P&S Modern SSDs
Understanding and Designing Modern NAND Flash-Based SSDs (Solid-State Drives)

Dr. Mohammad Sadrosadati
Prof. Onur Mutlu
ETH Zürich
Spring 2023
10 March 2023
Course Info: Who Are We? (I)

- **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/](https://people.inf.ethz.ch/omutlu/)
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  - [https://people.inf.ethz.ch/omutlu/projects.htm](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
  - ...
Prof. Mutlu’s SAFARI Research Group

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

Think BIG, Aim HIGH!

https://safari.ethz.ch
SAFARI Newsletter: December 2021

Think Big. Aim High

View in your browser
December 2021

https://safari.ethz.ch/safari-newsletter-december-2021
Course Info: Who Are We? (II)

Dr. Mohammad Sadrosadati

- Senior researcher and lecturer
  - @ SAFARI research group since 2021
- Senior researcher @ IPM 2019–2021
- PhD from Sharif University of Technology
- Research Area: Computer Architecture, memory/storage systems, near-data processing, bioinformatics
- mohammad.sadrosadati@safari.ethz.ch

Rakesh Nadig

- PhD Student @ SAFARI research group since 2021
- Senior staff engineer @ Samsung Electronics India 2014-2021
- MS from University of California Irvine
- Research Area: computer architecture, memory system design, multi-core architectures, near-memory processing, non-volatile memory
- rakesh.nadig@safari.ethz.ch
Course Info: Who Are We? (III)

- Geraldo F. Oliveira
  - PhD Student @ SAFARI research group since 2018
  - MS from Federal University of Rio Grande do Sul, Brazil
  - Research Area: computer architecture, memory system design, system performance, processing-in-memory, emerging memory technologies
  - geraldod@safari.ethz.ch
P&S: Modern SSDs (I)

227-0085-44L Projects & Seminars: Understanding and Designing Modern SSDs (Solid-State Drives)

Semester: Spring Semester 2023
Lecturers: S. Sadrosadati
Periodicity: every semester recurring course
Language of instruction: English
Comment: Course can only be registered for once. A repeatedly registration in a later semester is not chargeable.

Courses

<table>
<thead>
<tr>
<th>Number</th>
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<tr>
<td>227-0085-44 P</td>
<td>Projekte &amp; Seminare: Understanding and Designing Modern SSDs (Solid-State Drives)</td>
<td>3 hrs</td>
<td>S. Sadrosadati</td>
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Catalogue data

Abstract
The category of "Laboratory Courses, Projects, Seminars" includes courses and laboratories in various formats designed to impart practical knowledge and skills. Moreover, these classes encourage independent experimentation and design, allowing for explorative learning and teaching the methodology of project work.

Objective
NAND flash memory is the de facto standard for architecting a storage device in modern computing systems. As modern computing systems process a large amount of data at an unprecedented scale, a storage device needs to meet high requirements on storage capacity and I/O performance. A NAND flash-based solid-state drive (SSD) can provide orders-of-magnitude higher I/O performance compared to traditional hard disk drives (HDDs), with a much lower cost-per-bit value over SSDs based on emerging non-volatile memory (NVM) technologies.

NAND flash memory has several unique characteristics, such as the erase-before-write property (i.e., a flash cell needs to be first erased before programmed), limited lifespan (i.e., a cell can sustain a certain number of overwrites or program/erase cycles), and...
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NAND flash memory has several unique characteristics, such as the erase-before write property (i.e., a flash cell needs to be first erased before programming it), limited lifetime (i.e., a cell cannot reliably store data after experiencing a certain number of program/erase (P/E) cycles), and large operation units (e.g., modern NAND flash memory typically reads/writes data in a page (e.g., 16 KiB) granularity). To achieve high performance and large capacity of the storage system while hiding the unique characteristics of NAND flash memory, it is critical to design efficient SSD firmware, commonly called Flash-Translation Layer (FTL). An FTL is responsible for many critical management tasks, such as address translation, garbage collection, wear leveling, and I/O scheduling, which significantly affect the performance, reliability, and lifetime of the SSD.

In this course, we will cover how a modern NAND flash-based SSD is organized and operates, from the basics of underlying NAND flash devices and various SSD-management tasks at the FTL level. We will also examine other emerging memory technologies for building SSDs, such as Phase Change Memory, 3D XPoint (e.g., Intel Optane SSD) and more.
P&S Modern SSDs: Contents

- We will introduce **how a modern NAND flash-based SSD is organized and operates** to provide high I/O performance while hiding unique characteristics of NAND flash memory.

- You will learn **fundamentals and challenges** in designing modern SSDs.

- You will review existing approaches that are widely adopted in modern SSDs and will **get familiar with new research proposals**.

- You will **work hands-on**: projects related to storage systems and NAND flash memory.
Modern SSD Architecture

- A modern SSD is a complicated system that consists of multiple cores, HW controllers, DRAM, and NAND flash memory packages.

Why So Complicated?

- To provide backward compatibility with traditional HDDs
  - Smaller sectors than file-system blocks: 512 Bytes vs. 4KiB
  - Support overwrites

- While hiding unique characteristics of NAND flash memory
  - Large operation units
  - Erase-before-write property
  - Asymmetry in operation units
  - Limited endurance
  - Various error sources
  - Asymmetry in operation latencies
Unique Characteristics of NAND Flash (I)

- Large operation units
  - Read/write granularity: page (4 – 16 KiB)

- Erase-before-write property
  - A page needs to be first erased before programming

- Operation-unit asymmetry
  - Erase granularity: block (hundreds or thousands of pages)

In-place update (i.e., overwrite) is very inefficient for NAND flash memory
→ Out-of-place write & garbage collection
Unique Characteristics of NAND Flash (II)

- Limited endurance
  - A flash cell cannot reliably store data after experiencing a certain number of program and erase (P/E) cycles
  - SLC (Single-Level Cell): > 100K P/E cycles
  - MLC (Multi-Level Cell): ~ 10K P/E cycles
  - TLC (Triple-Level Cell): < 3K P/E cycles
  - QLC (Quad-Level Cell): < 1K P/E cycles

Requires proper lifetime management techniques (e.g., wear-leveling)
Flash Translation Layer (FTL)

- Sophisticated SSD firmware

  Logical Block (4 KiB, overwritable)

  Storage-device view at operating systems:
  A series of blocks

  Flash Translation Layer (FTL)
  - Address translation (out-of-place write)
  - Garbage collection
  - Lifetime management (wear-leveling)
  - Reliability management (ECC, data refresh)
  - I/O scheduling
SSD Optimization

- Requires comprehensive understandings of
  - Microarchitecture of underlying NAND flash chips (HW)
  - Various internal management tasks (HW and SW)
  - OS & workload characteristics (SW)

- Optimization at one level may affect and/or be affected by the efficiency of designs at other levels.

We need an SSD simulator that accurately models various functionalities and components
What You Will Do

- **Phase 1:** Learning *fundamentals of NAND flash-based SSDs*
  - Several background lectures on
    - Organization of NAND flash memory and NAND flash-based SSDs
    - NAND flash operations
    - SSD management tasks
    - SSD reliability
  - Literature review

- **Phase 2:** Hands-on projects on storage systems and NAND flash memory
Key Takeaways

This P&S aims at improving your

- **Knowledge** in Computer Architecture with a focus on modern storage systems
- **Technical skills** required for good research
- **Critical thinking and analysis**
Prerequisites of the Course

- Digital Design and Computer Architecture (or equivalent course)

- Familiarity with C++ programming (or high motivation to acquire it)

- Interest in
  - Computer architecture and systems
  - Discovering why things do or do not work
  - Solving problems
  - Designing an efficient and practical system
Course Info: How About You?

- Let us know your background, interests
- Why did you join this P&S?

- HW0 – Student Information (Due: 13 March 2023)
Course Requirements and Expectations

- Attendance required for all meetings
- Study the learning materials
- Each student will work on a hands-on project
- Participation
  - Ask questions, contribute thoughts/ideas
Course Website


- Useful information about the course

- Check your email frequently for announcements
Meeting 1

Required Materials
- MQSim GitHub Repository: https://github.com/CMU-SAFARI/MQSim

Recommended Materials
- Computer Architecture Fall 2020 – Lecture 26: Flash Memory and Solid-State Drives
  - https://www.youtube.com/watch?v=rninK6KWBeM
  - PDF and PPT
- Computer Architecture Fall 2020 – Lecture 14: Simulation (with a Focus on Memory)
  - https://www.youtube.com/watch?v=3cI4zOoDk9Q
  - PDF and PPT
Next Meetings

- We will meet weekly
- Provide background lectures
- Q&A for any difficulties in the previous week and directions for next weeks
- Presentation of your work
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