Parallel and Distributed Computation

Introduction

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https://kevinsuo.github.io/

Outline

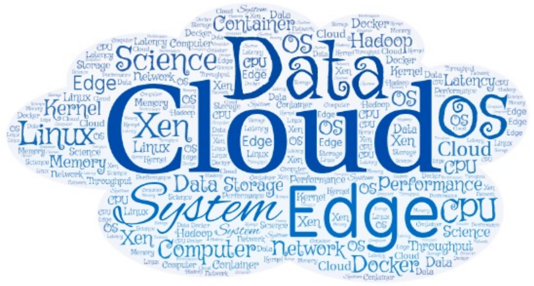
- Why study parallel and distributed computation?
- What to learn?
- Course structure
- Course policy
- An example of parallel and distributed computation

Self Introduction

- Kun Suo, Ph.D.
  - Homepage, https://kevinsuo.github.io/

- Research interests:
  - Cloud computing and virtualization;
  - Parallel and Distributed Computation, containers and kubernetes;
  - Software defined network (SDN) and network function virtualization (NFV)
  - Big data systems and machine learning systems

- Projects you may be interested in:
  - Several projects in Cloud & Data & Edge
  - https://kevinsuo.github.io/code-lab.html



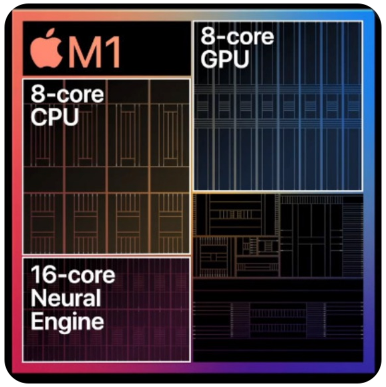
Now it's your turn

- Name, program/year, where from
- Your interests in Computer Science
- Have you ever used or heard of parallel and distributed system? Can you name some of them? What do you expect from this course?

https://www2.eecs.berkeley.edu/Research/Areas/CS/

If you are in the online course, introduce yourself in D2L, Discussions → Self-Introduction

Example of parallel and distributed system



personal computer

internet

cloud

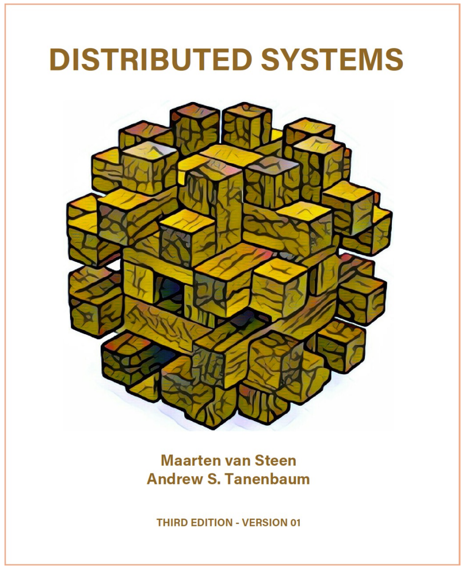
Social system

Course Information

- Instructor: Dr. Kun Suo
- Office: J-318
- Email: ksuo@kennesaw.edu
  - Only reply to e-mails that are sent from KSU student email accounts and title the course number [CS4504]
- Office Hours:
  - Email or Microsoft Teams
  - By appointment
- Course Materials
  - Homework assignments, lecture slides, and other materials will be posted in the webpage (https://kevinsuo.github.io/teaching.html) and D2L.

Reference Book

- "Distributed Systems 3rd edition (2017)" by M. van Steen and A.S. Tanenbaum:
  - ISBN-13: 978-1543057386
  - You can get a digital copy of this book for free: https://www.distributed-systems.net/index.php/books/ds3/



Prerequisites

- Computer basics that are supposed to covered in *(CS 3502) Operating Systems* and *(CS 3503) Computer Organization and Architecture* course.
- C programming (code reading, kernel development and debugging). (Famous projects in C)
- Linux command line environment (compiling, Makefile, debugging, simple shell programming).

For C and Linux beginners

- C tutorial
  - https://www.tutorialspoint.com/cprogramming/
  - https://www.learn-c.org
  - https://www.cprogramming.com/tutorial/c-tutorial.html

- Linux tutorial
  - https://ryanstutorials.net/linuxtutorial/
  - http://www.ee.surrey.ac.uk/Teaching/Unix/
  - https://www.tutorialspoint.com/unix/

Project Environment

- Recommend project environment (local)
  - VirtualBox + Ubuntu + Linux

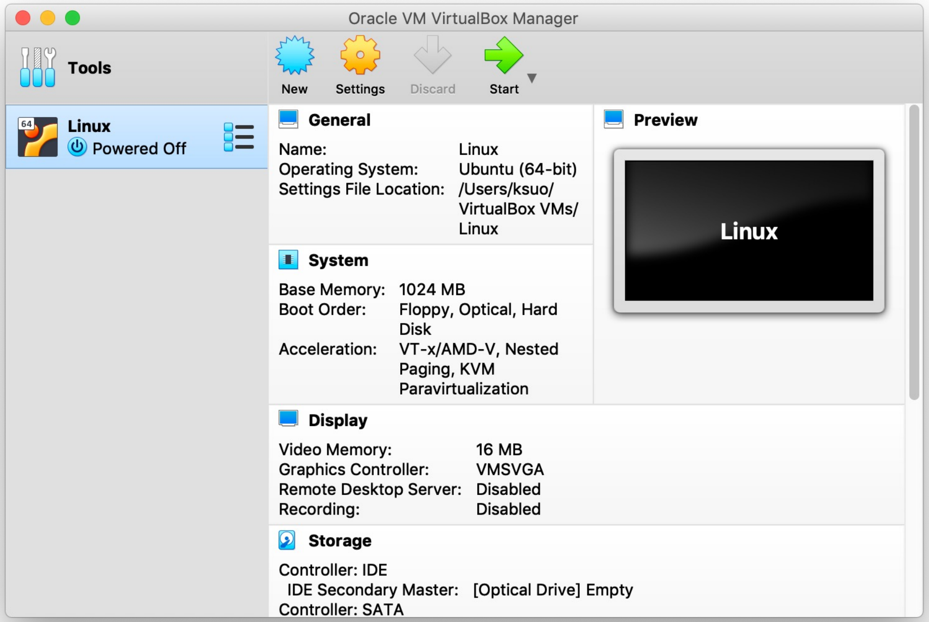
Virtual machine

VM OS

VM OS Kernel

https://www.virtualbox.org/

https://ubuntu.com/download/desktop



General

Name: Linux
Operating System: Ubuntu (64-bit)
Settings File Location: /Users/ksuo/VirtualBox VMs/Linux

System

Base Memory: 1024 MB
Boot Order: Floppy, Optical, Hard Disk
Acceleration: VT-x/AMD-V, Nested Paging, KVM Paravirtualization

Display

Video Memory: 16 MB
Graphics Controller: VMSVGA
Remote Desktop Server: Disabled
Recording: Disabled

Storage

Controller: IDE
IDE Secondary Master: [Optical Drive] Empty
Controller: SATA

Project Environment

- Recommend project environment (local)
  - VirtualBox + Ubuntu + Linux
- New to VirtualBox?
  - https://oracle-base.com/articles/vm/virtualbox-creating-a-new-vm
  - https://www.youtube.com/watch?v=sB_5fqiysi4
  - https://youtu.be/GDoCrfPma2k (MacOS)

- You can access to VMs in KSU data centers (cloud) through https://cseview.kennesaw.edu/,
  - username: administration; password: linuxadmin

Why study parallel and distributed computation?

- Most computer systems today are a certain form of parallel/distributed systems
  - Internet, datacenters, super computers, mobile devices
  - Most of the applications are parallel or even distributed apps (example: debug decompress file app, link, starts at 2:33)
- To learn useful techniques to build large systems
  - A system with 10,000 nodes is different from one with 100 nodes
- How to deal with imperfections
  - Machines can fail; network is slow; topology is not flat

What to learn

- Parallel:
  - Library (Pthread, OpenMP, MPI)
- Distribute:
  - Architectures
  - Processes
  - Communication
  - Synchronization
  - Consistency and replication
  - Fault tolerance and reliability
  - Distributed file systems, distributed scheduling systems, …

Expected Outcomes

- Familiar with popular parallel programming libraries (Pthread, OpenMP, MPI)
- Familiar with fundamentals of distributed systems
- The ability to
  - Evaluate the performance of parallel and distributed systems
  - Write simple parallel and distributed programs
  - Understand the tradeoffs in distributed system design

Course Structure

- Lectures
  - Time/Location
  - D2L/Course website
- Projects
  - 4 programming assignments
  - 1 paper/project presentation
- Exams (open books)
  - Midterm: online D2L, TBA.
  - Final: online D2L, TBA

Course Policy

- Grading scale

Percentage	Grade
90 - 100	A
80 - 89	B
70 - 79	C
60 - 69	D
Below 60	F

Grading Policy (cont.)

- Grading percentage
  - Projects (x4): 40%
  - Presentation: 10%, including project or paper presentation
  - Midterm: 20%
  - Final exam: 30%

Late submission policy: late submission will **not be accepted** and **no credits**

Academic Integrity

- Academic dishonesty

https://scai.kennesaw.edu/KSU_Codes_of_Conduct_2019-2020.pdf

  - Cheating
  - Plagiarism
  - Collusion
  - The submission for credit of any work or materials that are attributable in whole or in part to another person
  - Taking an examination for another person
  - Any act designed to give unfair advantage to a student or the attempt to commit

Receiving, attempting to receive, knowingly giving or attempting to give unauthorized assistance…

Do not upload course documents to 3rd party website without author's permission

Where to go for help ?

- Ask questions in class

- Ask questions outside class
  - Classmates and friends

- Attend office hours
  - Send Dr. Kun Suo emails or leave message on teams

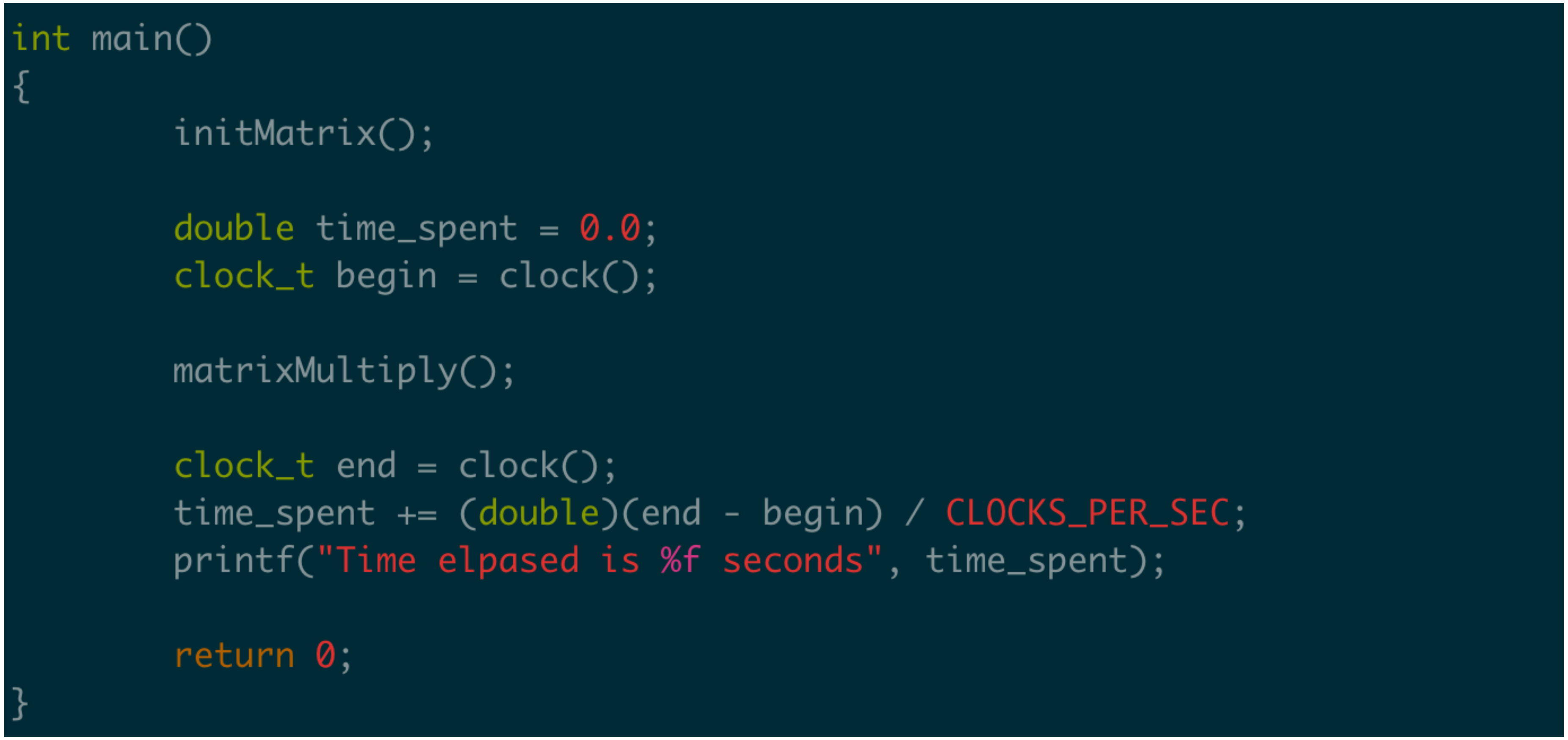
- Search on the web
  - Stand on the shoulder of giants

An example of parallel and distributed computation: Matrix multiplication

$$\begin{array}{cccccc} & & & \begin{array}{cc}\vec{b_1} & \vec{b_2}\\ \downarrow & \downarrow\end{array} & & \\ \begin{array}{c}\vec{a_1}\rightarrow\\ \vec{a_2}\rightarrow\end{array} & \begin{bmatrix}1 & 7\\ 2 & 4\end{bmatrix} & \cdot & \begin{bmatrix}3 & 3\\ 5 & 2\end{bmatrix} & = & \begin{bmatrix}\vec{a_1}\cdot\vec{b_1} & \vec{a_1}\cdot\vec{b_2}\\ \vec{a_2}\cdot\vec{b_1} & \vec{a_2}\cdot\vec{b_2}\end{bmatrix} \\ & A & & B & & C\end{array}$$

Matrix multiply

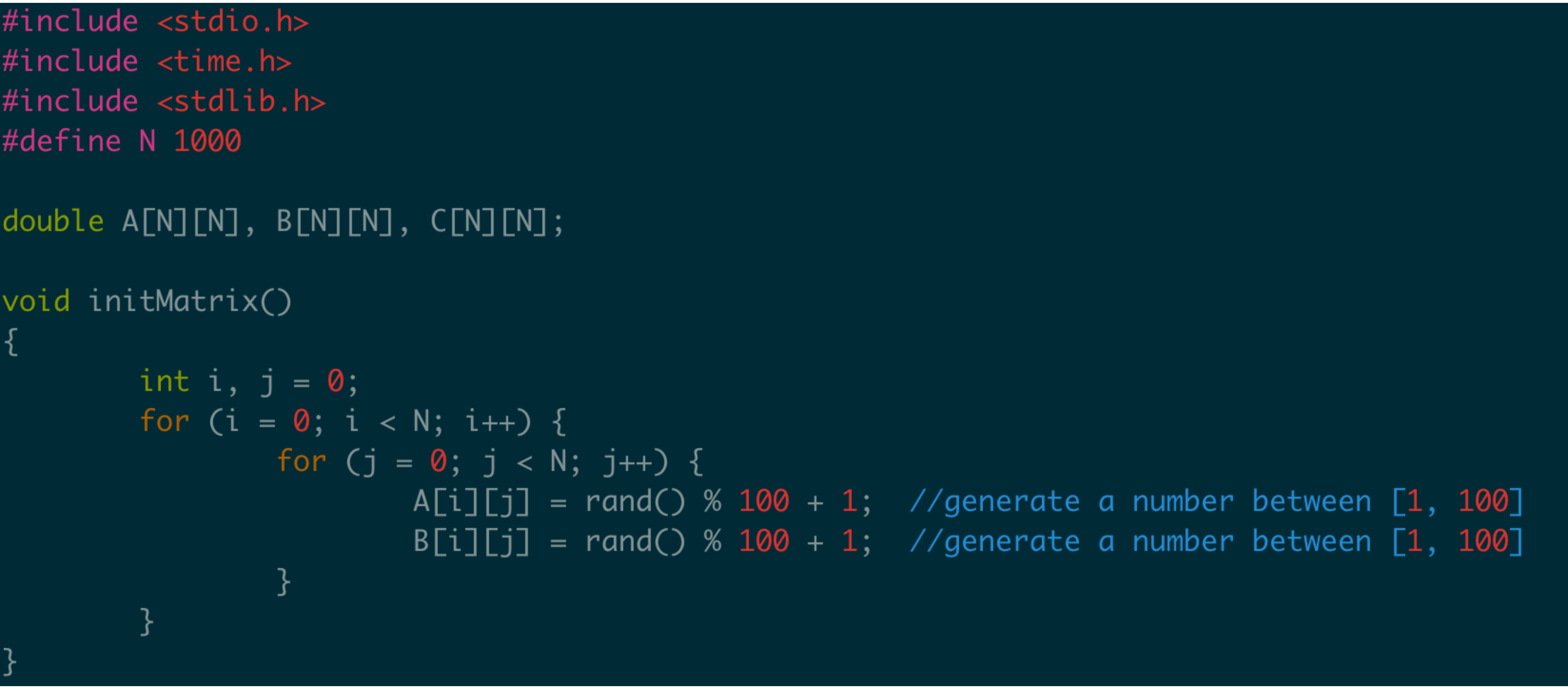
https://github.com/kevinsuo/CS7172/blob/master/matrix.c



```c
int main()
{
        initMatrix();

        double time_spent = 0.0;
        clock_t begin = clock();

        matrixMultiply();

        clock_t end = clock();
        time_spent += (double)(end - begin) / CLOCKS_PER_SEC;
        printf("Time elpased is %f seconds", time_spent);

        return 0;
}
```

Matrix multiply

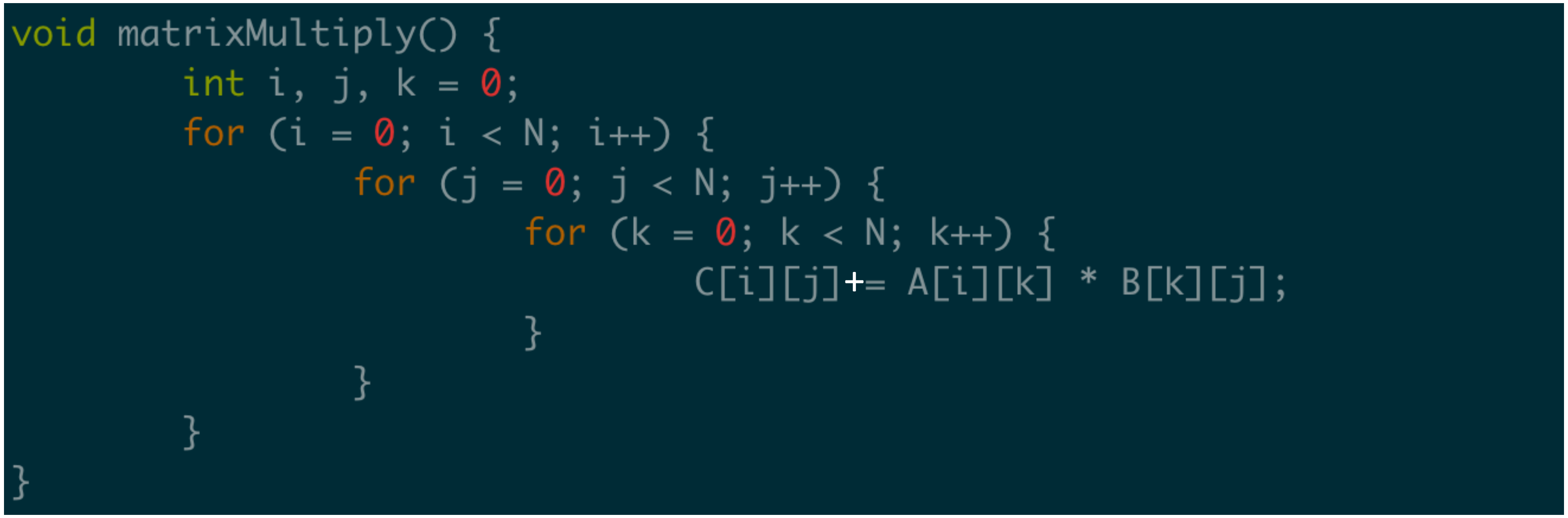
https://github.com/kevinsuo/CS7172/blob/master/matrix.c



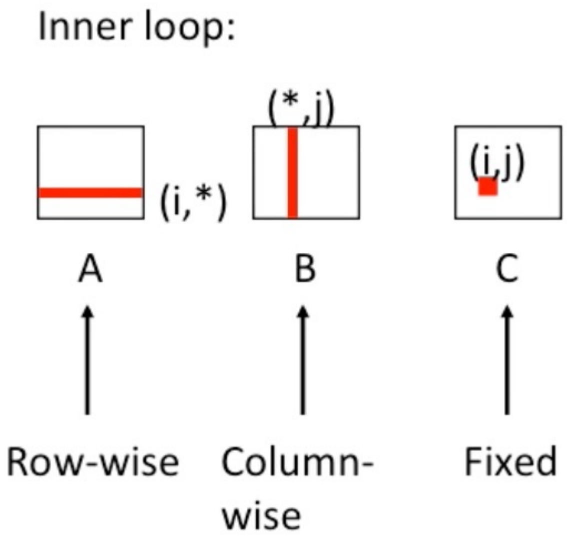
```c
#include <stdio.h>
#include <time.h>
#include <stdlib.h>
#define N 1000

double A[N][N], B[N][N], C[N][N];

void initMatrix()
{
        int i, j = 0;
        for (i = 0; i < N; i++) {
                for (j = 0; j < N; j++) {
                        A[i][j] = rand() % 100 + 1;  //generate a number between [1, 100]
                        B[i][j] = rand() % 100 + 1;  //generate a number between [1, 100]
                }
        }
}
```

Matrix multiply

https://github.com/kevinsuo/CS7172/blob/master/matrix.c

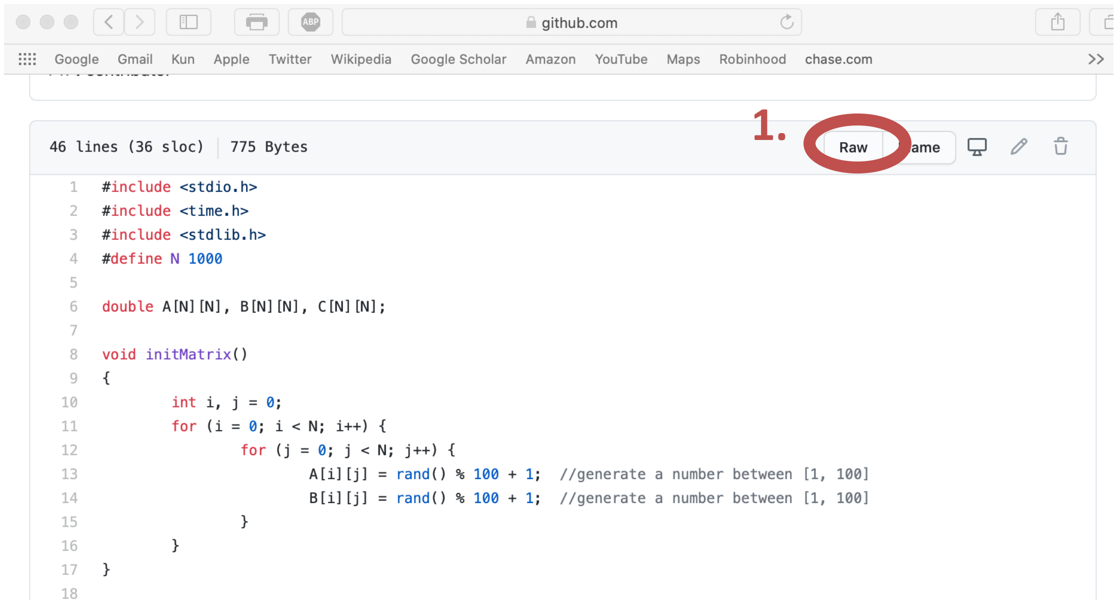


```c
void matrixMultiply() {
        int i, j, k = 0;
        for (i = 0; i < N; i++) {
                for (j = 0; j < N; j++) {
                        for (k = 0; k < N; k++) {
                                C[i][j]+= A[i][k] * B[k][j];
                        }
                }
        }
}
```



Matrix multiply

https://github.com/kevinsuo/CS7172/blob/master/matrix.c

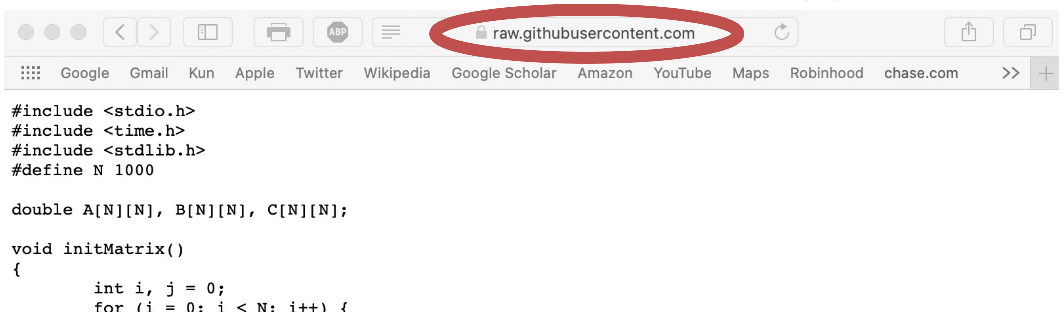

github.com
Google Gmail Kun Apple Twitter Wikipedia Google Scholar Amazon YouTube Maps Robinhood chase.com
46 lines (36 sloc) | 775 Bytes
Raw
ame

1.

```
#include <stdio.h>
#include <time.h>
#include <stdlib.h>
#define N 1000

double A[N][N], B[N][N], C[N][N];

void initMatrix()
{
        int i, j = 0;
        for (i = 0; i < N; i++) {
                for (j = 0; j < N; j++) {
                        A[i][j] = rand() % 100 + 1;  //generate a number between [1, 100]
                        B[i][j] = rand() % 100 + 1;  //generate a number between [1, 100]
                }
        }
}

```

```
ksuo@ltksup50143mac ~>
```

2. Copy the URL


raw.githubusercontent.com
Google Gmail Kun Apple Twitter Wikipedia Google Scholar Amazon YouTube Maps Robinhood chase.com

```
#include <stdio.h>
#include <time.h>
#include <stdlib.h>
#define N 1000

double A[N][N], B[N][N], C[N][N];

void initMatrix()
{
        int i, j = 0;
```

3.

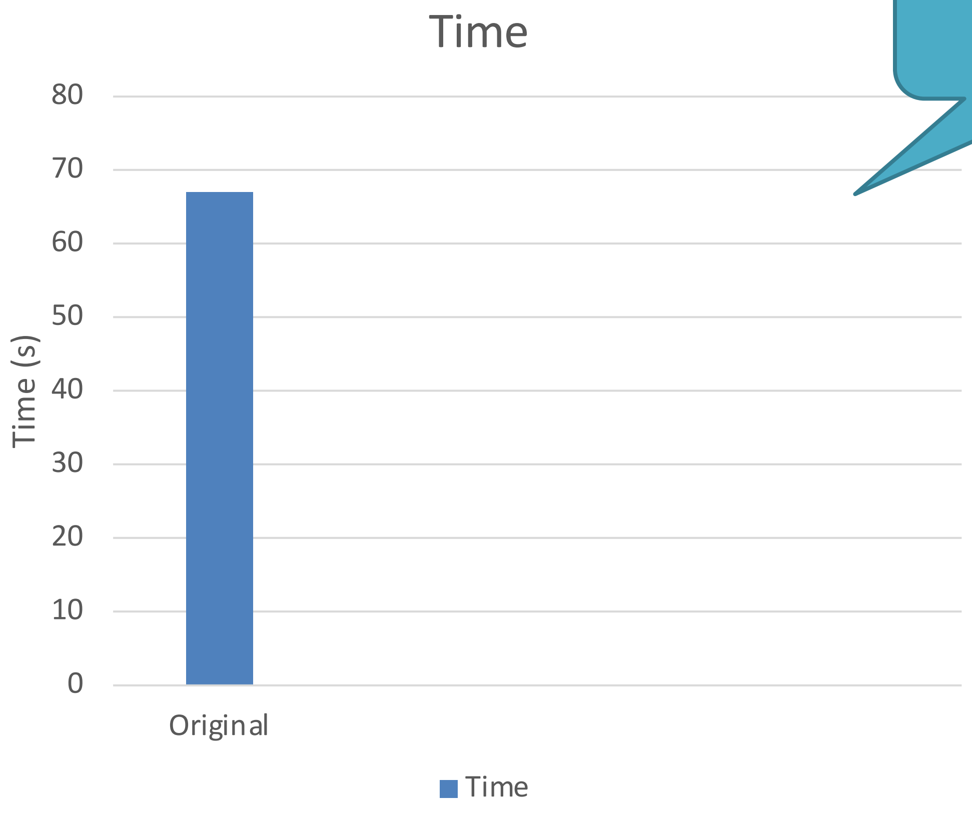
$ wget URL

$ gcc filename.c –o filename.o

$ ./filename.o

(if no wget/gcc,
$ sudo apt install wget, gcc)

Matrix multiply

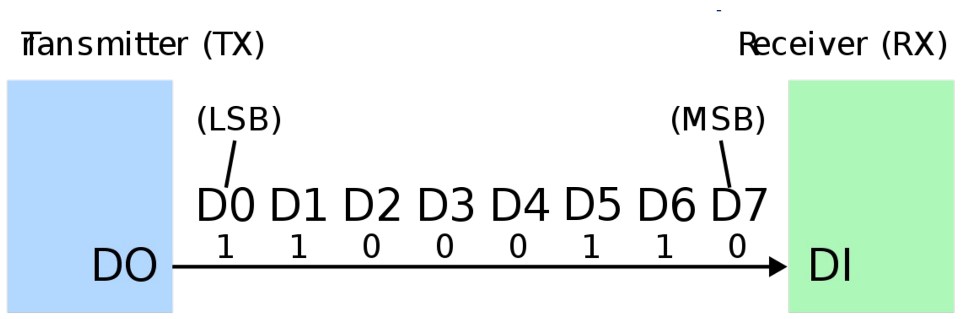


How to run it faster?

1. Accelerate serial execution

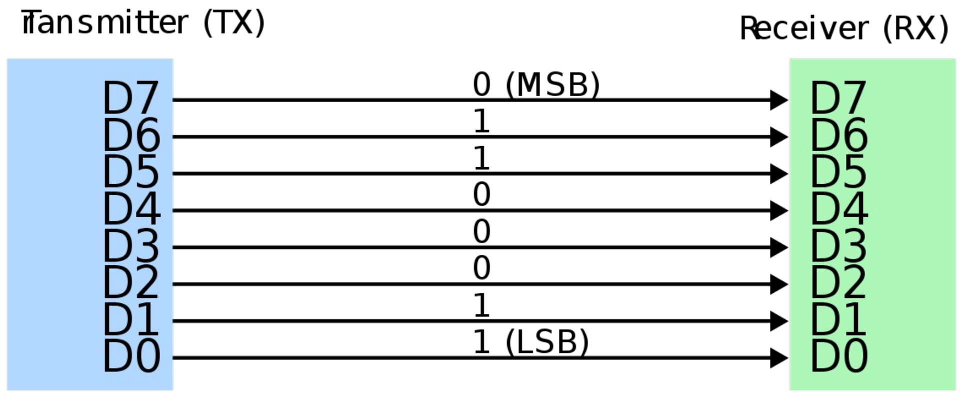
2. Accelerate in parallel

How to run it faster?

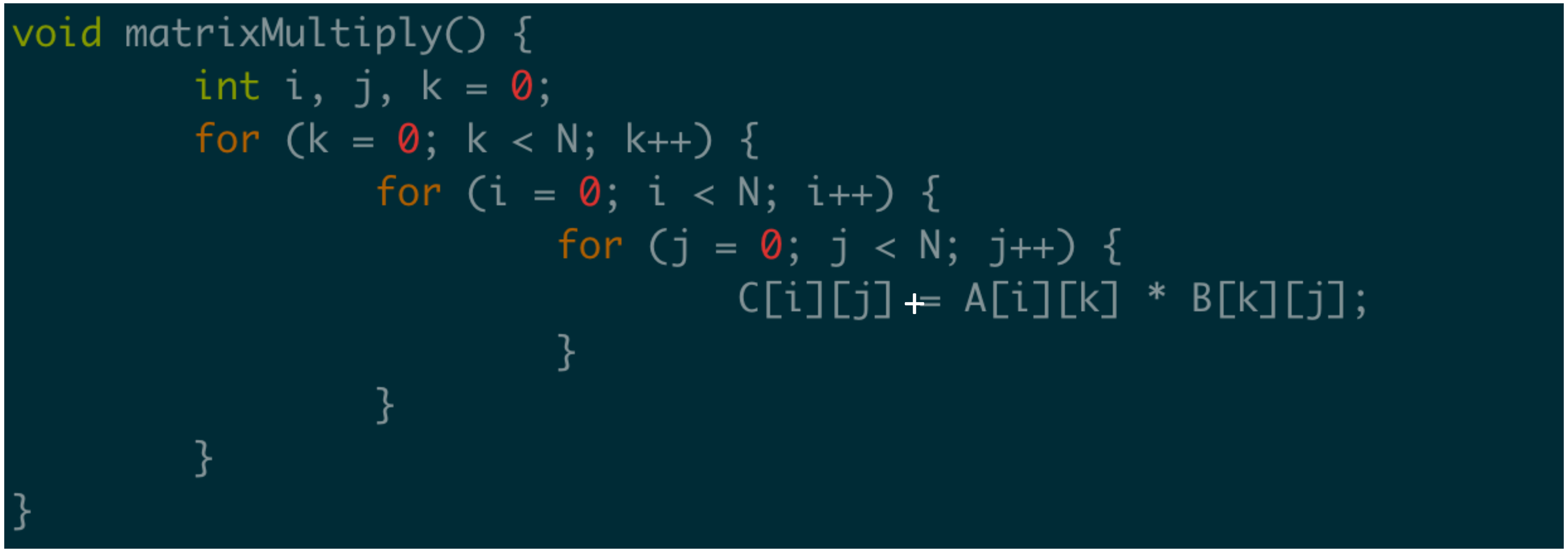


1. Accelerate serial execution
Reduce unnecessary steps

2. Accelerate in parallel

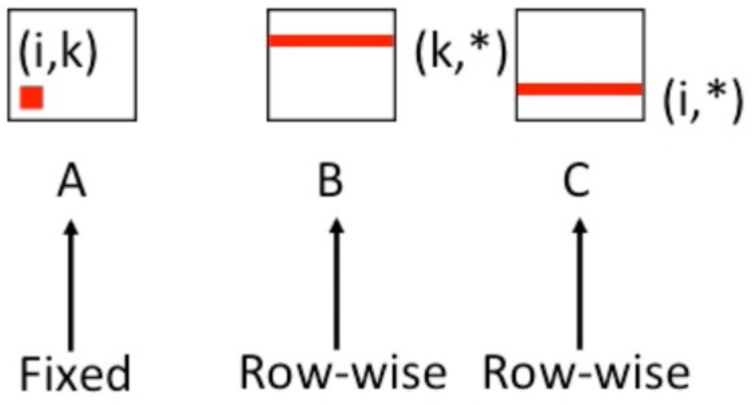


Option 1: Optimization using locality



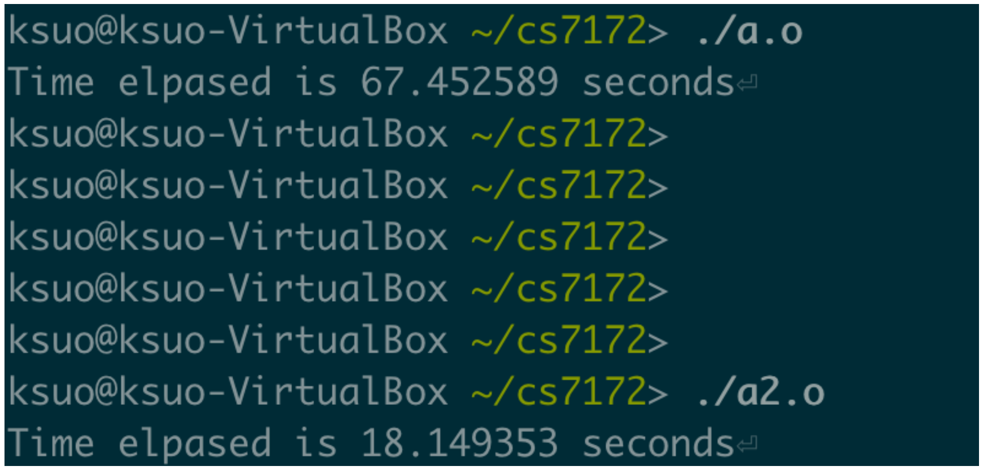
```
void matrixMultiply() {
        int i, j, k = 0;
        for (k = 0; k < N; k++) {
                for (i = 0; i < N; i++) {
                        for (j = 0; j < N; j++) {
                                C[i][j] += A[i][k] * B[k][j];
                        }
                }
        }
}
```

Inner loop:



https://github.com/kevinsuo/CS7172/blob/master/matrix-opt.c

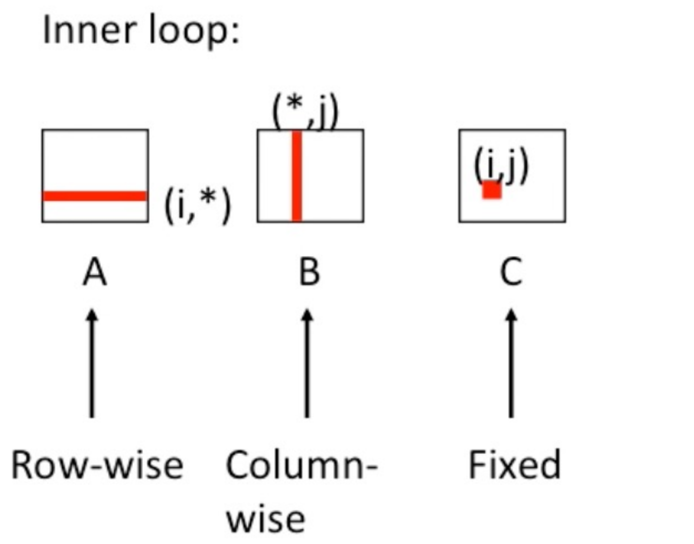
Option 1: Optimization using locality

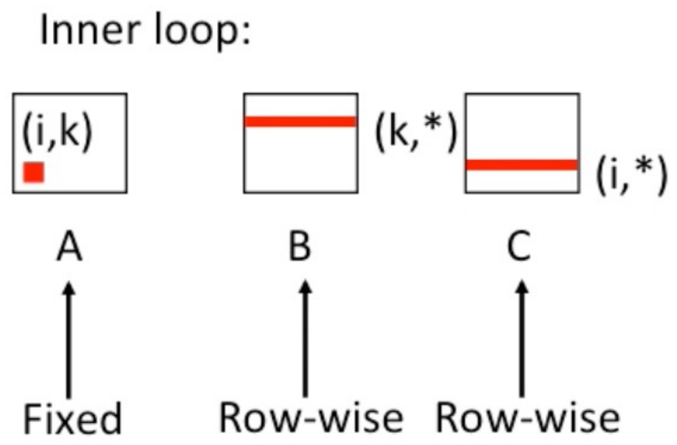


```
ksuo@ksuo-VirtualBox ~/cs7172> ./a.o
Time elpased is 67.452589 seconds⏎
ksuo@ksuo-VirtualBox ~/cs7172>
ksuo@ksuo-VirtualBox ~/cs7172>
ksuo@ksuo-VirtualBox ~/cs7172>
ksuo@ksuo-VirtualBox ~/cs7172>
ksuo@ksuo-VirtualBox ~/cs7172>
ksuo@ksuo-VirtualBox ~/cs7172> ./a2.o
Time elpased is 18.149353 seconds⏎
```

N=2000

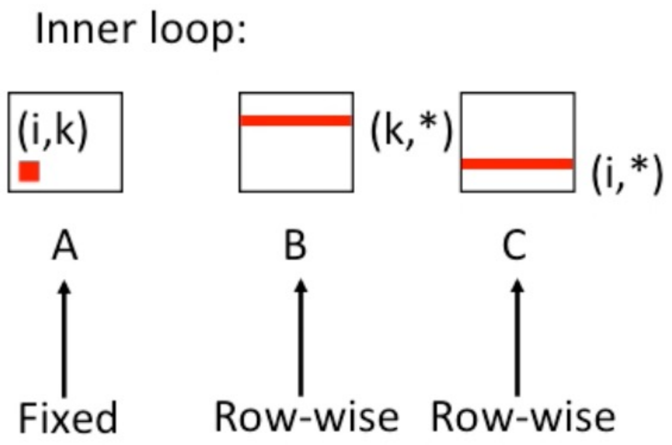
3.7x



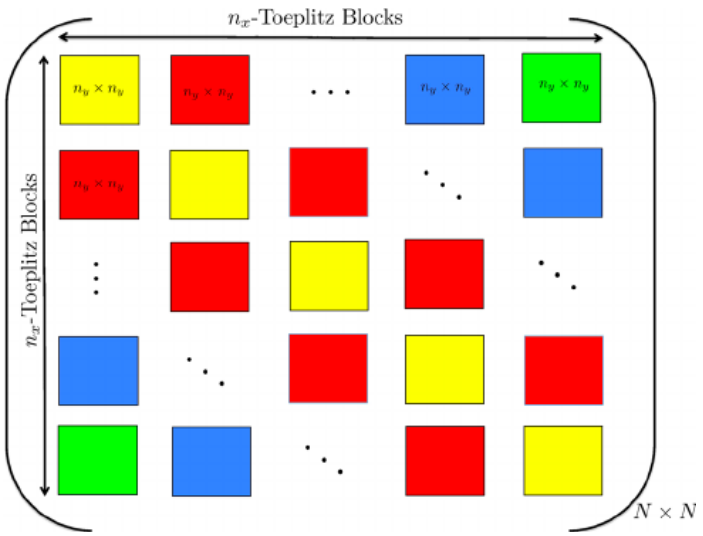


Option 1: Optimization using locality

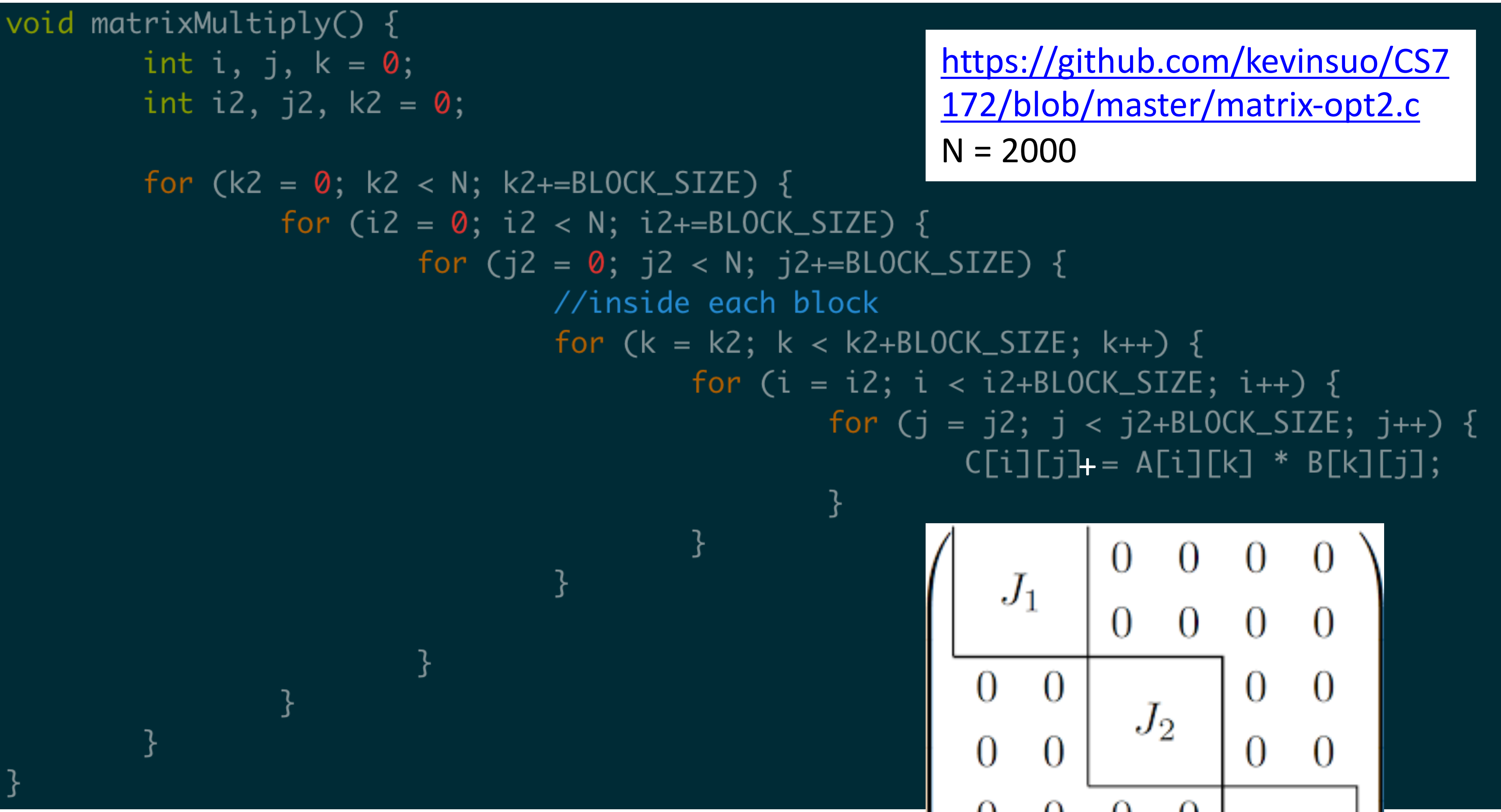
- Temporal locality
  - Every inner loop reuse the value of A[i, k]



- Spatial locality
  - Divide the large matrix into smaller ones and put it inside the cache during calculation



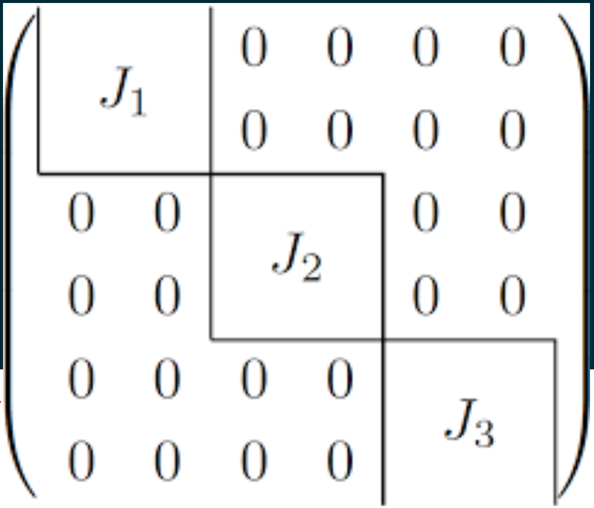
Option 1: Optimization using locality



```
void matrixMultiply() {
        int i, j, k = 0;
        int i2, j2, k2 = 0;

        for (k2 = 0; k2 < N; k2+=BLOCK_SIZE) {
                for (i2 = 0; i2 < N; i2+=BLOCK_SIZE) {
                        for (j2 = 0; j2 < N; j2+=BLOCK_SIZE) {
                                //inside each block
                                for (k = k2; k < k2+BLOCK_SIZE; k++) {
                                        for (i = i2; i < i2+BLOCK_SIZE; i++) {
                                                for (j = j2; j < j2+BLOCK_SIZE; j++) {
                                                        C[i][j]+= A[i][k] * B[k][j];
                                                }
                                        }
                                }

                        }
                }
        }
}
```

https://github.com/kevinsuo/CS7172/blob/master/matrix-opt2.c

N = 2000



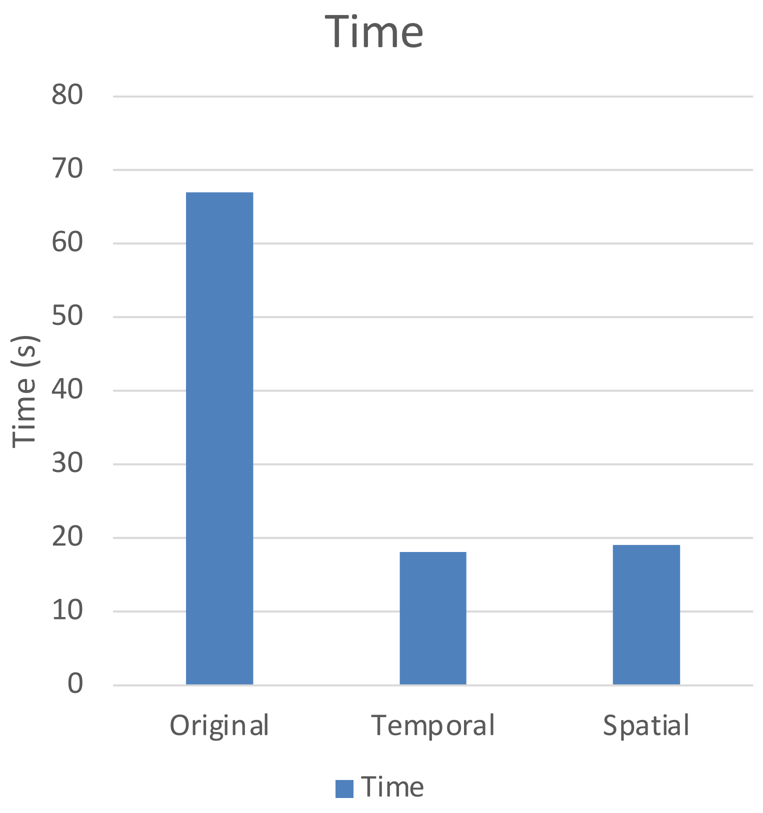
Option 1: Optimization using locality

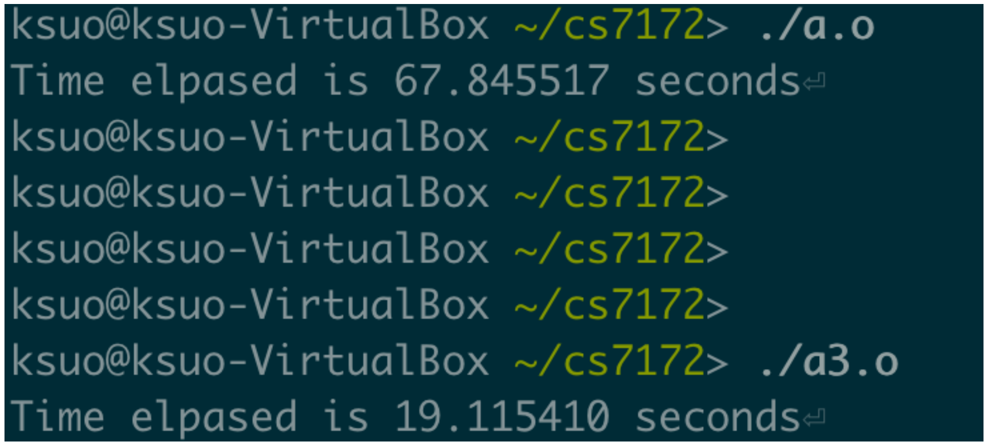
$$A = \left(\begin{array}{cc|cc} a_{11} & a_{12} & a_{13} & a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ \hline a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{array}\right) \Longrightarrow \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix}$$

$$A_{11} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}, A_{12} = \begin{pmatrix} a_{13} & a_{14} \\ a_{23} & a_{24} \end{pmatrix}$$

$$A_{21} = \begin{pmatrix} a_{31} & a_{32} \\ a_{41} & a_{42} \end{pmatrix}, A_{22} = \begin{pmatrix} a_{33} & a_{34} \\ a_{43} & a_{44} \end{pmatrix}$$

Option 1: Optimization using locality





```
ksuo@ksuo-VirtualBox ~/cs7172> ./a.o
Time elpased is 67.845517 seconds⏎
ksuo@ksuo-VirtualBox ~/cs7172>
ksuo@ksuo-VirtualBox ~/cs7172>
ksuo@ksuo-VirtualBox ~/cs7172>
ksuo@ksuo-VirtualBox ~/cs7172>
ksuo@ksuo-VirtualBox ~/cs7172> ./a3.o
Time elpased is 19.115410 seconds⏎
```

Optimal 2: Optimization using parallel

$$\begin{pmatrix} A_{1,1} & A_{1,2} \\ A_{2,1} & A_{2,2} \end{pmatrix} \cdot \begin{pmatrix} B_{1,1} & B_{1,2} \\ B_{2,1} & B_{2,2} \end{pmatrix} \rightarrow \begin{pmatrix} C_{1,1} & C_{1,2} \\ C_{2,1} & C_{2,2} \end{pmatrix}$$

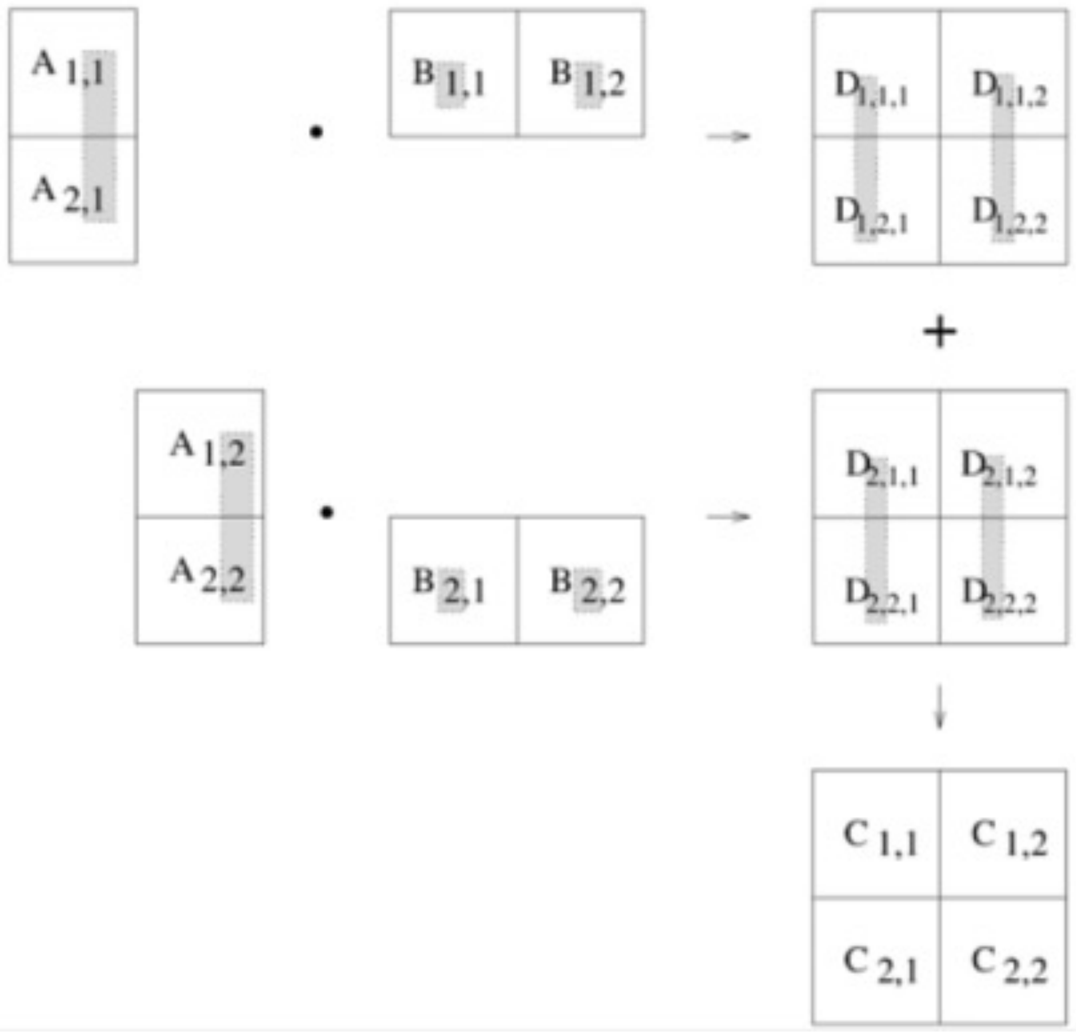
(a)

Task 1: $C_{1,1} = A_{1,1}B_{1,1} + A_{1,2}B_{2,1}$
Task 2: $C_{1,2} = A_{1,1}B_{1,2} + A_{1,2}B_{2,2}$
Task 3: $C_{2,1} = A_{2,1}B_{1,1} + A_{2,2}B_{2,1}$
Task 4: $C_{2,2} = A_{2,1}B_{1,2} + A_{2,2}B_{2,2}$

Optimal 2: Optimization using parallel

Thread 1:

Thread 2:



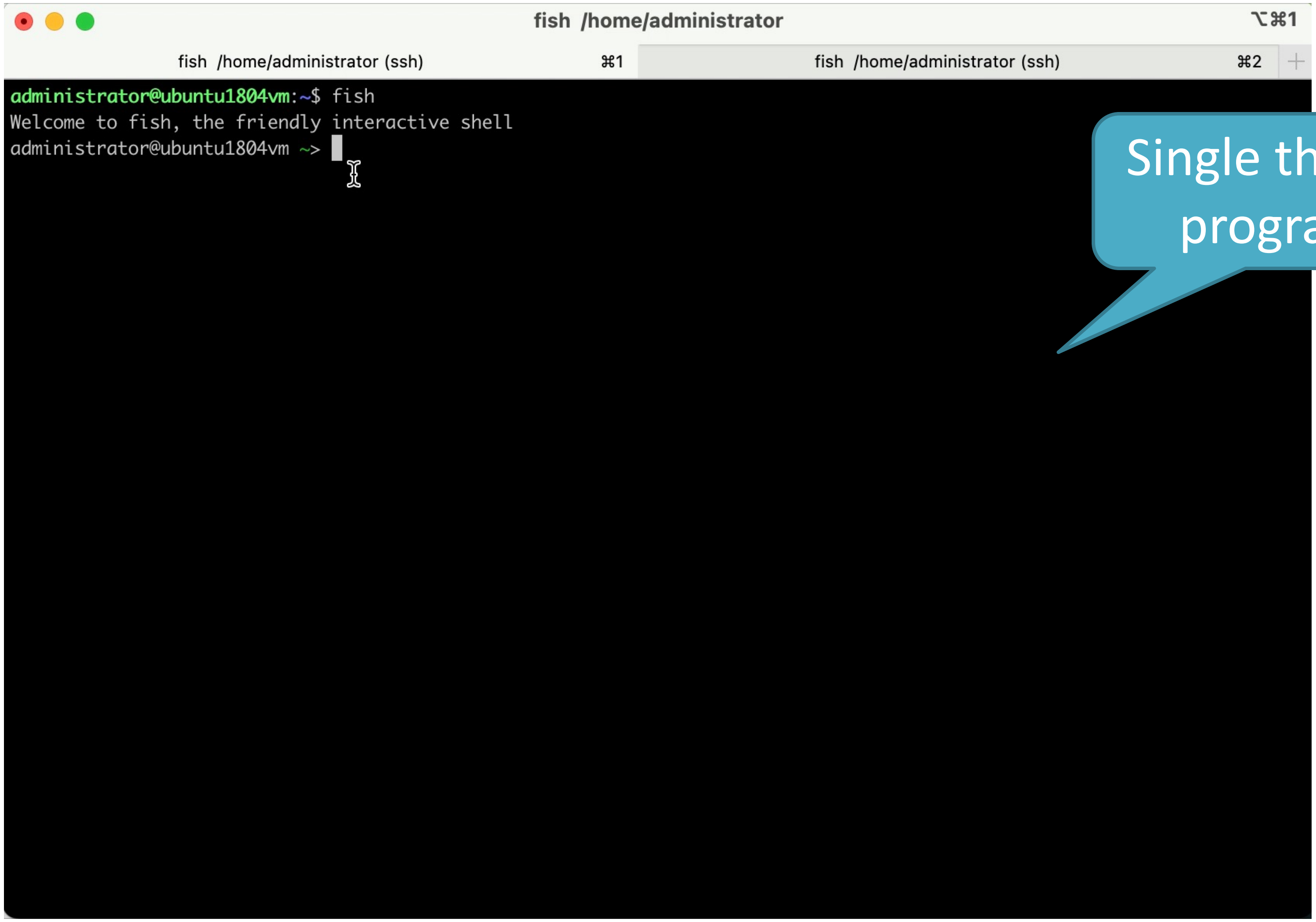
Optimization and Speedup

	N=200	N=400	N=800	N=1600
matrix				
matrix-opt1				
matrix-opt2				

	N=200	N=400	N=800	N=1600
matrix				
matrix-opt1				
matrix-opt2				

Single thread app demo

https://youtu.be/dIsBhvhQ9mA

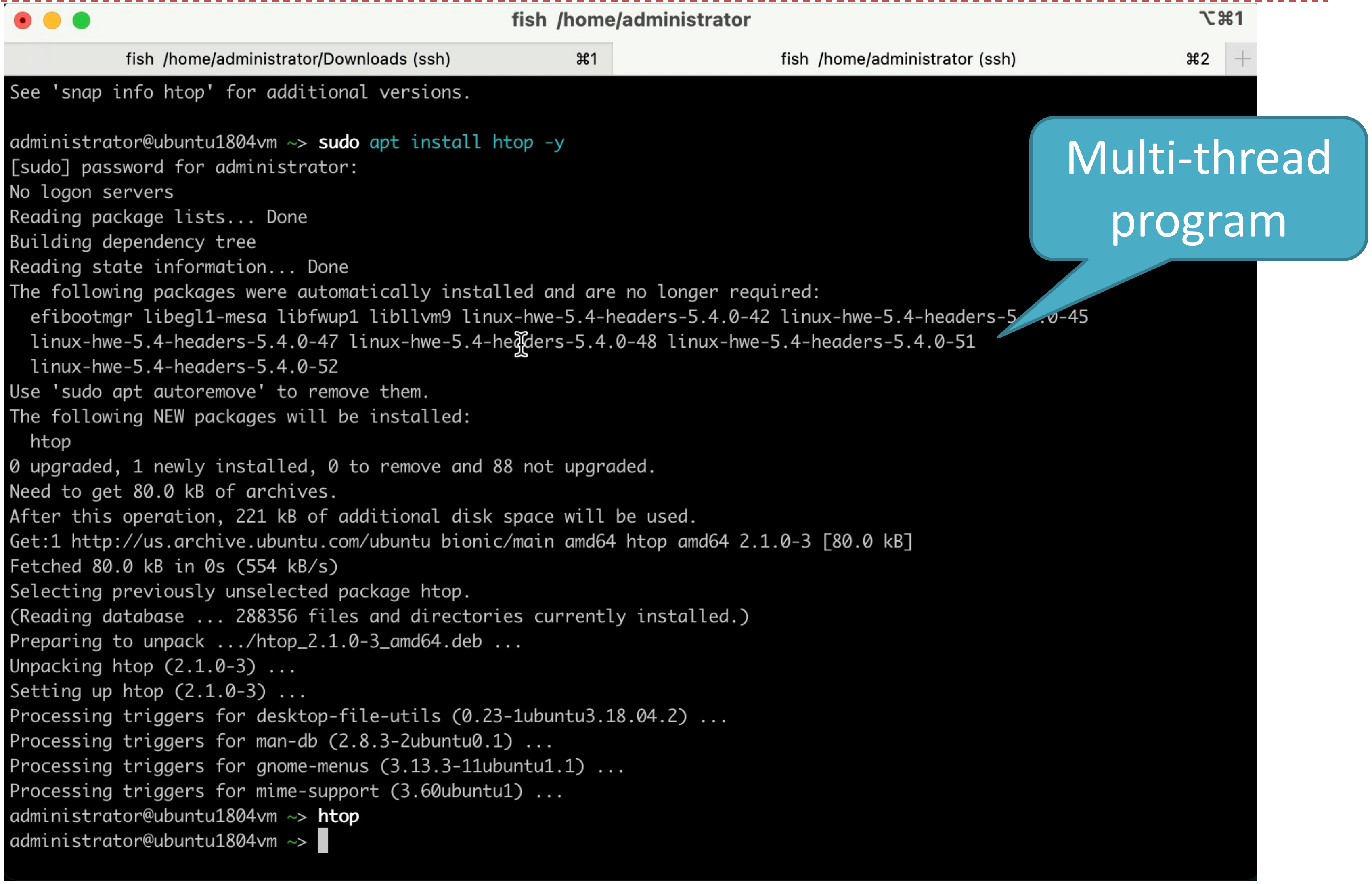

fish /home/administrator ⌥⌘1
fish /home/administrator (ssh) ⌘1
fish /home/administrator (ssh) ⌘2

```
administrator@ubuntu1804vm:~$ fish
Welcome to fish, the friendly interactive shell
administrator@ubuntu1804vm ~> 
```

Single thread program

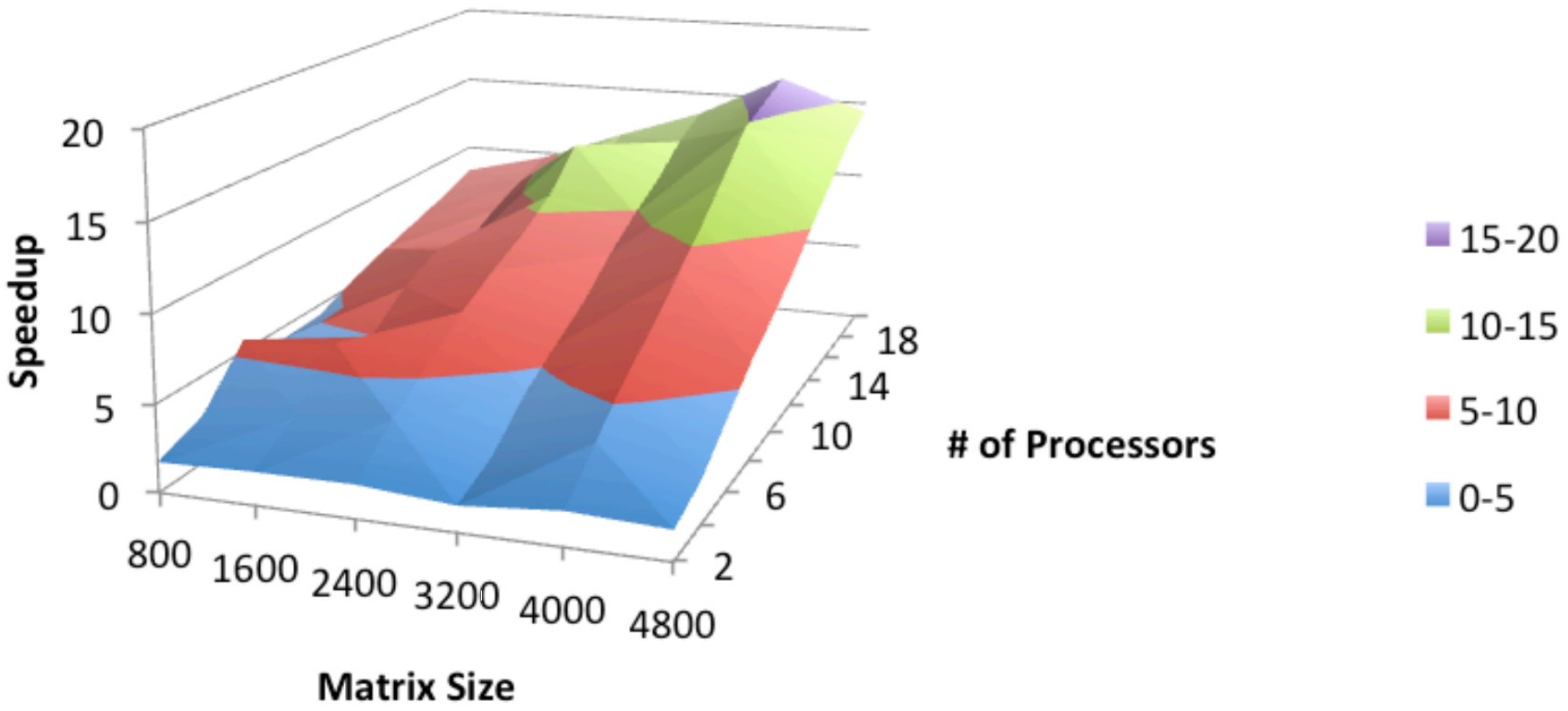
Multi-thread app demo

https://youtu.be/ubLB2fb8cdc


fish /home/administrator ⌥⌘1
fish /home/administrator/Downloads (ssh) ⌘1
fish /home/administrator (ssh) ⌘2
Multi-thread program

```
See 'snap info htop' for additional versions.

administrator@ubuntu1804vm ~> sudo apt install htop -y
[sudo] password for administrator:
No logon servers
Reading package lists... Done
Building dependency tree
Reading state information... Done
The following packages were automatically installed and are no longer required:
  efibootmgr libegl1-mesa libfwup1 libllvm9 linux-hwe-5.4-headers-5.4.0-42 linux-hwe-5.4-headers-5.4.0-45
  linux-hwe-5.4-headers-5.4.0-47 linux-hwe-5.4-headers-5.4.0-48 linux-hwe-5.4-headers-5.4.0-51
  linux-hwe-5.4-headers-5.4.0-52
Use 'sudo apt autoremove' to remove them.
The following NEW packages will be installed:
  htop
0 upgraded, 1 newly installed, 0 to remove and 88 not upgraded.
Need to get 80.0 kB of archives.
After this operation, 221 kB of additional disk space will be used.
Get:1 http://us.archive.ubuntu.com/ubuntu bionic/main amd64 htop amd64 2.1.0-3 [80.0 kB]
Fetched 80.0 kB in 0s (554 kB/s)
Selecting previously unselected package htop.
(Reading database ... 288356 files and directories currently installed.)
Preparing to unpack .../htop_2.1.0-3_amd64.deb ...
Unpacking htop (2.1.0-3) ...
Setting up htop (2.1.0-3) ...
Processing triggers for desktop-file-utils (0.23-1ubuntu3.18.04.2) ...
Processing triggers for man-db (2.8.3-2ubuntu0.1) ...
Processing triggers for gnome-menus (3.13.3-11ubuntu1.1) ...
Processing triggers for mime-support (3.60ubuntu1) ...
administrator@ubuntu1804vm ~> htop
administrator@ubuntu1804vm ~>
```

Optimal 2: Optimization using parallel



https://www.cse.unr.edu/~fredh/class/415/Nolan/matrix_multiplication/writeup.pdf

Example of distributed system: sorting

- Sorting on a single machine, e.g., Database

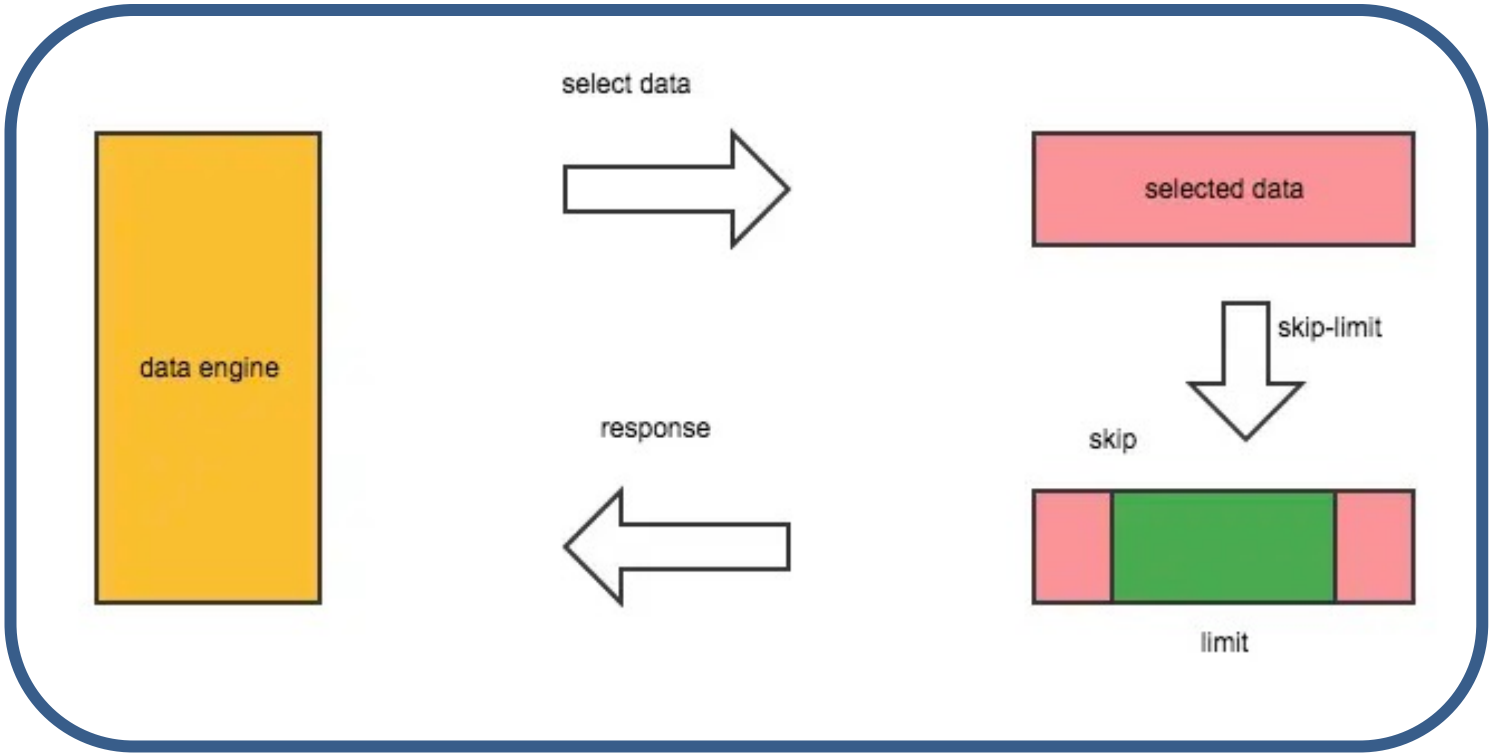
```
select field_a from table_b order by field_a limit 100, 10;

db.collection_b
.find()
.sort({"field_a":1})
.skip(100)
.limit(10);
```

	field_a	field_b	field_c
100			
…			
…			
110			

From line 100 to the next 10 lines of data

Example of distributed system: sorting

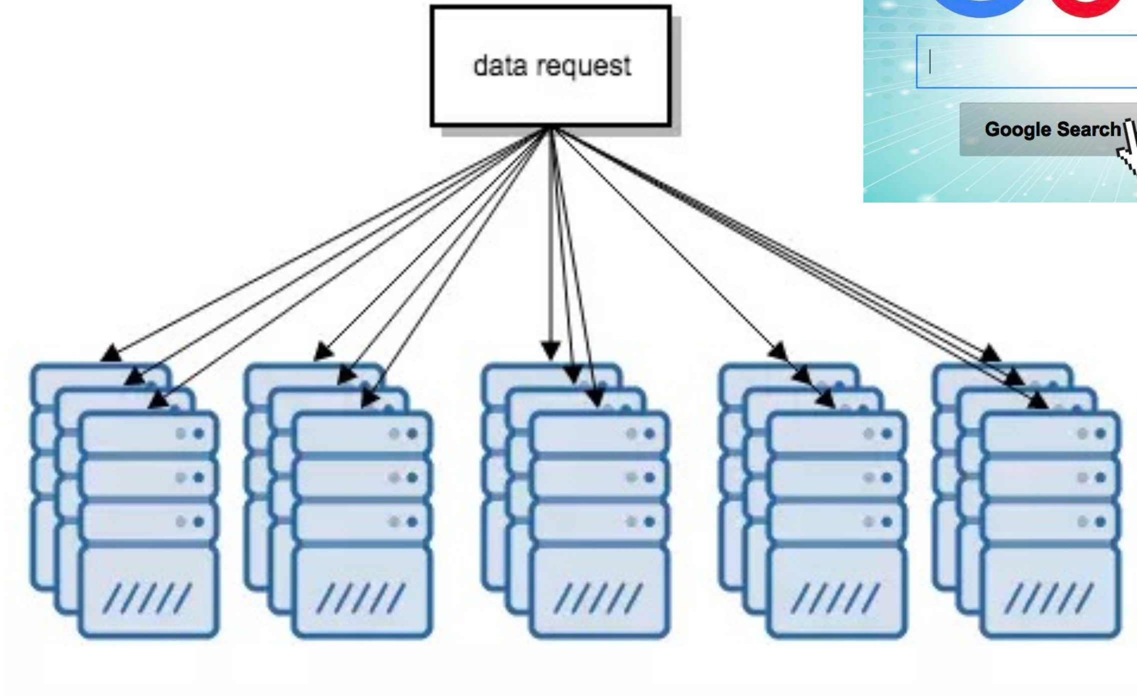
- Workflow on a single node



One server

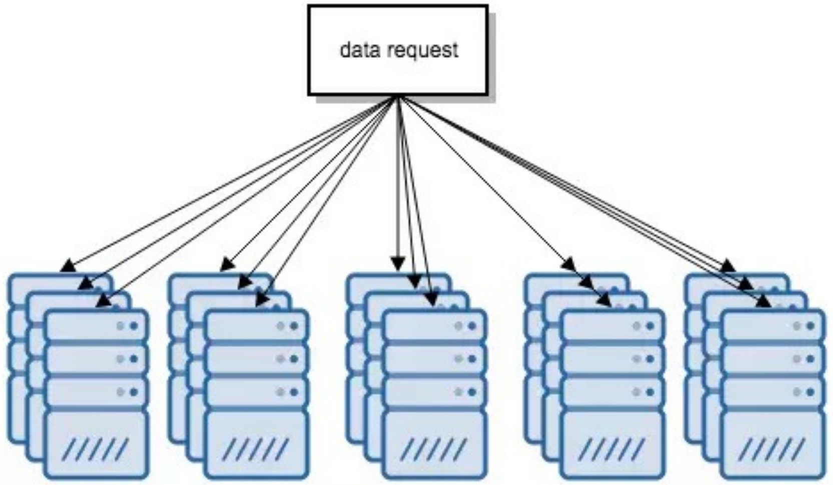
Example of distributed system: sorting

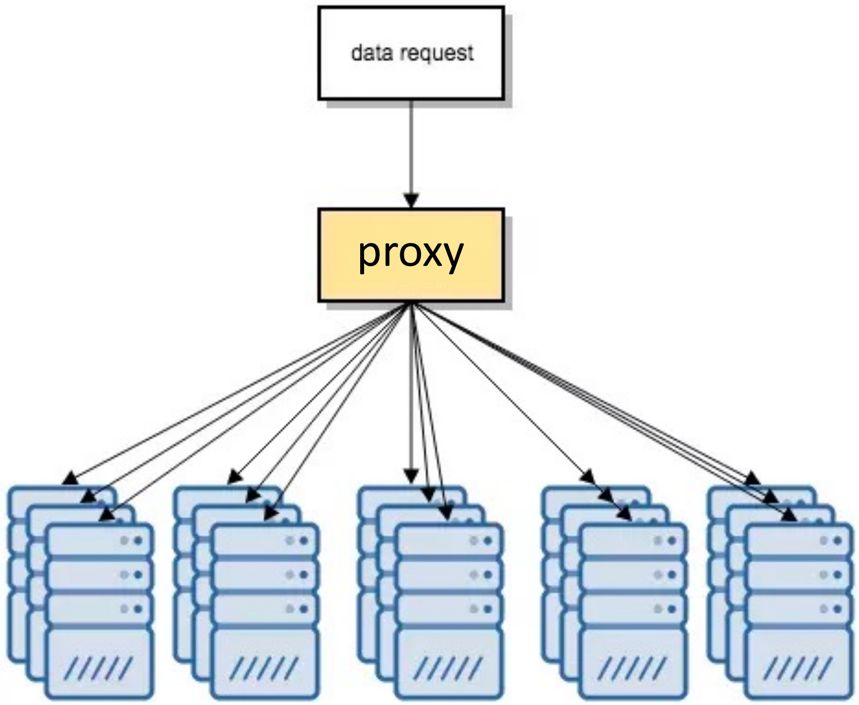
- If the data is too much and single node cannot hold



Example of distributed system: sorting

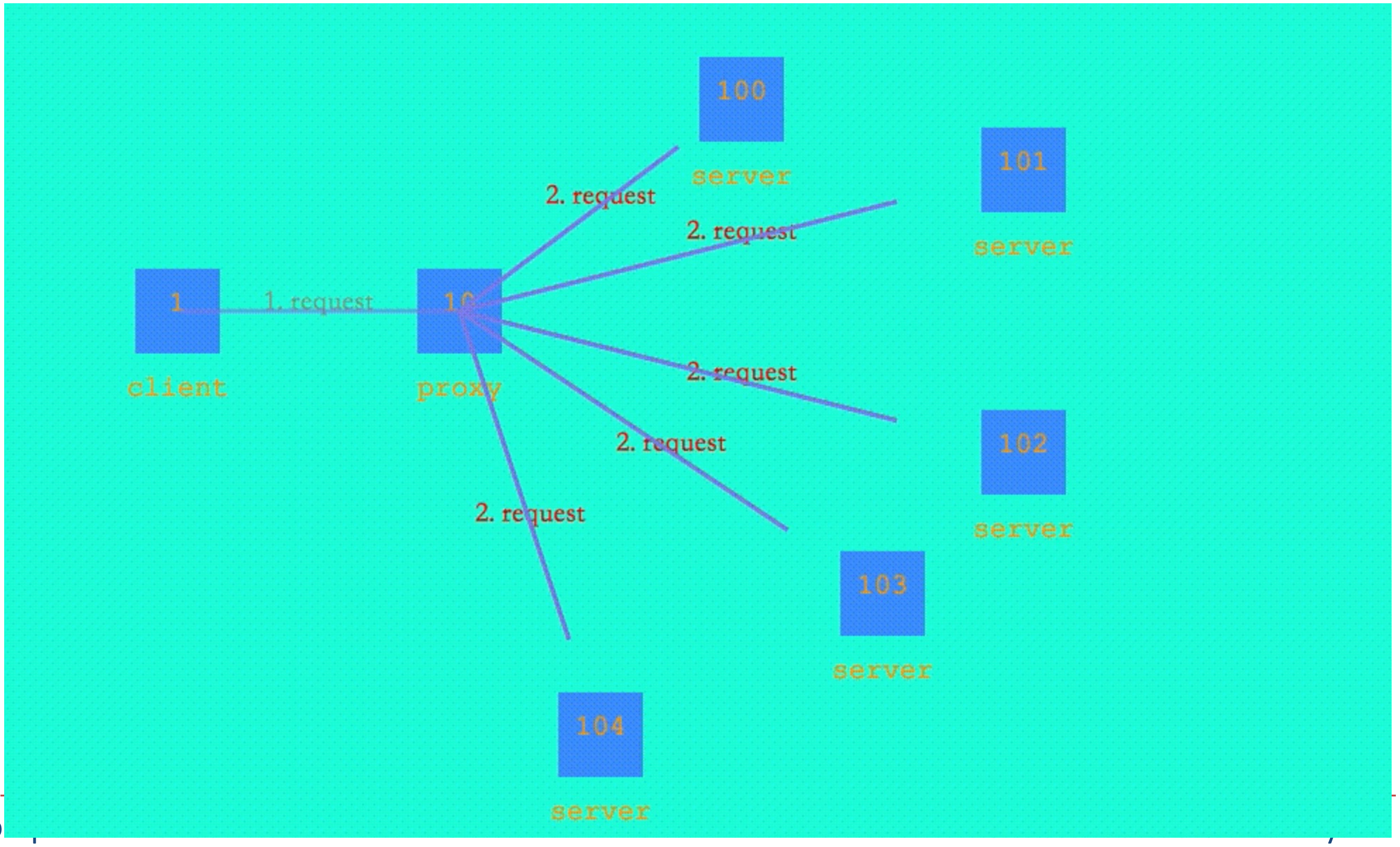
- Choose a node for merge processing





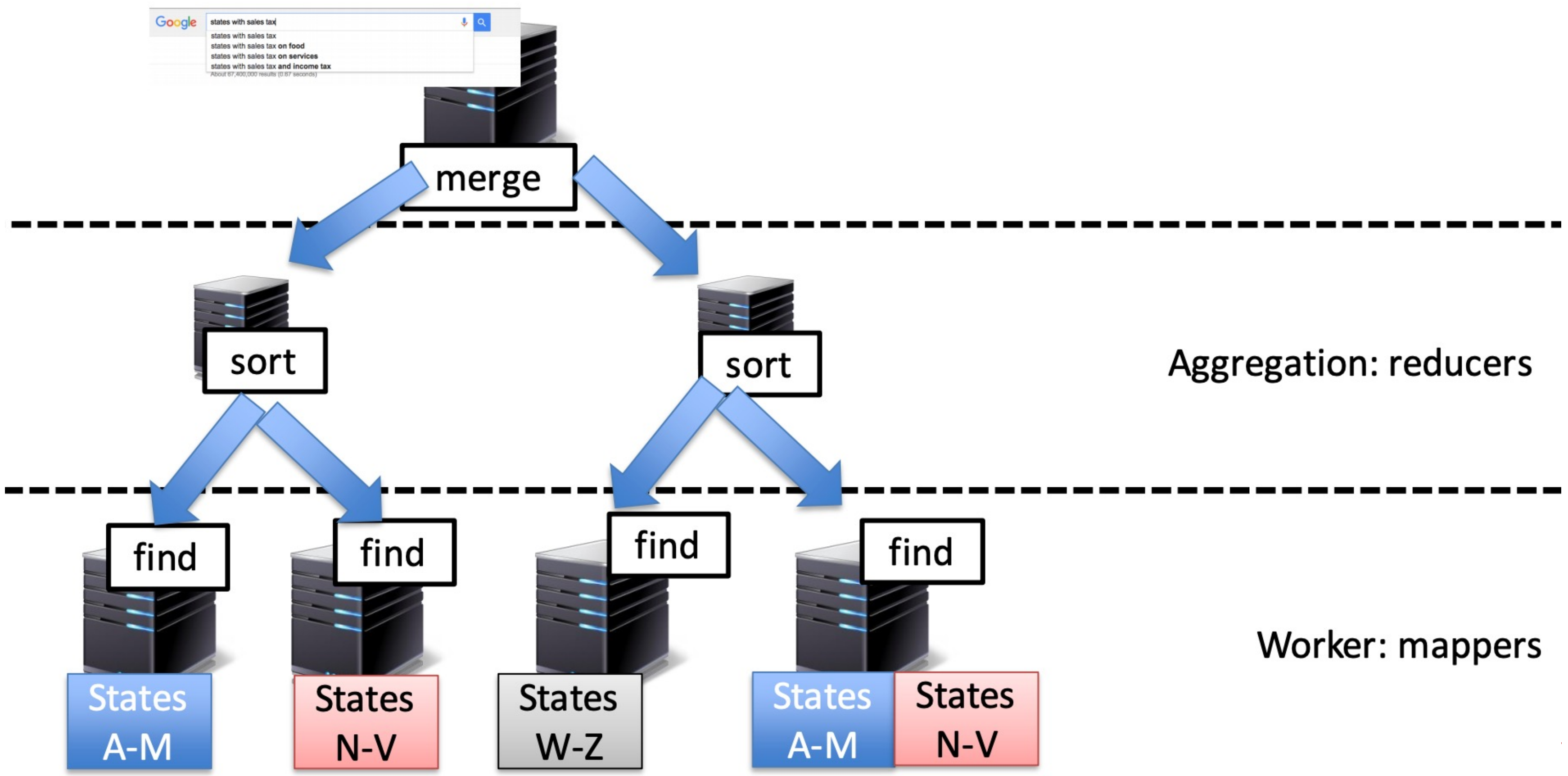
Example of distributed system: sorting

- Workflow



Example of distributed system: sorting

- How Do Request Get Processed in a Data Center



Example of distributed system: sorting

- How Google Search Works
- https://www.youtube.com/watch?v=0eKVizvYSUQ

Conclusion

- Why study parallel and distributed computation?
- What to learn?
- Course structure
- Course policy
- An example of parallel and distributed computation