Operating Systems: Concurrency

Programs and processes

- A program is a series of instructions
  - code for a single "process" of control
- Process: running program + state
  - State: Input, output, memory, code, files, etc.
- Processes are one of the main abstractions provided by the operating system
- A "Thread" is an execution context with register state, a program counter (PC) and a stack
  - "Thread of execution"
- Multiple processes can be running the same program, even sharing the code in the same memory space
  - reduces memory overhead, which is important in limited memory environments like embedded OSes

Processes as Distributed System Components

- Processes are isolated from each other, and thus "independent and autonomous"
- Each process is running its own code, with its own memory address space (local variables etc)
  - We will assume that the only way to communicate is explicit messages
    - Using networking protocol
  - Reading/writing to any shared object is communication!
    - Any variables/data structures in memory
    - Or files on disk
- If you don't share (too much) state, then it doesn't matter where they run
- For most assignments, all processes will be running on the same machine (for convenience)
  - But, your design should work even if the processes run on different machines!

Concurrent Execution

```
# main.py . Driver program
import os, subprocess

p1 = subprocess.Popen('python3 alice.py', shell=True)
p2 = subprocess.Popen('python3 bob.py', shell=True)
```

```
# Alice.py
import os,sys,time

while True:
    time.sleep(1)
    print("Alice here!")
```

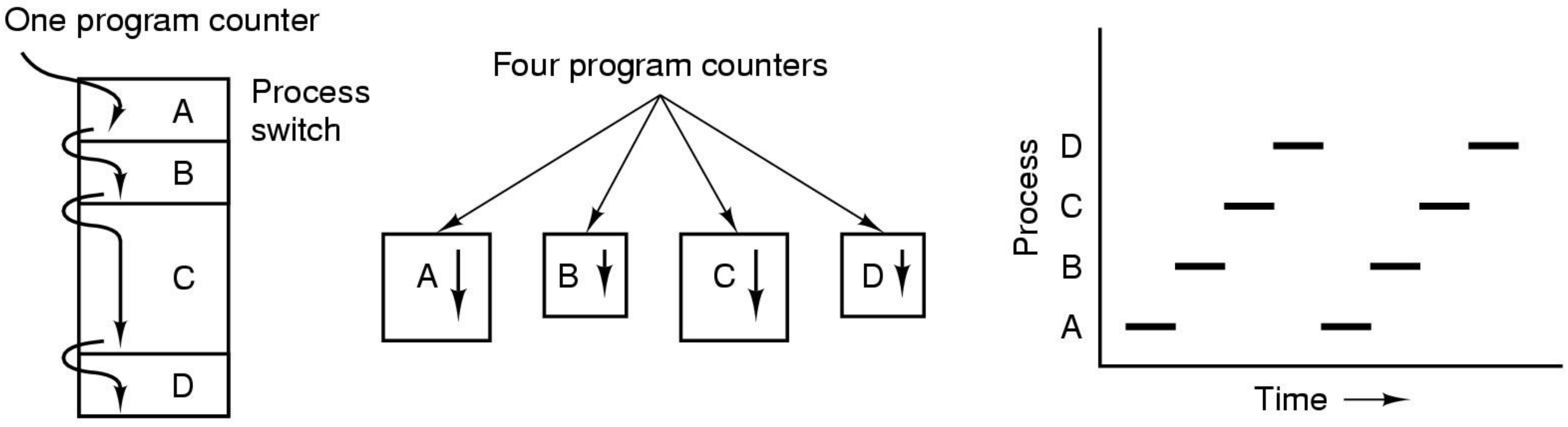
```
# Bob.py
import os,sys,time

while True:
    time.sleep(1)
    print(”Bob here!")
```

- Popen will launch in background and will not block
  - Wait for p1 to finish using p1.wait()
  - Can also grab output of p1 using capture_output
  - See subprocess documentation!!
- Careful around full pathnames
  - Best practice: os.getcwd()+’alice.py’
  - Shell=True passes envmt variables

Process Creation in UNIX/Bash

- `>./my-program.o &`
- #This creates a process that runs my-program.o, and runs it in the background
- Typical setup: spawn multiple processes :
- `>./dist-program --node-id=1 --type=primary-node &`
- `>./dist-program --node-id=2 --type=primary-node &`
- `>./dist-program --node-id=3 --type=secondary-node &`
- Exercise: Get comfortable with process creation and termination in your language/environment
  - Python subprocess

The process abstraction

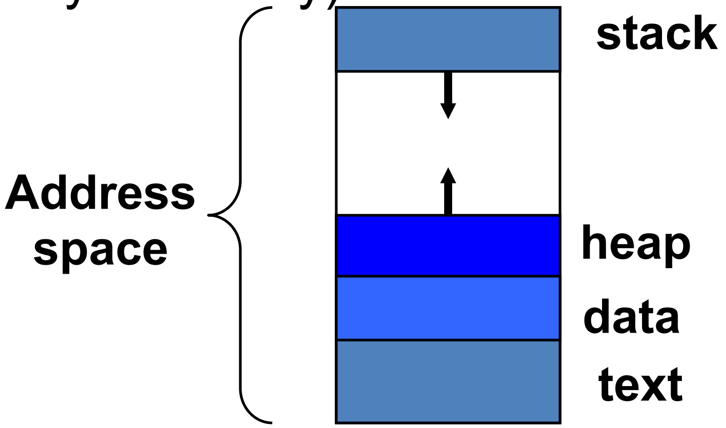


(a) (b) (c)

- Multiprogramming of four programs in the same address space
- Conceptual model of 4 independent, sequential processes
- Only one program active at any instant

UNIX Process Address Space

- Memory locations a process is allowed to address
- Each process runs in its own virtual memory *address space* that consists of:
  - *Stack space* – used for function and system calls
  - *Data space* – static variables, initialized globals
  - *Heap space* – dynamically allocated variables
  - *Text* – the program code (usually read only)



- Invoking the same program multiple times results in the creation of multiple distinct address spaces

UNIX Process Creation

- Parent processes create child processes, which, in turn create other processes, forming a tree of processes
- Resource sharing options
  - Parent and children share all resources
  - Children share subset of parent’s resources
  - Parent and child share no resources
- Execution options
  - Parent and children execute concurrently
  - Parent waits until children terminate

UNIX Process Creation (Cont.)

- Address space
  - Child duplicate of parent
  - Child has a program loaded into it
- UNIX examples
  - **fork** system call creates new process
  - **exec** system call used after a **fork** to replace the process’ memory space with a new program

CPU Virtualization

- Processes create the illusion of multiple “virtual” CPUs that programs fully control
- Process PCB contains program counter and other register state, allowing it to be “resumed”
- Timesharing: OS switches process running on physical CPU at high frequency (context switch)
- Virtualization is a key OS principle
  - Applies to CPU, memory, I/O, …

Example: process creation in UNIX

sh (pid = 22)

```
…

pid = fork()
if (pid == 0) {
  // child…
  …
  exec();
  }
else {
  // parent
  wait();
  }
…
```

Process creation in UNIX example

sh (pid = 22)

```
…
pid = fork()
if (pid == 0) {
   // child…
   …
   exec();
   }
else {
   // parent
   wait();
   }
…
```

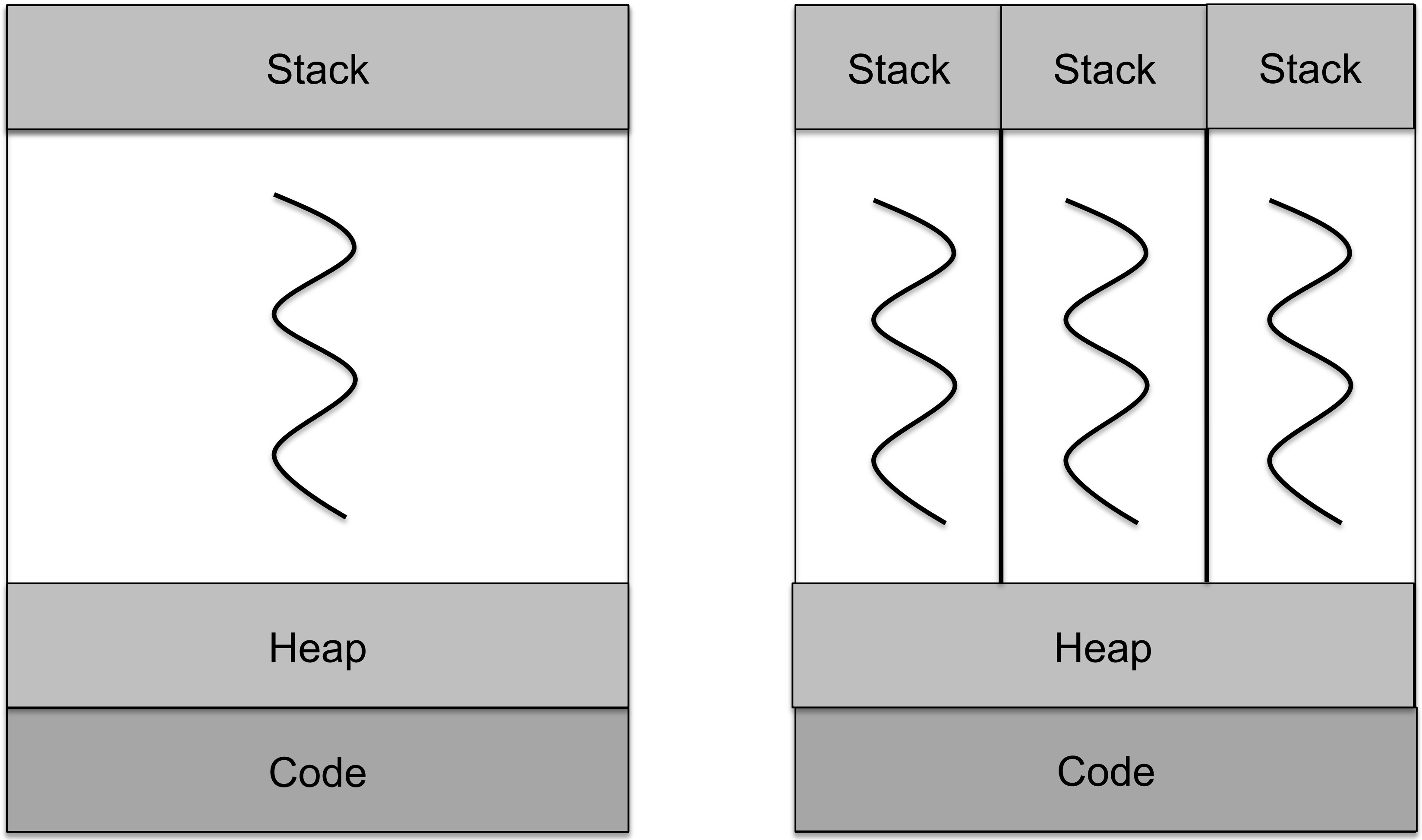
sh (pid = 24)

```
…
pid = fork()
if (pid == 0) {
   // child…
   …
   exec();
   }
else {
   // parent
   wait();
   }
…
```

UNIX Threads

- Creation of a process using `fork()` is expensive (time and machine effort)
  - Memory copying to create a copy of the process
    - In many cases just to call `exec()` and replace it
    - There are ways to mitigate creating a complete copy
  - Coordinating activities across process boundaries requires effort
- Threads are sometimes called *lightweight processes*
  - What we have called a process is sometimes considered a *heavyweight* process
  - A thread contains the necessary state for a distinct activity (process in the most general sense)

Single and Multithreaded Processes



One Thread

Multiple Threads

Benefits of Threads

- Efficiency / economy
  - Less memory, fewer system resources
- Responsiveness
  - Lower startup time
- Easier resource sharing
  - Natural sharing of memory, open files, etc.
  - With caveats that we will discuss
- Concurrency
  - Utilization of multiple processors or cores
- You can use threads as distributed system nodes, as long as you don’t use shared memory

Different Threading Models

- OS support for threads/kernel threads (pthreads):
  - Linux sees threads as 'tasks' and treats them same as processes for scheduling etc.
- Language runtime 'userspace' threads:
  - Runtime switches the stack
  - Python: Threading.thread(target=thread_func, args=..)
  - Go and goroutines
- Other concurrency abstractions:
  - Actor model (Erlang etc)

Example app: TCP server

Python TCPServer

create TCP welcoming socket

server begins listening for incoming TCP requests

loop forever

server waits on accept() for incoming requests, new socket created on return

read bytes from socket (but not address as in UDP)

close connection to this client (but *not* welcoming socket)

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind(('',serverPort))
serverSocket.listen(1)
print 'The server is ready to receive'
while 1:
    connectionSocket, addr = serverSocket.accept()

    sentence = connectionSocket.recv(1024)
    time.sleep(10)
    capitalizedSentence = sentence.upper()
    connectionSocket.send(capitalizedSentence)
    connectionSocket.close()
```

Example app: Threaded TCP server

Python TCPServer

create TCP welcoming socket

server begins listening for incoming TCP requests

loop forever

server waits on accept() for incoming requests, new socket created on return

read bytes from socket (but not address as in UDP)

close connection to this client (but *not* welcoming socket)

```
 from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind((‘’,serverPort))
serverSocket.listen(1)
print ‘The server is ready to receive’
while 1:
    connectionSocket, addr = serverSocket.accept()
    threading.thread(handle_client, connectionSocket)
        sentence = connectionSocket.recv(1024)
        time.sleep(10)
        capitalizedSentence = sentence.upper()
        connectionSocket.send(capitalizedSentence)
        connectionSocket.close()
```

Race Conditions

- Thread 1
- x=’a’
- Print(x)

- Thread 2
- x=‘b’
- Print(x)

- Output depends on order of execution of the threads
- Data Race: Whichever thread “wins” the race decides outcome

Synchronization Primitives: Mutual Exclusion

- Critical section: only one thread allowed at a time
- Lock = Threading.Lock()
- Lock.acquire()
  - Manipulate global/shared state
  - If (x==0):
    - y = x + 1
- Lock.release()

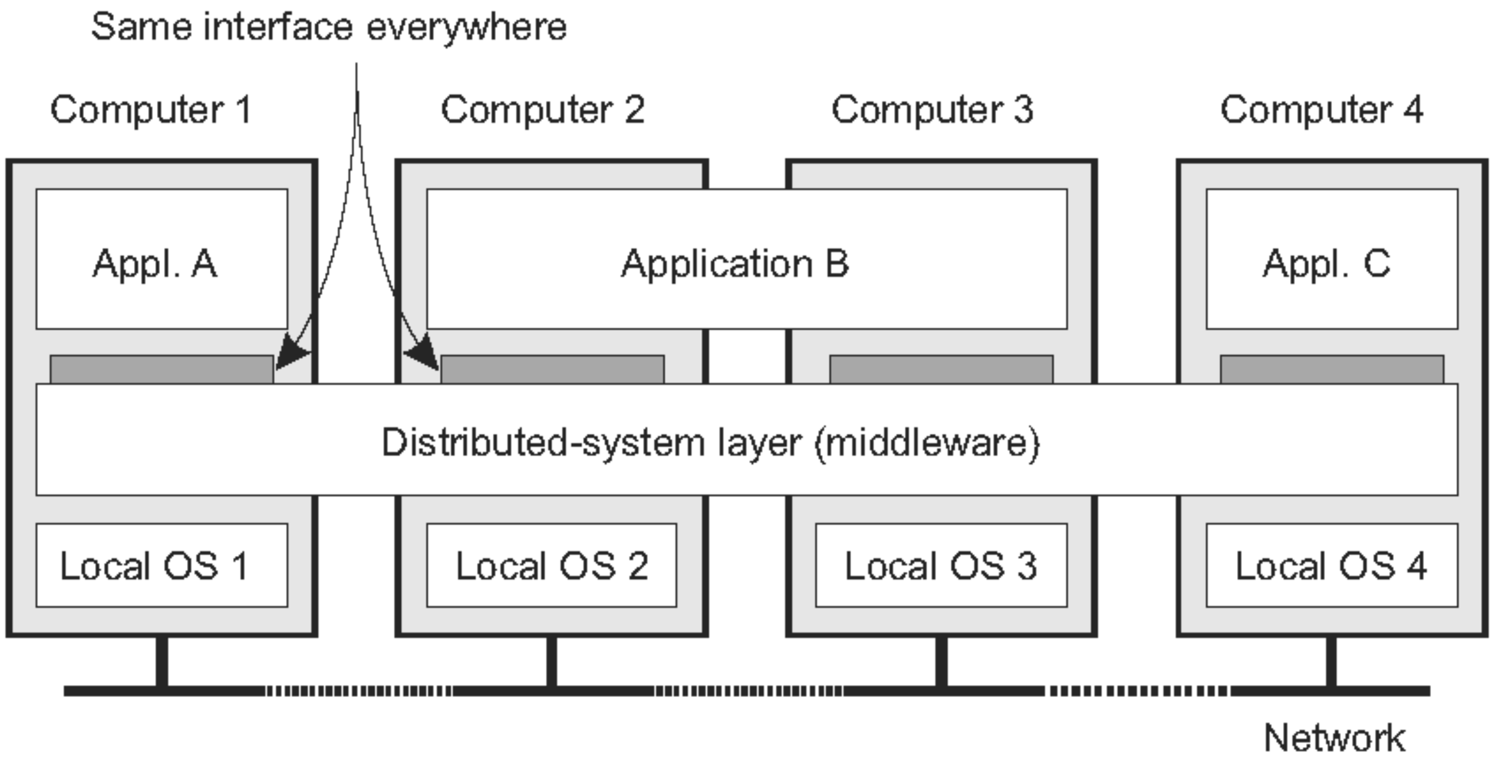
Concurrency

- **Video: Concurrency is not Parallelism by Rob Pike**
- Concurrency:
  - Compose independently executing things together
  - Ability to deal with >1 thing happening simultaneously
  - Mainly about program/system structure and communication
- Parallelism:
  - Actually doing multiple things at the same time
  - Ex: Massively parallel vector dot product, hardware level parallelism, etc.

Distributed Operating Systems

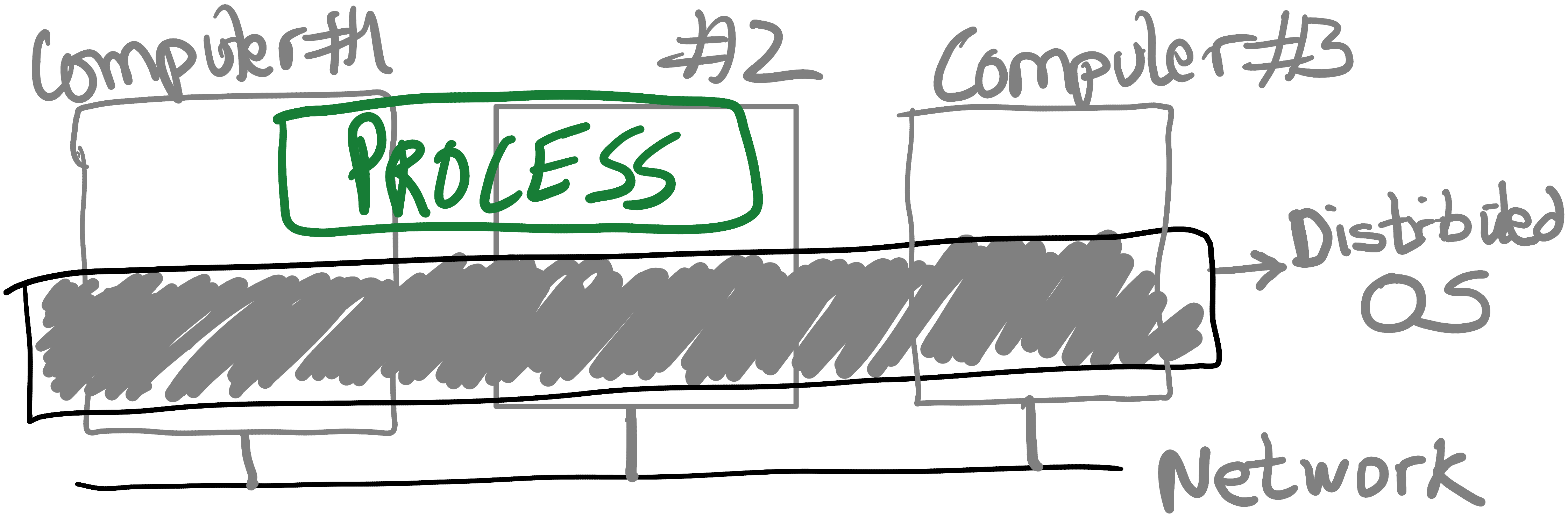
Middleware: The OS of Distributed Systems

- Commonly used components and functions for distributed applications



Distributed Operating System

- An OS that spans multiple computers
- Same OS services, functionality, and abstractions as single-machine OS



Distributed OS Challenges

- Providing the process abstraction and resource virtualization is hard
- Resource virtualization must be transparent
  - But in distributed settings, there's always a distinction between local and remote resources
- In a single-machine OS, processes don't care where their resources are coming from:
  - Which CPU cores, when they are scheduled, which physical memory pages they use, etc.
- In fact, providing abstract, virtual resources is one of the main OS services

Processes In Distributed OS

PROCESS

Process state:

- Code segment
- Memory pages
- Files
- Sockets
- Security permissions

Distributed OS

R-Computer

G-Computer

Transparency Issues In Distributed OS

PROCESS

Process state:

- Code segment
- Memory pages
- Files
- Sockets
- Security permissions

Distributed OS

R-Computer

G-Computer

- Where does code run?
- Which memory is used?
  - Local vs. remote
- How are files accessed?

Process Migration

PROCESS

Process state:
- Code segment
- Memory pages
- Files
- Sockets
- Security permissions

OS

R-Computer

OS

G-Computer

- Move all process state from one computer to another
- Process state can be vast
- Also entangled with other process states
    - Shared files?
    - IPC (pipes etc)

Partial Process Migration

PROCESS

Process state:

- Code segment
- Memory pages
- Files
- Sockets
- Security permissions

OS

R-Computer

OS

G-Computer

- Migrate some state
- Other state, if required, is accessed over the network
- Example: migrate only fraction of pages. Other pages are copied over the network on access.
- Can also be used to access remote hardware devices (GPUs)