CSCI-UA.0201

Computer Systems Organization

Introduction

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What we will learn in this course

- What happens under the hood when you boot your computer and start running applications?
- How do software and hardware interact?
- This course is programmer-centric
  - Understanding of underlying system makes you a more effective programmer and helps you find hidden bugs!
  - Bring out the hidden hacker in everyone
  - Be way more efficient debugger
  - Tune your programs for performance

But also we want

- To use what you have learned in *MANY* different contexts
- To start your research project if you want
- To know the big picture of the whole computing stack.

Course Information and Resources

- Course web page (general info, syllabus, etc.)

  http://cs.nyu.edu/wies/teaching/cso-fa19/

- Piazza (announcements, course related discussions)

  https://piazza.com/class/jznb6uqqbcd4e6

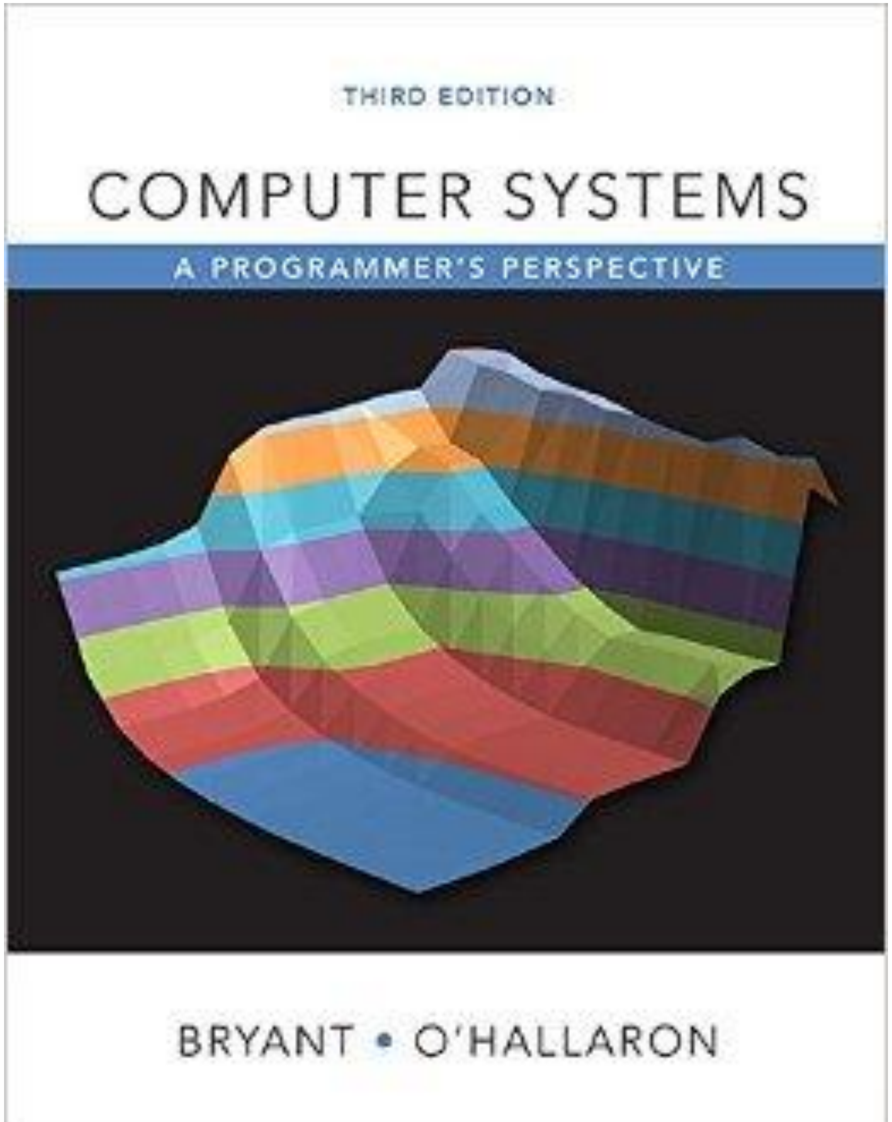
  You should already be enrolled. Please complete the questionnaire!

- Github (sample code, assignment submission)

  https://github.com/nyu-cso-005-fa19

- NYU classes (grade distribution only)

Textbook



Randy Bryant

Dave O'Hallaron

Important Dates

- Class meetings
  - Monday and Wednesdays, 3:30-4:45pm
- Recitations (Goktug Saatcioglu)
  - Thursdays, 12:30-1:45pm
- Office hours
  - Thomas Wies: Tuesdays, 4-5pm in 60FA 403
  - Goktug Saatcioglu: Fridays, 3-4pm in WWH 905
  - or by appointment
- Midterm exam
  - Wednesday, Oct 23, 3:30-4:45pm
- Final exam
  - Wednesday, Dec 18, 4:00-5:50pm

Course Components

- **Lectures**
  - Higher level concepts
  - slides + reading material from the textbook
- **Assignments and Programming labs** (30%)
  - roughly bi-weekly
  - provide in-depth understanding of some aspect of systems
  - also serve as exam preparation
- **Midterm Exam** (30%)
- **Final Exam** (40%)

Submission Policy

- You must work alone on all assignments

- Pay attention to due dates/times
(announced on Piazza).

- Submission is via Github (more on that later).

- Late submissions will be graded with a 10% penalty per (started) day of late submission.

- No solutions will be accepted one week after the submission deadline.

Integrity and Collaboration

- What is **cheating**?
  - **Sharing code**: by copying, retyping, **looking at**, or supplying a file
  - **Describing code**: verbal description of code from one person to another.
  - **Coaching**: helping your friend to write a lab, line by line
  - **Searching the Web** for solutions
  - **Copying code from a previous course or online solution**
    - You are only allowed to use code we supply

- What is NOT cheating?
  - Explaining how to use systems or tools
  - Helping others with high-level design issues

- Ignorance is not an excuse

We have sophisticated tools for detecting code plagiarism

Main Topics

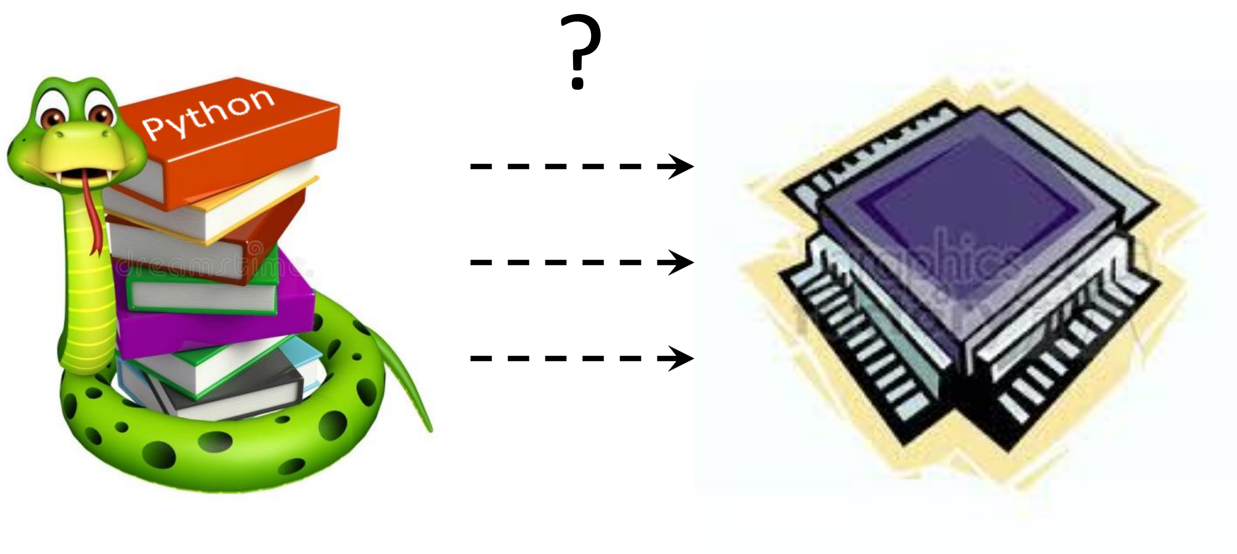
- Basic C Programming
- Representation of programs and data
- Memory hierarchy and systems hardware
- Basic Assembly Programming
- Dynamic memory allocation
- Virtual Memory
- Concurrency & Processes

Abstraction in Computer Science

The effective exploitation of his powers of abstraction must be regarded as one of the most vital activities of a competent programmer. Edsger Dijkstra

- Computer system can be viewed as layers of abstractions
- Most CS courses emphasize abstraction
  - e.g. data types, high-level programming languages

Abstraction in Computer Science

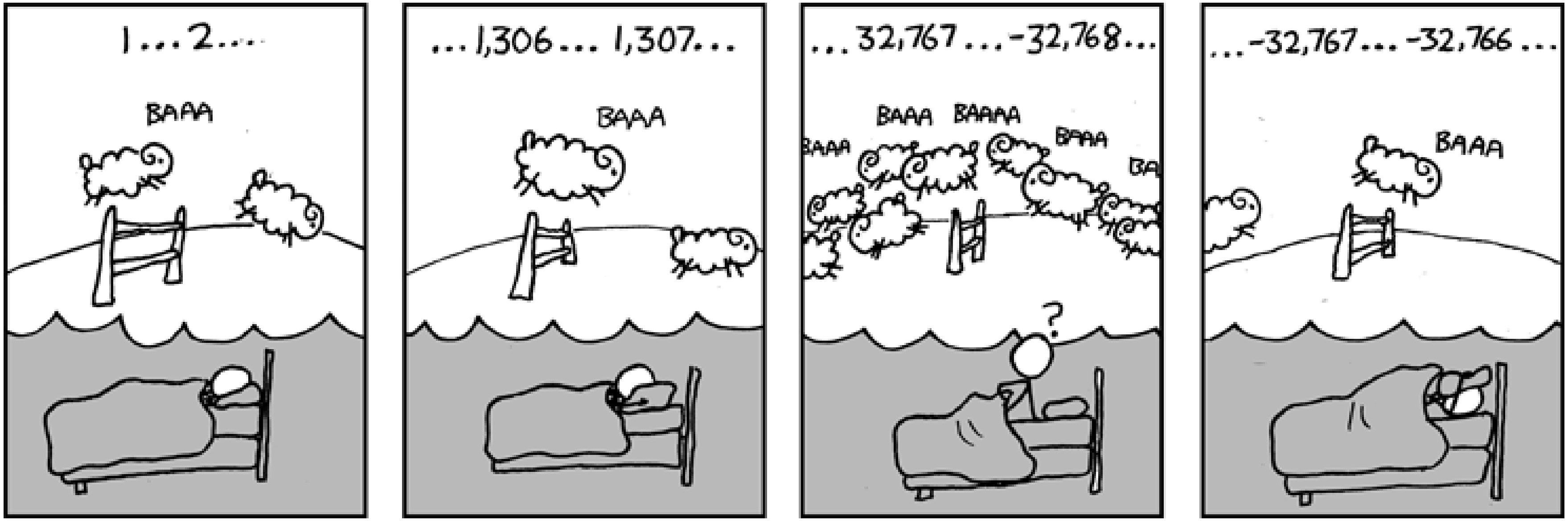


[Computer scientists] are individuals who can rapidly change levels of abstraction, simultaneously seeing things 'in the large' and 'in the small'. Donald Knuth

Course Goals

- Computer system can be viewed as layers of abstractions
- Sometimes you must break through these abstractions
- This class helps you:
  - peek *under-the-hood*
  - understand these layers to see the big and the small picture
  - become more effective programmers
    - Debug problems
    - Tune performance
  - prepare for later courses in CS
    - Compilers, Operating Systems, Computer Architecture, Distributed Systems, parallel computing, …

Reality #1:
Ints are not Integers
Floats are not Reals



Source: xkcd.com/571

- $x^2 \geq 0$? Overflow!!
- $(x + y) + z = x + (y + z)$? $10^{20}+(-10^{20}+3.14)$!= 3.14

Arithmetic Overflow

Ariane 5 maiden flight

Cause: software error in inertial reference system
64 bit floating point number relating to the horizontal velocity of the rocket with respect to the platform was converted to a 16 bit signed integer.

Reality #2: You've Got to Know Assembly

- Usually no need to program in assembly
- Knowledge of assembly helps one understand machine-level execution
  - Debugging
  - Performance tuning
  - Writing system software (e.g. compilers , OS)
  - Creating / fighting malware
    - x86 assembly is the language of choice!

Reality #3: Memory Matters

- Memory is not unbounded
  - It must be allocated and managed
- Memory referencing bugs especially wicked
- Memory performance is not uniform
  - Cache and virtual memory effects can greatly influence performance

Memory Referencing Errors

- C/C++ let programmers make memory errors
  - Out of bounds array references
  - Invalid pointer values
  - Double free, use after free
- Errors can lead to nasty bugs
  - Corrupt program objects
  - Security vulnerabilities
  - Effect of bug observed long after the corruption

Memory Referencing Bug Example

```
double fun(int i)
{
  int a[2];
  double d[1] = {3.14};
  a[i] = 1073741824; /* Possibly out of bounds */
  return d[0];
}
```

```
fun(0)  =    3.14
fun(1)  =    3.14
fun(2)  =    ?
fun(3)  =    ?
fun(4)  =    ?
```

Heartbleed Bug - I love OpenSSL

```
/* Read type and payload length first */
hbtype = *p++;
n2s(p, payload);
pl = p;
/* Enter response type, length and copy payload */
*bp++ = TLS1_HB_RESPONSE;
s2n(payload, bp);
memcpy(bp, pl, payload);
```

value of payload controlled by attacker
memcpy may copy memory beyond payload buffer

Reality #4: Asymptotic performance is not always sufficient

- Factors like memory access, communication, etc. matter
- Even operation count might not predict performance
- Must understand system to optimize performance
  - How are programs compiled and executed?
  - How to measure performance and identify bottlenecks?
  - How to improve performance without destroying code modularity and generality?

Memory System Performance Example

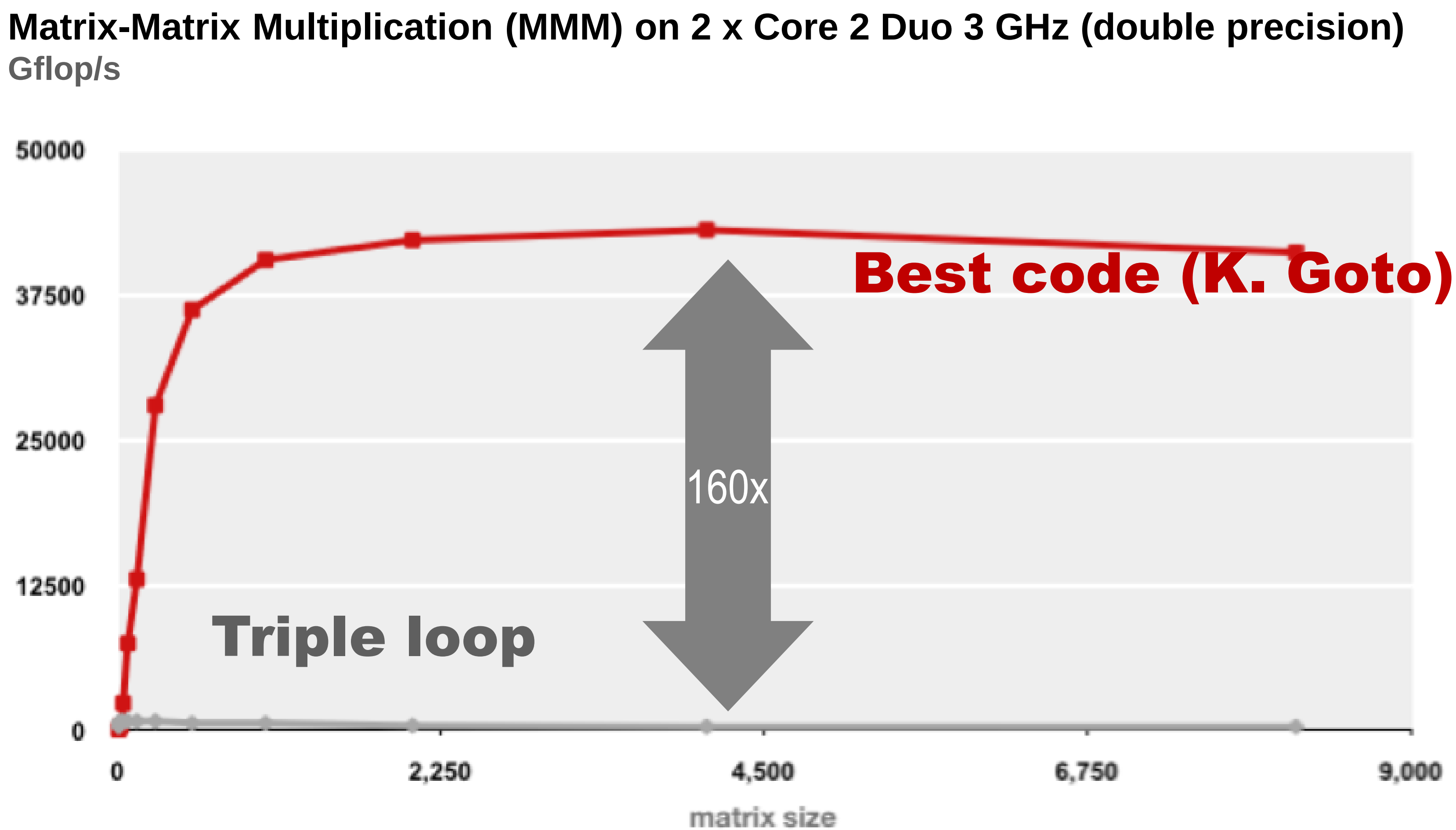
```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

```
void copyji(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];
}
```

~21 times slower

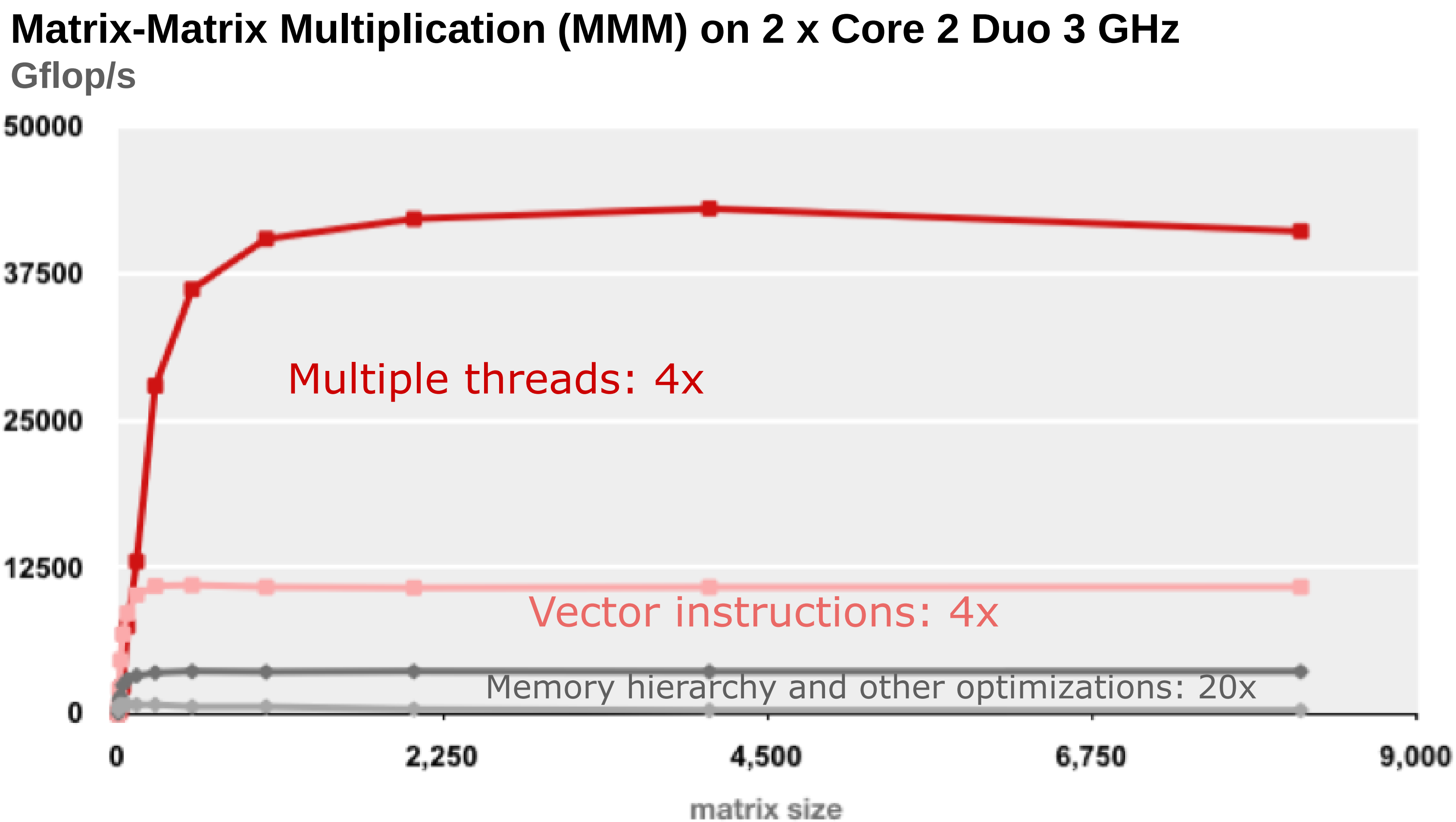
- Performance depends on access patterns

Example Matrix Multiplication



- Standard desktop computer and compiler
- Both implementations have exactly the same operations count ($2n^3$)

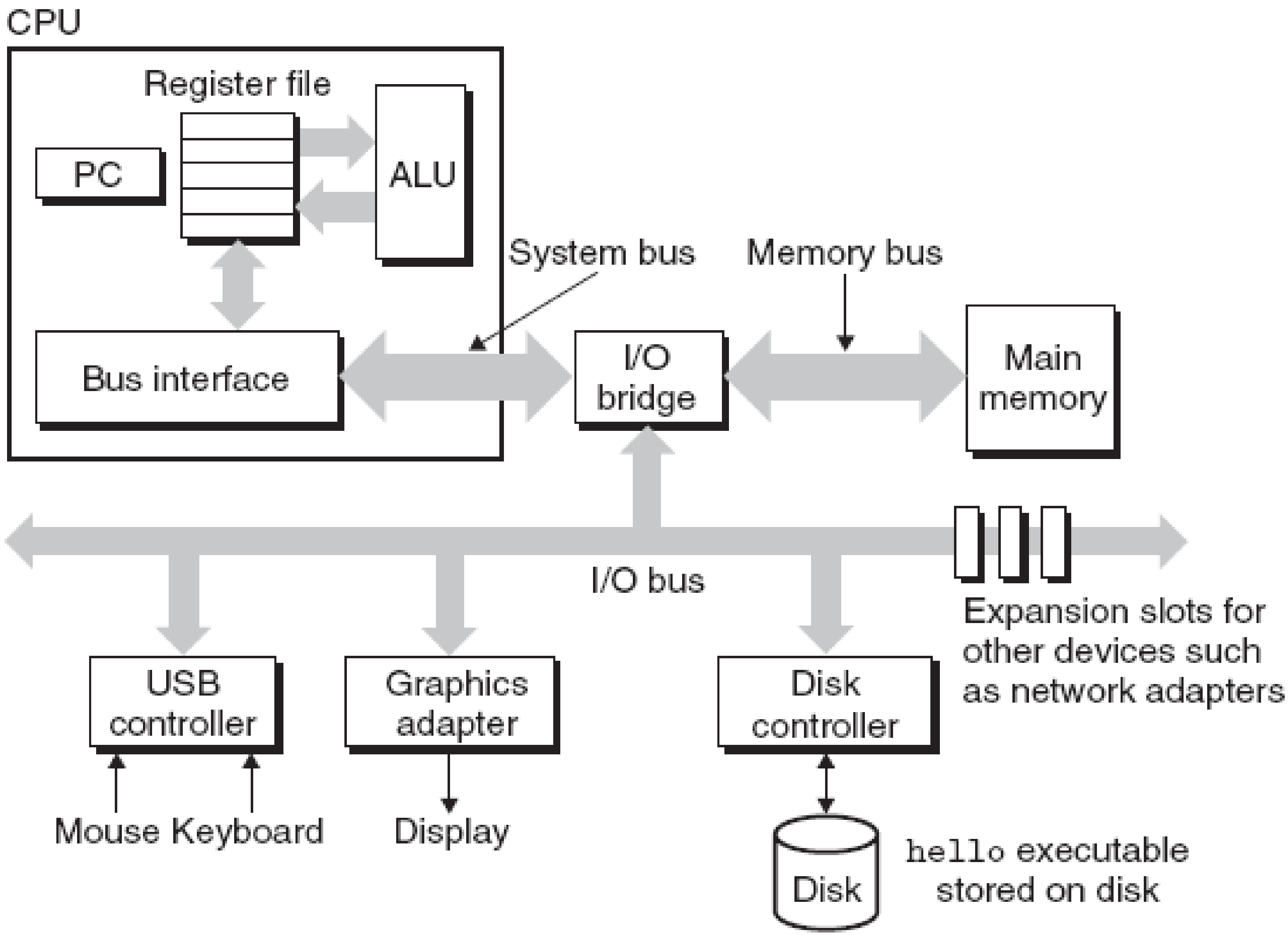
MMM Plot: Analysis



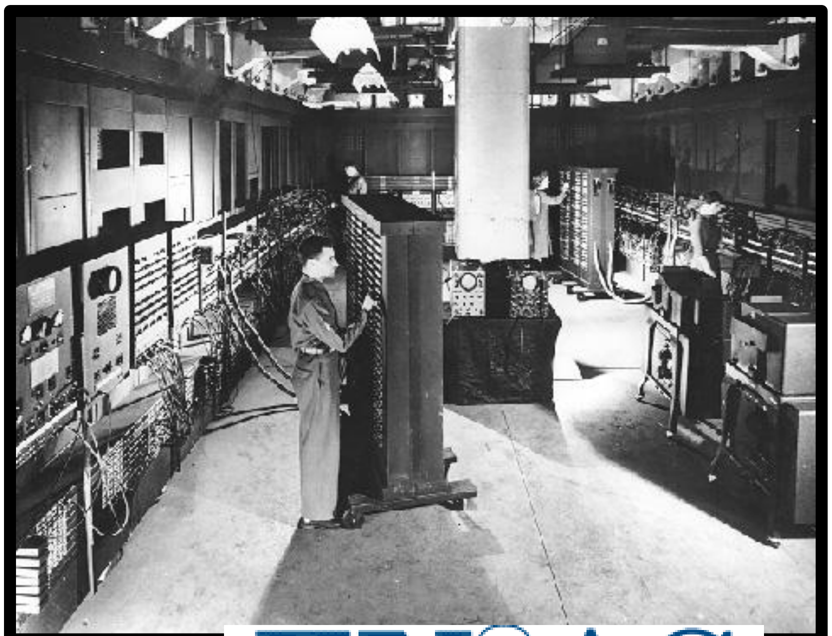
- Reason for 20x: Blocking or tiling, loop unrolling, array scalarization
- ***Effect: fewer register spills, L1/L2 cache misses, and TLB misses***

Reality #5: Computers are more than the CPU

- They need to do I/O (get data in and out)
- They communicate with each other over networks
  - Concurrent operations by autonomous processes
  - Coping with unreliable media
  - Cross platform compatibility
  - Complex performance issues


CPU
Register file
PC
ALU
System bus
Memory bus
Bus interface
I/O bridge
Main memory
I/O bus
Expansion slots for other devices such as network adapters
USB controller
Graphics adapter
Disk controller
Mouse Keyboard
Display
Disk
hello executable stored on disk

A Little Bit of History



ENIAC

Eckert and Mauchly

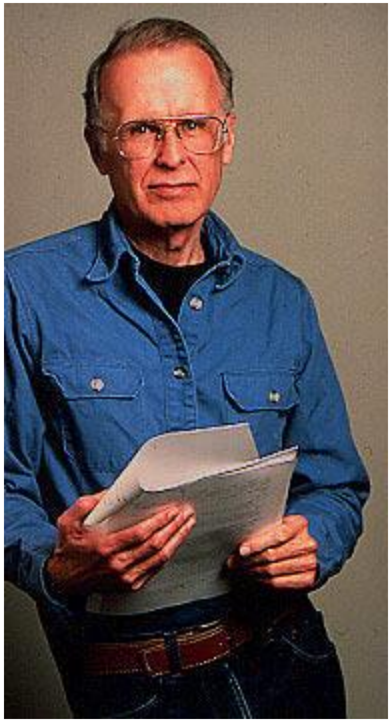
- 1^{st} working electronic computer (1946)
- 18,000 Vacuum tubes
- 1,800 instructions/sec
- 3,000 ft^3

A Little Bit of History

- 1954 IBM developed 704
- All programming done in assembly
- Software costs exceed hardware costs!

A Little Bit of History

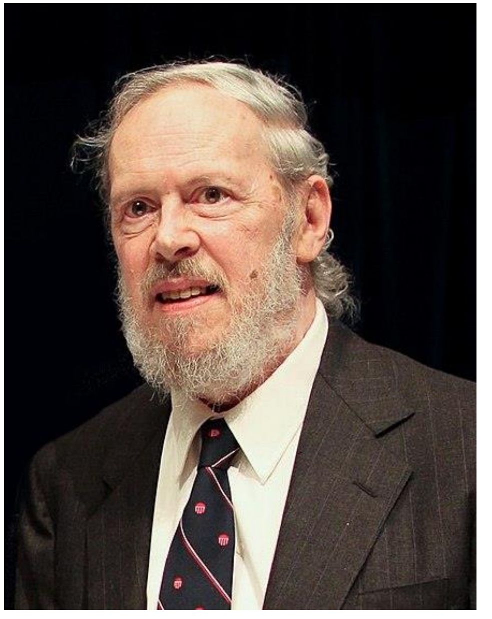
- Fortran I (project 1954-57)
- The main idea is to translate high-level language to assembly
- Many thought this was impossible!
- In 1958 more than 50% of software in assembly!
- Development time halved!



John Backus
(December 3, 1924 – March 17, 2007)

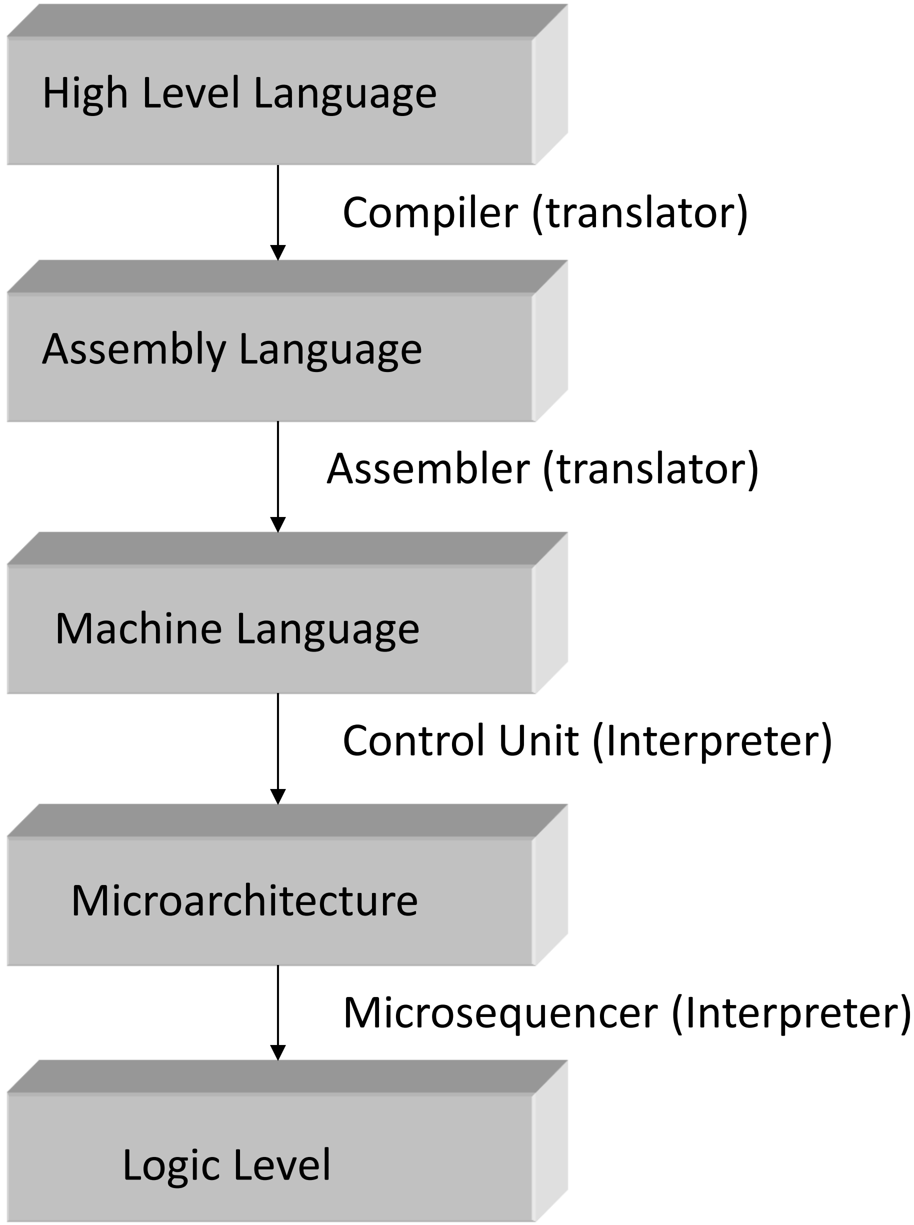
A Little Bit of History

- C (1973)
- General purpose language that efficiently translates to assembly.
- Still de facto the language of choice for systems programming
- Current standard: C18



Dennis Ritchie
(September 9, 1941 – October 12, 2011)

Problem → Algorithm Development → Programmer



Device Level → Semiconductors → Quantum

Source Code to Execution