How to Build
an Impactful Research Group

Onur Mutlu

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2 June 2019

DAC Early Career Workshop Panel

SAFARI   **ETH**zürich   **Carnegie Mellon**

Intro & Research Group

A Bit About Myself

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

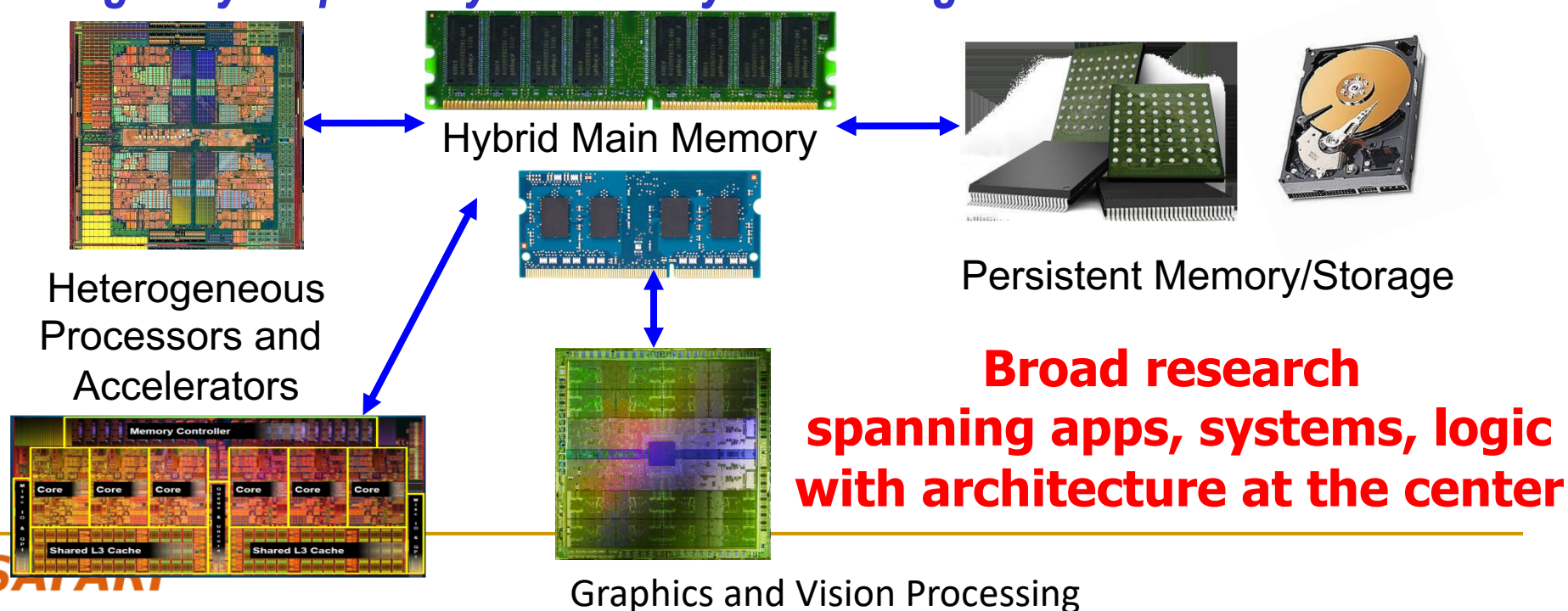- **Research and Teaching in:**
  - Computer architecture, computer systems, hardware security, bioinformatics
  - Memory and storage systems
  - Hardware security, safety, predictability
  - Fault tolerance
  - Hardware/software cooperation
  - Architectures for bioinformatics, health, medicine
  - …

Current Research Focus Areas

Research Focus: _Computer architecture, HW/SW, bioinformatics, security_

- **_Memory and storage (DRAM, flash, emerging), interconnects_**
- **_Heterogeneous & parallel systems, GPUs, systems for data analytics_**
- **_System/architecture interaction, new execution models, new interfaces_**
- **_Hardware security, energy efficiency, fault tolerance, performance_**
- **_Genome sequence analysis & assembly algorithms and architectures_**
- **_Biologically inspired systems & system design for bio/medicine_**

Hybrid Main Memory

Heterogeneous Processors and Accelerators

Persistent Memory/Storage

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

Graphics and Vision Processing

Research & Teaching: Some Overview Talks

https://www.youtube.com/watch?v=kgiZlSOcGFM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl

- **Future Computing Architectures**
  - https://www.youtube.com/watch?v=kgiZlSOcGFM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=1

- **Enabling In-Memory Computation**
  - https://www.youtube.com/watch?v=oHqsNbxgdzM&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=7

- **Accelerating Genome Analysis**
  - https://www.youtube.com/watch?v=hPnSmfwu2-A&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=9

- **Rethinking Memory System Design**
  - https://www.youtube.com/watch?v=F7xZLNMIY1E&list=PL5Q2soXY2Zi8D_5MGV6EnXEJHnV2YFBJl&index=3

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Accelerated Memory Course (~6.5 hours)

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

- **Website for the Course including Videos, Slides, Papers**
  - https://people.inf.ethz.ch/omutlu/acaces2018.html
  - https://www.youtube.com/playlist?list=PL5Q2soXY2Zi-HXxomthrpDpMJm05P6J9x

- **All Papers are at:**
  - https://people.inf.ethz.ch/omutlu/projects.htm
  - Final lecture notes and readings (for all topics)

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safari.ethz.ch

Think BIG, Aim HIGH!

https://safari.ethz.ch

SAFARI Group Members @ ETH Zurich

4 Post-doctoral Researchers

8 PhD Students + 4 at CMU

5 Interns

15 Master's and Bachelor's Researchers

Dr. Mohammed Alser — Dr. Lois Orosa — Dr. Yaohua Wang — Dr. Juan Gómez-Luna
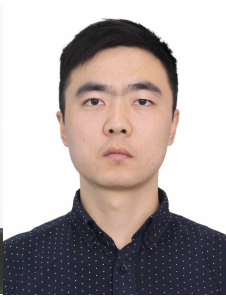
Jeremie Kim — Hasan Hassan — Minesh Patel — Ivan Puddu — Lukas Breitwieser — Giray Yaglikci — Can Firtina — Geraldo F. de Oliveira

Nika Mansouri — Skanda Koppula — Konstantinos Kanellopoulos — Nisa Bostanci — Ataberk Olgun — Rokneddin Azizi — Christina Giannoula — Taha Shahroodi

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Example Research Topics (I)

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

Onur Mutlu[a,b], Saugata Ghose[b], Juan Gómez-Luna[a], Rachata Ausavarungnirun[b,c]

[a]ETH Zürich
[b]Carnegie Mellon University
[c]King Mongkut's University of Technology North Bangkok

Onur Mutlu, Saugata Ghose, Juan Gomez-Luna, and Rachata Ausavarungnirun,
"Processing Data Where It Makes Sense: Enabling In-Memory Computation"
*Invited paper in Microprocessors and Microsystems (**MICPRO**)*, June 2019.
[arXiv version]

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9

Example Research Topics (II)

- Onur Mutlu,
  "The RowHammer Problem and Other Issues We May Face as Memory Becomes Denser"
  Invited Paper in Proceedings of the Design, Automation, and Test in Europe Conference (**DATE**), Lausanne, Switzerland, March 2017.
  [Slides (pptx) (pdf)]

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

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

Example Research Topics (III)

- Onur Mutlu,
  "Memory Scaling: A Systems Architecture Perspective"
  Technical talk at MemCon 2013 (**MEMCON**), Santa Clara, CA, August 2013. [Slides (pptx) (pdf)]
  [Video] [Coverage on StorageSearch]

Memory Scaling: A Systems Architecture Perspective

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

Example Research Topics (IV)

INVITED
PAPER

Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

This paper reviews the most recent advances in solid-state drive (SSD) error characterization, mitigation, and data recovery techniques to improve both SSD's reliability and lifetime.

By Yu Cai, Saugata Ghose, Erich F. Haratsch, Yixin Luo, and Onur Mutlu

https://arxiv.org/pdf/1706.08642

Example Research Topics (V)

- Onur Mutlu and Jeremie Kim,
  "RowHammer: A Retrospective"
  IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (**TCAD**) *Special Issue on Top Picks in Hardware and Embedded Security*, 2019.
  [Preliminary arXiv version]

RowHammer: A Retrospective

Onur Mutlu[§‡] Jeremie S. Kim[‡§]
[§]ETH Zürich [‡]Carnegie Mellon University

Teaching: Online Courses and Lectures

- **Freshman Digital Circuits and Computer Architecture Course Lecture Videos** (**2018**, **2017**)

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

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

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

- https://people.inf.ethz.ch/omutlu/teaching.html
- https://www.youtube.com/channel/UCIwQ8uOeRFgOEvBLYc3kc3g
- https://www.youtube.com/user/cmu18447

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Some Open Source Tools (I)

- **Rowhammer – Program to Induce RowHammer Errors**
  - https://github.com/CMU-SAFARI/rowhammer

- **Ramulator – Fast and Extensible DRAM Simulator**
  - https://github.com/CMU-SAFARI/ramulator

- **MemSim – Simple Memory Simulator**
  - https://github.com/CMU-SAFARI/memsim

- **NOCulator – Flexible Network-on-Chip Simulator**
  - https://github.com/CMU-SAFARI/NOCulator

- **SoftMC – FPGA-Based DRAM Testing Infrastructure**
  - https://github.com/CMU-SAFARI/SoftMC

- **Other open-source software from my group**
  - **https://github.com/CMU-SAFARI/**
  - **http://www.ece.cmu.edu/~safari/tools.html**

Some Open Source Tools (II)

- MQSim – A Fast Modern SSD Simulator
  - https://github.com/CMU-SAFARI/MQSim

- Mosaic – GPU Simulator Supporting Concurrent Applications
  - https://github.com/CMU-SAFARI/Mosaic

- IMPICA – Processing in 3D-Stacked Memory Simulator
  - https://github.com/CMU-SAFARI/IMPICA

- SMLA – Detailed 3D-Stacked Memory Simulator
  - https://github.com/CMU-SAFARI/SMLA

- HWASim – Simulator for Heterogeneous CPU-HWA Systems
  - https://github.com/CMU-SAFARI/HWASim

- Other open-source software from my group
  - **https://github.com/CMU-SAFARI/**
  - **http://www.ece.cmu.edu/~safari/tools.html**

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More Open Source Tools (III)

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

Papers

- All are available at

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

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

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

Revisiting the Entire Stack

Problem

Algorithm

Program/Language

System Software

SW/HW Interface

Micro-architecture

Logic

Devices

Electrons
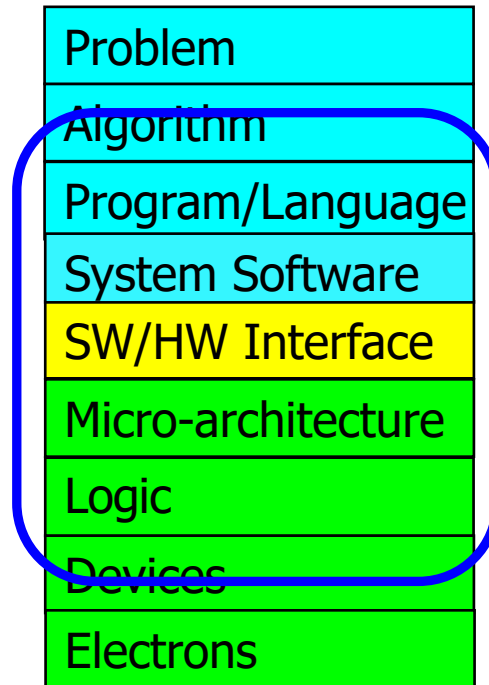
Panel Questions

Question 1

- *Which are the best practices that you would suggest to your peers as the essential one for the success of an academic team?*

Before I Start…

- There is no single way of having impact.

- The following is my way, methods and principles.

- There definitely are other ways.

- The critical thing is finding the way that works well for you and your goals.
  - That you can own, cherish and optimize

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Principle: Personalized Methods

Find the methods that work for you

Motivation & Mindset

Start out with the right

motivation and mindset

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Motivation Sets The Culture and Goals

- Mindset 1: change the world positively, have high influence
- Mindset 2: enable students to achieve a potential that they did not even think they could ever achieve

- Not papers
- Not fame
- Not money

- …

- Motivation correction may be needed at times – be ready

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Get motivated students

Build a team of excellence

Focus on

learning and scholarship

Some Basics of Research

Slides used in several of my courses:
e.g., https://www.youtube.com/watch?v=M0y_Nvb9rGA

How To Do Research & Advanced Dev.

- We will talk a lot about this in this course

- Learning by example
  - Reading and evaluating strong and seminal papers & designs

- Learning by doing
  - Semester-long research/design projects, masters' projects, PhD thesis

- Learning by open, critical discussions
  - Paper reading groups, frequent brainstorming and discussions
  - Design sessions
  - Collaborations

Slides used in several of my courses: e.g., https://www.youtube.com/watch?v=M0y_Nvb9rGA 30

Create an environment that values

free exploration, openness, collaboration, hard work, creativity

What Is The Goal of Research?

- To generate new insight
  - that can enable what previously did not exist

- Research is a hunt for insight that can eventually impact the world

Principle: Insight and Ideas

Focus on Insight

Encourage New Ideas

Some Basic Advice for Good Research

- **Choose great problems to solve: Have great taste**
  - Difficult
  - Important
  - High impact

- **Read heavily and critically**

- **Think big (out of the box)**
  - Do not restrain yourself to tweaks or constraints of today
  - Yet, think about adoption issues

- **Aim high**

- **Write and present extremely well**

Many Principles
on the Previous Slide

Principle: Bar

Set the Bar High

Set the Bar High

- The goal should be to enable students to achieve a potential that they did not even think they could ever achieve

- "Think big, aim high, enable positive change"

- Reward good, positive behavior that helps with this culture

- Recommended reading:
  - Hamming, "You and Your Research," Talk at Bell Labs, 1986.

Fundamentals and scholarship are critical

(hypes come and go)

Choose Great Problems and guide your group toward them (but give them freedom)

Principle: Teaching and Research

...

Teaching drives Research

Research drives Teaching

...

More on Teaching and Research

- **Care about teaching immensely**

- Teaching and research are two sides of the same coin → scholarship

- Both long-term and short-term is affected by teaching

- Research motivates teaching motivates research
  - ❑ I introduce RowHammer, Processing in Memory, Meltdown/Spectre, DRAM Refresh, Various Technology Scaling problems, and research examples in my Freshman course:
    - https://safari.ethz.ch/digitaltechnik/spring2019/
  - ❑ All courses can have research examples

Principle: Focus on Communication

Emphasize

Clarity and Rigor

in Communication

(critical for high impact)

Do Everything to Have High Impact

- Engage with companies

- Engage and collaborate with researchers who fit your mindset
  - Collaborate, not fight

- Strive for the highest excellence

Foster collaboration (within group) (across groups) (with companies)

Principle: Reach Out

Inspire and Reach Out

Principle: Reach Out

- Give talks

- Educate others on your work and research

- Listen to everyone
  - Especially your students

- Teach, educate, collaborate

Principle: Feedback

Receive & Address Feedback

(but do not get derailed)

Principle: Receive & Address Feedback

- Address reviewer feedback
  - Take them positively
  - They can be helpful

- Feedback is not always right
  - Need to apply corrections to it

- Do not let rejection derail you – be ready for it
- Remind and encourage your students:
  - https://www.sciencealert.com/these-8-papers-were-rejected-before-going-on-to-win-the-nobel-prize

Principle: Resilience

Be Resilient

Principle: Passion

Follow Your Passion

If In Doubt, See Other Doubtful Technologies

- A very "doubtful" emerging technology
  - for at least two decades

INVITED PAPER

Proceedings of the IEEE, Sept. 2017

Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

This paper reviews the most recent advances in solid-state drive (SSD) error characterization, mitigation, and data recovery techniques to improve both SSD's reliability and lifetime.

By Yu Cai, Saugata Ghose, Erich F. Haratsch, Yixin Luo, and Onur Mutlu

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https://arxiv.org/pdf/1706.08642

Principle: Build Infrastructure

Build Infrastructure to Enable Your Passion

(Big Projects)
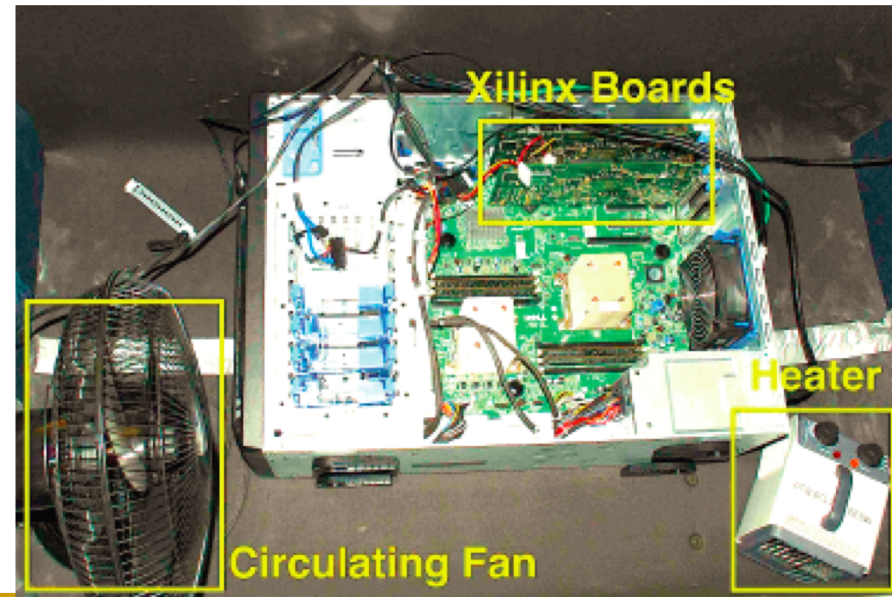
Example: Our DRAM Infrastructure (since 2012)

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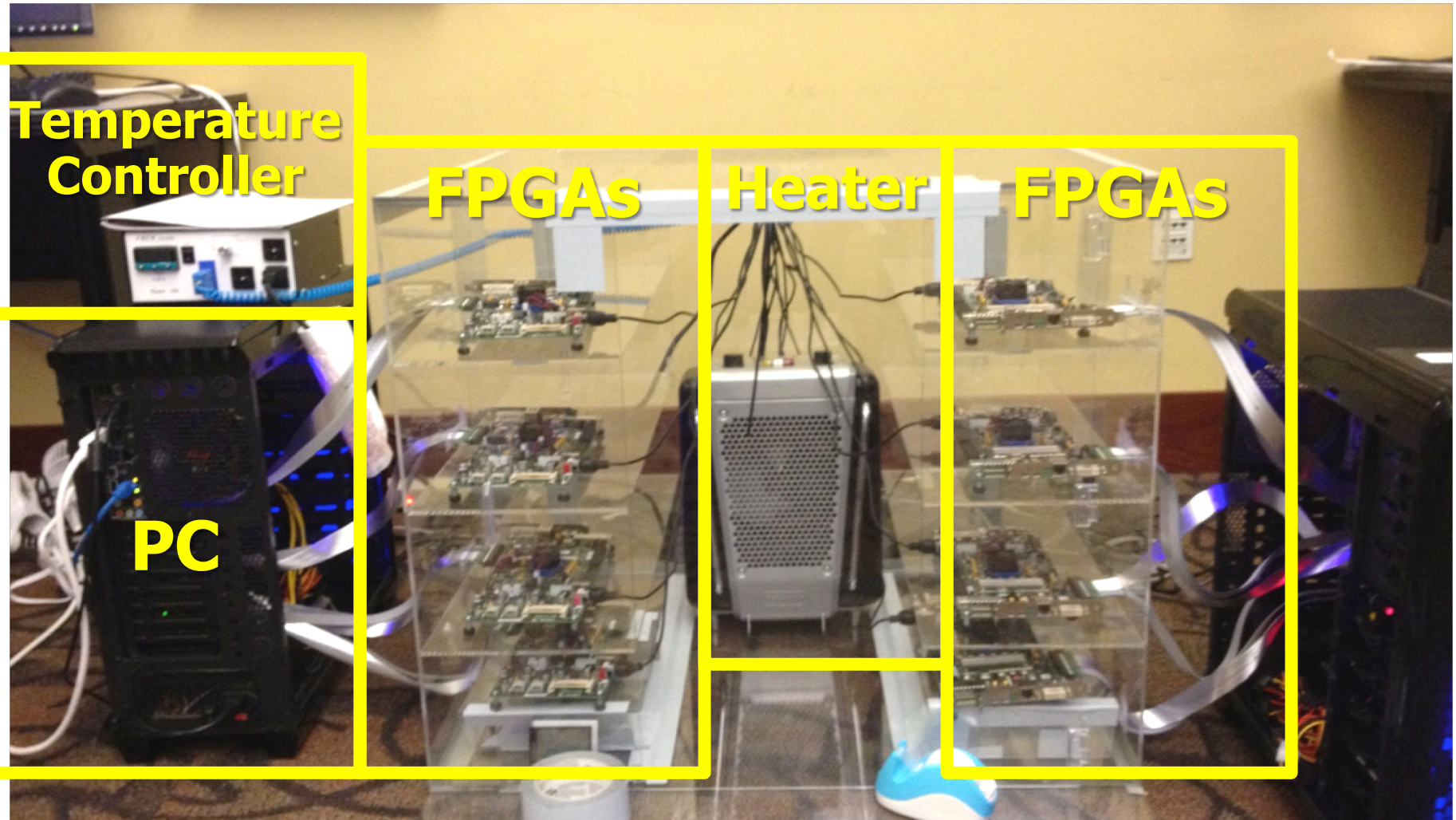
Adaptive-Latency DRAM: Optimizing DRAM Timing for the Common-Case (Lee et al., HPCA 2015)

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

Example: Our DRAM Infrastructure (since 2012)

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

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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
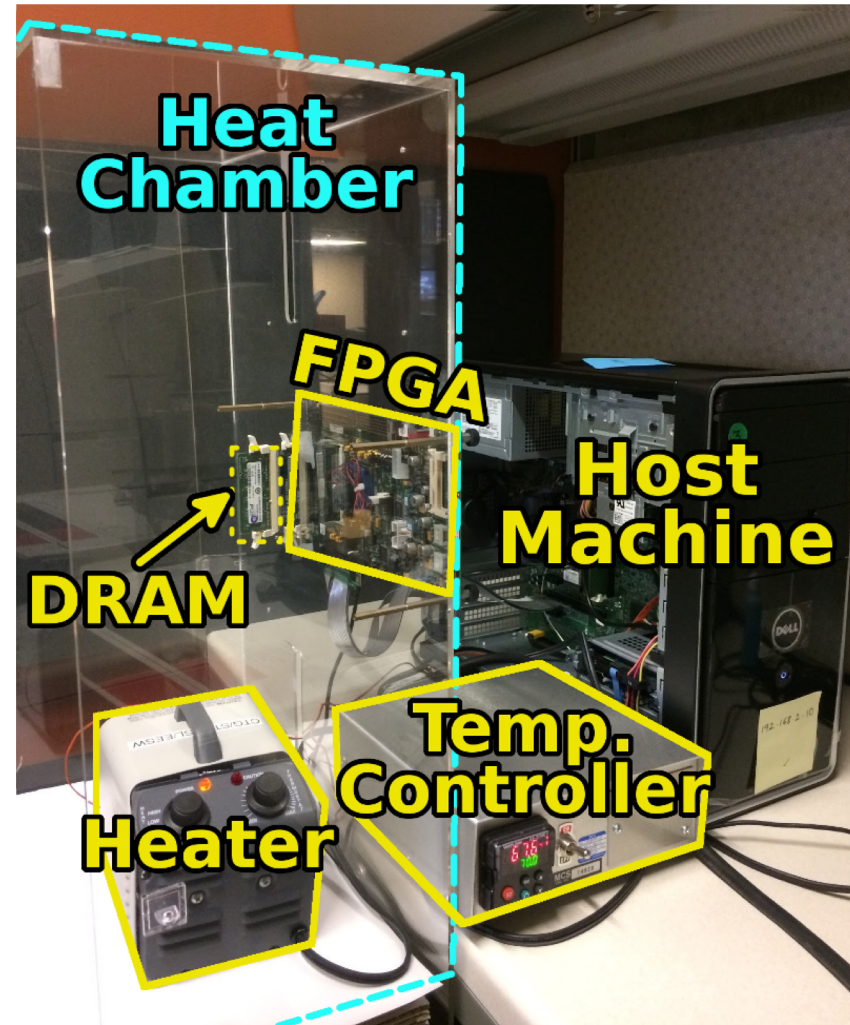
Infrastructure Enabled Research: RowHammer

- 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[1]   Ross Daly*   Jeremie Kim[1]   Chris Fallin*   Ji Hye Lee[1]

Donghyuk Lee[1]   Chris Wilkerson[2]   Konrad Lai   Onur Mutlu[1]

[1]Carnegie Mellon University   [2]Intel Labs

Infrastructure Enabled Research: RowHammer
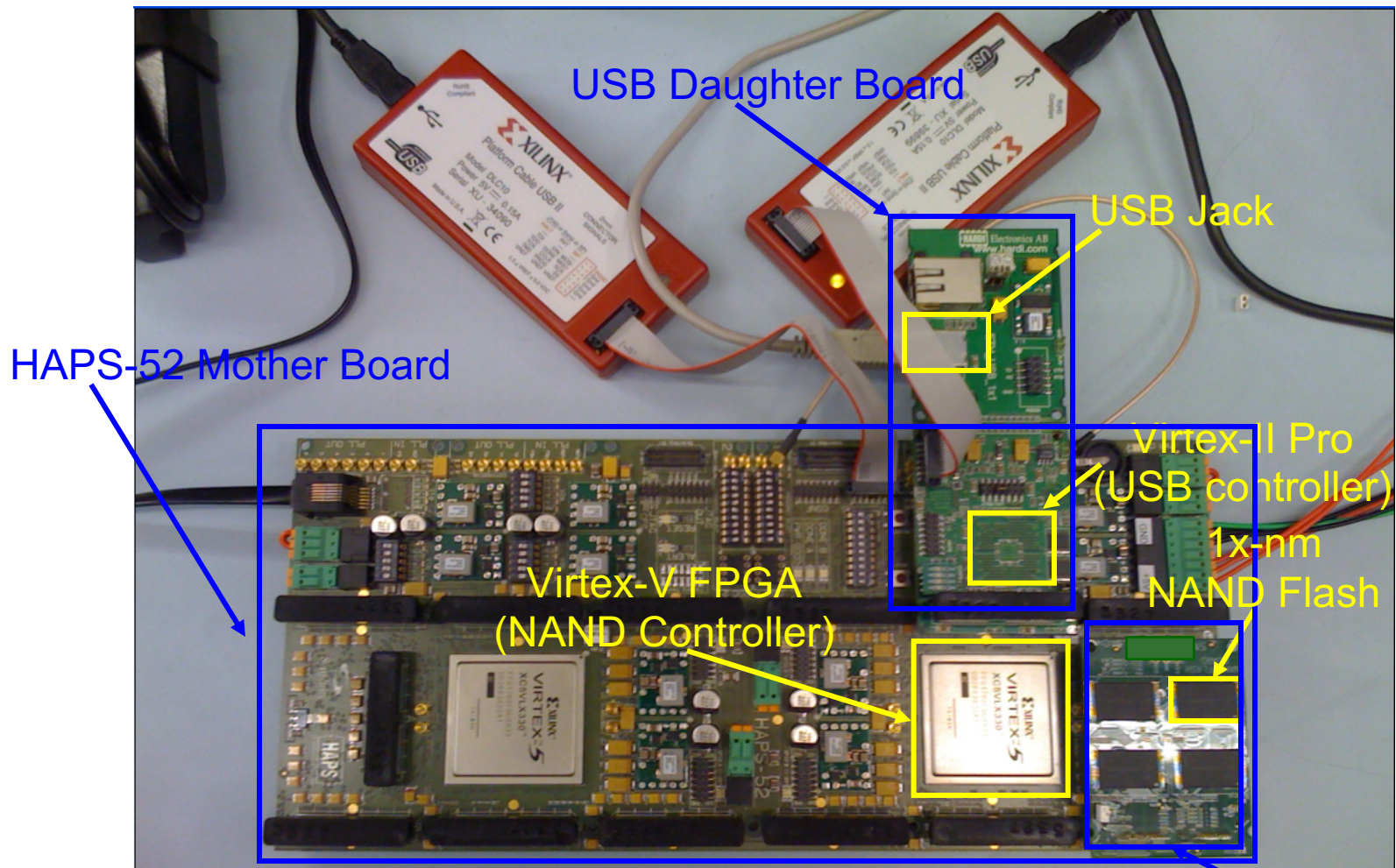
- Onur Mutlu and Jeremie Kim,
  "RowHammer: A Retrospective"
  IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (**TCAD**) *Special Issue on Top Picks in Hardware and Embedded Security*, 2019.
  [Preliminary arXiv version]

RowHammer: A Retrospective

Onur Mutlu[§‡]   Jeremie S. Kim[‡§]
[§]ETH Zürich   [‡]Carnegie Mellon University

Our NAND Flash Infrastructure

USB Daughter Board

USB Jack

HAPS-52 Mother Board

Virtex-II Pro
(USB controller)

1x-nm
NAND Flash

Virtex-V FPGA
(NAND Controller)

NAND Daughter Board

[DATE 2012, ICCD 2012, DATE 2013, ITJ 2013, ICCD 2013, SIGMETRICS 2014, HPCA 2015, DSN 2015, MSST 2015, JSAC 2016, HPCA 2017, DFRWS 2017, PIEEE 2017, HPCA 2018, SIGMETRICS 2018]

Cai+, "Error Characterization, Mitigation, and Recovery in Flash Memory Based Solid State Drives," Proc. IEEE 2017.

Infrastructure Enabled Research: SSD Errors

Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

This paper reviews the most recent advances in solid-state drive (SSD) error characterization, mitigation, and data recovery techniques to improve both SSD's reliability and lifetime.

By Yu Cai, Saugata Ghose, Erich F. Haratsch, Yixin Luo, and Onur Mutlu

https://arxiv.org/pdf/1706.08642

Ramulator – DRAM Simulation Infrastructure

Segment	DRAM Standards & Architectures
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

Kim+, "Ramulator: A Flexible and Extensible DRAM Simulator", IEEE CAL 2015.

Ramulator Paper and Source Code

- Yoongu Kim, Weikun Yang, and Onur Mutlu,
"Ramulator: A Fast and Extensible DRAM Simulator"
IEEE Computer Architecture Letters (**CAL**), March 2015.
[Source Code]

- Source code is released under the liberal MIT License
  - https://github.com/CMU-SAFARI/ramulator

Ramulator: A Fast and Extensible DRAM Simulator

Yoongu Kim[1]   Weikun Yang[1,2]   Onur Mutlu[1]
[1]Carnegie Mellon University   [2]Peking University

Infrastructure Enabled Research: PIM (I)

- 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[1]   Saugata Ghose[1]   Youngsok Kim[2]
Rachata Ausavarungnirun[1]   Eric Shiu[3]   Rahul Thakur[3]   Daehyun Kim[4,3]
Aki Kuusela[3]   Allan Knies[3]   Parthasarathy Ranganathan[3]   Onur Mutlu[5,1]

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

Onur Mutlu[a,b], Saugata Ghose[b], Juan Gómez-Luna[a], Rachata Ausavarungnirun[b,c]

[a]*ETH Zürich*
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"Processing Data Where It Makes Sense: Enabling In-Memory Computation"
*Invited paper in Microprocessors and Microsystems (**MICPRO**)*, June 2019.
[arXiv version]

Question 2

- *How much is important the heterogeneity of the group? What about the inclusion?*

Principle: Diversity

- Diversity is very important

- No two people are the same -- everyone brings perspective

- Critical to be diverse, accepting, inclusive
  - Age
  - Gender
  - Experience level
  - Education level
  - Geography (natural in our field)

- Critical for open, expressive culture
- Set a common goal and common culture

Create an environment that values

free exploration, openness, collaboration, hard work, creativity

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Question 3

- *Which are the main characteristics and skills one should take into account when choosing PhD students and researchers for new and (possibly) impactful research groups?*

How to Select PhD Students & Researchers

- Motivation and Mindset

- Creativity

- Resilience

- Hard work

- Boldness

- Perseverance, commitment

- Intellectual strength

- Openness to feedback

- Communicativeness

- ...

Question 4 and Answer

- *Can mentoring young students and managing a group be taught?*

- Answer: Yes

- Mentoring is a critical part of a PhD

Question 5 and Answer

- *Emotional intelligence is considered today a key skill for managers and entrepreneurs. Do you believe that is it crucial also for research groups leaders?*

- Answer: Yes

- Communication, understanding, mindset are all critical
  - And part of Emotional Intelligence

Question 6 and Answer

- *How does the group's internal hierarchy impact work effectiveness? Is a strong hierarchy implying a reduction of diversity and heterogeneity or not?*

- Answer: Flat hierarchy is better.

- Openness and valuing of every single person and idea, regardless of level or experience
- Valuing of mentorship
  - Inexperienced folks learn from experienced ones
- Everyone collaborates
- No artificial barriers between people
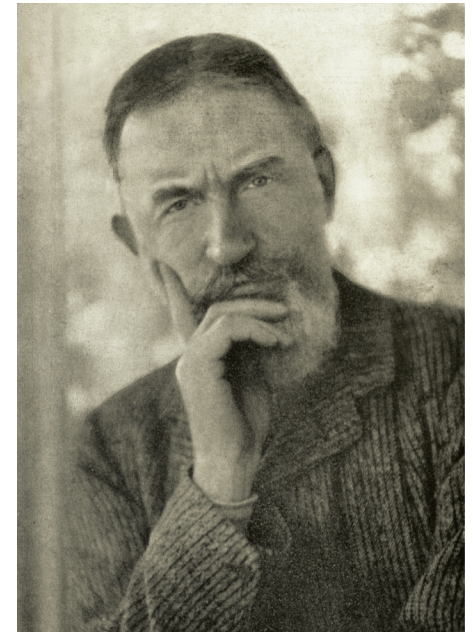
Food for Thought: Two Quotes

The reasonable man adapts himself to the world;

The unreasonable one persists in trying adapt the world to himself.

Therefore all progress depends on the unreasonable man.

George Bernard Shaw

Progress is impossible without change, and those who cannot change their minds cannot change anything.

How to Build
an Impactful Research Group

Onur Mutlu

omutlu@gmail.com

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

2 June 2019

DAC Early Career Workshop Panel

SAFARI   **ETH** zürich   **Carnegie Mellon**