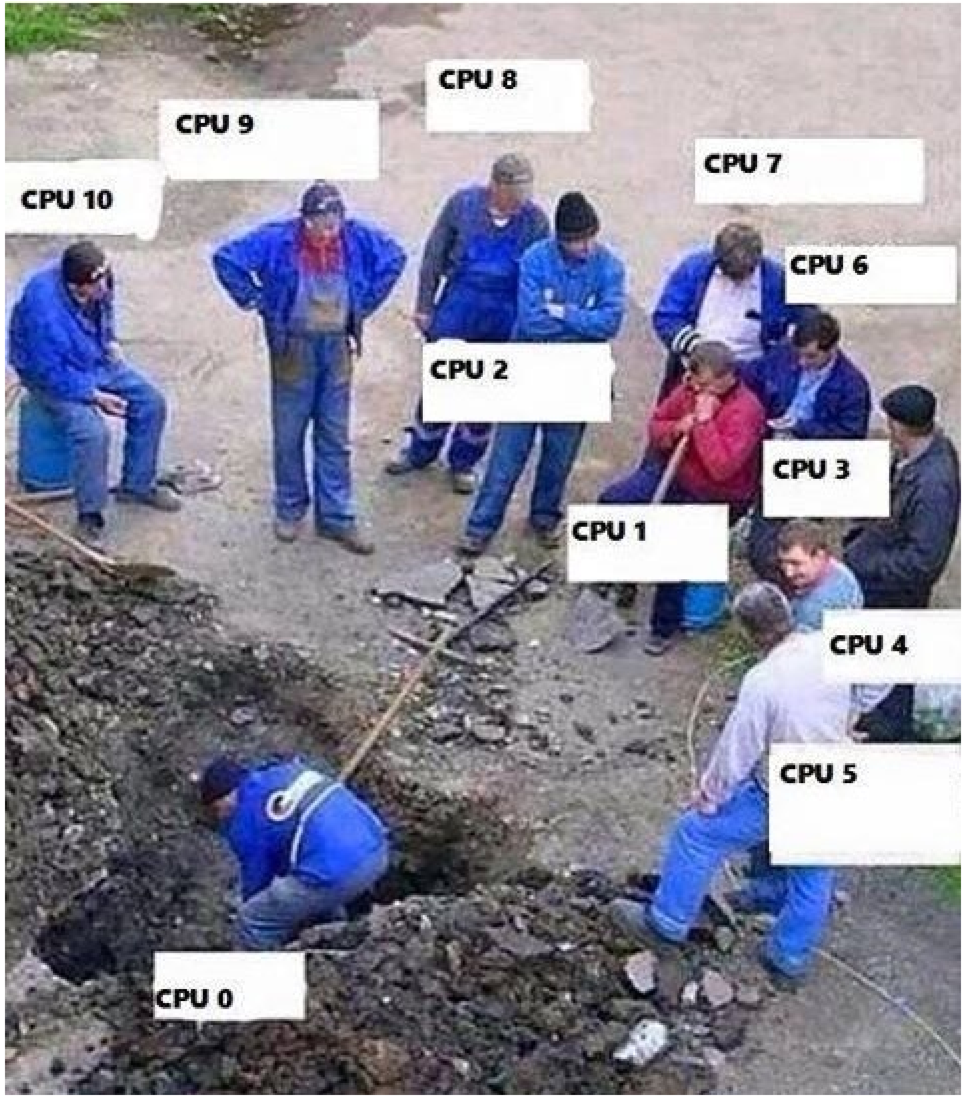
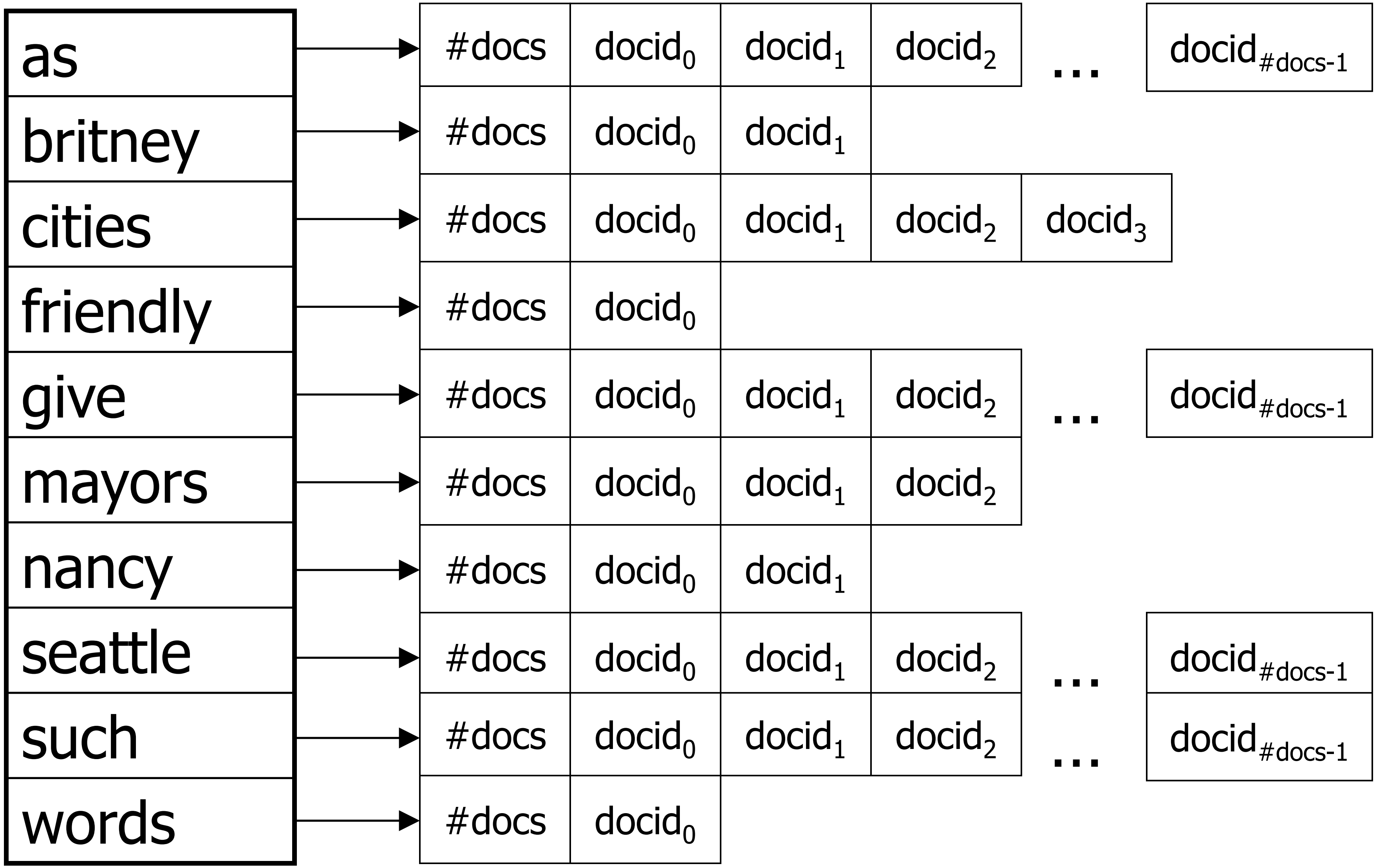
OS and Parallelism



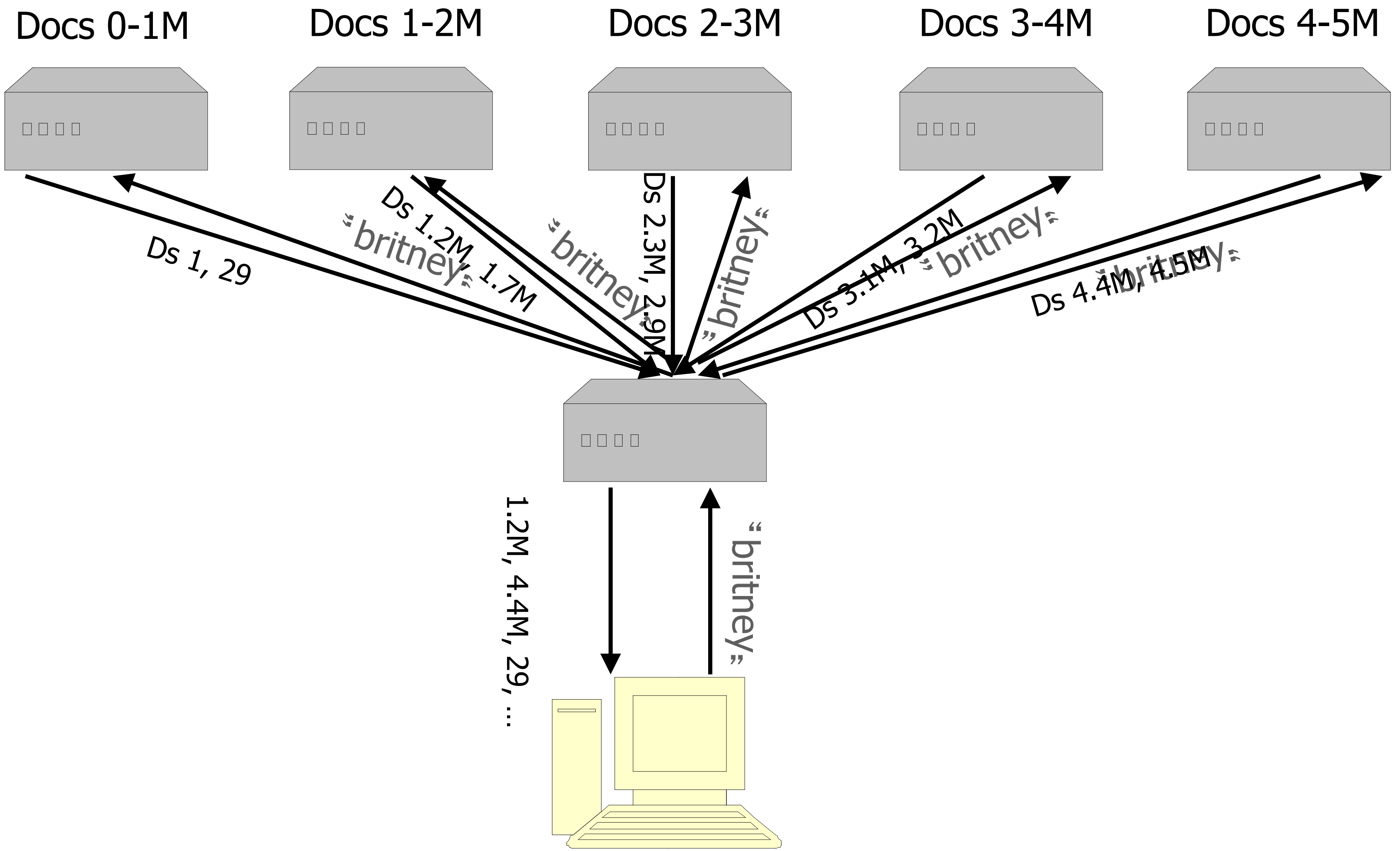
Review: Information Retrieval

- IR is the problem of finding **relevant documents** among an **index** that relate to some **query**
- We can rank documents by language features (e.g., tf-idf vectors) and *compare vectors of documents*
- We can rank documents based on their relative **prestige** using **PageRank**
- We can construct an **inverted index** by mapping *keywords* to *lists of documents*
- **Web Search** can be thought of as a *distributed task* in which the **index** can be split among multiple **workers**

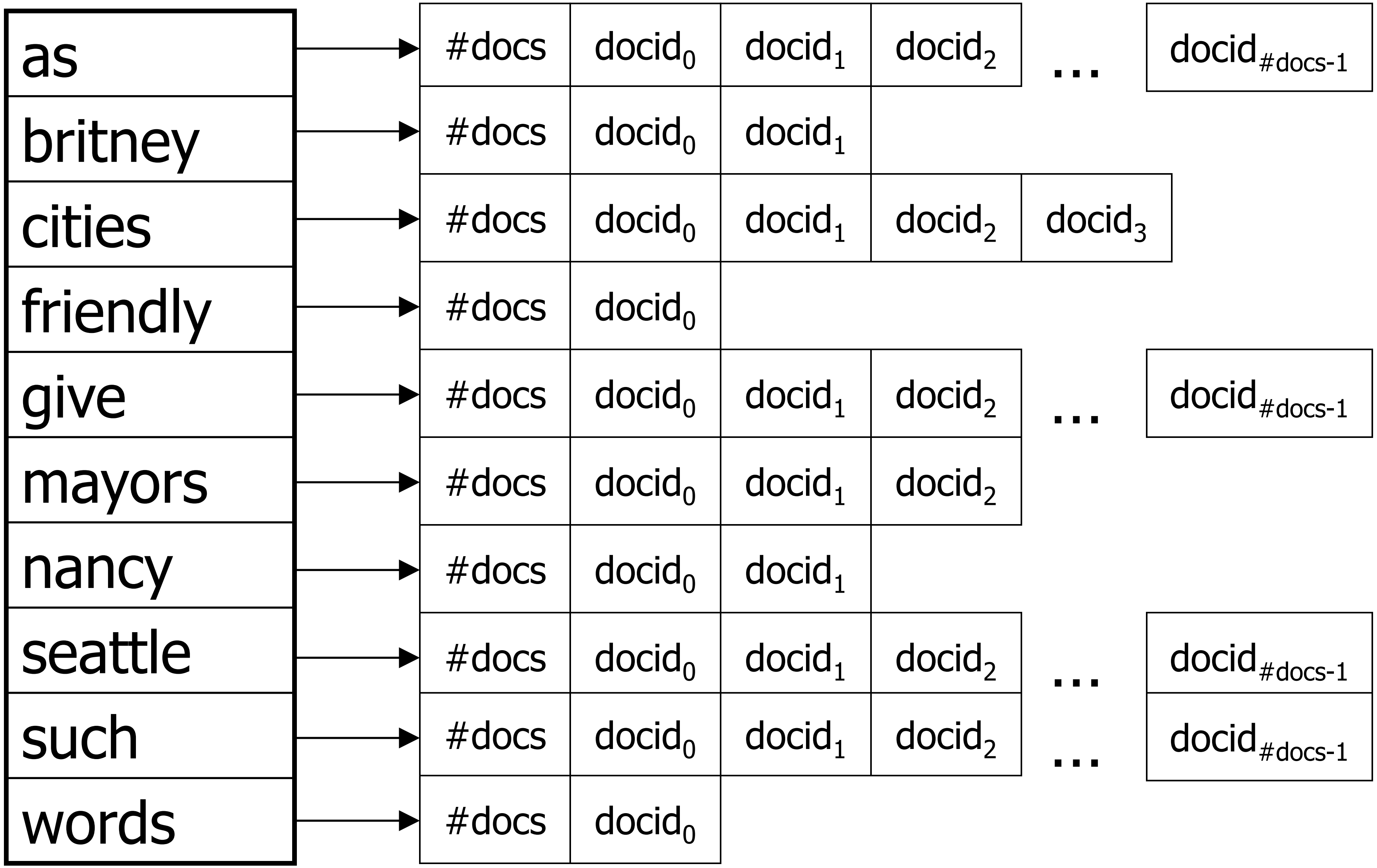
Segment by document (divide cols)



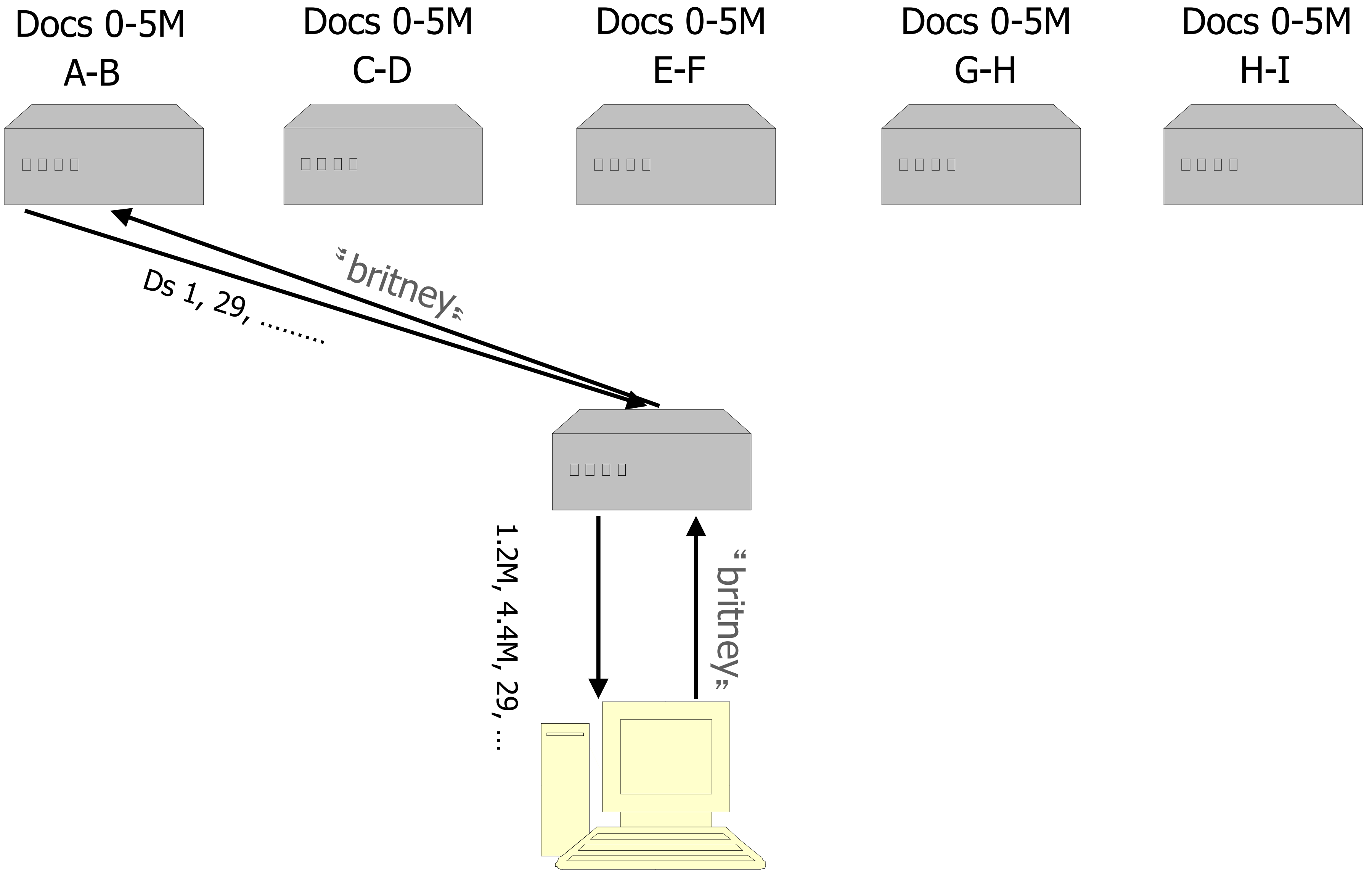
Segment by document



Segment by term (divide rows)



Segment by term



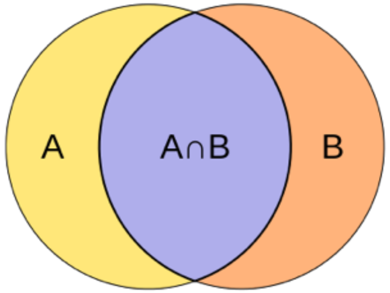
Review: Deduplication

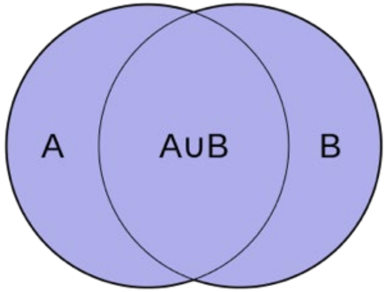
- We **deduplicate** portions of the index to save re-computation and storage requirements
- The **Jaccard similarity coefficient** is a way of comparing sets
  - Each **document** can be broken up into **shingles,** which are k-long sequences of tokens in each document
  - Thus, each **document** can be represented by a *set of shingles* that can be used to compare documents for duplication
- The **MinHash** algorithm leverages statistical properties of sets to *estimate* the Jaccard coefficient

Jaccard similarity coefficient

- Jaccard similarity coefficient compares the similarity of the two sets of shingles (A and B)
- Size of the intersection / size of the union

$$J(A,B) = \frac{|A \cap B|}{|A \cup B|}.$$





- 0 for disjoint sets, 1 for equal sets
- What is the complexity of computing Jaccard?
- Assume A and B are size O(N)

One-Slide Summary: Processes, Threads, Sockets

- A **process** is a data structure used by the operating system to manage the execution of a program
  - Processes have their own address space, file handles, networking, etc.
- Processes can create one or more **threads** to execute tasks in parallel
  - Example: UI thread that runs separately from computation
  - Example: A Webserver with thousands of concurrent clients connected
  - Threads share the same address space as the host process
- Networked applications can use **sockets** to communicate with each other
  - Server binds, listens, accepts, recvs.   Client connects and sends

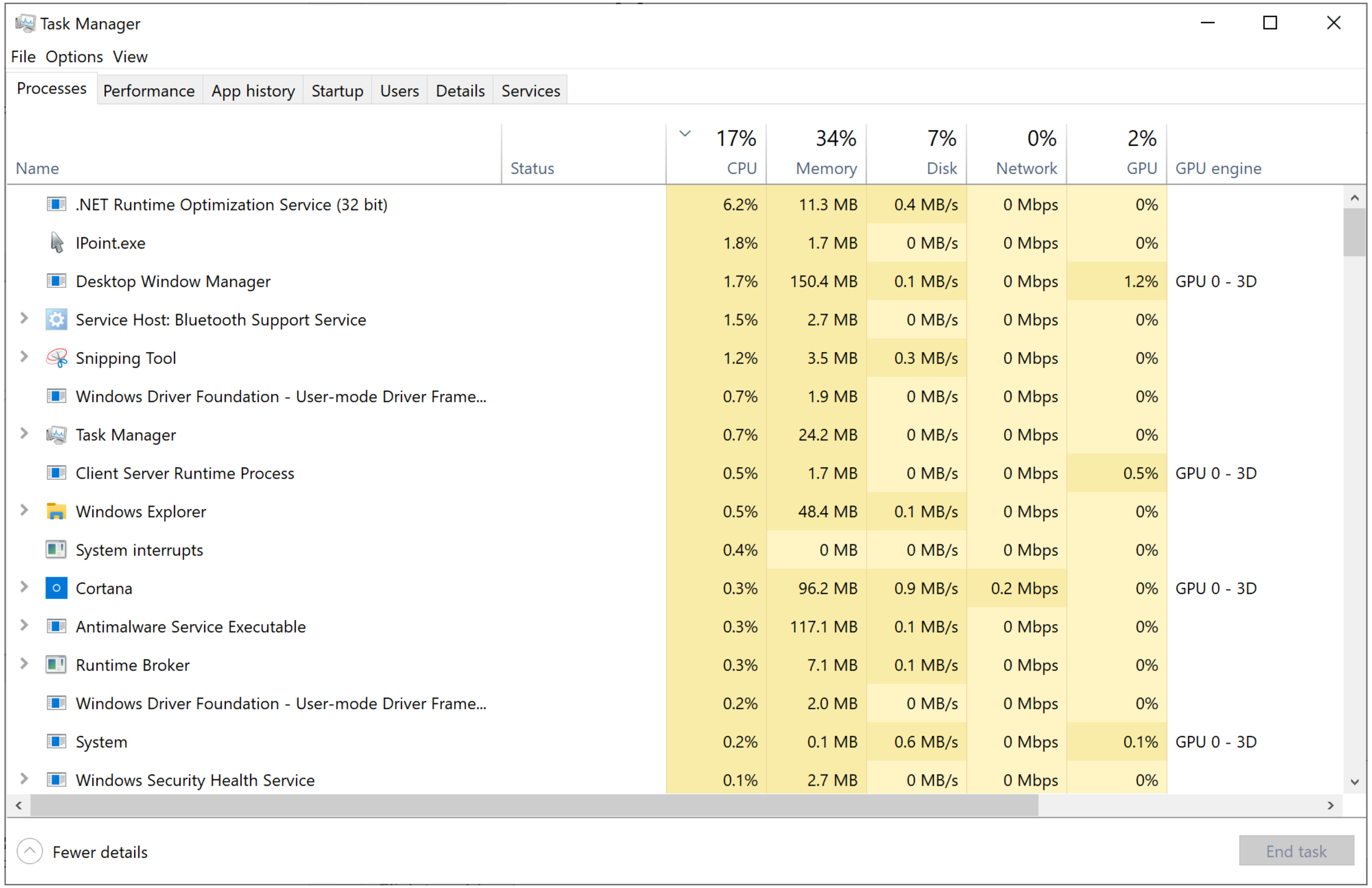
Project 4: MapReduce

- MapReduce: divide computation among many computers

- P4: simulate this on one computer
  - Multiple programs (processes): master and workers
  - Multiple threads: do computation at same time as waiting for network

Processes

- Process: a running program



Name	Status	17% CPU	34% Memory	7% Disk	0% Network	2% GPU	GPU engine
.NET Runtime Optimization Service (32 bit)		6.2%	11.3 MB	0.4 MB/s	0 Mbps	0%	
IPoint.exe		1.8%	1.7 MB	0 MB/s	0 Mbps	0%	
Desktop Window Manager		1.7%	150.4 MB	0.1 MB/s	0 Mbps	1.2%	GPU 0 - 3D
Service Host: Bluetooth Support Service		1.5%	2.7 MB	0 MB/s	0 Mbps	0%	
Snipping Tool		1.2%	3.5 MB	0.3 MB/s	0 Mbps	0%	
Windows Driver Foundation - User-mode Driver Frame...		0.7%	1.9 MB	0 MB/s	0 Mbps	0%	
Task Manager		0.7%	24.2 MB	0 MB/s	0 Mbps	0%	
Client Server Runtime Process		0.5%	1.7 MB	0 MB/s	0 Mbps	0.5%	GPU 0 - 3D
Windows Explorer		0.5%	48.4 MB	0.1 MB/s	0 Mbps	0%	
System interrupts		0.4%	0 MB	0 MB/s	0 Mbps	0%	
Cortana		0.3%	96.2 MB	0.9 MB/s	0.2 Mbps	0%	GPU 0 - 3D
Antimalware Service Executable		0.3%	117.1 MB	0.1 MB/s	0 Mbps	0%	
Runtime Broker		0.3%	7.1 MB	0.1 MB/s	0 Mbps	0%	
Windows Driver Foundation - User-mode Driver Frame...		0.2%	2.0 MB	0 MB/s	0 Mbps	0%	
System		0.2%	0.1 MB	0.6 MB/s	0 Mbps	0.1%	GPU 0 - 3D
Windows Security Health Service		0.1%	2.7 MB	0 MB/s	0 Mbps	0%	

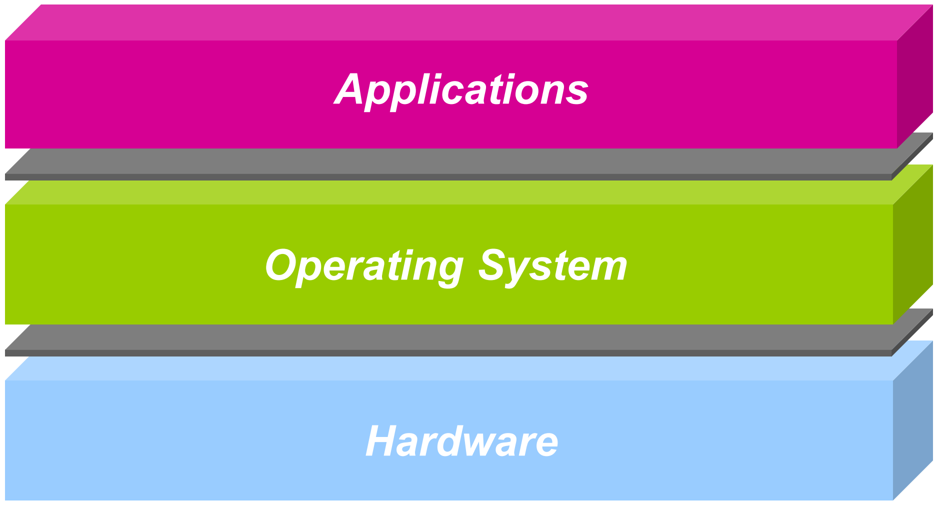
The process abstraction

- The process is the OS abstraction for execution
  - Also sometimes called a job or a task
- A process is a program in execution
  - Programs are static entities with potential for execution

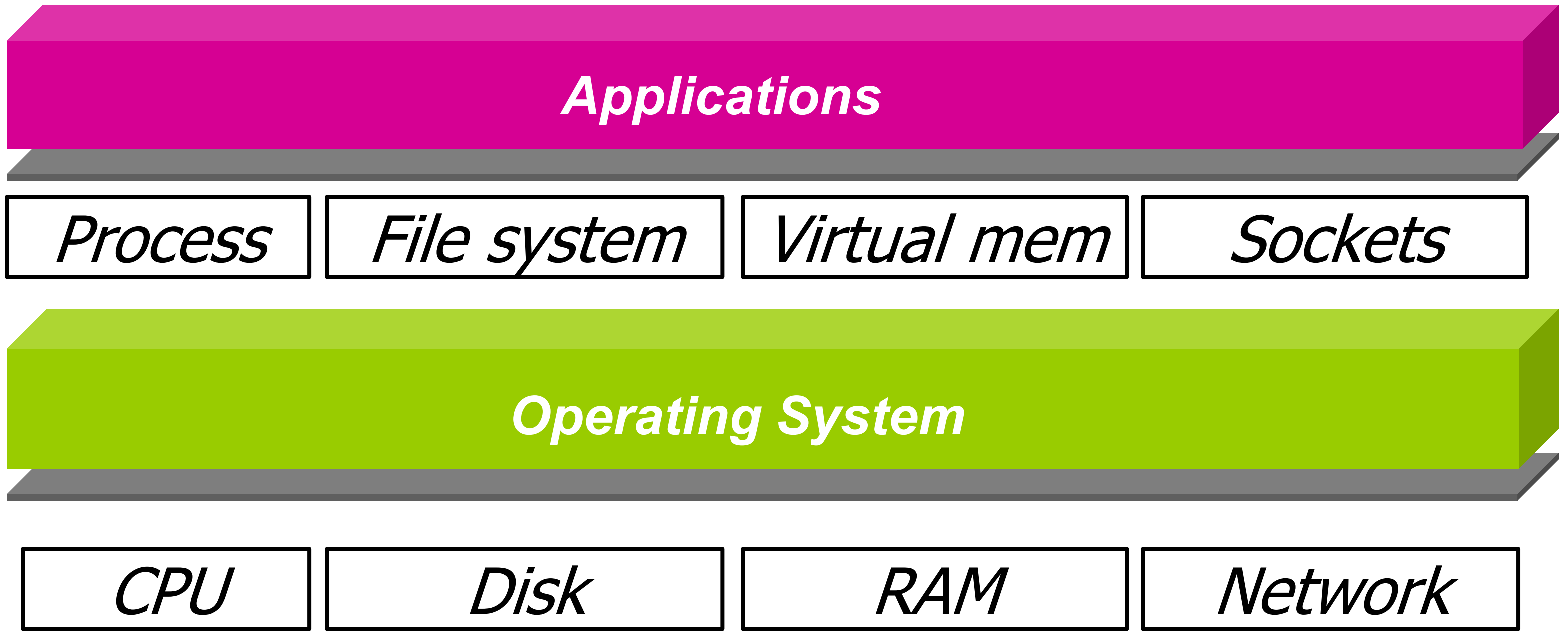
- Process consists of:
  - A unique process ID (PID)
  - An address space (memory)
  - 1 or more threads (sequences of computation)
  - Some other resources (file handles, open sockets,...)

What does the OS do?

- Create abstractions to make hardware easier to use
  - Abstractions “nicer” than raw hardware interfaces
- Manage shared hardware resources



Operating system abstractions



The process abstraction

- What interface does hardware provide?
- Hardware interface: single computer (CPU & memory), executing instructions from a mix of many different applications

- What interface does OS provide?
- OS interface: several dedicated "computers" (one per application process)

- Process interface differs from hardware interface

Process example

```
from multiprocessing import Process
from time import sleep

def worker(worker_id):
    print("Hello from process {}".format(worker_id))
    sleep(10)


if __name__ == "__main__":
    for i in range(3):
        p = Process(target=worker, args=(i,))
        p.start()
```

```
$ python3 test_multiprocessing.py
Hello from process 0
Hello from process 1
Hello from process 2
```

Example

```
$ python3 test_multiprocessing.py
Hello from process 0
Hello from process 1
Hello from process 2

$ pgrep -lf test_multiprocessing  # macOS
$ pgrep -af test_multiprocessing  # Linux/WSL
16571 python test_multiprocessing.py
16572 python test_multiprocessing.py
16573 python test_multiprocessing.py
16574 python test_multiprocessing.py
```

Example

```
$ python3 test_multiprocessing.py
Hello from process 0
Hello from process 1
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$ pgrep -lf test_multiprocessing  # macOS
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16571 python test_multiprocessing.py
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```
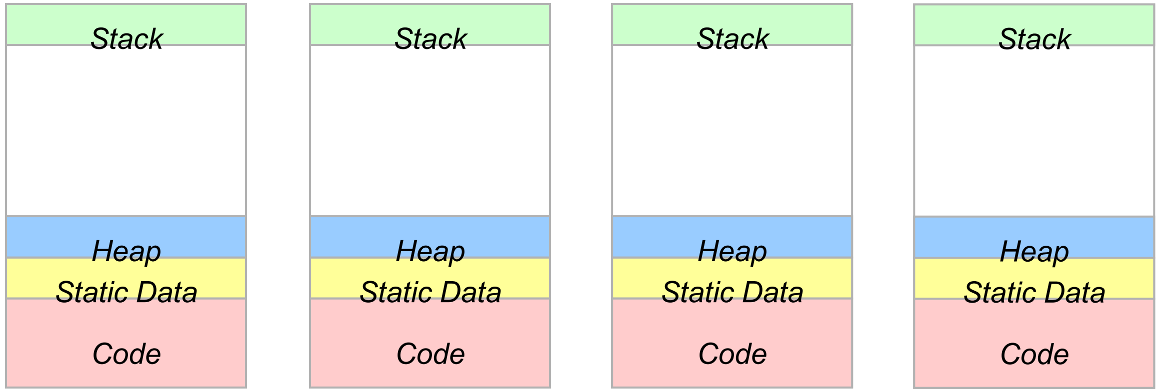



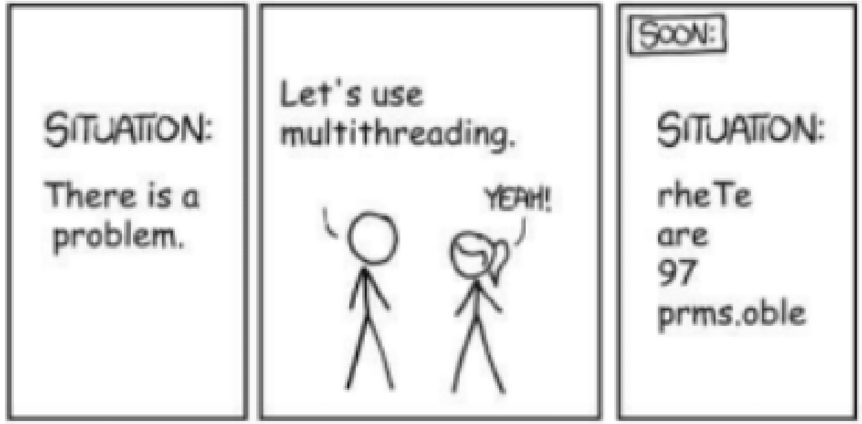
4 separate processes

Agenda

- Processes
- **Threads**
- Synchronization
  - Atomic operations
- Sockets

Threads

- A thread is a sequential set of executing instructions
- Active object: describes the execution itself!
- Unit of concurrency
  - How many computations can happen at once?
  - Maximum: # of threads in the program
- Each thread has
  - The program counter (PC) indicating the next instruction
  - A set of general-purpose registers with current values



Thread example

```
# test_threading.py
from threading import Thread
from time import sleep


def worker(worker_id):
    print("Hello from thread {}".format(worker_id))
    sleep(10)

if __name__ == "__main__":
    for i in range(3):
        t = Thread(target=worker, args=(i,))
        t.start()
```

```
$ python3 test_threading.py
Hello from thread 0
Hello from thread 1
Hello from thread 2
```

Thread example

```
$ python3 test_threading.py
Hello from thread 0
Hello from thread 1
Hello from thread 2

$ pgrep -lf test_threading  # macOS
$ pgrep -af test_threading  # Linux/WSL
16976 python3 test_threading.py

$ ps -M 16976  # macOS
$ ps -m 16976  # Linux/WSL
awdeorio        17006 s001    0.0 S    31T   0:00.01   0:00.02
                17006        56.5 R    31T   0:18.65   0:10.97
                17006        56.2 R    31T   0:18.53   0:10.94
                17006        56.9 R    31T   0:18.71   0:11.17
```

Thread example

```
$ python3 test_threading.py
Hello from thread 0
Hello from thread 1
Hello from thread 2

$ pgrep -lf test_threading  # macOS
$ pgrep -af test_threading  # Linux/WSL
16976 python3 test_threading.py

$ ps -M 16976  # macOS
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awdeorio        17006 s001    0.0 S    31T   0:00.01   0:00.02
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                17006        56.2 R    31T   0:18.53   0:10.94
                17006        56.9 R    31T   0:18.71   0:11.17
```
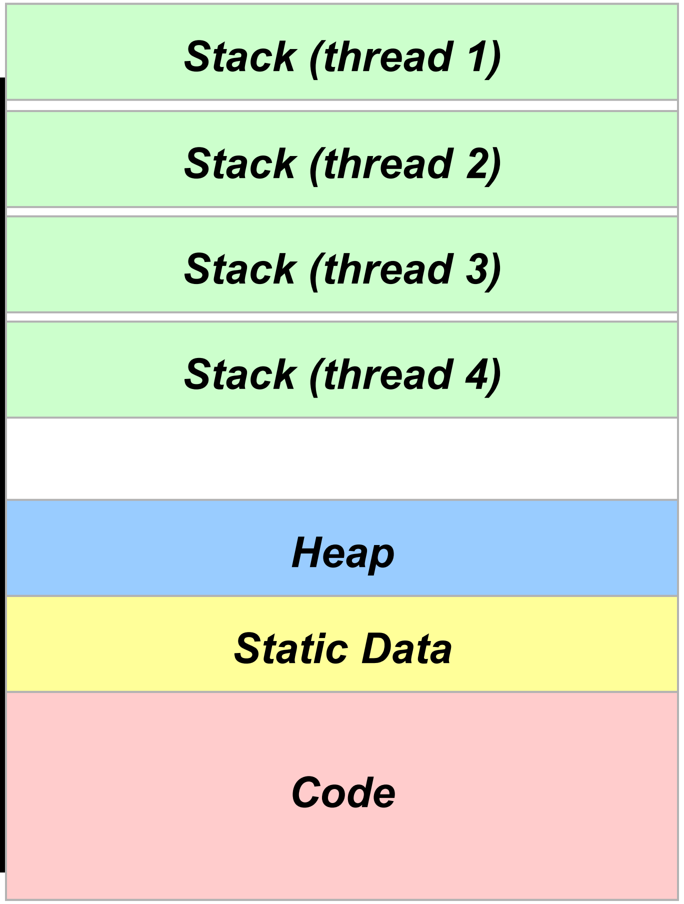
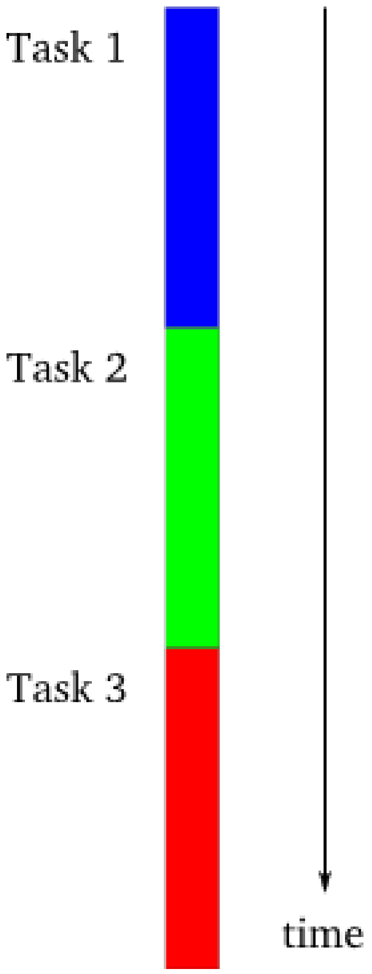



Option 1: One request at a time

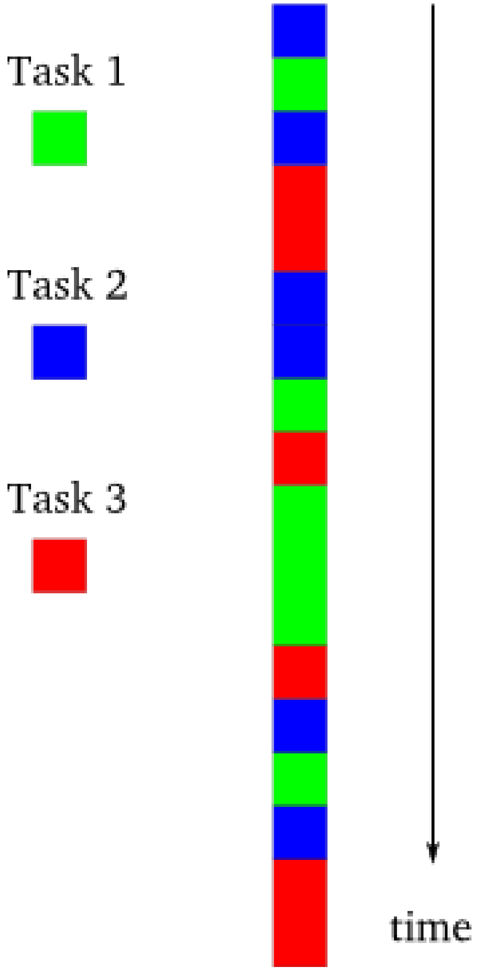
- Example execution schedule:
  - Request 1 arrives
  - Server receives request 1
  - Server starts disk I/O 1
  - Request 2 arrives
  - Server waits for I/O 1 to finish

- Easy to program, but slow
  - Why slow?
  - Can’t overlap disk requests with computation, or with network receives



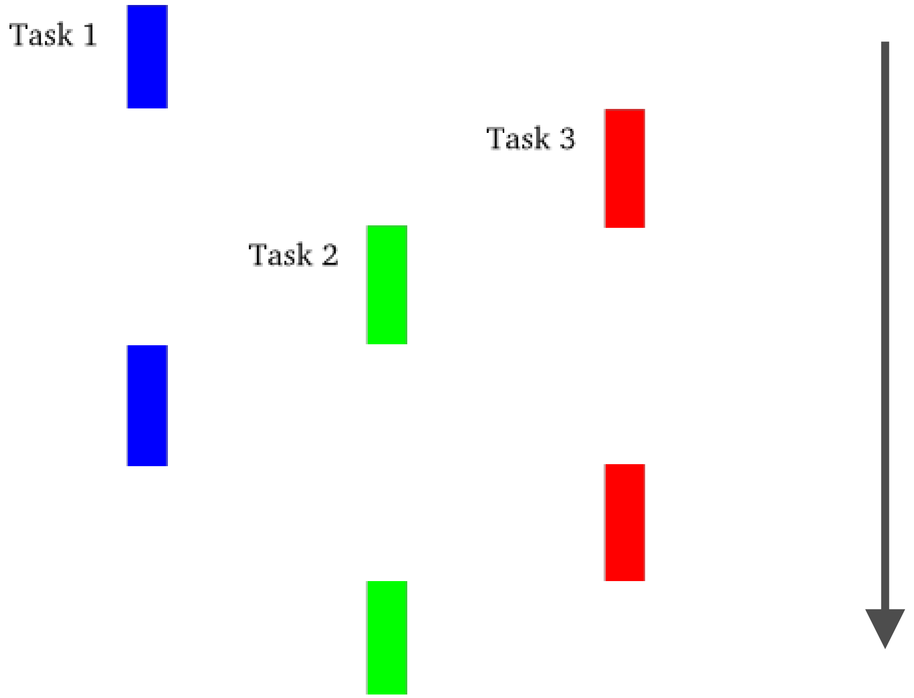
Option 2: event-driven web server

- Asynchronous I/O: issue I/O, but don’t wait for them to complete
  - Request 1 arrives
  - Server receives request 1
  - Server starts disk I/O 1 to satisfy request 1
  - Request 2 arrives
  - Server receives request 2
  - Server starts disk I/O 2 to satisfy request 2
  - Disk I/O 1 finishes
- Fast, but complicated to program
  - Keep track of multiple requests, what stage they’re in, outstanding disk I/O, outstanding network I/O



Option 3: multi-threaded web server

- One thread per request
  - Thread issues disk (or n/w) I/O, then waits for it to finish
  - Though thread is blocked on I/O, other threads can run



Option 3: multi-threaded web server

- One thread per request
  - Thread issues disk (or n/w) I/O, then waits for it to finish
  - Though thread is **blocked** on I/O, other threads can run
  - Where is the state of each request stored?

Thread 1	*Thread 2*	*Thread 3*
Request 1 arrives		
Receive request 1		
Start disk I/O 1		
	Request 2 arrives	
	Receive request 2	
	Start disk I/O 2	
		Request 3 arrives
		Receive request 3
Disk I/O 1 finishes		
Continue handling request 1		

Benefits of threads

- Simpler programming model
  - The **illusion** of a dedicated CPU per thread
- Thread manager takes care of CPU sharing
  - Other threads can **progress** when one thread issues blocking I/O
  - **Private state** for each thread, but memory shared with process

Cooperating threads

- How can multiple threads cooperate on a single task?
  - Example: Ticketmaster’s webserver
  - Assume each thread has a dedicated processor
- Problem:
  - Ordering of events across threads is non-deterministic
  - Speed of each processor is unpredictable

    Thread A --->

    Thread B -   -   -   -   -   -   -   -   -   >

    Thread C ->
- Consequences:
  - Many possible global ordering of events
  - Some may produce incorrect results

Non-deterministic ordering → Non-deterministic results

Thread 1
print ABC

Thread 2
print 123

- Printing example
  - Possible outputs?
    - ABC123, AB1C23, AB12C3, AB123C, A1BC23, A12BC3, A123BC, 1ABC23, 1A2BC3, …
  - Impossible outputs?
    - ABC321,…
- Ordering within thread is sequential, but many ways to merge per-thread order into a global order
- What's being shared between these threads?
  - The output stream

Another example

- x is initially 0
  - x could take many values after execution
- We say that multi-threaded applications have **interleavings**
  - The order of execution of each line in each thread can differ from run to run
- Some **interleavings** may lead to **race conditions**
  - Multiple threads may **race** to execute a certain piece of code

Thread A	*Thread B*
x = 1	*x = -1*

Thread A	*Thread B*
x = 0	*x = 0*
x = x + 1	*x = x - 1*

Agenda

- Processes
- Threads
- **Synchronization**
  - **Atomic operations**
- Sockets

Atomic operations

- Before we can reason at all about cooperating threads, we must know what operations are **atomic**
  - Indivisible, i.e., happens in its entirety or not at all
  - No events from other threads can occur in between

- Print example:
  - What if each print statement were atomic?
  - What if printing a single character were not atomic?

- Most computers
  - Memory load and store are atomic on a single core
  - Other instructions are not atomic (double-prec. Floating pt.)
  - Modern compilers, multicore architectures not seq. consistent
  - Need an atomic operation to build a bigger atomic operation

Atomic operations in Python

- The following operations are atomic in Python:
  - Update, insert, read, etc. of dictionaries, lists
  - Reads/writes of built-in types
  - Read and assignment of instance variables

- Safe to perform these operations simultaneously from different threads
- But combinations of above are not atomic:
  - Safe to execute x = 1 and x = 0 in different threads
  - Not safe to execute x = x + 1 in different threads!

Locks for mutual exclusion

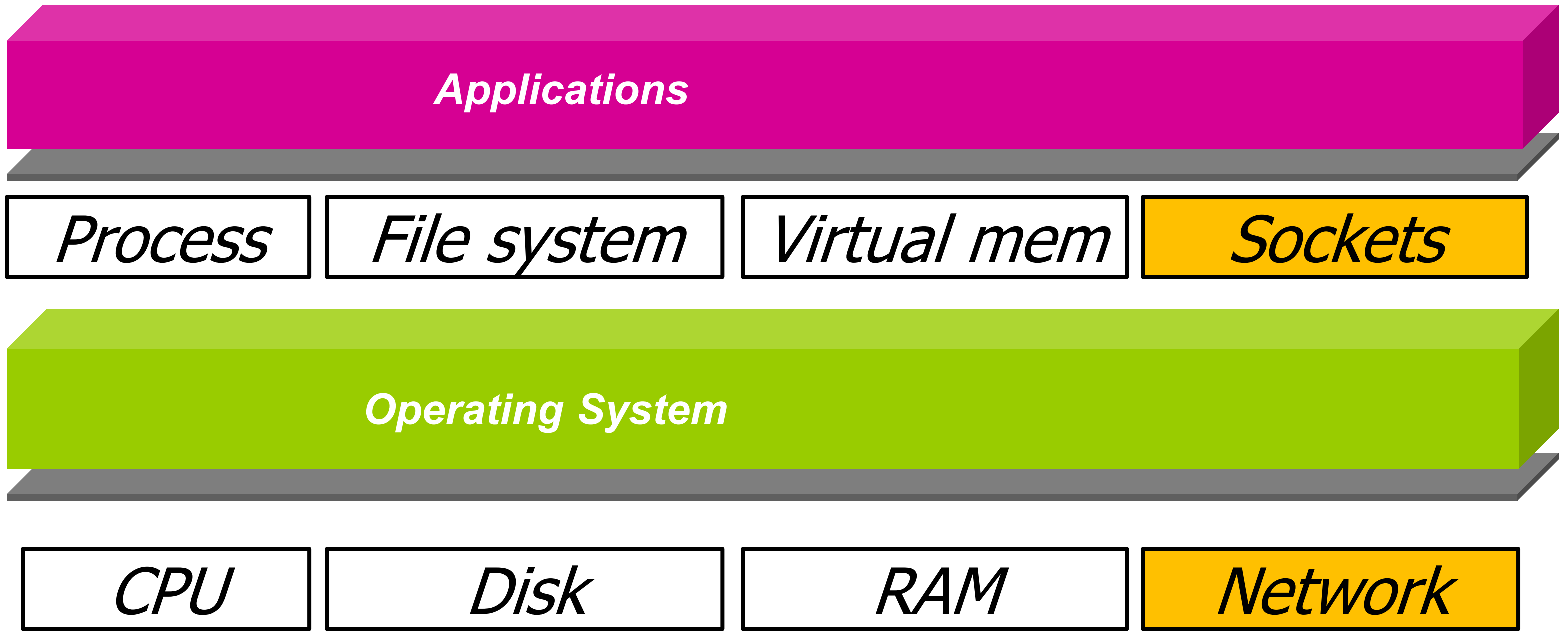
- How can we make x=x+1 safe?

```
from threading import Thread, Lock

def worker (myLock, i):
    global x
      myLock.acquire()
      x = x + 1
      myLock.release()

if __name__ == "main":
      myLock = Lock()
      for i in range(3):
            t = Thread(target=worker, args=(myLock,i)
            t.start()
```

Agenda

- Processes
- Threads
- Synchronization
  - Atomic operations
- **Sockets**

The OS network abstraction



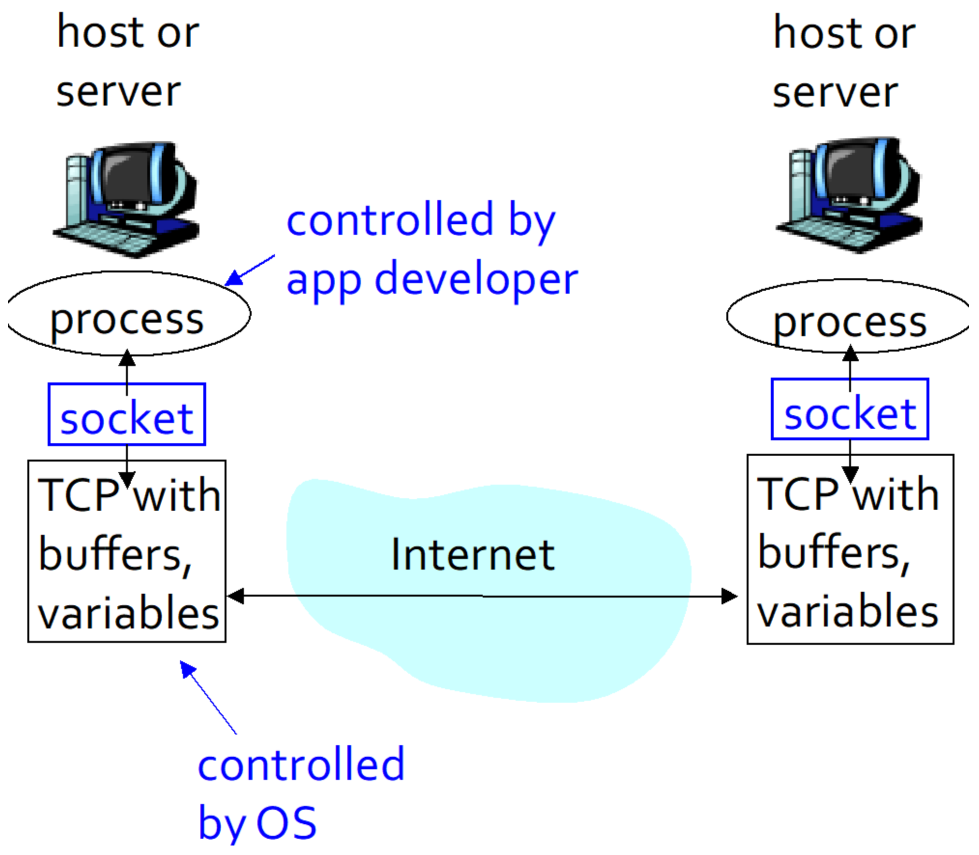
Sockets

- How do we share the network?
  - One (or a few) network interface cards/IP addresses
  - But many applications sending/receiving data

- A network **socket** provides virtual NIC for a process
  - Specify sender or receiver by both IP address and port #
  - TCP establishes connection between two sockets
  - UDP sends packets from one socket to another
- **Socket API** is provided by the operating system, and lets application programs use network sockets

Sockets

- A process sends messages to its socket
- A process receives messages from its socket



Sockets at the command line

Server

```
# macOS
$ nc -l localhost 8000
hello world

# Linux
$ nc -l -p 8000
```

Client

```
# macOS
$ echo "hello world" |
    nc localhost 8000
```

Socket example

```
$ echo "hello world" |
    nc localhost 8000
```

At the client

- Translate `localhost` into IP address `127.0.0.1`
- Decide to use the TCP protocol
- Create a socket
- `connect` to `127.0.0.1` at port `8000`
- `send` the data
- Close the connection

Socket example

```
$ nc -l localhost 8000
hello world
```

At the receiver (server)

- Note: receiver was started first
- Create socket
- Decide to use TCP
- `bind` the socket to port `8000`
- `listen` on the socket
- `accept` the connection request
- `recv` the packets (until connection closed)
- Close the socket

Socket server in Python

```
import socket
if __name__ == "__main__":
    sock = socket.socket(
        socket.AF_INET,
        socket.SOCK_STREAM,
    )

    sock.setsockopt(
        socket.SOL_SOCKET, socket.SO_REUSEADDR, 1)

    sock.bind(("localhost", 8000))

    # ...
```

Create socket

IPv4 (`AF_INET6` for IPv6)

TCP (`SOCK_DGRAM` for UDP)

Avoid "[ERROR] Address already in use"

`bind` the socket to port `8000`

Socket server in Python

```python
#...
sock.listen(5)

clientsocket, address = sock.accept()
print("Connection from", address)

message_chunks = []
while True:
    data = clientsocket.recv(4096)
    if not data:
        break
    message_chunks.append(data)
# ...
```

`listen` on the socket, queue up as many as 5 connect requests before refusing outside connections

`accept` a connection request

`recv()` returns up to 4096 bytes. Loop to receive all data. Assumes sender cleanly closes connection.

Socket server in Python

```
#...
clientsocket.close()
```

Close the socket

```
message_bytes = b''.join(message_chunks)
message_str = message_bytes.decode("utf-8")
print(message_str)
```

Join together chunks of bytes, then interpret as a UTF-8 string

Socket server in Python

Server

```
$ python3 test_server.py
Server: connection from
('127.0.0.1', 60980)
hello world
```

Client

```
$ echo "hello world" |
    nc localhost 8000
```

Socket server in Python

Server

```
$ python3 test_server.py
Server: connection from
('127.0.0.1', 60980)
hello world
```

Client

- When a TCP server accepts a new client, it returns a new socket to communicate with the client
- Allows the server to communicate with multiple clients

Socket client in Python

```
import socket

if __name__ == "__main__":
    # create an INET, STREAMing socket
    s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)

    # connect to the server
    s.connect(("localhost", 8000))

    # send a message
    message = "hello world!"
    sock.sendall(message.encode('utf-8'))
    s.close()
```

Socket client in Python

Server

```
$ nc -l localhost 8000
hello world
```

Client

```
$ python3 test_client.py
```

Socket client/server in Python

Server

```
$ python3 test_server.py
Server: connection from
('127.0.0.1', 60980)
hello world
```

Client

```
$ python3 test_client.py
```

Sockets and project 4

- Project 4 uses processes, threads and sockets to implement a Map Reduce server
- We need to do multiple things in parallel
  - Example: a master and N workers
    - N+1 processes
  - Example: a worker's task (a map function) and a worker's heartbeat (“I’m alive” message)
    - 2 threads
- Communicate between several machines
  - Master communicates with workers using sockets