

High Performance Programming and Systems

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Agenda

What are computer systems?

Motivation

- Why do computer numbers behave strangely?

- Why are some languages faster than others?

- How do we access memory efficiently?

- What does “efficiency” or “performance” even mean?

- Course perspective

Course organisation

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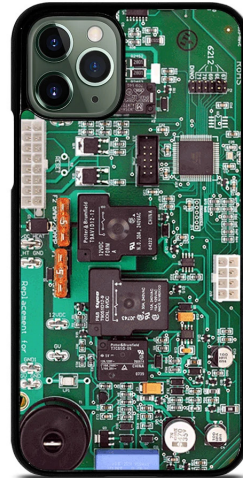
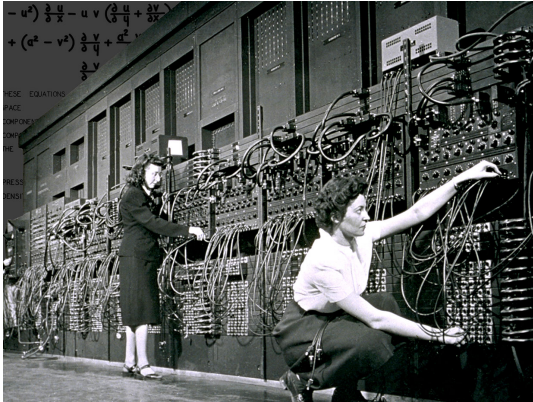
What does “efficiency” or “performance” even mean?

Course perspective

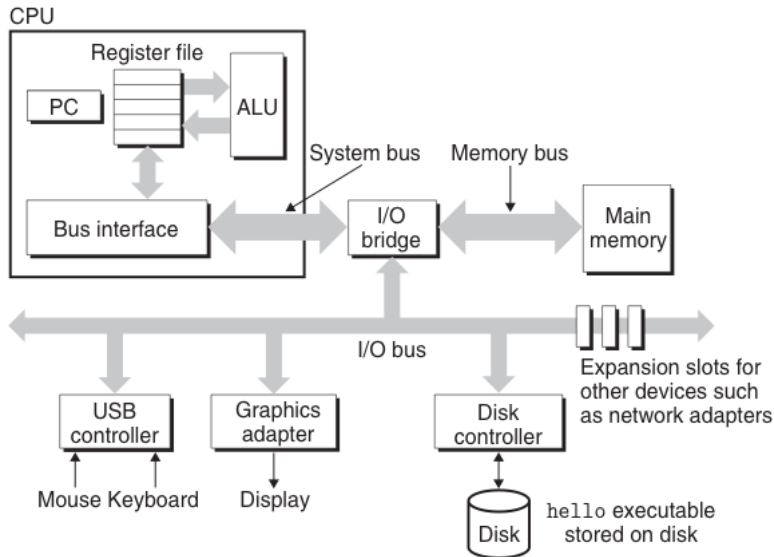
Course organisation

What is a computer system for you?

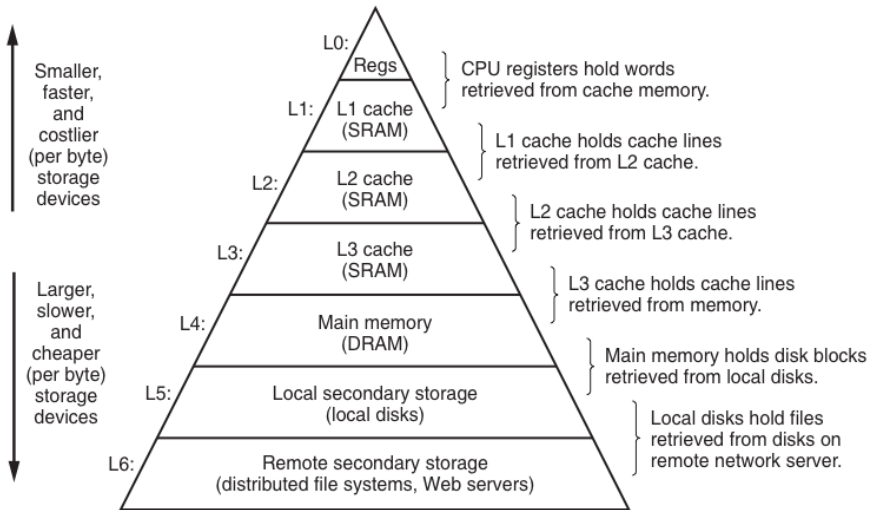
- **5 minutes!** What is a “computer” to you? What does it do?



Computer System: Hardware

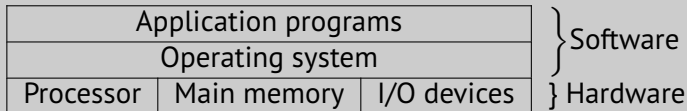


Computer System: Memory Hierarchy

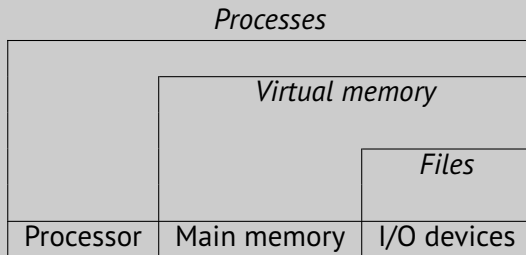


Computer System: Abstraction Layers

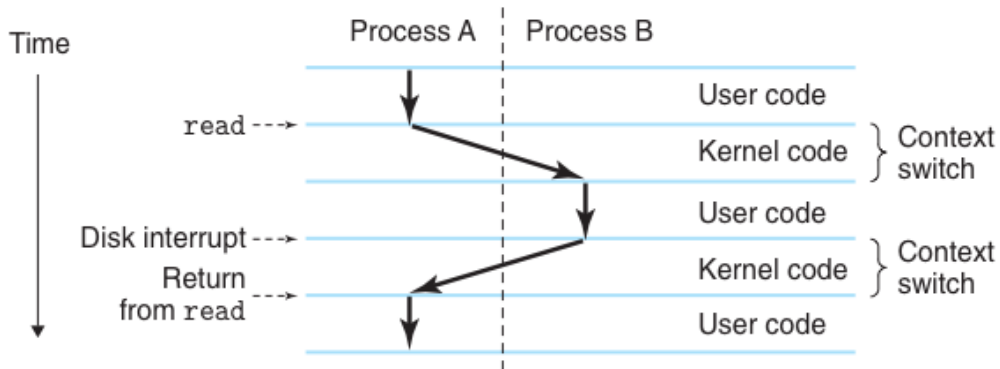
Layered view of computer system



Abstractions provided by operating system



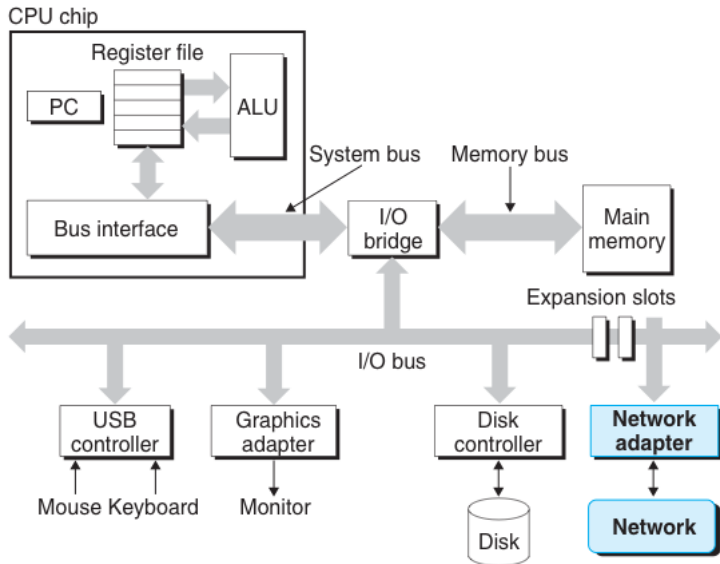
Processes



- Time-sharing via *context switching*.
- Each process has the illusion of exclusive access to the system.

The network

- Networks are systems of systems.
- How do they communicate?
- How are they made robust?



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Why do we force you to study this?

- **This course exists for two reasons**

1. The bureaucratic reason: For DS/DatØk-students to be eligible for the Master's Programme in CS, you must have been taught computer systems and network programming.
2. A better reason: Because data analysis and simulation is often performance-critical, and performance depends on understanding the abstraction layers you use.

Questions we can answer at the end of the course

- Why do computer numbers behave strangely?
- Why are some languages faster than others?
- Why are network programs often fragile?
- How do we access data efficiently?
- What does “efficiency” or “performance” even mean, and how do we quantify it?
- **What is the difference between representation and interpretation?**

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ints are not integers, floats are not reals

■ Is $x^2 \geq 0$?

▶ float: Yes!

▶ int:

▶ $40000 \times 40000 \rightarrow 1600000000$

▶ $50000 \times 50000 \rightarrow -1794967296$

■ Is $(x + y) + z = x + (y + z)$?

▶ int: Yes!

▶ float:

▶ $(10^{20} + -10^{20}) + 3.14 \rightarrow 3.14$

▶ $10^{20} + (-10^{20} + 3.14) \rightarrow 0.00$

Computer arithmetic

- Does not generate random values:
 - ▶ **Deterministic rules.**
 - ▶ Useful mathematical properties.
 - ▶ ...but not always intuitive.
- Finiteness of representation loses some usual mathematical properties:
 - ▶ `ints` are rings: Commutativity, associativity, distributivity.
 - ▶ `floats` are ordered: Monotonicity, signs.
 - Well, almost...
- What do we gain?
 - + **Performance:** hardware is *fast* at working with fixed-size data.
 - + If we understand the rules, we can write very efficient (and correct!) code.
 - + Can build slower but “more mathematical” numbers on top, as an abstraction layer.

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Summing in Python versus C

```
double s = 0;
int i = 0;
while (i < n) {
    s += i;
    i += 1;
}
```

9ms for $n = 10^7$.

```
s = 0
i = 0
while i < n:
    s += i
    i += 1
```

1604ms for $n = 10^7$.

- Why this enormous difference?
 - ▶ Computers execute *machine code instructions*.
 - ▶ C is *compiled to machine code*, Python is *interpreted by another program*.
- Is a C program always vastly faster than a Python program?
 - ▶ No: libraries like Numpy let Python perform well.
 - ▶ ...so how do they work?
 - ▶ Choice of language is not the only thing that matters.

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Memory system performance example—2.0 GHz Intel Core i7 Haswell

```
void copyij(int src[2048][2048],
            int dst[2048][2048]) {
    int i,j;
    for (i = 0; i < 2048; i++)
        for (j = 0; j < 2048; j++)
            dst[i][j] = src[i][j];
}
```

4.3ms

```
void copyij(int src[2048][2048],
            int dst[2048][2048]) {
    int i,j;
    for (j = 0; j < 2048; j++)
        for (i = 0; i < 2048; i++)
            dst[i][j] = src[i][j];
}
```

81.8ms

- Performance depends on access pattern.
- C lays out arrays in *row-major order*:

src[0][0], src[0][1], ..., src[0][2047], src[1][0], src[1][1], ...

- ▶ **Left** traverses elements with stride 1.
- ▶ **Right** traverses elements with stride 2048.

- **Locality is key to performance!**

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Quantifying performance

- **If you want to improve something, you need to be able to measure it.**
 - ▶ (At least when it comes to machines; don't treat people like machines.)
- **Previously:**
 - ▶ C: 9ms
 - ▶ Python: 1604ms
 - ▶ Clearly “the C program is faster”, but how do we report this in a standard way?
- **Different kinds of performance:**
 - ▶ **Latency** — how fast you respond or complete a task.
 - ▶ **Throughput** — how many tasks you complete per time unit.
 - ▶ **Discussion:** compare latency and throughput of cargo truck and cargo ship.
- **Scalability**
 - ▶ How does our system or program behave when we change the workload or run it on a faster machine?

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- **HPPS is programmer-centric.**

- ▶ By knowing more about the system, one becomes a more effective programmer.
 - + Faster programs.
 - + More reliable programs.
- ▶ Many of these properties are **universal**.
 - ▶ We teach you many low-level details...
 - ▶ ...but the concepts (e.g. locality) exist at every level.

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Course structure

Textbooks

HPPS: HPPS course notes (mandatory, free)

JG: Modern C (optional, free)

Assignments

- **Six** weekly group assignments.
- Preferably **three students per group**.
- **Graded** with 0-4 points.
- **No resubmissions.**
- Exam qualification: at least 10 points and **at least one point** per assignment, excluding the last one.
- **First one handed out this Thursday.**

Physical teaching

Lecture: Tuesday 10:00-12:00 (Aud 05, HCØ)

Exercises: Thursday 10:00-12:00 (locations below)

Lecture: Thursday 13:00-15:00 (Aud 05, HCØ)

Exercises: Thursday 15:00-17:00 (locations below)

Assignment café: Every Friday 13:00-15:00 (Lille UP1, DIKU)

Exercise locations

Hold 1: 10:00-12:00: 1-0-04 (DIKU)

15:00-17:00: 2.1.I.156 (NBB)

Hold 2: 10:00-12:00: Auditorium Syd (NEXS)

15:00-17:00: NBB 2.2.I.158 (NBB)

Hold 3+4: 10:00-12:00: 4-0-32 (Biocenter)

15:00-17:00: 4-0-32 (Biocenter)

Resources

Absalon

- Used for handins, announcements, and discussion forum.

Material

- <https://github.com/diku-dk/hpps-e2023-pub/>
- Handout of all material (info, assignments, exercises, slides).
- You do *not* need to use Git; just treat it as a website.

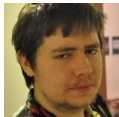
Discord

- Invite link: <https://discord.gg/9bQuzwtFKH>
- Real-time discussion.

Videos

- We made some last year that we will link when relevant.
- BOH authors have recorded their lectures, which might be interesting: <https://www.youtube.com/playlist?list=PLmBgORqEQCWy58EIwLSWwMPfkWLOLRM5R>

Teachers



Troels Henriksen:
Machine architecture,
operating systems



David Gray Marchant:
Network programming,
concurrency

Teaching assistants (TAs)

- Riasat Abbas
- Axel Højmark
- Rasmus Pallisgaard
- Jonatan Ruiz-Molsgaard

TAs may also help with:

- Group members.

Groups

Size

2-3 student advised. 1 can be accepted but not recommended. More than 3 is only allowed under special circumstances.

- Sign up for classes with your group-mates on Absalon.
- If you need one or more members:
 - ▶ Post on Discord
 - ▶ Post on the Absalon discussion board
 - ▶ Ask a TA
 - ▶ **Do it as soon as possible!**

Assignment rules

Core rule

Each group must construct their own solution.

This means

- You can talk with other people about the assignments: Teachers, TAs, other students, etc.
- You cannot share written code with other groups.
- You are not allowed to use code that you did not write yourself, without proper citation.
- You cannot share written text with other groups.
- You are not allowed to use text of material, without proper citation
 - ▶ This also includes material provided by the course.

Assignments versus exercises

- Note! Both are important.
- The exercises
 - ▶ Most exercises essentially have you develop the code handed out for the assignment.
 - ▶ For the assignment, can use either your own code or the assignment code handout.
- **Assignments assume that you have solved the related exercises.**
 - ▶ Assignment code handout may be hard to understand otherwise.

Tools

- C compiler – gcc or clang.
- C debugger – gdb on Linux or lldb on macOS.
- You can also install all tools on your laptop
 - ▶ Linux: available through your package manager.
 - ▶ macOS: available through Homebrew.
 - ▶ Windows: Windows Subsystem for Linux.
- Set up your tool chain
 - ▶ We recommend using Git to share code and reports in your group.
 - ▶ Sign-up at GitHub today and apply for the *Student Developer Pack*.
 - ▶ <https://education.github.com/>.

Exam

- **Three-day individual take home exam.**
 - ▶ (Designed for 20 hours of labour; the exam office keeps changing how many days this is actually spread over.)
- Intended to be very similar to assignments:
 - ▶ Analyse a program based on what you have learnt.
 - ▶ Rewrite it to make it faster.
 - ▶ Write a (short!) report.
- The course curriculum is the exercises, assignments and reading material.
- Examples of previous exams will be made available.

QUESTIONS?