Processes

CSE 351 Summer 2021

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REFRESH TYPE	EXAMPLE SHORTCUTS	EFFECT
SOFT REFRESH	GMAIL [REFRESH] BUTTON	REQUESTS UPDATE WITHIN JAVASCRIPT
NORMAL REFRESH	F5, CTRL-R, ⌘R	REFRESHES PAGE
HARD REFRESH	CTRL-F5, CTRL-⇧, ⌘⇧R	REFRESHES PAGE INCLUDING CACHED FILES
HARDER REFRESH	CTRL-⇧-HYPER-ESC-R-F5	REMOTELY CYCLES POWER TO DATACENTER
HARDEST REFRESH	CTRL-⌘-⊞-⇧-#-R-F5-F-5-ESC-O-0-Ø-⏏-SCROLL LOCK	INTERNET STARTS OVER FROM ARPANET

http://xkcd.com/1854/

Gentle, Loving Reminders

- hw16 due Tonight! hw17 due Friday!
- Lab 4 due Monday (8/9)!
  - hw16 should be helpful preparation
  - Caches, caches, caches

- Final deadline for US#2 is tomorrow!
  - Today by 8pm for one late day

Learning Objectives

Understanding this lecture means you can:

- Explain the role of exceptions, and one way that they're implemented (exception tables)
- Differentiate between synchronous and asynchronous exceptions, and explain how systems respond to both
- Explain how we can have multiple processes running on a single processor, and how we can create new processes
- Describe the first operating systems, in context with the first computers, and the first programmers

Leading Up to Processes

- System Control Flow
  - **Control flow**
  - **Exceptional control flow**
  - Asynchronous exceptions (interrupts)
  - Synchronous exceptions (traps & faults)

Control Flow

- **So far:** we've seen how the flow of control changes as a *single program* executes
- **Reality:** multiple programs running *concurrently*
  - How does control flow across the many components of the system?
  - *In particular: More programs running than CPUs*

Control Flow

- Processors do only one thing:
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions
  - This sequence is the CPU's *control flow* (or *flow of control*)

Physical control flow

time ↓

<startup>
$instr_1$
$instr_2$
$instr_3$
…
$instr_n$
<shutdown>

Altering the Control Flow

- Up to now, two ways to change control flow:
  - Jumps (conditional and unconditional)
  - Call and return
  - Both react to changes in *program state*
- Processor also needs to react to changes in *system state*
  - Unix/Linux user hits “Ctrl-C” at the keyboard
  - User clicks on a different application’s window on the screen
  - Data arrives from a disk or a network adapter
  - Instruction divides by zero
  - System timer expires
- Can jumps and procedure calls achieve this?
  - No – the system needs mechanisms for “*exceptional*” control flow!

Java Digression

This is extra (non-testable) material

- Java has exceptions, but they're *something different*
  - Examples: NullPointerException, MyBadThingHappenedException, …
  - `throw` statements
  - `try`/`catch` statements ("throw to youngest matching catch on the call-stack, or exit-with-stack-trace if none")
- Java exceptions are for reacting to (unexpected) program state
  - Can be implemented with stack operations and conditional jumps
  - A mechanism for "many call-stack returns at once"
  - Requires additions to the calling convention, but we already have the CPU features we need
- System-state changes on previous slide are mostly of a different sort (asynchronous/external except for

Control Flow

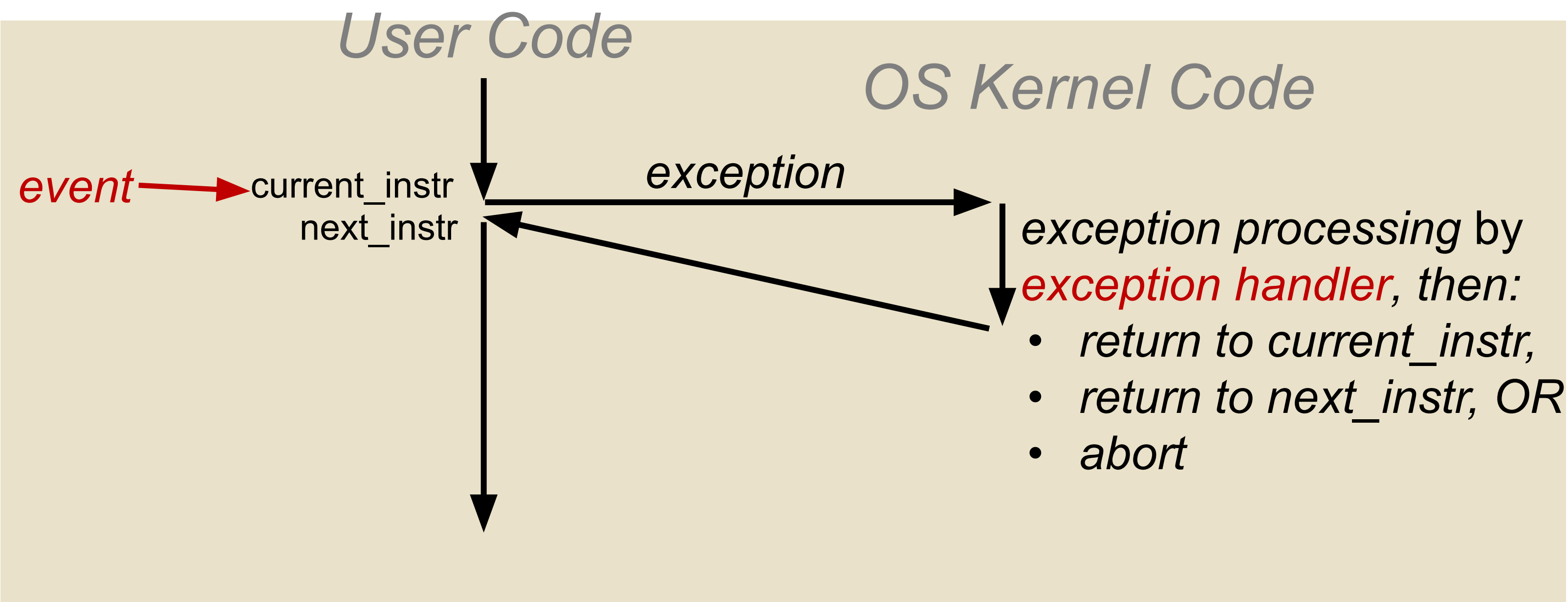
- **So far:** we've seen how the flow of control changes as a *single program* executes
- **Reality:** multiple programs running *concurrently*
  - How does control flow across the many components of the system?
  - In particular: More programs running than CPUs
- *Exceptional* control flow is the mechanism for:
  - Transferring control between *processes* and OS
  - Handling *I/O* and *virtual memory* within the OS
  - Implementing multi-process apps (shells, web servers)
  - Implementing concurrency

Exceptional Control Flow

- Exists at all levels of a computer system
- Low level mechanisms
  - **Exceptions**
    - Change in processor's control flow in response to a system event (*i.e.* change in system state, user-generated interrupt)
    - Implemented using a combination of hardware and OS software
- Higher level mechanisms
  - **Process context switch**
    - Implemented by OS software and hardware timer
  - **Signals**
    - Implemented by OS software
    - We won't cover these – see CSE451 and CSE/EE474

Exceptions

- An *exception* is transfer of control to the operating system (OS) kernel in response to some *event* (*i.e.* change in processor state)
  - Kernel is the memory-resident part of the OS
  - Examples: division by 0, page fault, I/O request completes, Ctrl-C



Exceptions

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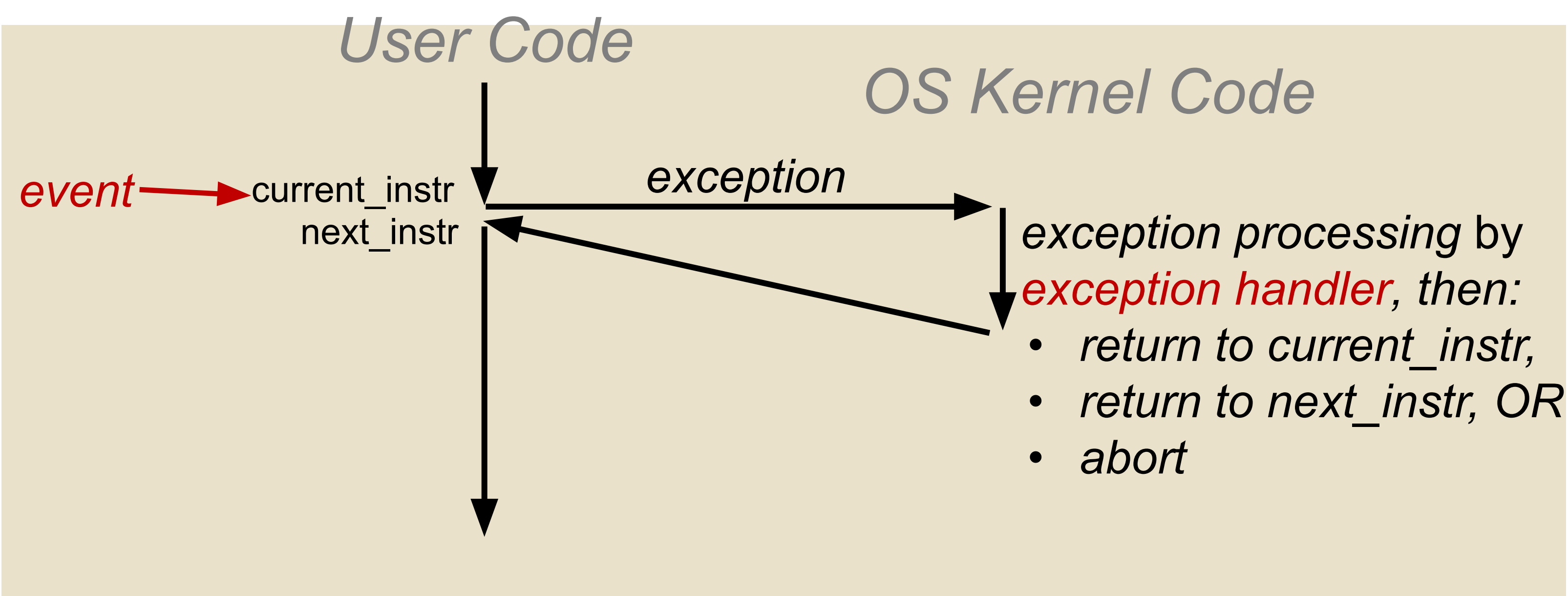
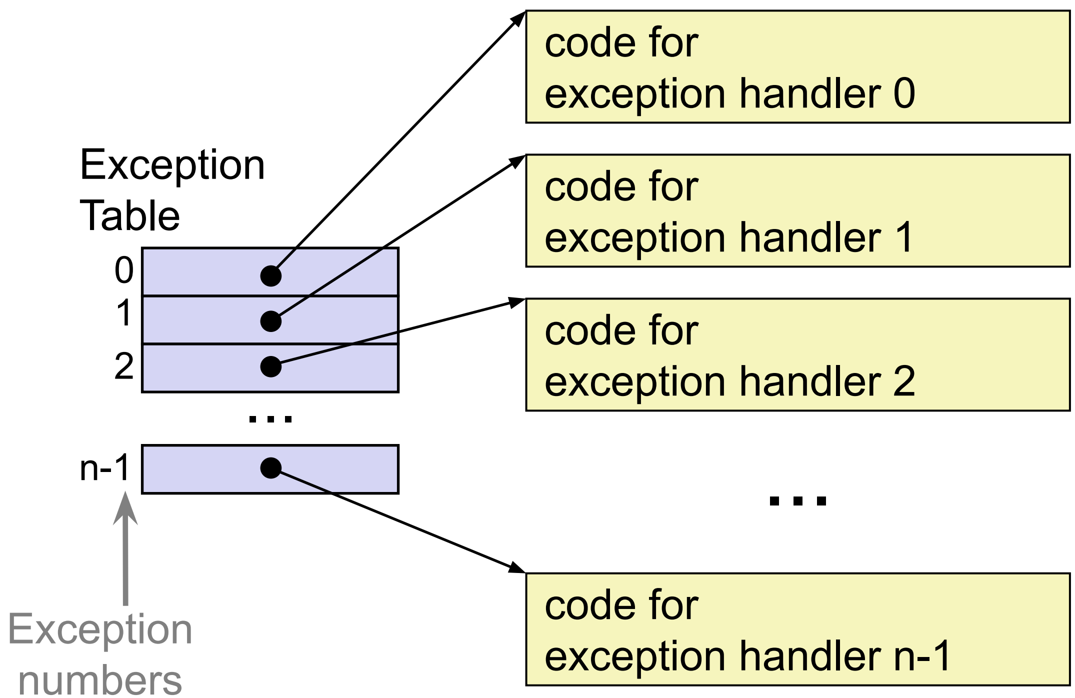


- *How does the system know where to jump to in the OS?*

Exception Table

This is extra (non-testable) material

- A jump table for exceptions (or, *Interrupt Vector Table*)
  - Each event type has an exception number *k*
  - *k* indexes into the exception table
  - Handler *k* is called each time exception #*k* occurs



Exception Table (Excerpt)

This is extra (non-testable) material

Exception Number	*Description*	*Exception Class*
0	Divide error	Fault
13	General protection fault	Fault
14	Page fault	Fault
18	Machine check	Abort
32-255	OS-defined	Interrupt or trap

How are you feeling about exceptions?

Leading Up to Processes

- System Control Flow
  - Control flow
  - Exceptional control flow
  - **Asynchronous exceptions (interrupts)**
  - **Synchronous exceptions (traps & faults)**

Asynchronous Exceptions (Interrupts)

- Caused by events external to the processor
  - Indicated by setting the processor's interrupt pin(s) (wire into CPU)
  - After interrupt handler runs, the handler returns to "next" instruction

- Examples:
  - I/O interrupts
    - Hitting Ctrl-C on the keyboard
    - Clicking a mouse button or tapping a touchscreen
    - Arrival of a packet from a network
    - Arrival of data from a disk
  - Timer interrupt
    - Every few milliseconds, an external timer chip triggers an interrupt
    - Used by the OS kernel to take back control from user programs

Synchronous Exceptions

- Caused by events that occur as a result of executing an instruction:
  - ***Traps***
    - **Intentional**: transfer control to OS to perform some function
    - Examples: *system calls*, breakpoint traps, special instructions
    - Returns control to "next" instruction
  - ***Faults***
    - **Unintentional** but possibly recoverable
    - Examples: *page faults*, segment protection faults, integer divide-by-zero exceptions
    - Either re-executes faulting ("current") instruction or aborts
  - ***Aborts***
    - **Unintentional** and unrecoverable
    - Examples: parity error, machine check (hardware failure detected)
    - Aborts current program

System Calls

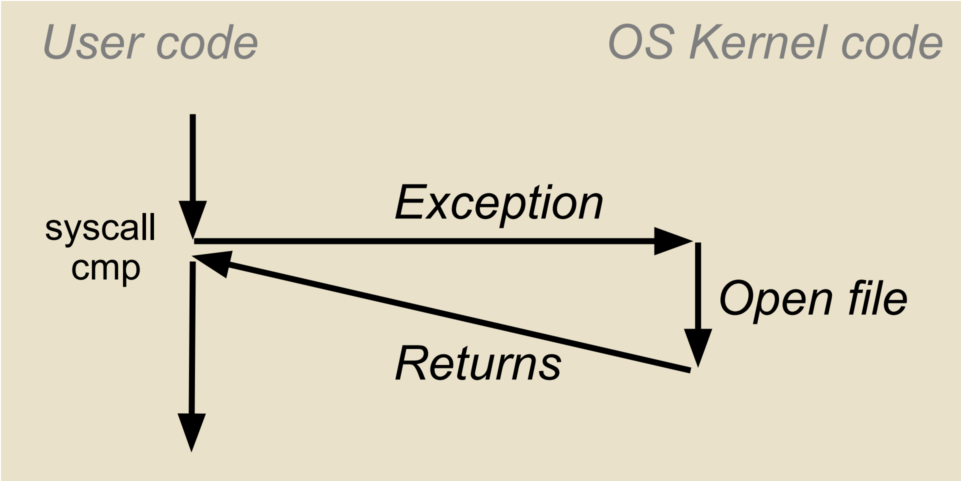
- Each system call has a unique ID number
- Examples for Linux on x86-64:

Number	*Name*	*Description*
0	`read`	Read file
1	`write`	Write file
2	`open`	Open file
3	`close`	Close file
4	`stat`	Get info about file
57	`fork`	Create process
59	`execve`	Execute a program
60	`_exit`	Terminate process
62	`kill`	Send signal to process

Traps Example: Opening File

- User calls `open(filename, options)`
- Calls `__open` function, which invokes system call instruction `syscall`

```
0000000000e5d70 <__open>:
...
e5d79:   b8 02 00 00 00      mov  $0x2,%eax  # open is syscall 2
e5d7e:   0f 05               syscall         # return value in %rax
e5d80:   48 3d 01 f0 ff ff   cmp  $0xfffffffffffff001,%rax
...
e5dfa:   c3                  retq
```



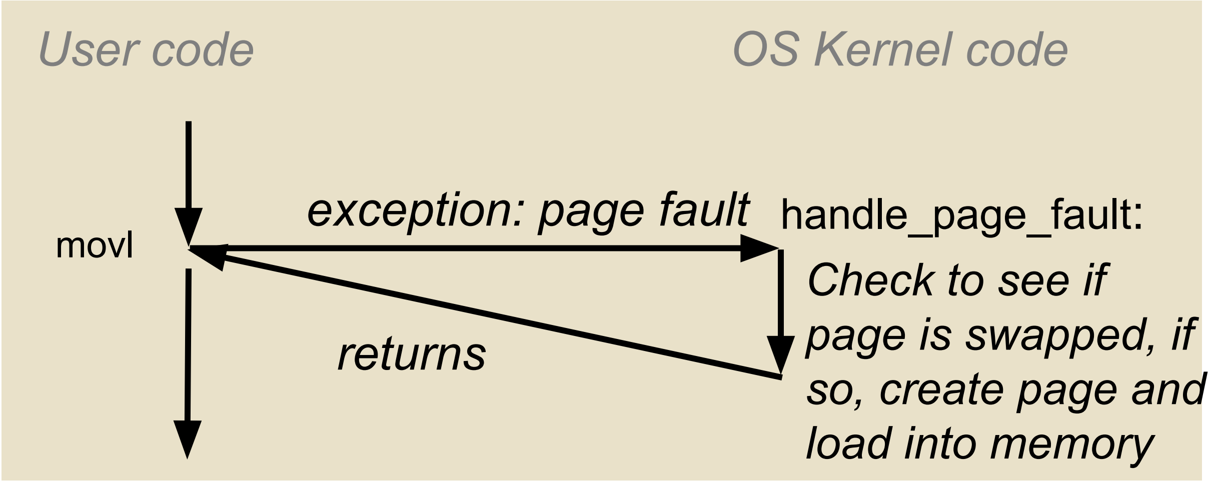
- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

Fault Example: Page Fault w/Swapped Page

- User writes to memory location
- That portion (page) of user's memory is currently swapped out (on disk)

```
int a[1000];
int main () {
  a[500] = 13;
}
```

```
80483b7:   c7 05 10 9d 04 08 0d    movl    $0xd,0x8049d10
```

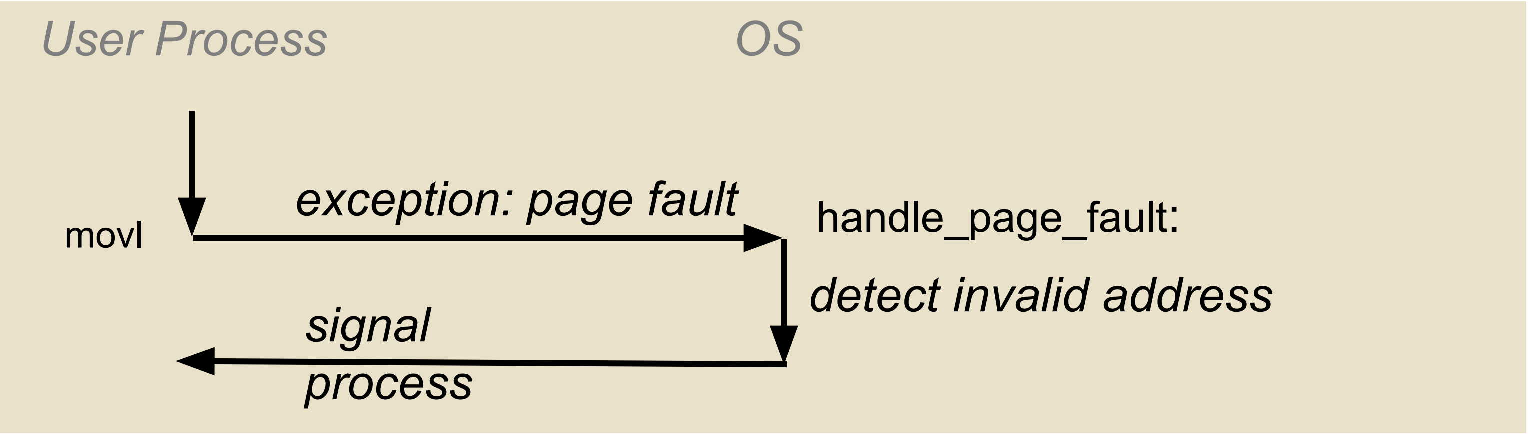


- Page fault handler must load page into physical memory
- Returns to faulting instruction: `mov` is executed again!
  - Successful on second try

Fault Example: Invalid Memory Reference

```
int a[1000];
int main() {
  a[5000] = 13;
}
```

```
80483b7:   c7 05 60 e3 04 08 0d    movl    $0xd,0x804e360
```



- Page fault handler detects invalid address
- Sends `SIGSEGV` signal to user process
- User process exits with “segmentation fault”

Summary

- Exceptions
  - Events that require non-standard control flow
  - Generated externally (interrupts) or internally (traps and faults)
  - After an exception is handled, 3 potential scenarios:
    - Re-execute the current instruction
    - Resume execution with the next instruction
    - Abort the process that caused the exception

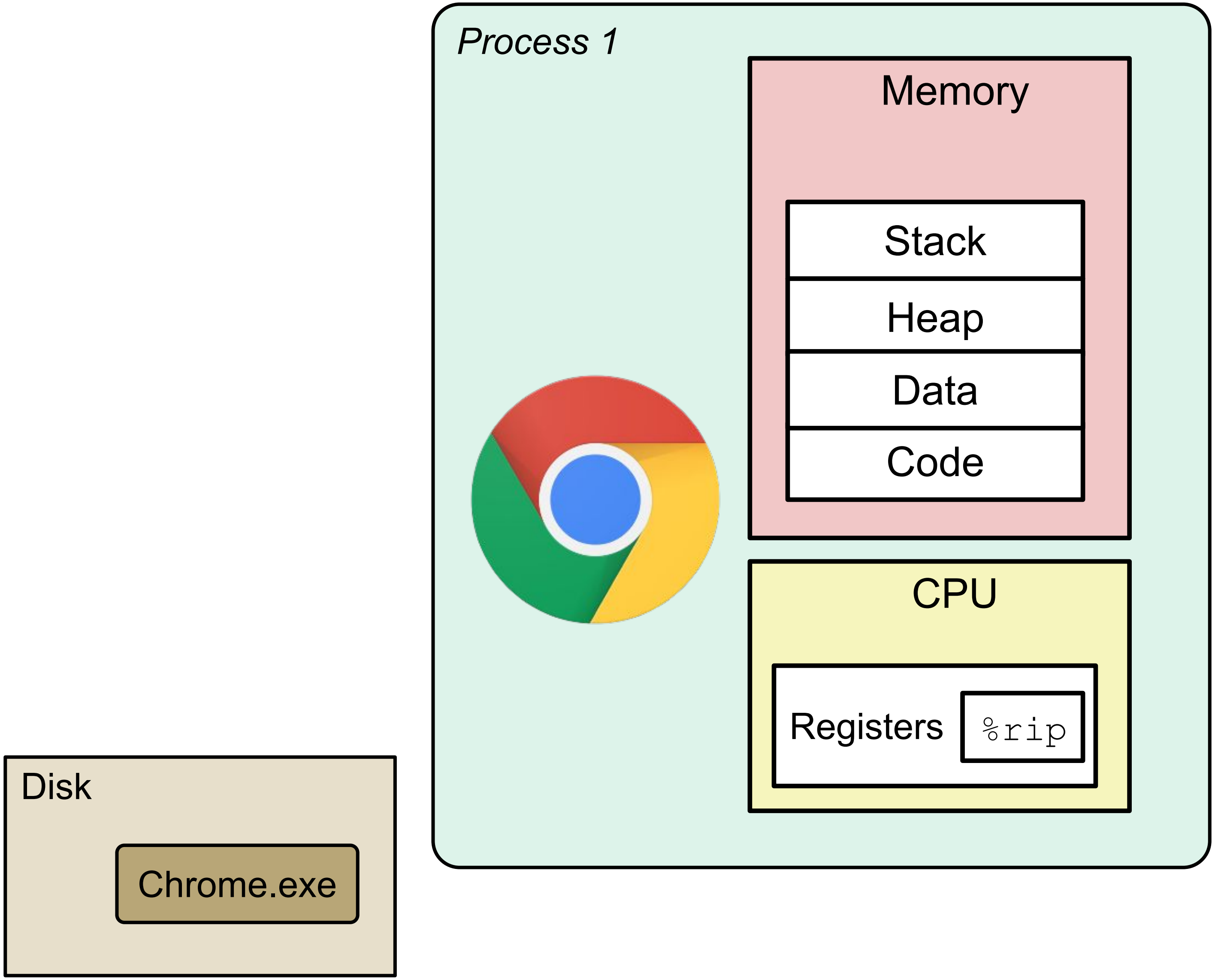
Exception flow, feeling ok?

Processes

- **Processes and context switching**
- Creating new processes
  - `fork()`, ~~`exec*()`, and `wait()`~~

What is a process?

It's an *abstraction*!

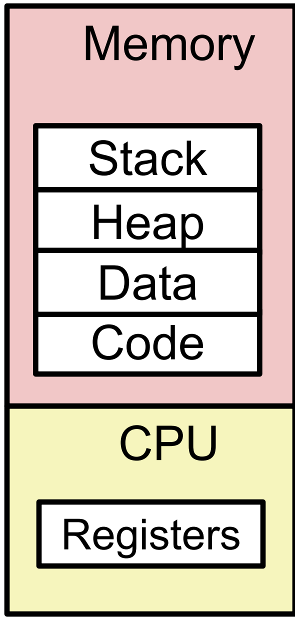


What is a process?

- Another *abstraction* in our computer system
  - Provided by the OS
  - OS uses a data structure to represent each process
  - Maintains the ***interface*** between the program and the underlying hardware (CPU + memory)
- What do *processes* have to do with *exceptional control flow*?
  - Exceptional control flow is the *mechanism* the OS uses to enable **multiple processes** to run on the same system
- What is the difference between:
  - A processor? A program? A process?

Processes

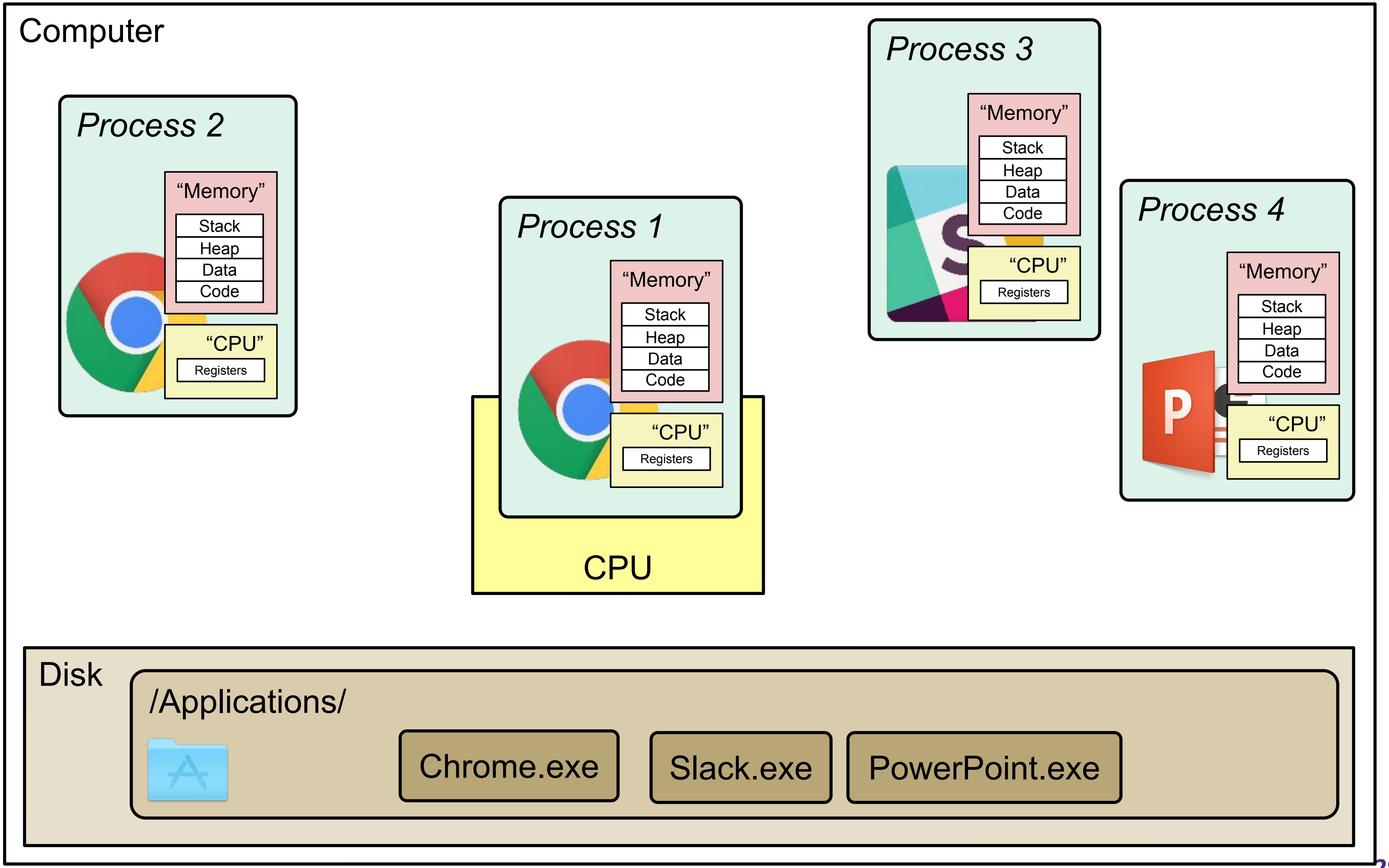
- A ***process*** is an instance of a running program
  - "One of the most profound ideas in computer science"
  - Not the same as "program" or "processor"



- Process provides each program with two key abstractions:
  - *Logical control flow*
    - Each program seems to have sole use of CPU
    - Provided via ***context switching***
  - *Private address space*
    - Each program seems to have sole use of memory
    - Provided via ***virtual memory***

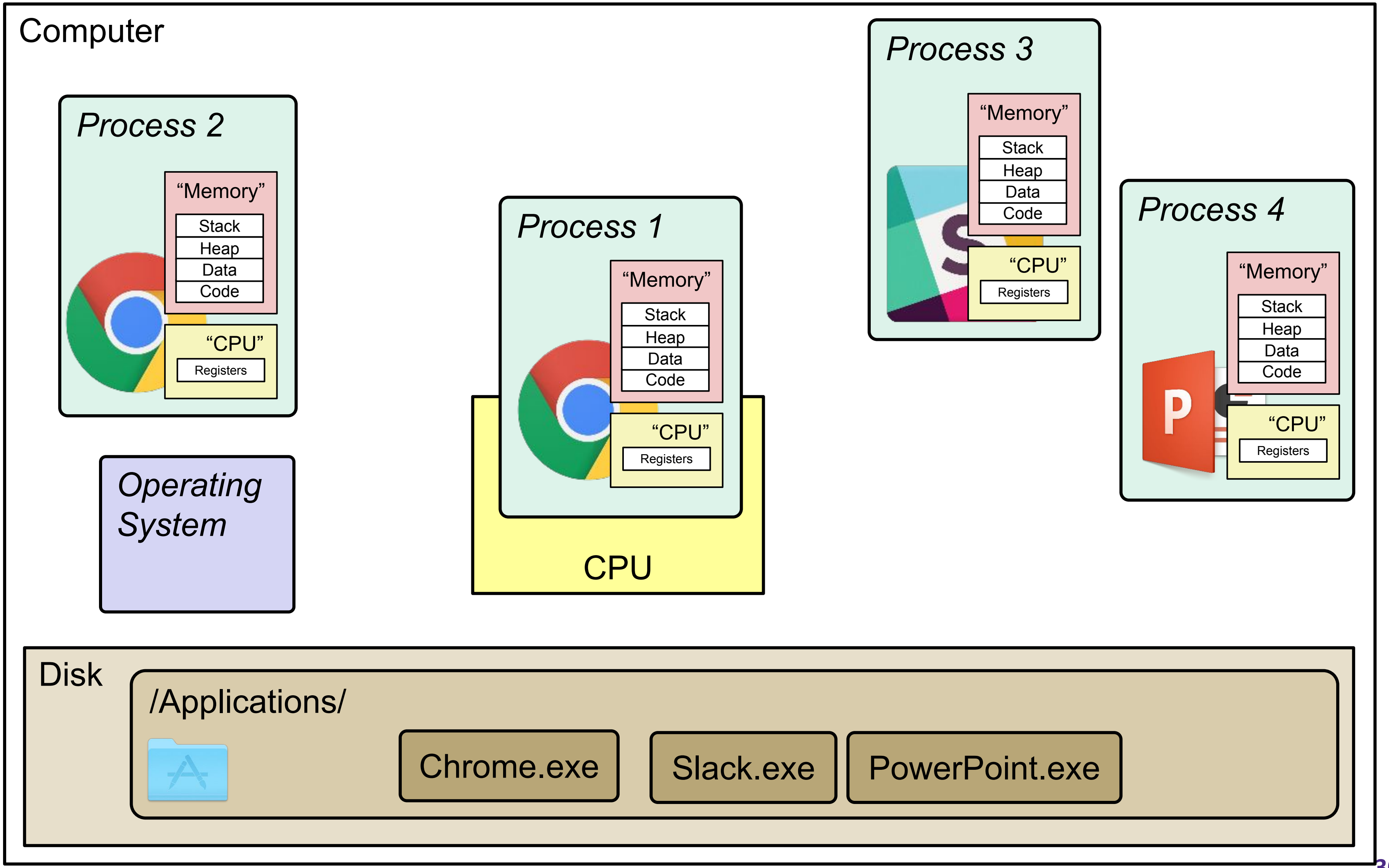
What is a process?

It's an *abstraction*!

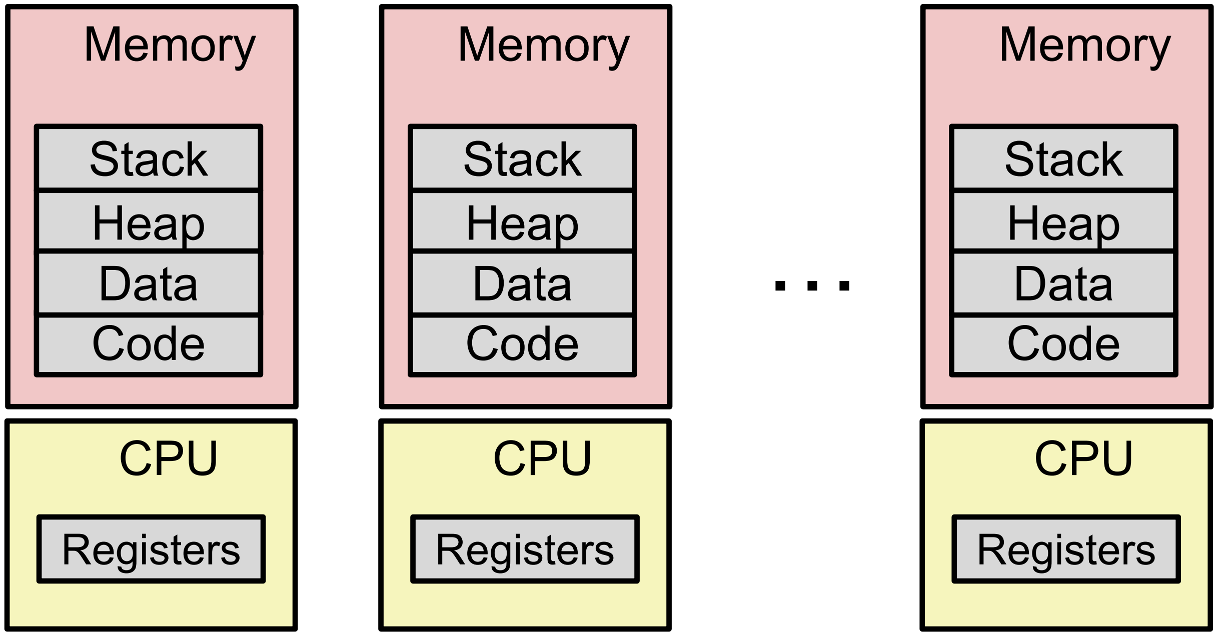


What is a process?

It's an *abstraction*!

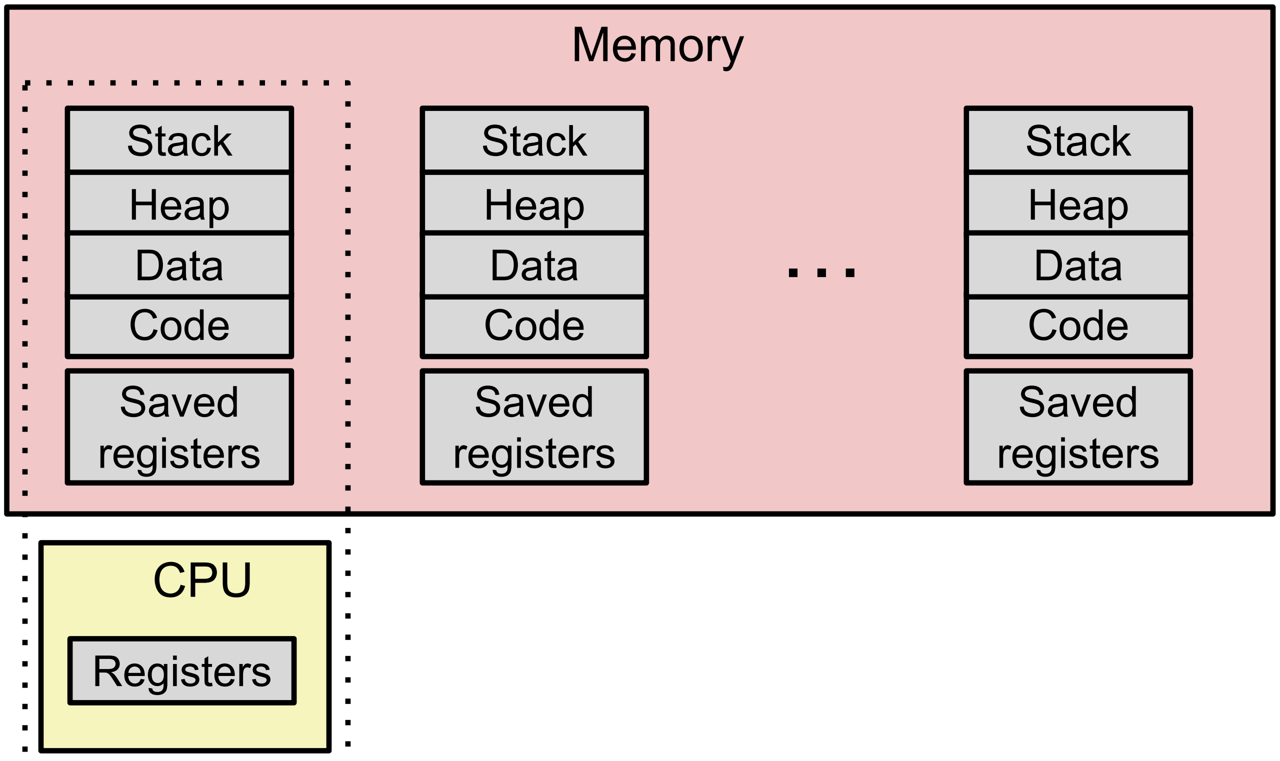


Multiprocessing: The Illusion



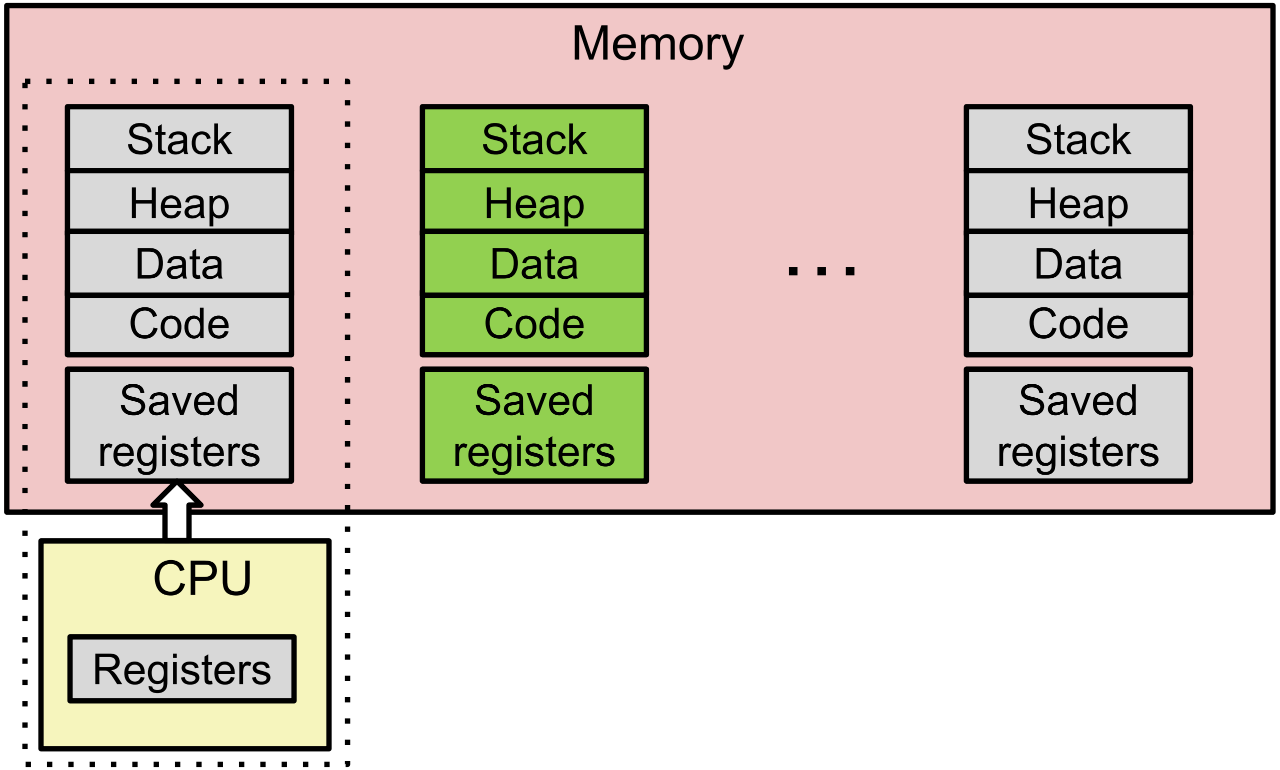
- Computer runs many processes simultaneously
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

Multiprocessing: The Reality



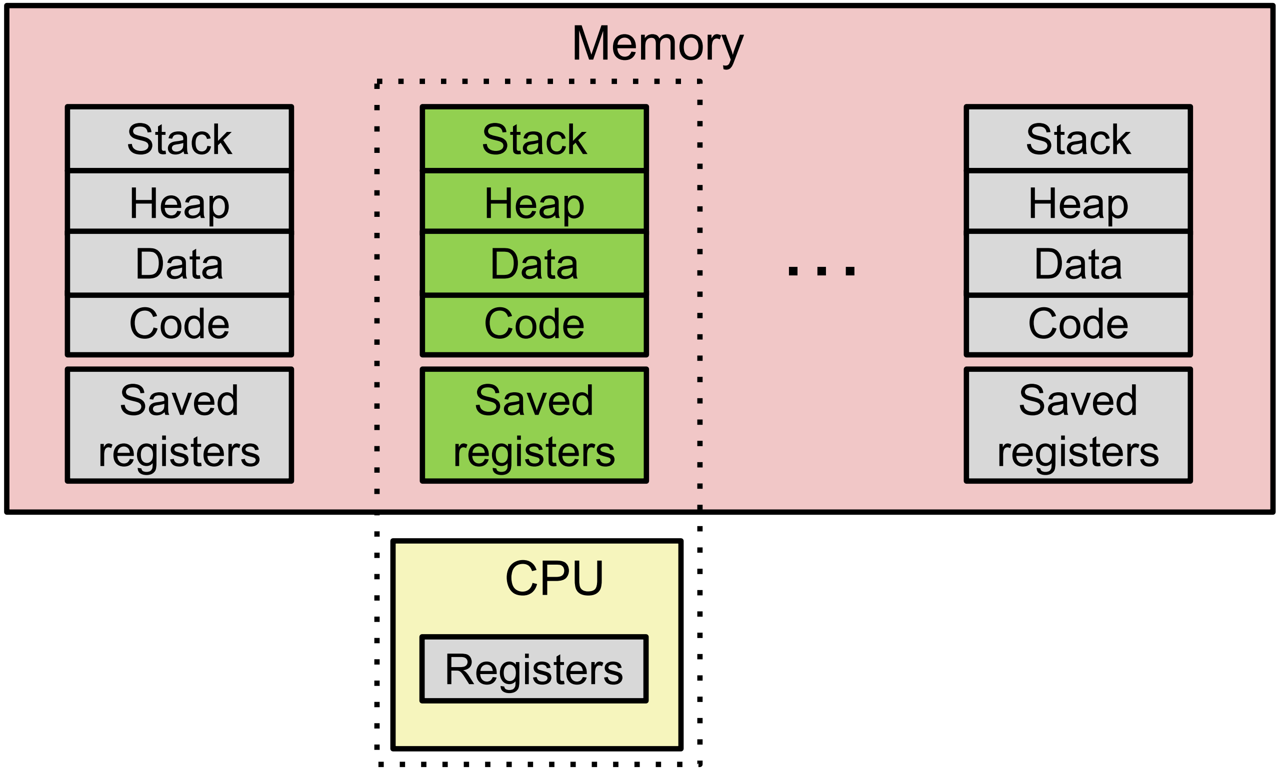
- Single CPU executes multiple processes *concurrently*
  - Process executions interleaved, CPU runs *one at a time*
  - Address spaces managed by **virtual memory** system
  - *Execution context* (register values, stack, …) for other processes saved in memory

Multiprocessing



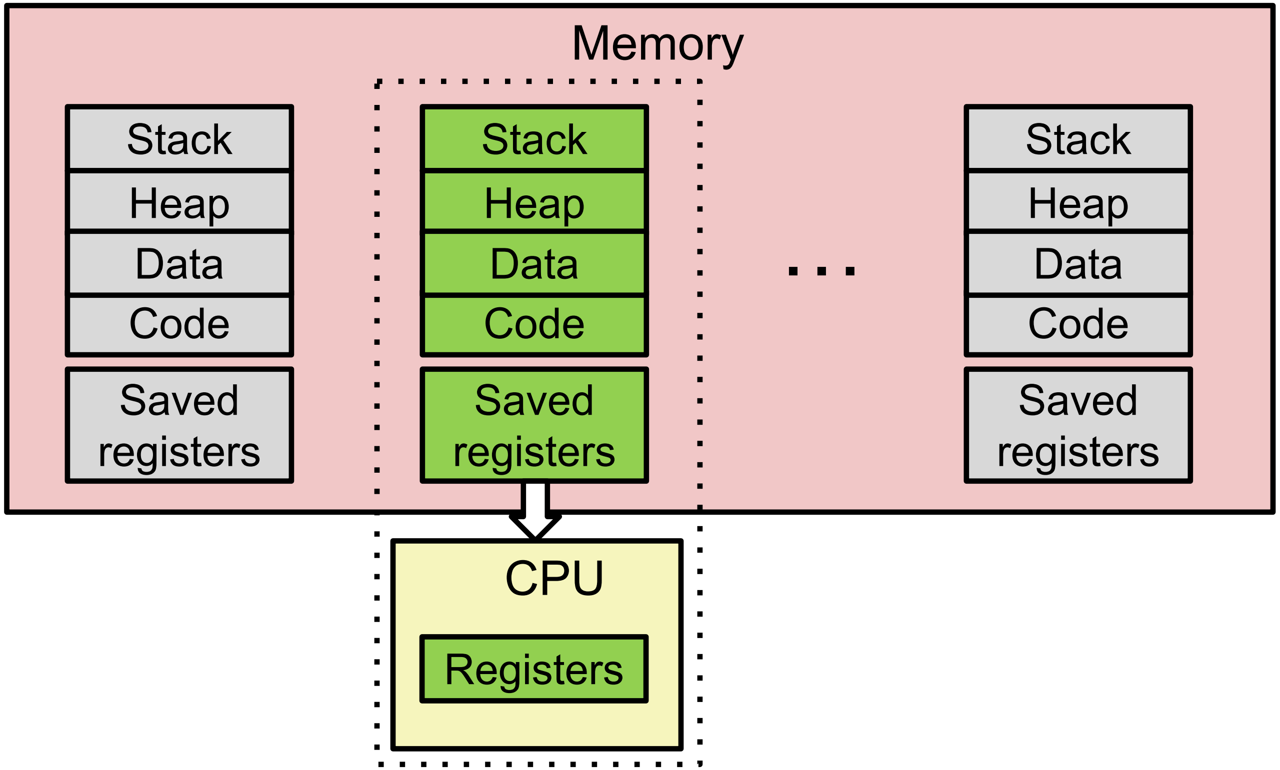
- Context switch
  1) **Save current registers in memory**

Multiprocessing



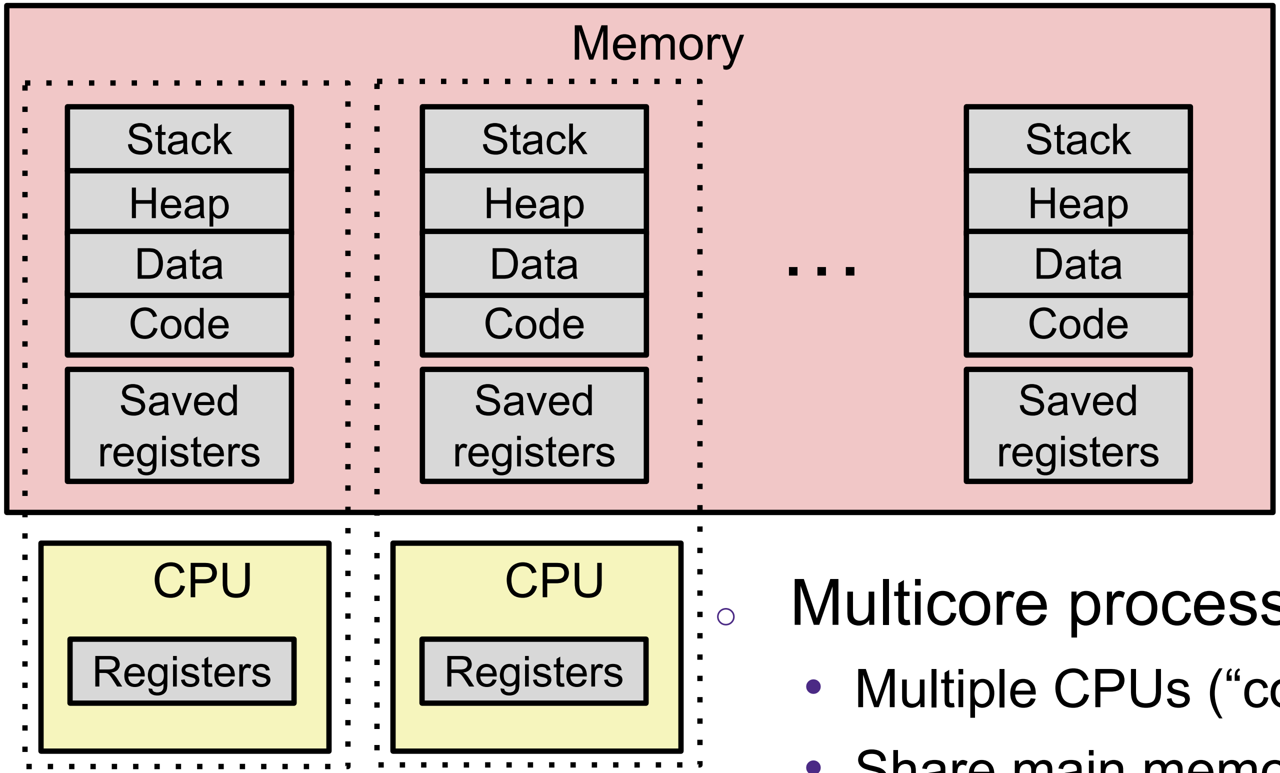
- Context switch
  1) Save current registers in memory
  2) **Schedule next process for execution**

Multiprocessing



- Context switch
  1) Save current registers in memory
  2) Schedule next process for execution
  3) **Load saved registers and switch address space**

Multiprocessing: The (Modern) Reality

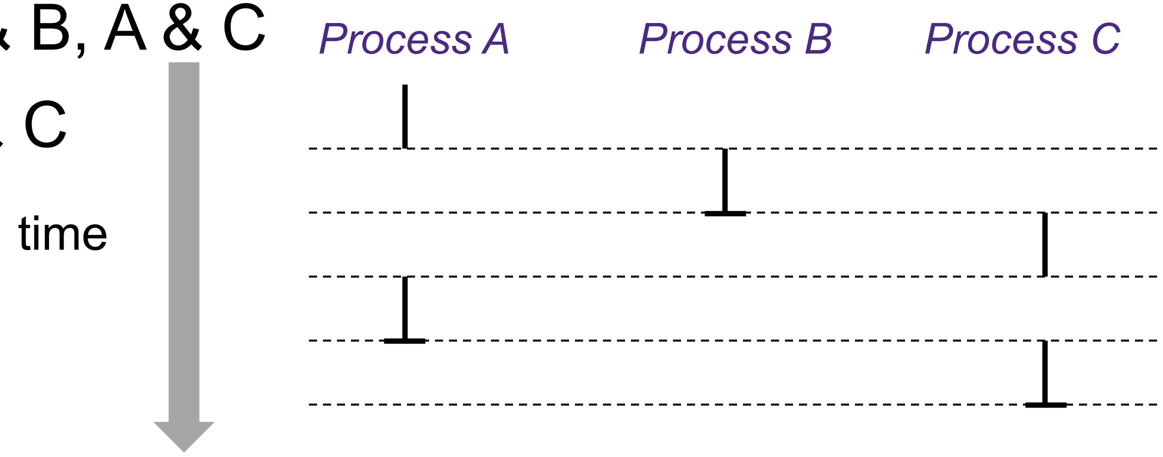


- Multicore processors
  - Multiple CPUs ("cores") on 1 chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Kernel schedules processes to cores
  - ***Still*** **constantly swapping processes**

Concurrent Processes

Assume only one CPU

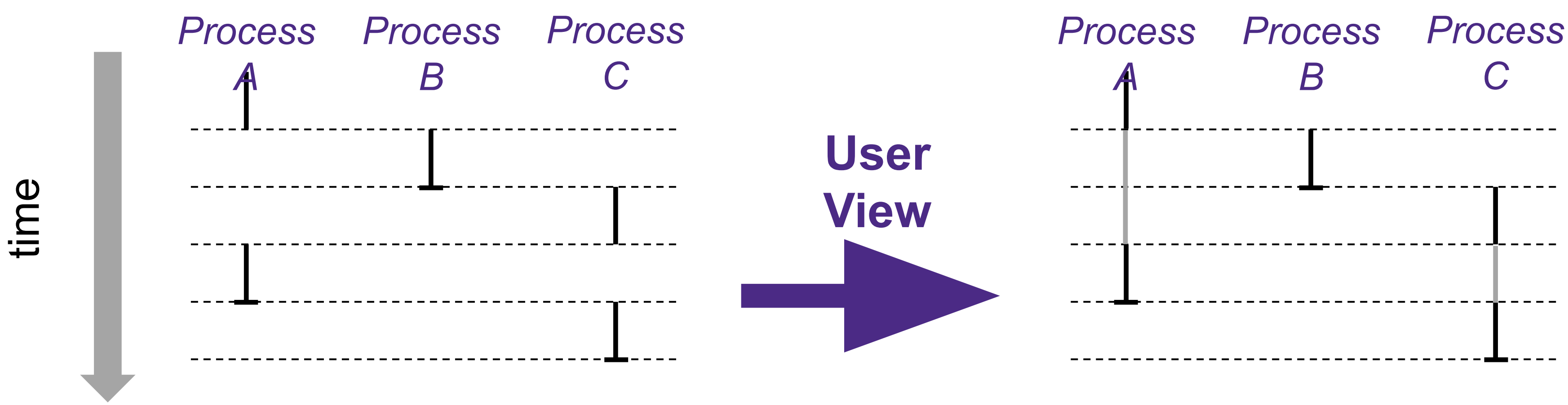
- Each process is a logical control flow
- Two processes *run concurrently* (are concurrent) if their instruction executions (flows) overlap in time
  - Otherwise, they are *sequential*
- Example: (running on single core)
  - Concurrent: A & B, A & C
  - Sequential: B & C



User's View of Concurrency

Assume only <u>one</u> CPU

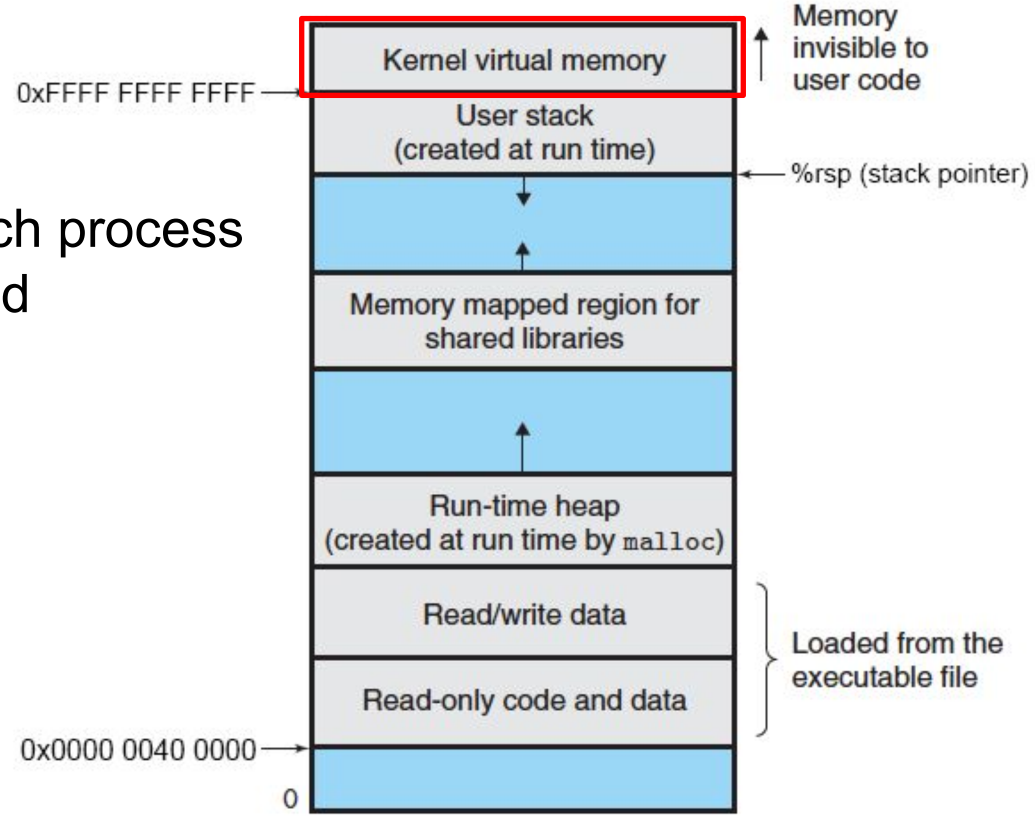
- Control flows for concurrent processes are physically disjoint in time
  - CPU only executes one process at a time
- However, the user can *think of* concurrent processes as executing at the same time, in *parallel*



Context Switching

Assume only one CPU

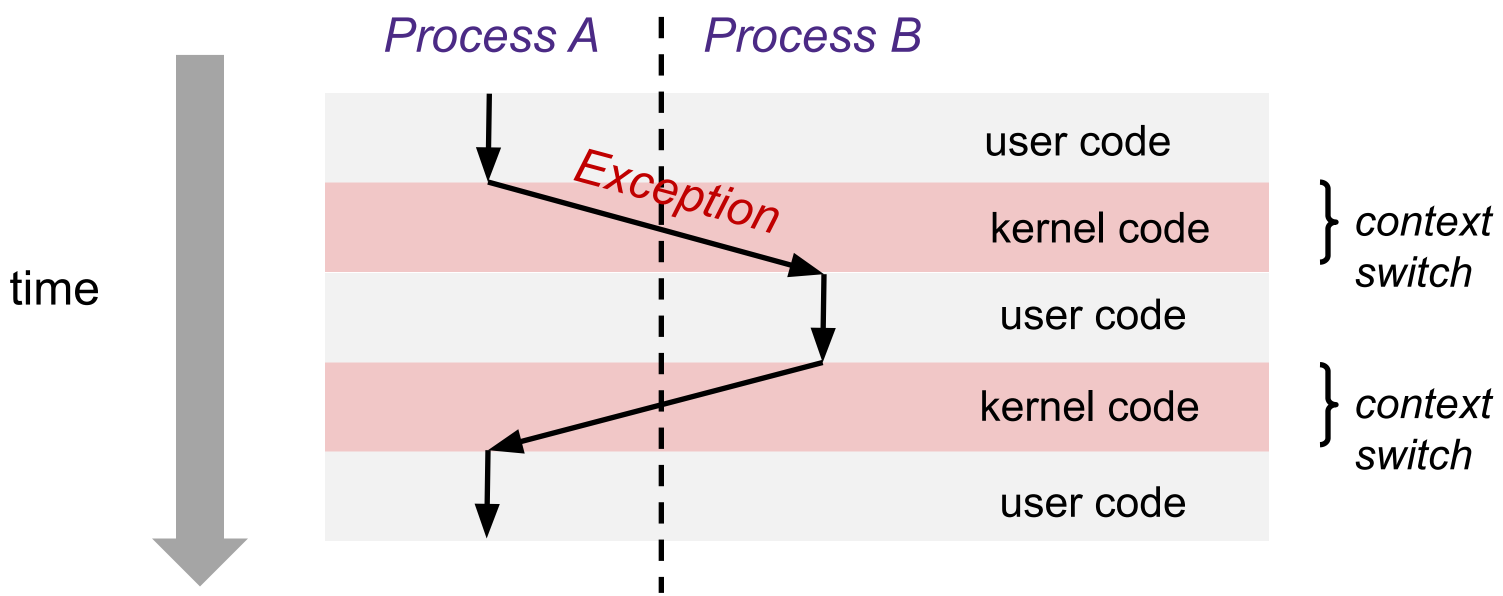
- Processes are managed by a *shared* chunk of OS code called the kernel
  - The kernel is not a separate process, but rather runs as part of a user process
- In x86-64 Linux:
  - Same address in each process refers to same shared memory location



Context Switching

Assume only one CPU

- Processes are managed by a *shared* chunk of OS code called the kernel
  - The kernel is not a separate process, but rather runs as part of a user process
- Context switch passes control flow from one process to another and is performed using kernel code



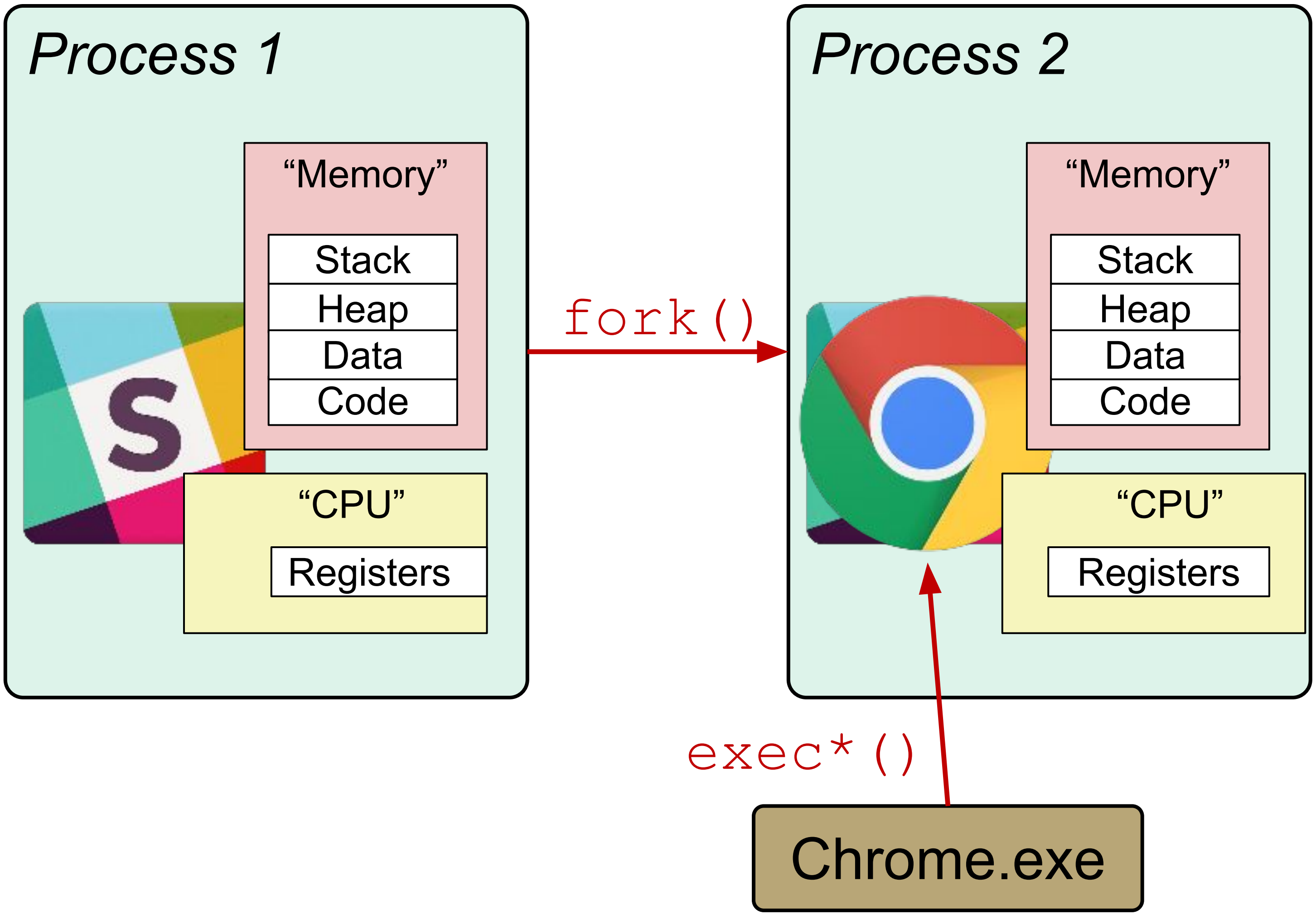
Context Switching, feeling ok?

Processes

- Processes and context switching
- **Creating new processes**
  - **`fork()`** ~~**`, exec*(), and wait()`**~~
- ~~Zombies~~

Take OS to learn more!

Creating New Processes & Programs



Creating New Processes & Programs

- fork-exec model (Linux):
  - `fork()` creates a copy of the current process
  - `exec*()` replaces the current process' code and address space with the code for a different program
    - Family: `execv`, `execl`, `execve`, `execle`, `execvp`, `execlp`
  - `fork()` and `execve()` are *system calls*

- Other system calls for process management:
  - `getpid()`
  - `exit()`
  - `wait()`, `waitpid()`

`fork`: Creating New Processes

- **`pid_t fork(void)`**
  - Creates a new "child" process that is *identical* to the calling "parent" process, including all state (memory, registers, etc.)
  - Returns 0 to the child process
  - Returns child's process ID (PID) to the parent process
- Child is *almost* identical to parent:
  - Child gets an identical (but separate) copy of the parent's virtual address space
  - Child has a different PID than the parent

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

- `fork` is unique (and often confusing) because it is called once but returns "twice"

Understanding `fork()`

Process X (parent; PID X)

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Process Y (child; PID Y)

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Understanding `fork()`

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pid_t fork_ret = fork();
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fork_ret = Y

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```

Process Y (child; PID Y)

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

fork_ret = 0

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Understanding `fork()`

Process X (parent; PID X)

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}
```

fork_ret = Y

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

hello from parent

Process Y (child; PID Y)

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

fork_ret = 0

```
pid_t fork_ret = fork();
if (fork_ret == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

hello from child

Which one appears first?

Fork Example

```
void fork1() {
    int x = 1;
    pid_t fork_ret = fork();
    if (fork_ret == 0) {
        printf("Child has x = %d\n", ++x);
    } else {
        printf("Parent has x = %d\n", --x);
    }
    printf("Bye from process %d with x = %d\n", getpid(), x);
}
```

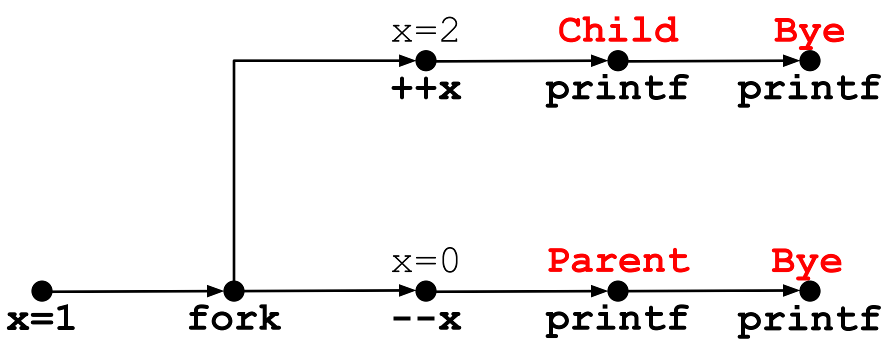
- Both processes continue/start execution after `fork`
  - Child starts at instruction after the call to `fork` (storing into `pid`)
- Can't predict execution order of parent and child
- Both processes start with `x` = `1`
  - Subsequent changes to `x` are independent
- Shared open files: stdout is the same in both parent and child

Modeling `fork` with Process Graphs

- A *process graph* is a useful tool for capturing the partial ordering of statements in a concurrent program
  - Each vertex is the execution of a statement
  - `a` → `b` means `a` happens before `b`
  - Edges can be labeled with current value of variables
  - `printf` vertices can be labeled with output
  - Each graph begins with a vertex with no inedges
- Any *topological sort* of the graph corresponds to a feasible total ordering
  - Total ordering of vertices where all edges point from left to right

Fork Example: Possible Output

```
void fork1() {
    int x = 1;
    pid_t fork_ret = fork();
    if (fork_ret == 0) {
        printf("Child has x = %d\n", ++x);
    } else {
        printf("Parent has x = %d\n", --x);
    }
    printf("Bye from process %d with x = %d\n", getpid(), x);
}
```



Checking in!

- Are the following sequences of outputs possible?

```
void nestedfork() {
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}
```

Seq 1:	Seq 2:
L0	L0
L1	Bye
Bye	L1
Bye	L2
Bye	Bye
L2	Bye

🐶 No No

🐈 No Yes

🐑 Yes No

🦄 Yes Yes

🥶 Help!

Summary

- Processes
  - At any time, system has multiple active processes
  - On a one-CPU system, only one can execute at a time, but each process appears to exclusively use the CPU
  - OS periodically "context switches" between processes
    - Implemented using *exceptional control flow*
- Process management
  - `fork`: one call, two returns
  - Take OS to learn more about `exec()` and `wait()`

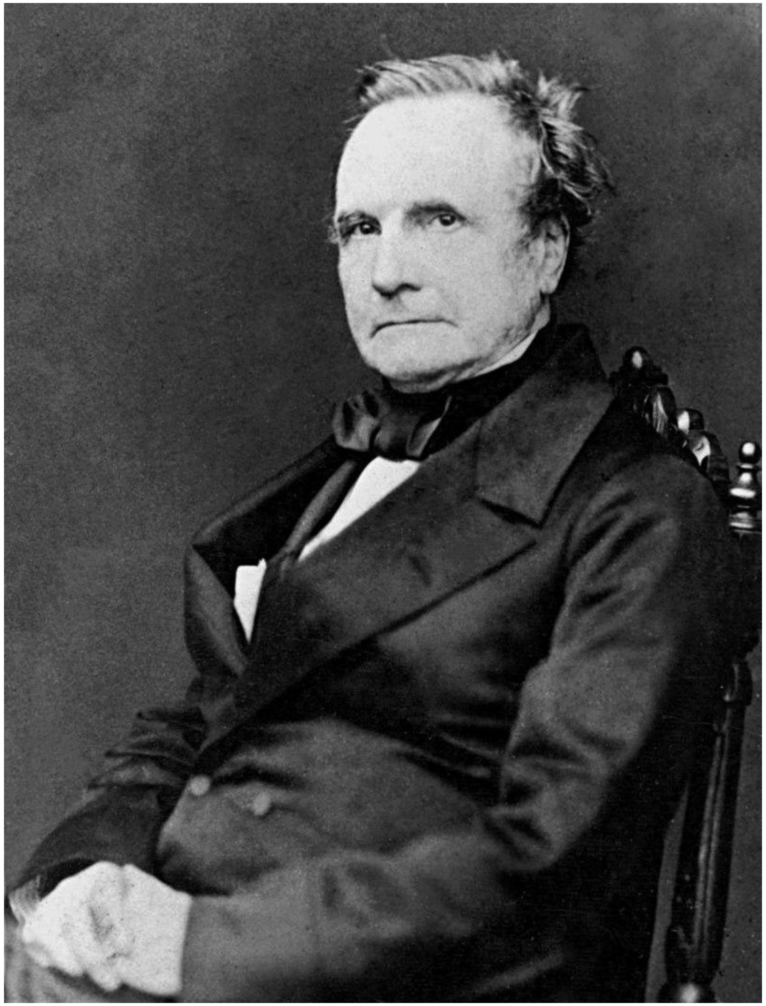
The first operating systems

The first computers

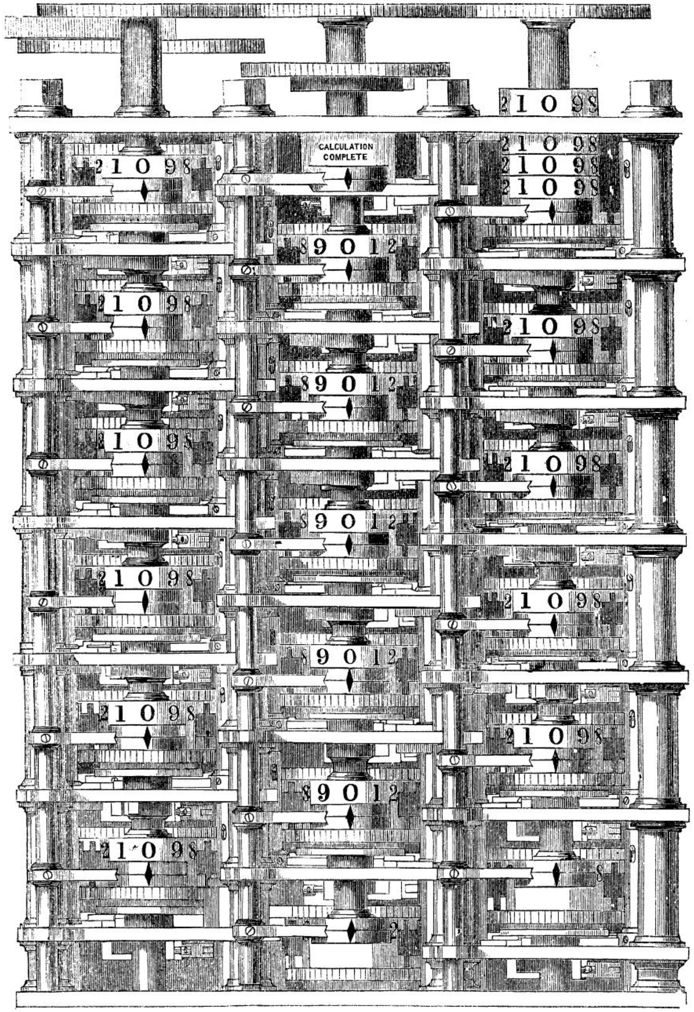
- **Computer**: one who computes

The women of Bletchley Park, Credit: BBC

The first Computer



"Great" man



PORTION OF BABBAGE'S DIFFERENCE ENGINE.

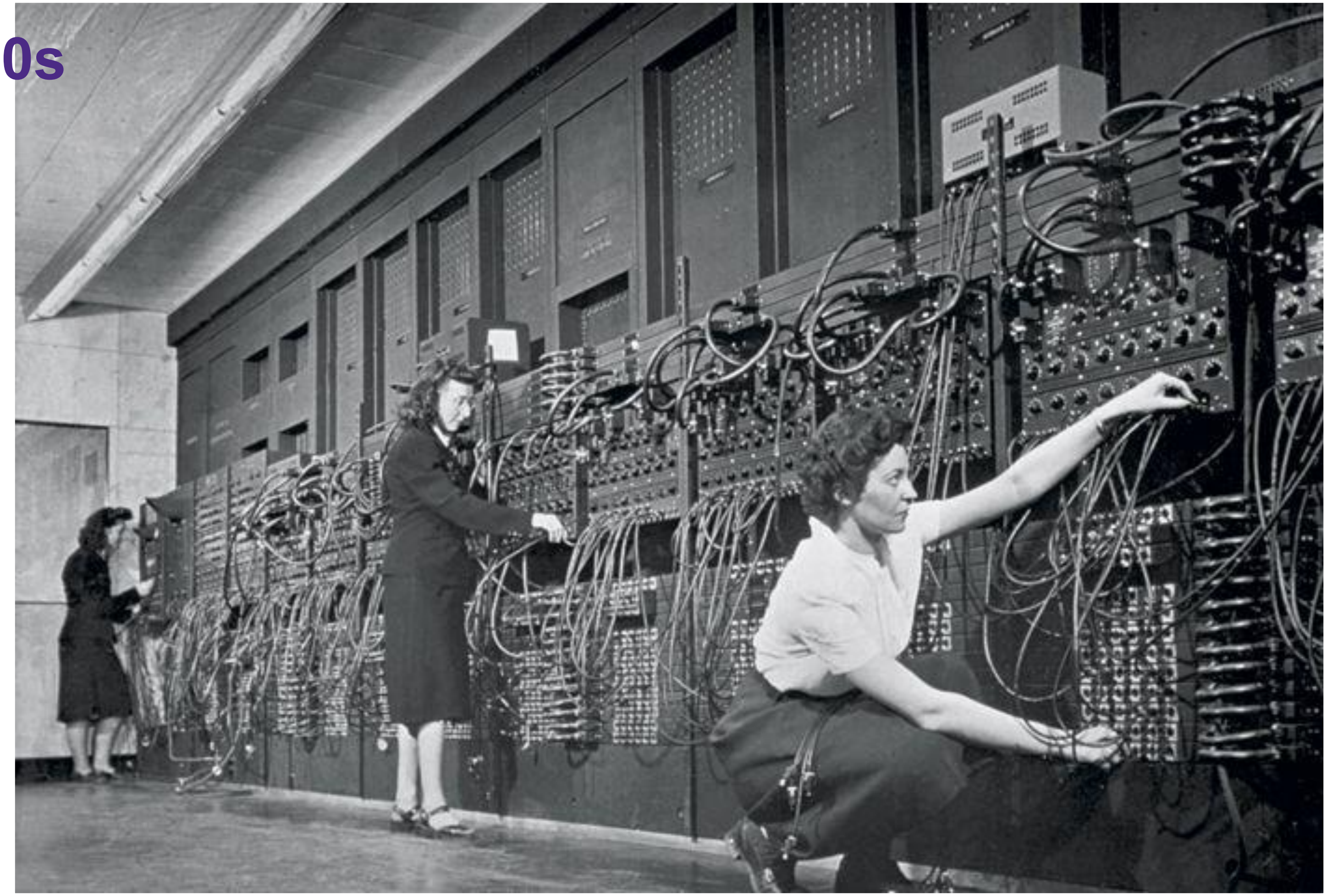
"Great" machine

Babbage, inspo by Gaspard De Prony

- Applied division of labor to produce logarithmic tables
- "…manufacture logarithms as one manufactures pins"
- 5 experts, 8 managers, 70 human computers

The first programmers

1940s



Jean Jennings (left), Marlyn Wescoff (center), and Ruth Lichterman program ENIAC at the University of Pennsylvania, circa 1946.
Photo: Corbis
http://fortune.com/2014/09/18/walter-isaacson-the-women-of-eniac/

What's an operating system?

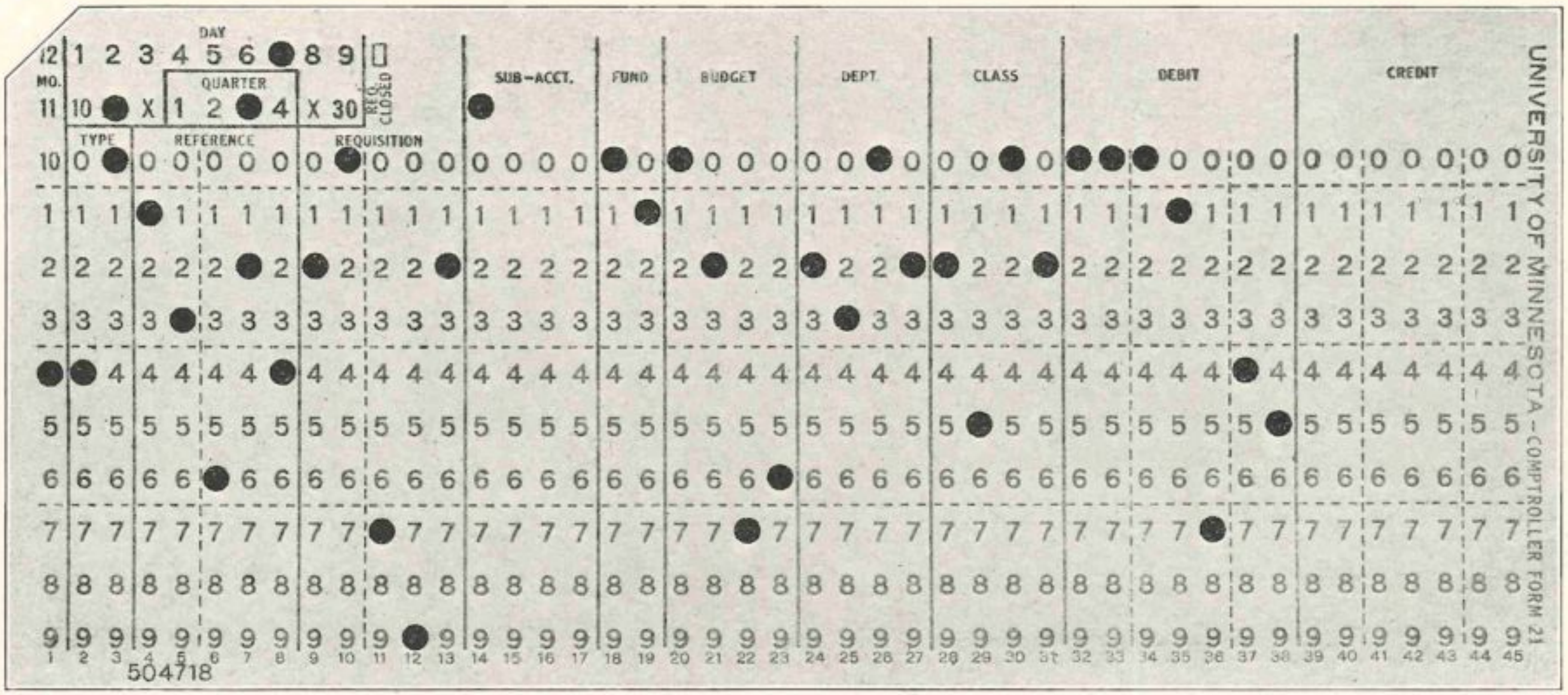
- Basically, a resource manager!
- Computers have all sorts of resources…
  - CPU, memory, disks, network cards, etc.
- Operating systems try to use those efficiently!
  - Ideally, the "user" only worries about their program

- Today: OS abstraction gives multi-process machines without any change from programmers
  - "Each program seems to have exclusive use of CPU/memory"

Why this abstraction?

Backwards compatibility! It's where we started!

Tabulating Cards



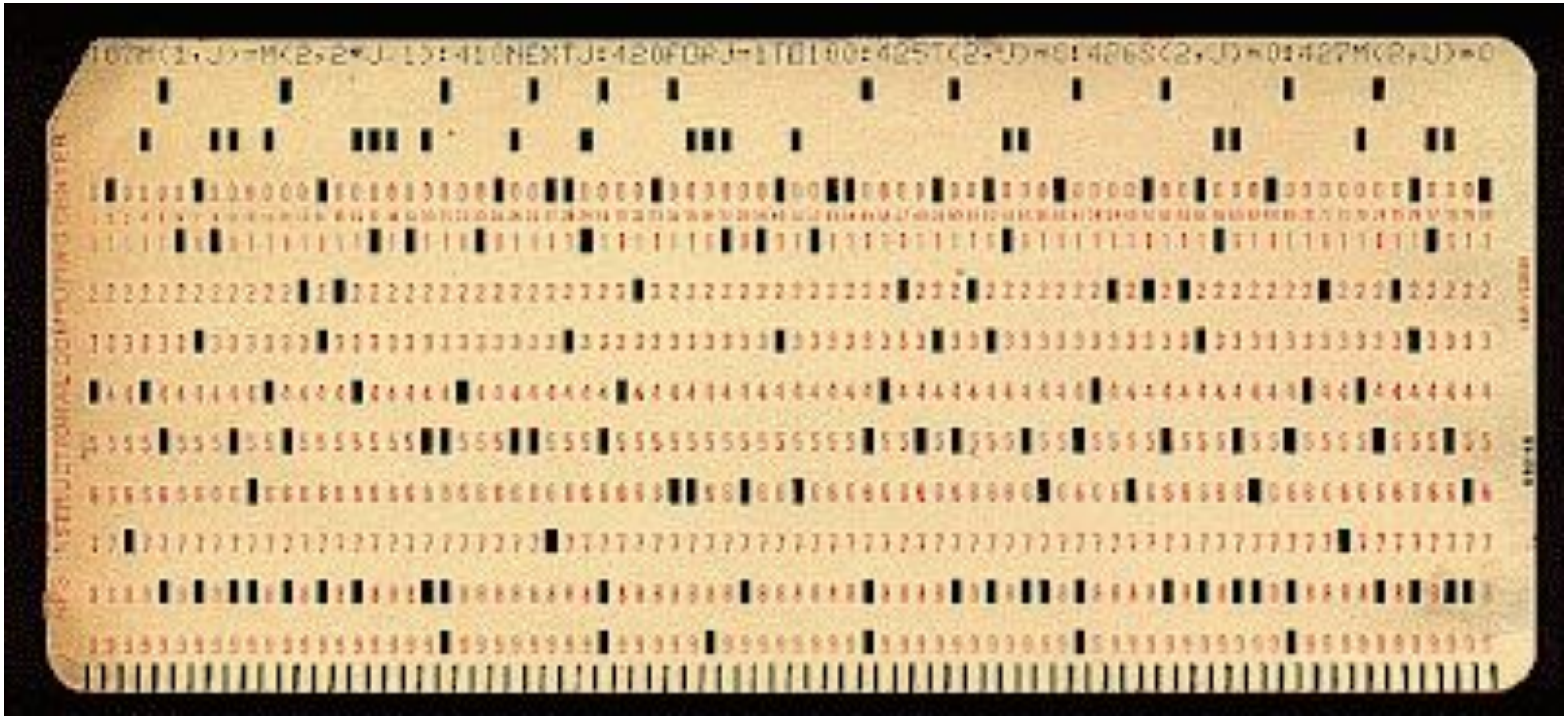
HOLLERITH TABULATING CARD

Date—April 27, 1927
Quarter—Third
Type—40 Invoice
Reference—Invoice No. 13624

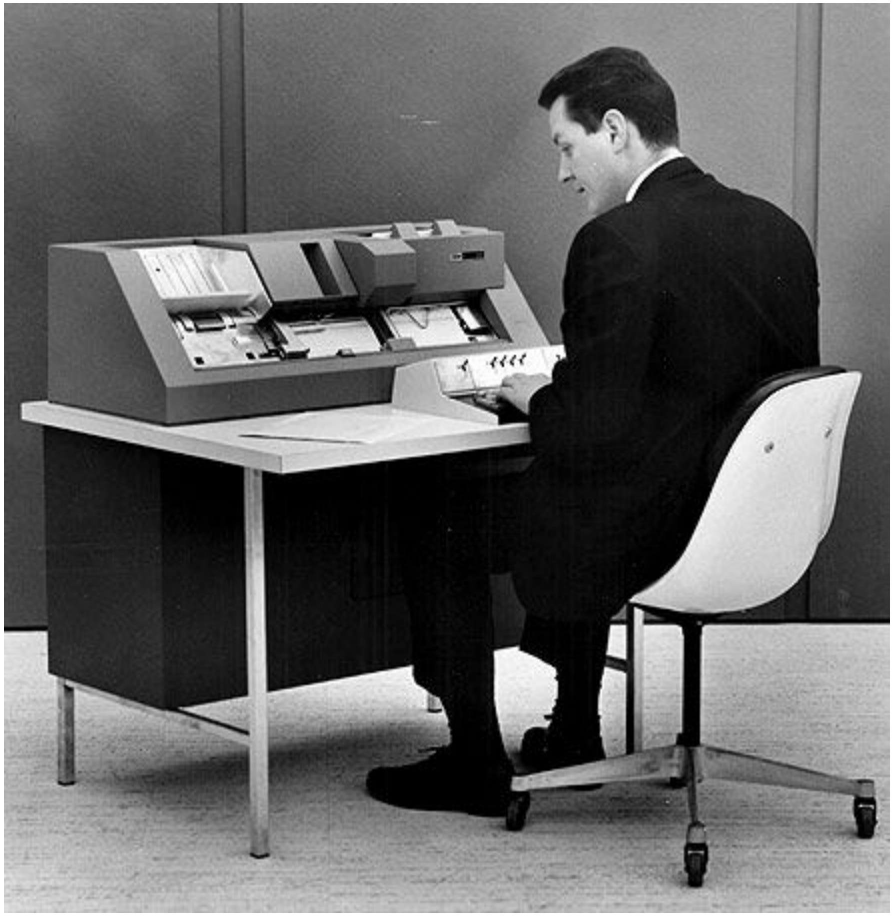
Requisition No. 20792 (Open)
Sub-Acct.—None
Fund—01 Support Fund
Budget—276 Bacteriology Supplies

Department—2302 Medical School—Bacteriology
Classification—2502 Chemicals
Amount—Debit $17.45

A single instruction, via punch card



Programs, via punch card



Computer Operators

First operating systems

- Early computational resources:
  - A very, very expensive machine that could only run one program at a time
  - Basically just a big, programmable calculator

- Operating computational machines meant:
  1. Receive punch card programs from all sorts of people
  2. Prioritize and run programs
  3. Record results, and return to programmer
  - Also, manage the machine if something goes wrong!
    - If a punch card jams the machine
    - If a program doesn't stop running

“Robot work” or “Human work”?

What happened?

- Computers slowly added more “features” that made the operators job easier
  - Security features: allow auditing of programs
  - Magnetic tape allows a digital “queue” that the computer could select from
- Slowly, operators jobs are automated away…
  - “optional” features become standard
  - “monitors” reassign HW resources as needed
- Good-paying job for women, gone

Summary

- Programs used to be physical stacks of cards that operators had to manage
- Operators maintained the OS abstraction
  - Potentially with more waiting time and a job queue
  - Viewed as “robot work” -- operating the machine
- Slowly, new computers can “operate themselves”
  - “Great! We won’t need to hire an operator!”

- We’ve seen this before, we’re seeing it now!
  - Computers, Programmers, Operating Systems