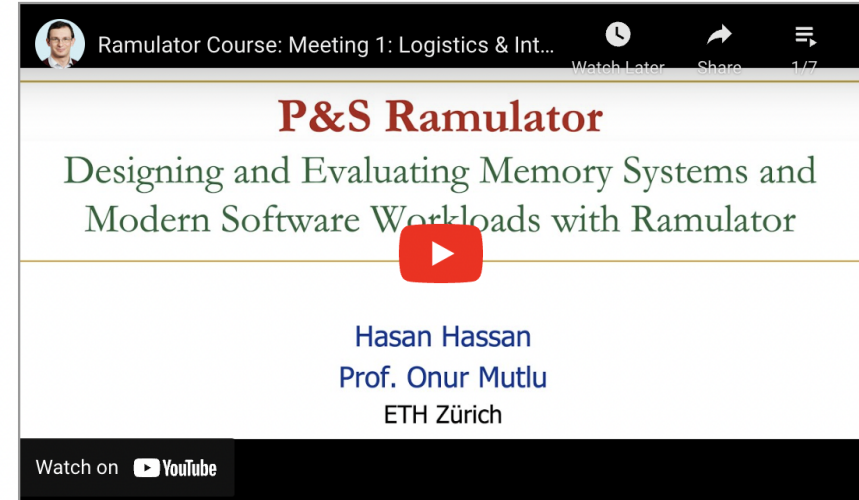
### Bachelor's course

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

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

### Lecture Video Playlist on YouTube

Lecture Playlist



### 2022 Meetings/Schedule (Tentative)

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

# Some Other Useful Simulators

# Many Simulators for Many Things

---

- **gem5** full-system multi-core simulation
  - **MQSim** for SSD simulation
  - **DiskSim** for Hard Disk simulation
  - **DAMOV-Sim** for Processing-near-Memory simulation
  - **Sniper** for fast Processor Simulation
  - **Scarab** for detailed Microarchitectural Simulation
  - **Simics, Bochs, QEMU** for full-system functional simulation
  - ...
- 
- Or, develop your own simulator for your purpose...



# DAMOV Simulator, Methods & Benchmarks

---

- Geraldo F. Oliveira, Juan Gomez-Luna, Lois Orosa, Saugata Ghose, Nandita Vijaykumar, Ivan fernandez, Mohammad Sadrosadati, and Onur Mutlu,  
**"DAMOV: A New Methodology and Benchmark Suite for Evaluating Data Movement Bottlenecks"**  
**IEEE Access**, 8 September 2021.  
*Preprint in arXiv*, 8 May 2021.  
[[arXiv preprint](#)]  
[[IEEE Access version](#)]  
[[DAMOV Suite and Simulator Source Code](#)]  
[[SAFARI Live Seminar Video](#) (2 hrs 40 mins)]  
[[Short Talk Video](#) (21 minutes)]

## **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, ETH Zürich, Switzerland

ONUR MUTLU, ETH Zürich, Switzerland

# DAMOV is Open Source

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

CMU-SAFARI / DAMOV

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About



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

Readme

Releases

No releases published  
[Create a new release](#)

Packages

No packages published  
[Publish your first package](#)

Languages



omutlu Update README.md

ce1b4ea 17 days ago 5 commits

simulator

Cleaning

19 days ago

README.md

Update README.md

17 days ago

get\_workloads.sh

DAMOV -- first commit

19 days ago

README.md



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

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

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

DAMOV-SIM

DAMOV  
Benchmarks

SAFARI

# DAMOV is Open Source

- We open-source our [benchmark suite](https://github.com/CMU-SAFARI/DAMOV) and our [toolchain](https://github.com/CMU-SAFARI/DAMOV)

CMU-SAFARI / DAMOV

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About

DAMOV is a benchmark suite and a

Get DAMOV at:

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

README.md

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

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

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Readme

### Releases

No releases published  
[Create a new release](#)

### Packages

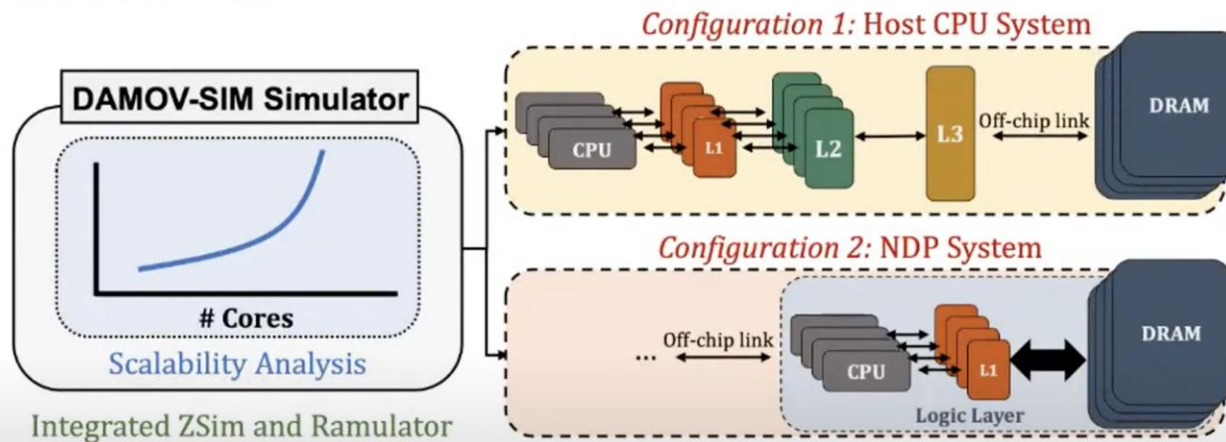
No packages published  
[Publish your first package](#)

### Languages

# 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

18 0 SHARE SAVE ...

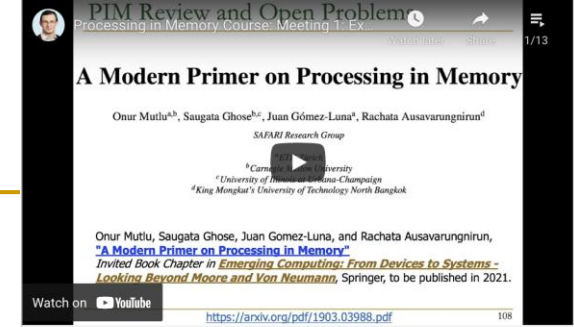


**Onur Mutlu Lectures**  
17.7K subscribers

ANALYTICS

EDIT VIDEO

# PIM Course (Spring 2022)



## ■ Spring 2022 Edition:

- ❑ [https://safari.ethz.ch/projects\\_and\\_seminars/spring2022/doku.php?id=processing\\_in\\_memory](https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=processing_in_memory)

## ■ Youtube Livestream:

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

## ■ Project course

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

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

**SAFARI**

Spring 2022 Meetings/Schedule

Week	Date	Livestream	Meeting	Learning Materials	Assignments
W1	10.03 Thu.	YouTube Live	M1: P&S PIM Course Presentation (PDF) (PPT)	Required Materials Recommended Materials	HW 0 Out
W2	15.03 Tue.		Hands-on Project Proposals		
	17.03 Thu.	YouTube Premiere	M2: Real-world PIM: UPMEM PIM (PDF) (PPT)		
W3	24.03 Thu.	YouTube Live	M3: Real-world PIM: Microbenchmarking of UPMEM PIM (PDF) (PPT)		
W4	31.03 Thu.	YouTube Live	M4: Real-world PIM: Samsung HBM-PIM (PDF) (PPT)		
W5	07.04 Thu.	YouTube Live	M5: How to Evaluate Data Movement Bottlenecks (PDF) (PPT)		
W6	14.04 Thu.	YouTube Live	M6: Real-world PIM: SK Hynix AIM (PDF) (PPT)		
W7	21.04 Thu.	YouTube Premiere	M7: Programming PIM Architectures (PDF) (PPT)		
W8	28.04 Thu.	YouTube Premiere	M8: Benchmarking and Workload Suitability on PIM (PDF) (PPT)		
W9	05.05 Thu.	YouTube Premiere	M9: Real-world PIM: Samsung AxDIMM (PDF) (PPT)		
W10	12.05 Thu.	YouTube Premiere	M10: Real-world PIM: Alibaba HB-PNM (PDF) (PPT)		
W11	19.05 Thu.	YouTube Live	M11: SpMV on a Real PIM Architecture (PDF) (PPT)		
W12	26.05 Thu.	YouTube Live	M12: End-to-End Framework for Processing-using-Memory (PDF) (PPT)		
W13	02.06 Thu.	YouTube Live	M13: Bit-Serial SIMD Processing using DRAM (PDF) (PPT)		
W14	09.06 Thu.	YouTube Live	M14: Analyzing and Mitigating ML Inference Bottlenecks (PDF) (PPT)		
W15	15.06 Thu.	YouTube Live	M15: In-Memory HTAP Databases with HW/SW Co-design (PDF) (PPT)		
W16	23.06 Thu.	YouTube Live	M16: In-Storage Processing for Genome Analysis (PDF) (PPT)		
W17	18.07 Mon.	YouTube Premiere	M17: How to Enable the Adoption of PIM? (PDF) (PPT)		
W18	09.08 Tue.	YouTube Premiere	SS1: ISVLSI 2022 Special Session on PIM (PDF & PPT)		

# MQSim for Modern SSD Simulation

---

- Arash Tavakkol, Juan Gomez-Luna, Mohammad Sadrosadati, Saugata Ghose, and Onur Mutlu,  
**"MQSim: A Framework for Enabling Realistic Studies of Modern Multi-Queue SSD Devices"**  
*Proceedings of the 16th USENIX Conference on File and Storage Technologies (FAST)*, Oakland, CA, USA, February 2018.  
[[Slides \(pptx\)](#)] [[pdf](#)]  
[[Source Code](#)]

## MQSim: A Framework for Enabling Realistic Studies of Modern Multi-Queue SSD Devices

Arash Tavakkol<sup>†</sup>, Juan Gómez-Luna<sup>†</sup>, Mohammad Sadrosadati<sup>†</sup>, Saugata Ghose<sup>‡</sup>, Onur Mutlu<sup>†‡</sup>  
<sup>†</sup>*ETH Zürich*                      <sup>‡</sup>*Carnegie Mellon University*



# Solid-State Drives Course (Spring 2022)

## ■ Spring 2022 Edition:

- ❑ [https://safari.ethz.ch/projects\\_and\\_seminars/spring2022/doku.php?id=modern\\_sds](https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=modern_sds)

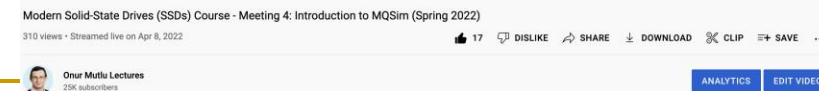
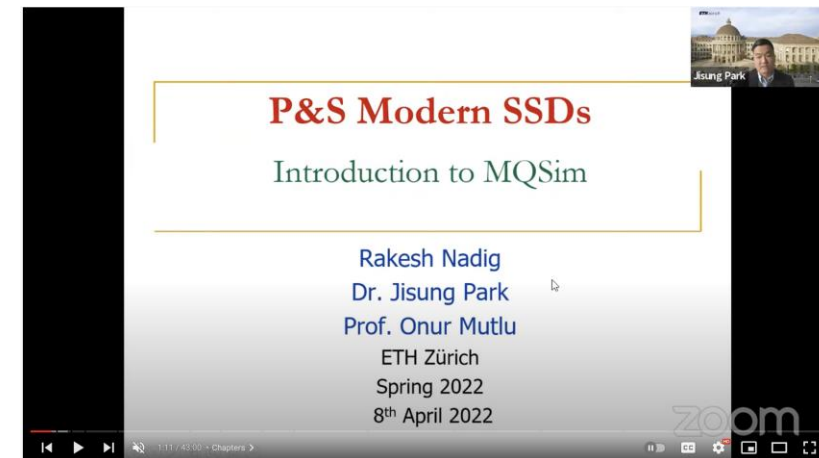
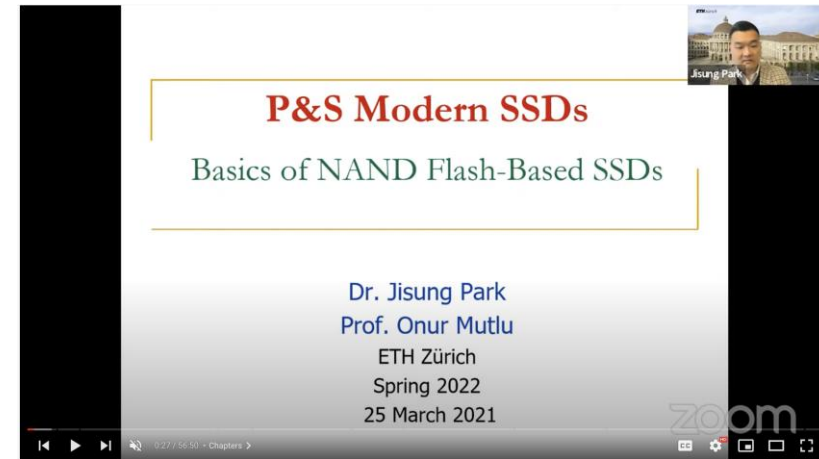
## ■ Youtube Livestream:

- ❑ <https://www.youtube.com/watch?v=q4rm71DsY4&list=PL5Q2soXY2Zi8vabcse1kL22DEcgMI2RAq>


## ■ Project course

- ❑ Taken by Bachelor's/Master's students
- ❑ SSD Basics and Advanced Topics
- ❑ Hands-on research exploration
- ❑ Many research readings

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





# Many More Simulators ...


**SAFARI Research Group at ETH Zurich and Carnegie Mellon University**  
Site for source code and tools distribution from SAFARI Research Group at ETH Zurich and Carnegie Mellon University.  
👤 125 followers 📍 ETH Zurich and Carnegie Mellon U... 🔗 <https://safari.ethz.ch/> ✉ [omutlu@gmail.com](mailto:omutlu@gmail.com)


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### Pinned


 **ramulator** Public  
A Fast and Extensible DRAM Simulator, with built-in support for modeling many different DRAM technologies including DDRx, LPDDRx, GDDRx, WIOx, HBMx, and various academic proposals. Described in the...  
● C++ ☆ 356 🍴 167

 **prim-benchmarks** Public  
PrIM (Processing-In-Memory benchmarks) is the first benchmark suite for a real-world processing-in-memory (PIM) architecture. PrIM is developed to evaluate, analyze, and characterize the first publ...  
● C ☆ 64 🍴 24

 **MQSim** Public  
MQSim is a fast and accurate simulator modeling the performance of modern multi-queue (MQ) SSDs as well as traditional SATA based SSDs. MQSim faithfully models new high-bandwidth protocol implement...  
● C++ ☆ 161 🍴 97

 **rowhammer** Public  
Source code for testing the Row Hammer error mechanism in DRAM devices. Described in the ISCA 2014 paper by Kim et al. at [http://users.ece.cmu.edu/~omutlu/pub/dram-row-hammer\\_isca14.pdf](http://users.ece.cmu.edu/~omutlu/pub/dram-row-hammer_isca14.pdf).  
● C ☆ 195 🍴 41

 **SparseP** Public  
SparseP is the first open-source Sparse Matrix Vector Multiplication (SpMV) software package for real-world Processing-In-Memory (PIM) architectures. SparseP is developed to evaluate and characteri...  
● C ☆ 37 🍴 7

 **SoftMC** Public  
SoftMC is an experimental FPGA-based memory controller design that can be used to develop tests for DDR3 SODIMMs using a C++ based API. The design, the interface, and its capabilities and limitatio...  
● Verilog ☆ 88 🍴 27



What We Discussed Is Applicable to  
Simulation in Other Domains

# Case Study: COVID-19 Spread Modeling and Prediction



# COVIDHunter: COVID-19 Pandemic Wave Prediction and Mitigation via Seasonality Aware Modeling

Mohammed Alser\*, Jeremie S. Kim, Nour Almadhoun Alser, Stefan W. Tell and Onur Mutlu

Department of Information Technology and Electrical Engineering (D-ITET), ETH Zurich, Zurich, Switzerland

## OPEN ACCESS

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COVIDHunter: COVID-19 Pandemic  
Wave Prediction and Mitigation via  
Seasonality Aware Modeling.  
Front. Public Health 10:877621.  
doi: 10.3389/fpubh.2022.877621

Early detection and isolation of COVID-19 patients are essential for successful implementation of mitigation strategies and eventually curbing the disease spread. With a limited number of daily COVID-19 tests performed in every country, simulating the COVID-19 spread along with the potential effect of each mitigation strategy currently remains one of the most effective ways in managing the healthcare system and guiding policy-makers. We introduce COVIDHunter, a flexible and accurate COVID-19 outbreak simulation model that evaluates the current mitigation measures that are applied to a region, predicts COVID-19 statistics (the daily number of cases, hospitalizations, and deaths), and provides suggestions on what strength the upcoming mitigation measure should be. The key idea of COVIDHunter is to quantify the spread of COVID-19 in a geographical region by simulating the average number of new infections caused by an infected person considering the effect of external factors, such as environmental conditions (e.g., climate, temperature, humidity), different variants of concern, vaccination rate, and mitigation measures. Using Switzerland as a case study, COVIDHunter estimates that we are experiencing a deadly new wave that will peak on 26 January 2022, which is very similar in numbers to the wave we had in February 2020. The policy-makers have only one choice that is to increase the strength of the currently applied mitigation measures for 30 days. Unlike existing models, the COVIDHunter model accurately monitors and predicts the daily number of cases, hospitalizations, and deaths due to COVID-19. Our model is flexible to configure and simple to modify for modeling different scenarios under different environmental conditions and mitigation measures. We release the source code of the COVIDHunter implementation at <https://github.com/CMU-SAFARI/COVIDHunter> and show how to flexibly configure our model for any scenario and easily extend it for different measures and conditions than we account for.

**Keywords:** epidemiological modeling, COVID-19 outbreak simulation, seasonal epidemic, outbreak prevention and control, vaccination

<https://arxiv.org/pdf/2102.03667.pdf>

## INTRODUCTION

*Coronavirus disease 2019* (COVID-19) is caused by SARS-CoV-2 virus, which has rapidly spread to nearly every corner of the globe and has been declared a pandemic in March 2020 by the World Health Organization (WHO) (1). As of November 2021, only about 40% of the entire world population is fully vaccinated and their protection wanes after a few months (2). Until an effective drug or vaccination is made widely available to everyone, early detection and isolation of

# COVID-19 Measures: Evaluation Methods

---

- How do we assess how an idea will affect a target metric X?
- A variety of evaluation methods are available:
  - Theoretical proof
  - Analytical modeling/estimation
  - Simulation (at varying degrees of abstraction and accuracy)
  - Prototyping with a real system (e.g., FPGAs)
  - Real implementation

# Simulating & Predicting COVID-19 Spread

---

- An architect is in part a dreamer, a creator
- Simulation is a key tool of the architect
  - Allows the evaluation & understanding of non-existent systems
- Simulation enables
  - The exploration of many dreams
  - A reality check of the dreams
  - Deciding which dream is better
- Simulation also enables
  - The ability to fool yourself with false dreams

# Simulating & Predicting COVID-19 Spread

To our knowledge, there is currently no model capable of accurately monitoring the current epidemiological situation and predicting future scenarios while considering a reasonably low number of parameters and accounting for the effects of environmental conditions (**Table 1**).

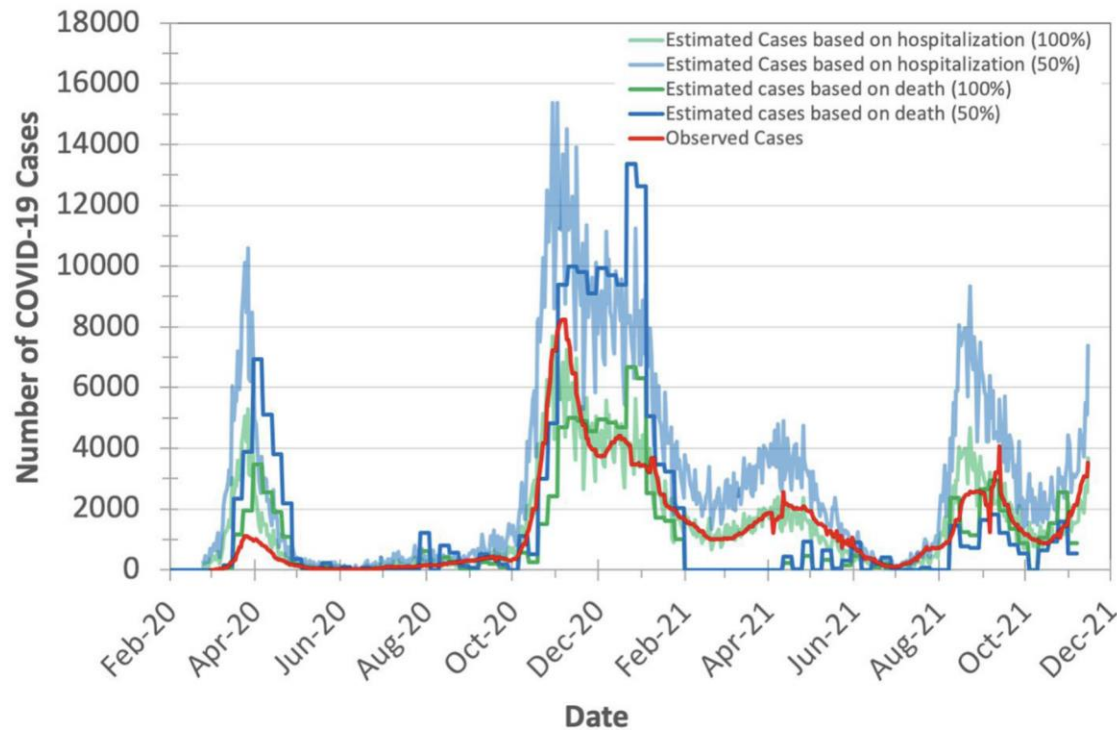
Our **goal** in this work is to develop and validate such a COVID-19 outbreak simulation model. To this end, we introduce COVIDHunter, a simulation model that evaluates the current mitigation measures (i.e., non-pharmaceutical intervention or NPI) that are applied to a region and provides insight into what strength the upcoming mitigation measure should be and for how long it should be applied, while considering the potential effect of environmental conditions. Our model accurately forecasts the

**TABLE 1** | Comparison to other models used to inform government policymakers, as of January 2021.

Model	Open source	Well documented <sup>#</sup>	Accounting for seasonality	Low number of parameters	Reported COVID-19 statistics
COVIDHunter (this work)	✓	✓	✓	✓	✓ ( $R$ , cases, hospitalizations, and deaths)
IBZ (11)	✓	✗	✗	✓	✗ (only $R$ )
LSHTM (7)	✓	✗	✗	✓	✗ (only cases)
ICL (9)	✓	✓	✗	✗	✓ ( $R$ , cases, hospitalizations, and deaths)
IHME (10)	✓*	✗	✗	✗	✗ (cases, hospitalizations, and deaths)

\*The available packages are configured only for the IHME infrastructure. # Based on the documentation available on each model's GitHub page (all models are available on GitHub).

# Simulating & Predicting COVID-19 Spread



**FIGURE 4** | Observed (officially reported) and expected number of COVID-19 cases in Switzerland during the years 2020 and 2021. We calculate the expected number of cases based on both the hospitalizations-to-cases and deaths-to-cases ratios for the second wave. We assume two certainty rate levels of 50 and 100%.

# Predicting Effectiveness of Measures

## Epidemiological Situation in Switzerland Using COVIDHunter

We use Switzerland as a use-case for all the experiments. However, our model is not limited to any specific region as the parameters of COVIDHunter are completely configurable. Using COVIDHunter on 20 November 2021, we make four key observations:

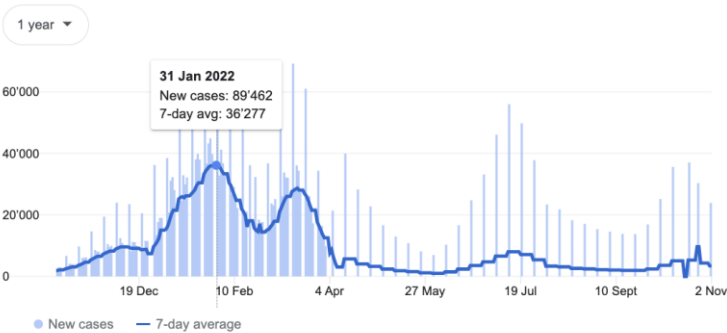
### Prediction

1. The spread of COVID-19 in Switzerland is **still active** as the reproduction number (R) is still greater than 1.0. The R number value will remain greater than 1 until at least February 2022.
2. COVIDHunter estimates that we are experiencing a deadly new wave that will peak on the last week of January 2022, which is very similar in numbers to the wave we had in February 2020.
3. The policy-makers have only one choice that is increasing the strength of the currently applied mitigation measures for 30 days. Relaxing the mitigation measures should not be an option before at least February 2022 as it would increase exponentially the number of cases, hospitalizations, and deaths by 5.5x.
4. COVIDHunter forecasts the effect of **relaxing the current mitigation measures on November 20, 2021** on the daily maximum number of COVID-19 cases, hospitalizations, and deaths as follows:

Strengths of the mitigation measures during November-December 2021	0.2	0.3	0.40	0.50	0.60	0.70
Mitigation measures with similar strength were applied on	29 February - 11 March 2020	1 October - 20 October 2020	28 February - 15 March 2020	24 June - 20 August 2020	12-29 October 2020	28 November - 22 December 2020
Predicted daily number of cases	7'822-43'518	5'706-22'413	3'401-10'714	542-1'310	70-410	3-104
Predicted daily number of hospitalizations	124-693	90-357	54-170	9-21	1-7	1-2
Predicted daily number of deaths	38-216	28-112	16-53	3-7	1-3	1-2

### Reality

#### Switzerland



#### All-time cases and deaths

Total cases	Total deaths
4.26M	14'080



# Recall: Goals in Simulation

---

- Explore the design space quickly and see what you want to
  - potentially implement in a next-generation platform
  - propose as the next big idea to advance the state of the art
  - the goal is mainly to see relative effects of design decisions
- Match the behavior of an existing system so that you can
  - debug and verify it at high accuracy
  - propose small tweaks to the design that can make a difference
  - the goal is very high accuracy
- Other goals in-between:
  - Refine the explored design space without going into full detailed modeling
  - Gain confidence in your design decisions made by higher-level design space exploration

# Recall: Tradeoffs in Simulation

---

- Three metrics to evaluate a simulator
  - Speed
  - Flexibility
  - Accuracy
- Speed: How fast the simulator runs (xIPS, xCPS, slowdown)
- Flexibility: How quickly one can modify the simulator to evaluate different algorithms and design choices?
- Accuracy: How accurate the performance (energy) numbers the simulator generates are vs. a real design (Simulation error)
- The relative importance of these metrics varies depending on where you are in the design process (what your goal is)

# Recall: Trading Off Speed, Flexibility, Accuracy

---

- Speed & flexibility affect:
  - How quickly you can make design tradeoffs
- Accuracy affects:
  - How good your design tradeoffs **may** end up being
  - How fast you can build your simulator (simulator design time)
- Flexibility also affects:
  - How much human effort you need to spend modifying the simulator
- You can **trade off between the three to achieve design exploration and decision goals**

# Recall: High-Level Simulation

---

- Key Idea: Raise the abstraction level of modeling to **give up some accuracy to enable speed & flexibility** (and quick simulator design)
- Advantage
  - + Can still make the right tradeoffs, and can do it quickly
    - + All you need is modeling the key high-level factors, you can omit corner case conditions
    - + All you need is to get the “relative trends” accurately, not exact performance numbers
- Disadvantage
  - Opens up the possibility of potentially wrong decisions
  - How do you ensure you get the “relative trends” accurately?

# Recall: Simulation as Progressive Refinement

---

- High-level models (Abstract, C)
- ...
- Medium-level models (Less abstract)
- ...
- Low-level models (RTL with everything modeled)
- ...
- Real design
  
- As you refine (go down the above list)
  - Abstraction level reduces
  - Accuracy (hopefully) increases (not necessarily, if not careful)
  - Flexibility reduces; Speed likely reduces except for real design
  - You can loop back and fix higher-level models

# Recall: Making The Best of Architecture

---

- A good architect is comfortable at all levels of refinement
  - Including the extremes
- A good architect knows when to use what type of simulation
  - And, more generally, what type of evaluation method
- Recall: A variety of evaluation methods are available:
  - Theoretical proof
  - Analytical modeling
  - Simulation (at varying degrees of abstraction and accuracy)
  - Prototyping with a real system (e.g., FPGAs)
  - Real implementation

# Computer Architecture

## Lecture 12a: Simulation II (with a Focus on Memory)

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