Processes and Multitasking

COMP402127: Introduction to Computer Systems

Hao Li
Xi’an Jiaotong University

Today

- **Processes**
- System Calls
- Process Control

Operating Systems

IBM 704 at Langley Research Center (NASA), 1957
https://commons.wikimedia.org/w/index.php?curid=6455009

Earliest days: One batch job at a time

IBM 704 at Langley Research Center (NASA), 1957
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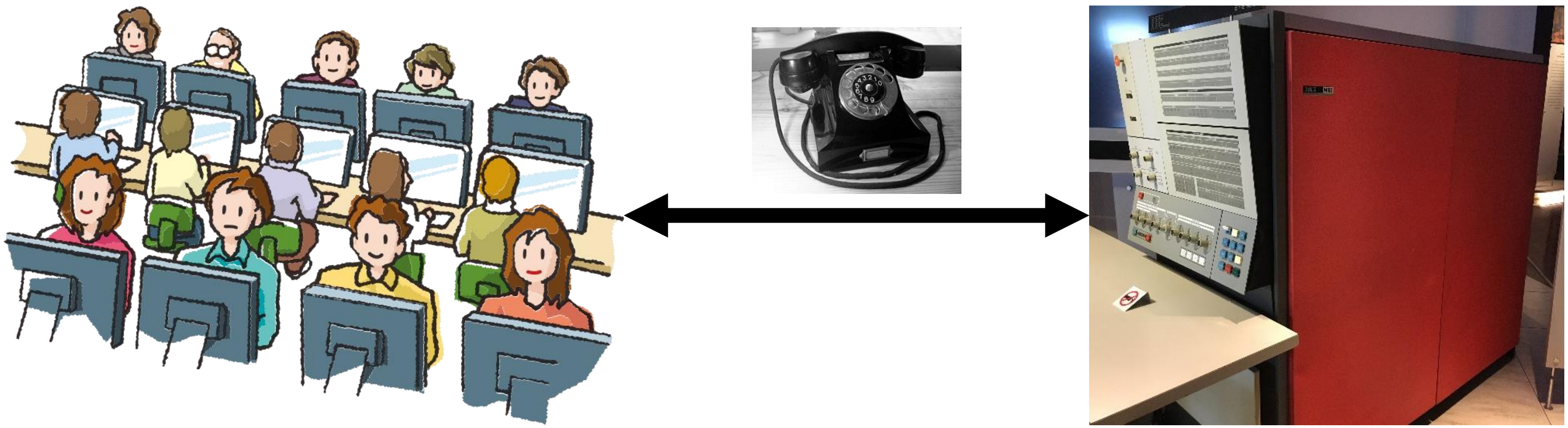
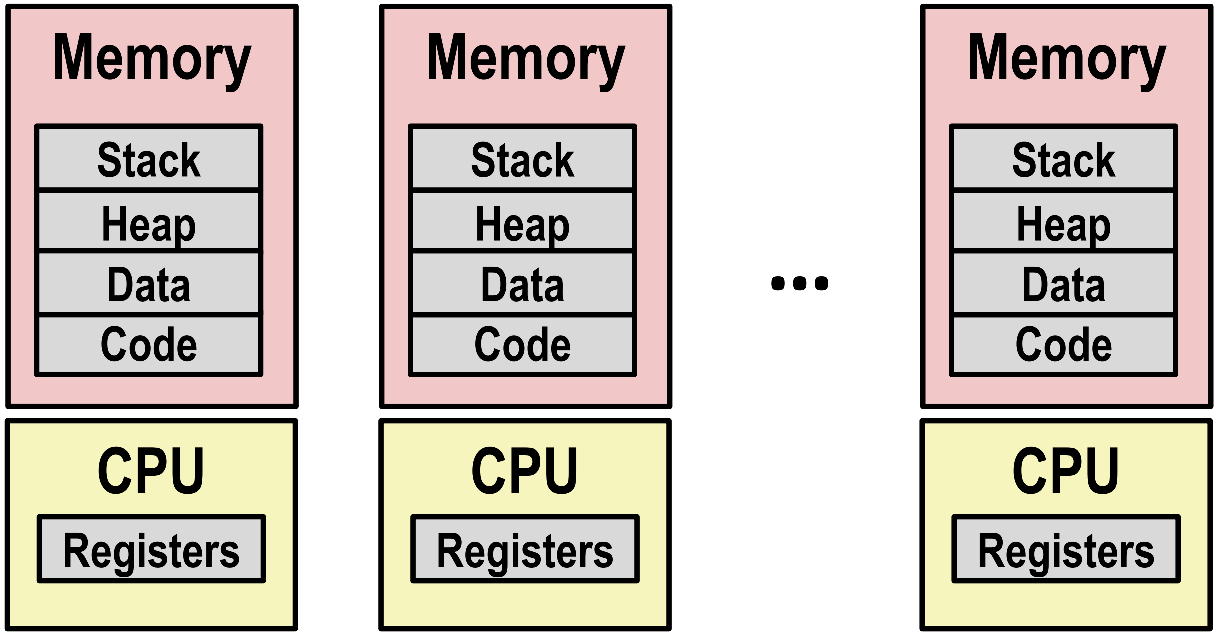
How can many people share one computer efficiently?



Multiprocessing



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

Multiprocessing Example

shark.ics.cs.cmu.edu - PuTTY

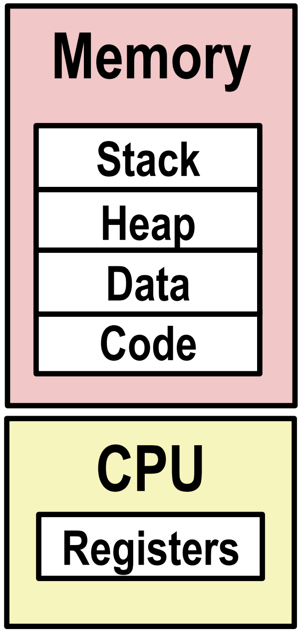
```
top - 12:52:25 up  7:50, 12 users,  load average: 4.94, 4.06, 2.72
Tasks: 425 total,   7 running, 418 sleeping,   0 stopped,   0 zombie
%Cpu(s): 11.2 us, 21.9 sy,  0.0 ni, 66.0 id,  0.0 wa,  0.0 hi,  0.9 si,  0.0 st
KiB Mem : 24508768 total, 19088248 free,  3228068 used,  2192452 buff/cache
KiB Swap:  1048572 total,  1048572 free,        0 used. 20822672 avail Mem

  PID USER      PR  NI    VIRT    RES    SHR S  %CPU %MEM     TIME+ COMMAND
30569 zilongz   20   0   20.0t  25896   1324 R 100.0  0.1   0:05.89 mdriver-dbg
26365 zilongz   20   0 2566560 231684   8428 S  92.4  0.9   6:20.52 cpptools
17759 julietf   20   0  164876   3864   1284 R  84.4  0.0  15:31.82 sshd
 1673 root      20   0       0      0      0 R  58.3  0.0   5:55.84 afs_rxlist+
20161 julietf   20   0   20.0t 112840   1348 R  57.6  0.5  10:36.80 mdriver-dbg
30624 jjli2     20   0  130708  16896   1692 R  36.4  0.1   0:01.10 ld
24896 root      20   0       0      0      0 S  11.6  0.0   0:17.94 kworker/5:1
29234 root      20   0       0      0      0 R   8.9  0.0   0:02.95 kworker/1:0
29616 root      20   0       0      0      0 S   6.6  0.0   0:02.54 kworker/13+
26141 root      20   0       0      0      0 S   4.3  0.0   0:13.43 kworker/3:1
29254 root      20   0       0      0      0 S   4.3  0.0   0:03.02 kworker/9:0
26787 root      20   0       0      0      0 S   4.0  0.0   0:08.78 kworker/11+
26785 root      20   0       0      0      0 S   2.0  0.0   0:09.53 kworker/13+
25644 zilongz   20   0 1051004 158028  19260 S   1.3  0.6   0:19.99 node
27858 bbendou   20   0  898344  64932  18832 S   1.3  0.3   0:03.01 node
15130 yixuey    20   0  903052  70108  18976 S   1.0  0.3   0:12.12 node
30194 zweinber  20   0  164268   2552   1568 R   1.0  0.0   0:00.27 top
```

- **Running program "top" on hammerheadshark**
  - System has 425 "tasks", 7 of which are active
  - Identified by Process ID (PID), user account, command name

Processes

- **Definition: 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:**
  - ***Private address space***
    - Each program seems to have exclusive use of main memory.
    - Provided by kernel mechanism called *virtual memory*
  - ***Logical control flow***
    - Each program seems to have exclusive use of the CPU
    - Provided by kernel mechanism called *context switching*

Control Flow

- **Processors do only one thing:**
  - From startup to shutdown, each CPU core simply reads and executes a sequence of machine instructions, one at a time *
  - This sequence is the CPU’s *control flow* (or *flow of control*)

Physical control flow

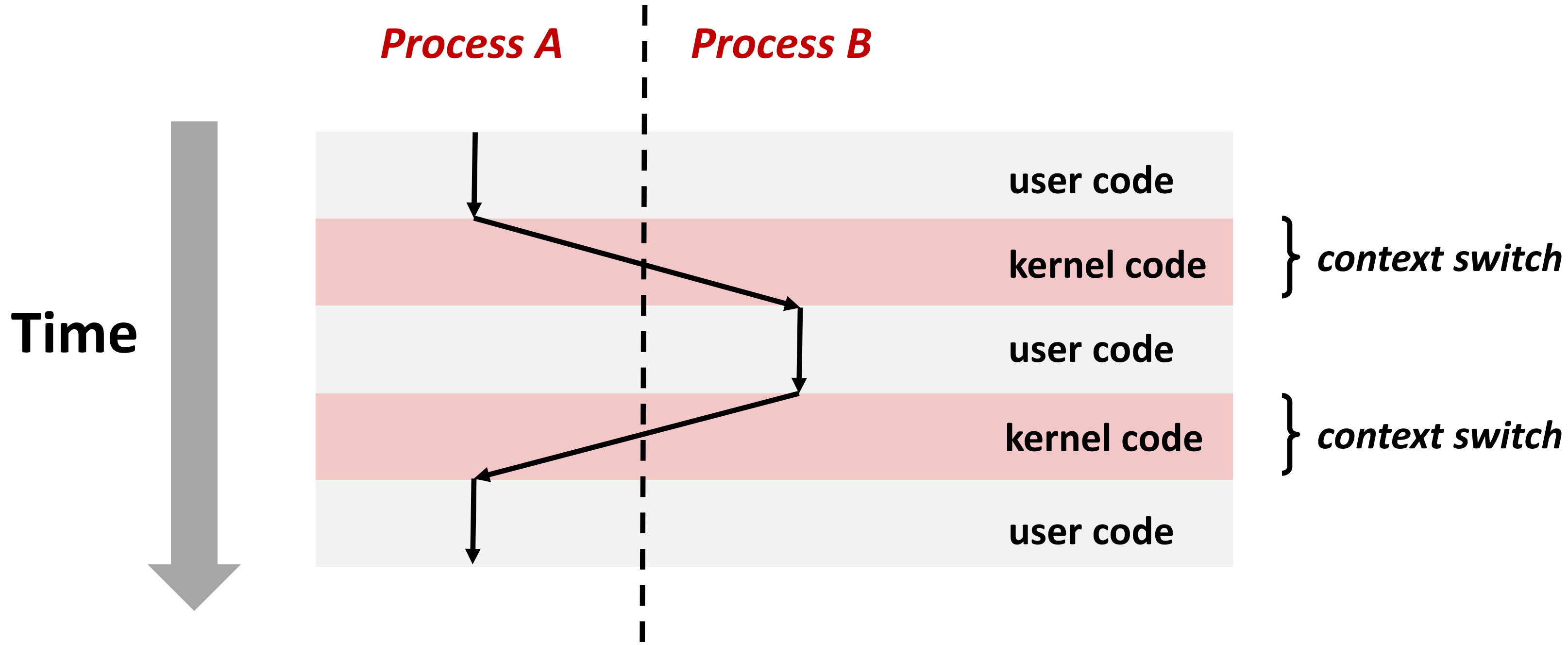
Time

<startup>
$inst_1$
$inst_2$
$inst_3$
…
$inst_n$
<shutdown>

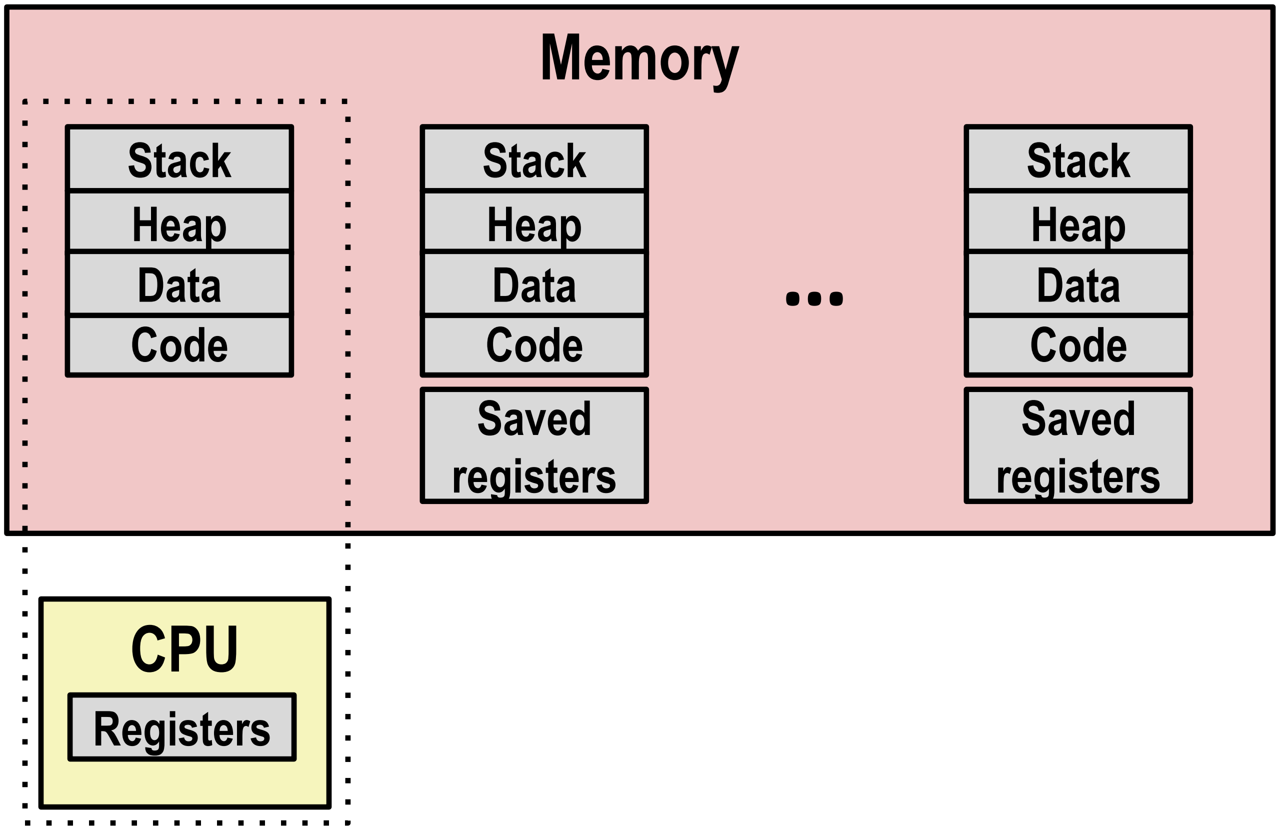
* many modern CPUs execute several instructions at once and/or out of program order, but this is invisible to the programmer

Context Switching

- **Processes are managed by a shared chunk of memory-resident OS code called the *kernel***
  - Important: the kernel is not a separate process, but rather runs as part of some existing process.
- **Control flow passes from one process to another via a *context switch***

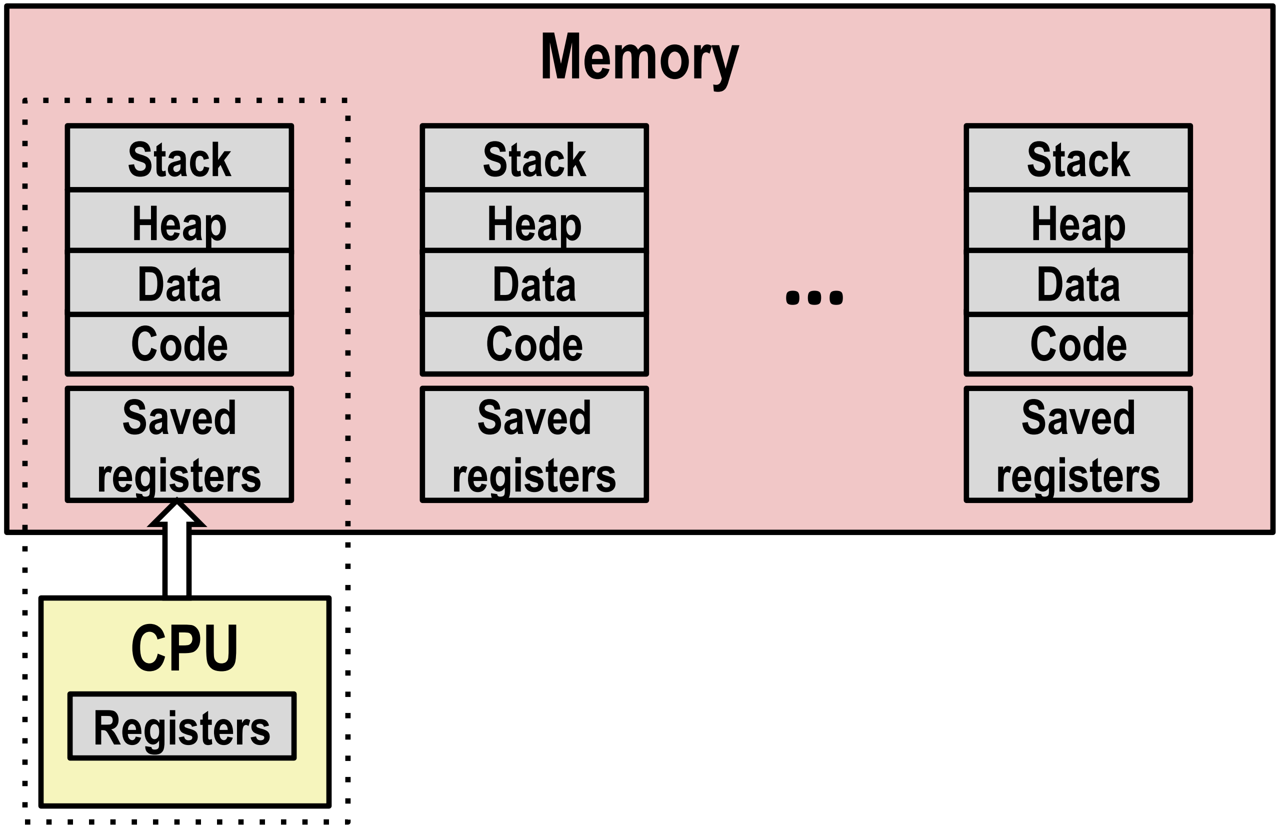


Context Switching (Uniprocessor)



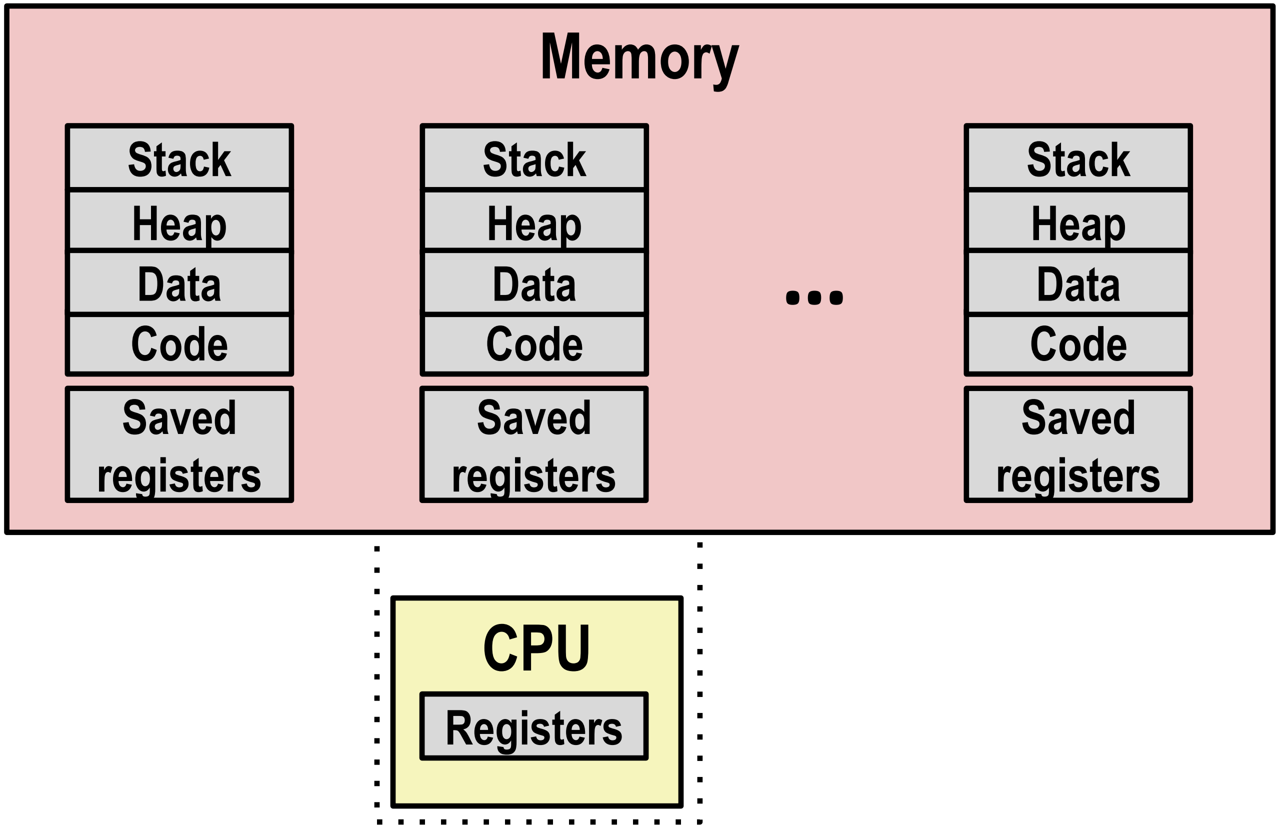
- **Single processor executes multiple processes concurrently**
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system (like last week)
  - Register values for nonexecuting processes saved in memory

Context Switching (Uniprocessor)



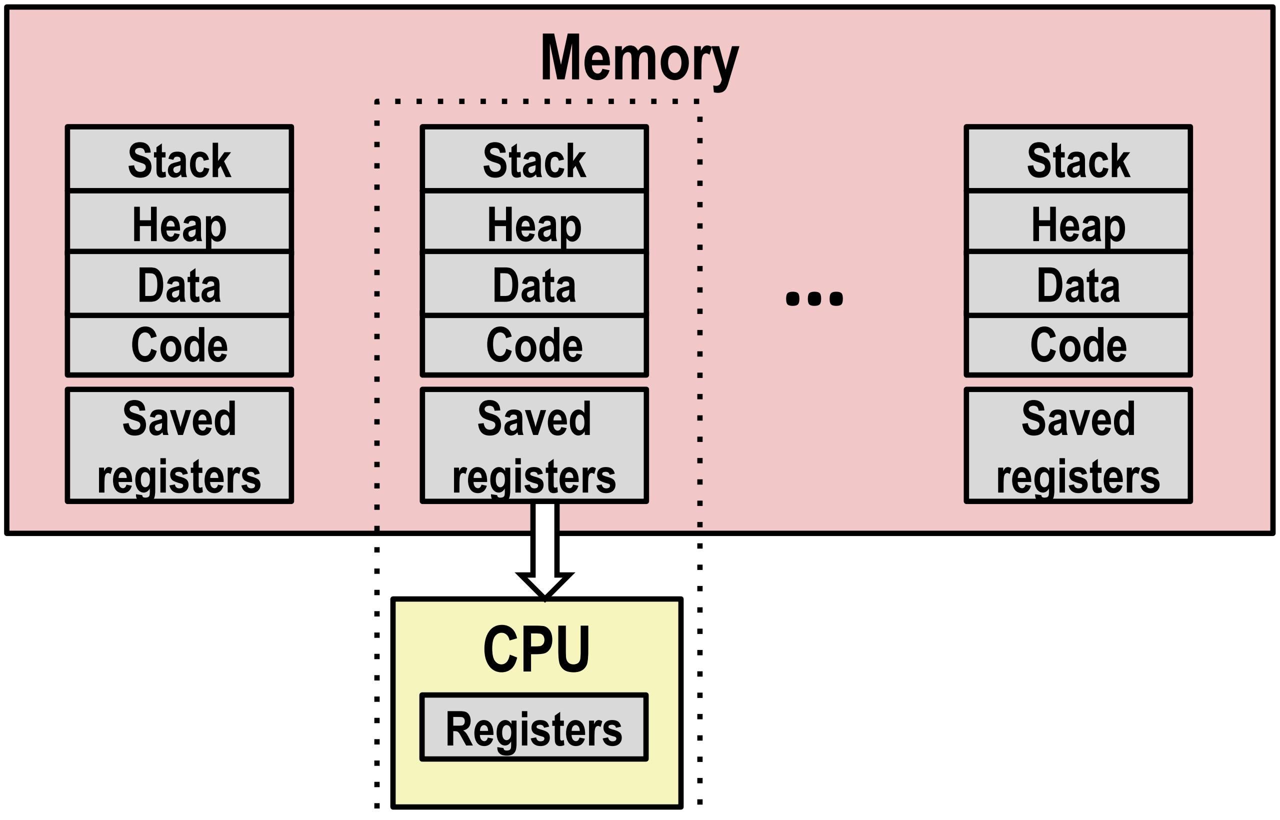
- Save current registers in memory

Context Switching (Uniprocessor)



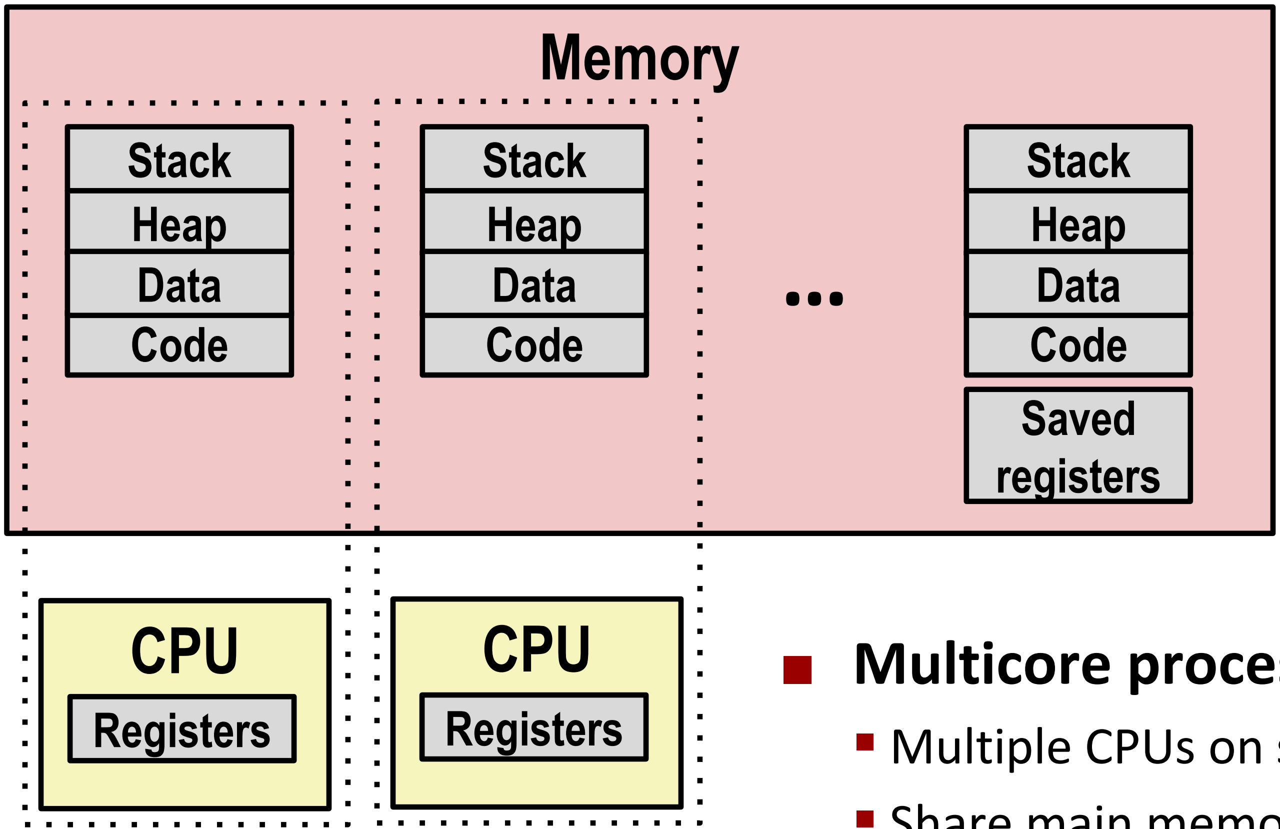
- Schedule next process for execution

Context Switching (Uniprocessor)



- Load saved registers and switch address space (context switch)

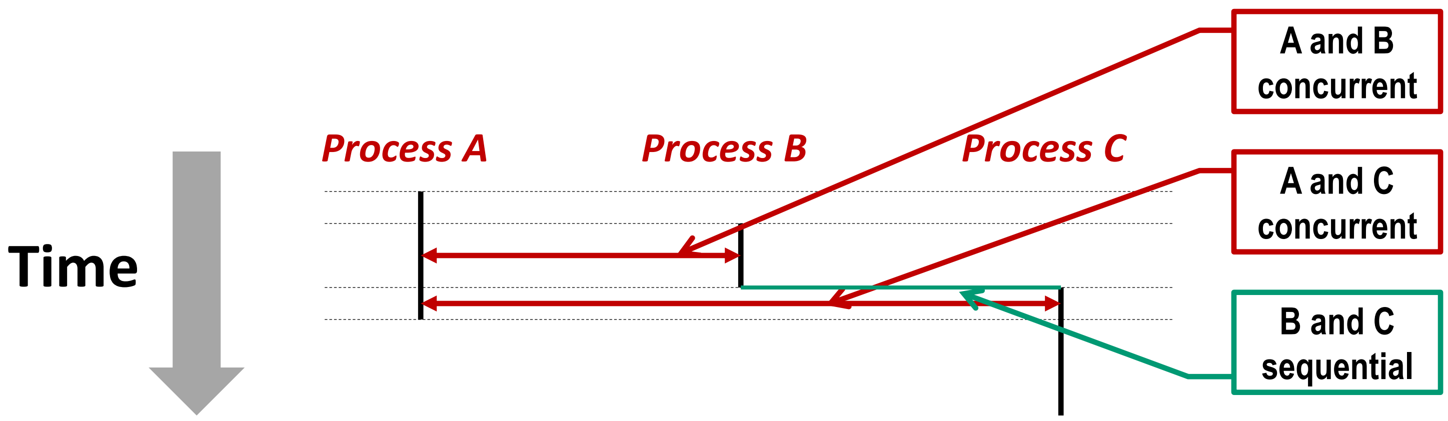
Context Switching (Multicore)



- **Multicore processors**
  - Multiple CPUs on single chip
  - Share main memory (and some caches)
  - Each can execute a separate process
    - Scheduling of processors onto cores done by kernel

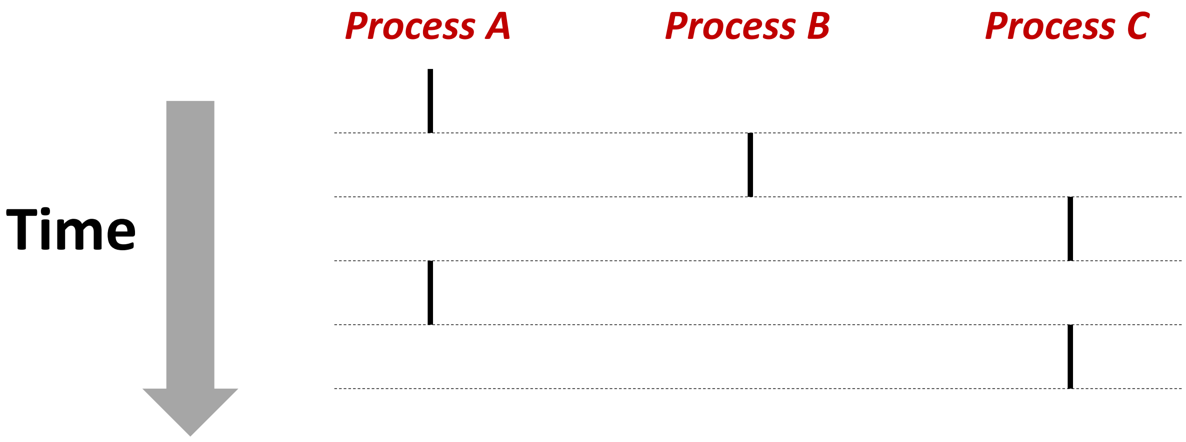
User View of Concurrent Processes

- **Two processes *run concurrently* (*are concurrent)* if their execution overlaps in time**
- **Otherwise, they are *sequential***
- **Appears as if concurrent processes run in parallel with each other**
  - This means they can interfere with each other (more on that in a couple weeks)



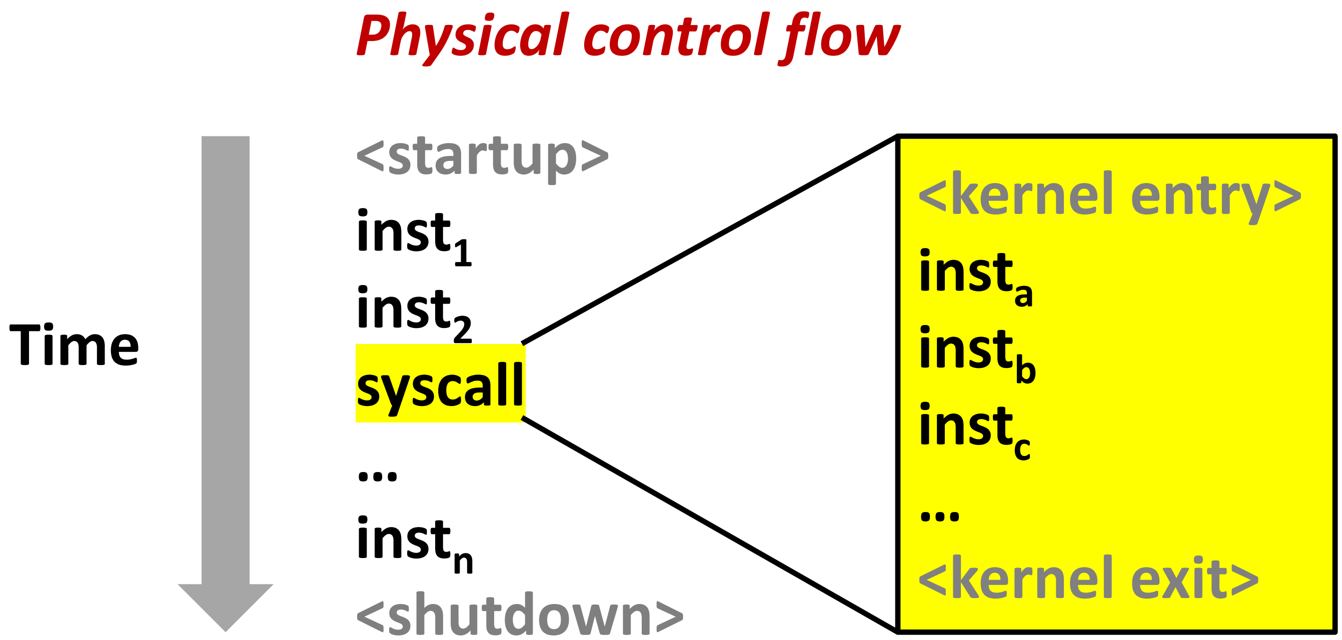
Traditional (Uniprocessor) Reality

- Only one process runs at a time
- A and B execution is *interleaved*, not truly concurrent
- Similarly for A and C
- Still possible for A and B / A and C to interfere with each other



How does the kernel take control?

- The CPU executes instructions in sequence
- We don't write "now run kernel code" in our programs…
  - *Or do we??*



Today

- Processes
- **System Calls**
- Process Control

System Calls

- **Whenever a program wants to cause an effect outside its own process, it must ask the kernel for help**
- **Examples:**
  - Read/write files
  - Get current time
  - Allocate RAM (sbrk)
  - Create new processes

```
// fopen.c
FILE *fopen(const char *fname,
            const char *mode) {
  int flags = mode2flags(mode);
  if (!flags) return NULL;
  int fd = open(fname, flags,
                DEFPERMS);
  if (fd == -1) return NULL;
  return fdopen(fd, mode);
}

// open.S
    .global open
open:
    mov $SYS_open, %eax
    syscall
    cmp $SYS_error_thresh, %rax
    ja  __syscall_error
    ret
```

All the system calls

accept
accept4
acct
add_key
adjtimex
bind
bpf
brk
capget
capset
chdir
chroot
clock_adjtime
clock_getres
clock_gettime
clock_nanosleep
clock_settime
clone
clone3
close
close_range
connect
copy_file_range
delete_module
dup
dup3
epoll_create1
epoll_ctl
epoll_pwait
epoll_pwait2
eventfd2
execve
execveat
exit
exit_group
faccessat
faccessat2
fallocate
fanotify_init
fanotify_mark
fchdir
fchmod
fchmodat
fchown
fchownat
fdatasync
fgetxattr
finit_module
flistxattr
flock
fremovexattr
fsconfig
fsetxattr
fsmount
fsopen
fspick
fsync
futex
futex_waitv
get_mempolicy
get_robust_list
getcpu
getcwd
getdents64
getegid
geteuid
getgid
getgroups
getitimer
getpeername
getpgid
getpid
getppid
getpriority
getrandom
getresgid
getresuid
getrlimit
getrusage
getsid
getsockname
getsockopt
gettid
gettimeofday
getuid
getxattr
init_module
inotify_add_watch
inotify_init1
inotify_rm_watch
io_cancel
io_destroy
io_getevents
io_pgetevents
io_setup
io_submit
io_uring_enter
io_uring_register
io_uring_setup
ioctl
ioprio_get
ioprio_set
kcmp
kexec_file_load
kexec_load
keyctl
kill
landlock_add_rule
landlock_create_ruleset
landlock_restrict_self
lgetxattr
linkat
listen
listxattr
llistxattr
lookup_dcookie
lremovexattr
lsetxattr
madvise
mbind
membarrier
memfd_create
memfd_secret
migrate_pages
mincore
mkdirat
mknodat
mlock
mlock2
mlockall
mount
mount_setattr
move_mount
move_pages
mprotect
mq_getsetattr
mq_notify
mq_open
mq_timedreceive
mq_timedsend
mq_unlink
mremap
msgctl
msgget
msgrcv
msgsnd
msync
munlock
munlockall
munmap
name_to_handle_at
nanosleep
nfsservctl
open_by_handle_at
open_tree
openat
openat2
perf_event_open
personality
pidfd_getfd
pidfd_open
pidfd_send_signal
pipe2
pivot_root
pkey_alloc
pkey_free
pkey_mprotect
ppoll
prctl
pread64
preadv
preadv2
prlimit64
process_madvise
process_mrelease
process_vm_readv
process_vm_writev
pselect6
ptrace
pwrite64
pwritev
pwritev2
quotactl
quotactl_fd
read
readahead
readlinkat
readv
reboot
recvfrom
recvmmsg
recvmsg
remap_file_pages
removexattr
renameat
renameat2
request_key
restart_syscall
rseq
rt_sigaction
rt_sigpending
rt_sigprocmask
rt_sigqueueinfo
rt_sigreturn
rt_sigsuspend
rt_sigtimedwait
rt_tgsigqueueinfo
sched_get_priority_max
sched_get_priority_min
sched_getaffinity
sched_getattr
sched_getparam
sched_getscheduler
sched_rr_get_interval
sched_setaffinity
sched_setattr
sched_setparam
sched_setscheduler
sched_yield
seccomp
semctl
semget
semop
semtimedop
sendmmsg
sendmsg
sendto
set_mempolicy
set_mempolicy_home_node
set_robust_list
set_tid_address
setdomainname
setfsgid
setfsuid
setgid
setgroups
sethostname
setitimer
setns
setpgid
setpriority
setregid
setresgid
setresuid
setreuid
setrlimit
setsid
setsockopt
settimeofday
setuid
setxattr
shmat
shmctl
shmdt
shmget
shutdown
sigaltstack
signalfd4
socket
socketpair
splice
statx
swapoff
swapon
symlinkat
sync
sync_file_range
sync_file_range2
syncfs
sysinfo
syslog
tee
tgkill
timer_create
timer_delete
timer_getoverrun
timer_gettime
timer_settime
timerfd_create
timerfd_gettime
timerfd_settime
times
tkill
umask
umount2
uname
unlinkat
unshare
userfaultfd
utimensat
vhangup
vmsplice
wait4
waitid
write
writev

System Call Error Handling

- **Almost all system-level operations can fail**
  - Only exception is the handful of functions that return `void`
  - You must explicitly check for failure
- **On error, most system-level functions return −1 and set global variable `errno` to indicate cause.**
- **Example:**

```
pid_t pid = fork();
if (pid == -1) {
    fprintf(stderr, "fork error: %s\n", strerror(errno));
    exit(1);
}
```

Error-reporting functions

- Can simplify somewhat using an *error-reporting function*:

```
void unix_error(char *msg) /* Unix-style error */
{
    fprintf(stderr, "%s: %s\n", msg, strerror(errno));
    exit(1);
}
```

```
  pid_t pid = fork();
  if (pid == -1)
    unix_error("fork error");
```

Note: csapp.c exits with 0.

- Not always appropriate to exit when something goes wrong.

Error-handling Wrappers

- We simplify the code we present to you even further by using Stevens[1]-style error-handling wrappers:

```
pid_t Fork(void)
{
    pid_t pid = fork();

    if (pid == -1)
        unix_error("Fork error");
    return pid;
}
```

```
pid = Fork(); // Only returns if successful
```

- NOT what you generally want to do in a real application

[1]e.g., in "UNIX Network Programming: The sockets networking API" W. Richard Stevens

Today

- Processes
- System Calls
- **Process Control**

Obtaining Process IDs

- `pid_t getpid(void)`
  - Returns PID of current process

- `pid_t getppid(void)`
  - Returns PID of parent process

Process States

At any time, each process is either:

- **Running**
  - Process is either executing instructions, or it *could be* executing instructions if there were enough CPU cores.
- **Blocked / Sleeping**
  - Process cannot execute any more instructions until some external event happens (usually I/O).
- **Stopped**
  - Process has been prevented from executing by user action (control-Z).
- **Terminated / Zombie**
  - Process is finished. Parent process has not yet been notified.

Terminating Processes

- **Process becomes terminated for one of three reasons:**
  - Receiving a signal whose default action is to terminate (next lecture)
  - Returning from the **`main`** routine
  - Calling the **`exit`** function

- **`void exit(int status)`**
  - Terminates with an *exit status* of **`status`**
  - Convention: normal return status is 0, nonzero on error
  - Another way to explicitly set the exit status is to return an integer value from the main routine

- **`exit` is called once but never returns.**

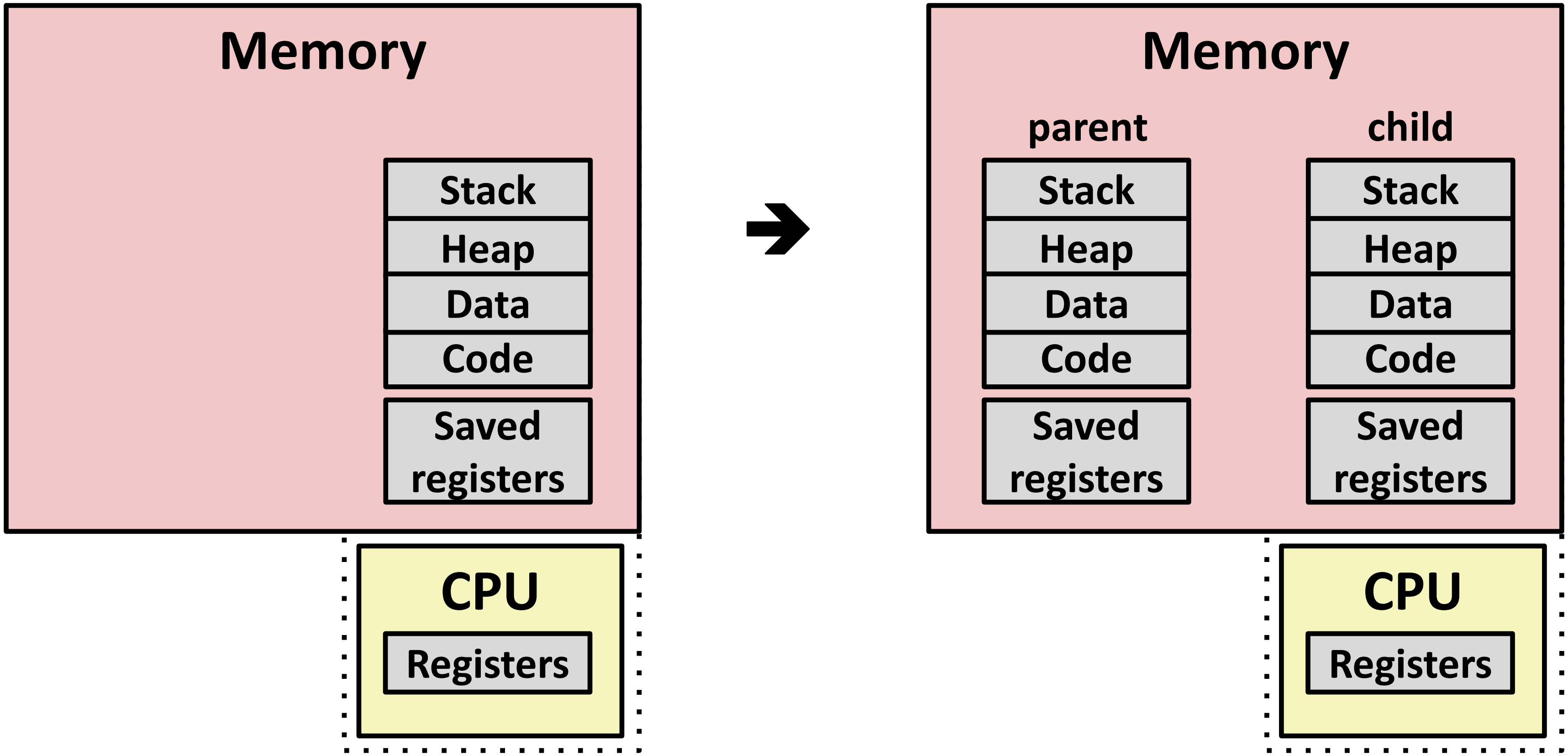
Creating Processes

- ***Parent process* creates a new running *child process* by calling `fork`**

- **`int fork(void)`**
  - Returns 0 to the child process, child's PID to parent process
  - Child is *almost* identical to parent:
    - Child get an identical (but separate) copy of the parent's virtual address space.
    - Child gets identical copies of the parent's open file descriptors
    - Child has a different PID than the parent

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

Conceptual View of `fork`



- **Make complete copy of execution state**
  - Designate one as parent and one as child
  - Resume execution of parent or child
  - (Optimization: Use copy-on-write to avoid copying RAM)

fork Example

```
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        return 0;
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    return 0;
}                                    fork.c
```

- Call once, return twice
- Concurrent execution
  - Can't predict execution order of parent and child

```
linux> ./fork
parent: x=0
child : x=2
```

```
linux> ./fork
child : x=2
parent: x=0
```

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parent: x=0
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child : x=2
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fork Example

```
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        return 0;
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    return 0;
}
```

```
linux> ./fork
parent: x=0
child : x=2
```

- Call once, return twice
- Concurrent execution
  - Can't predict execution order of parent and child
- Duplicate but separate address space
  - `x` has a value of 1 when fork returns in parent and child
  - Subsequent changes to `x` are independent
- Shared open files
  - `stdout` is the same in both parent and child

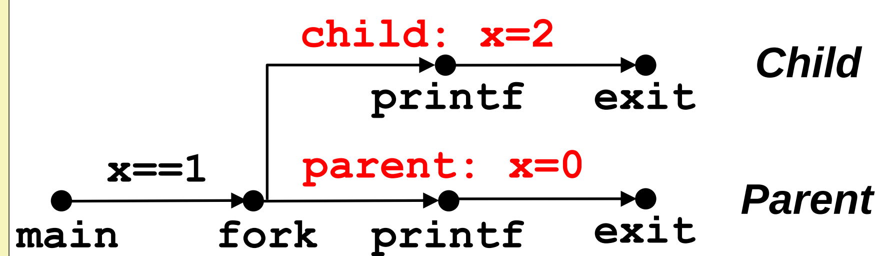
Modeling `fork` with Process Graphs

- **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

Process Graph Example

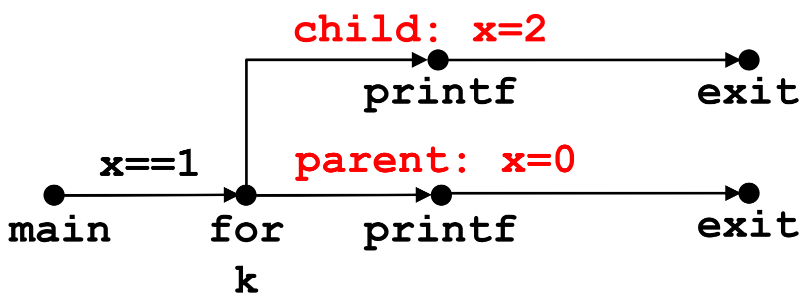
```c
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        return 0;
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    return 0;
}
```

fork.c

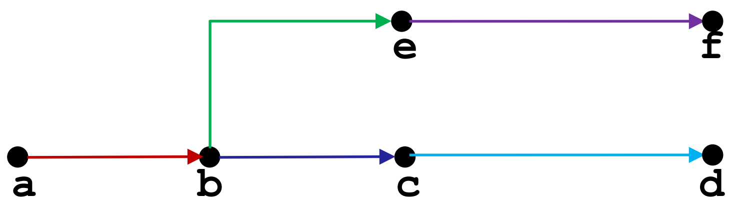


Interpreting Process Graphs

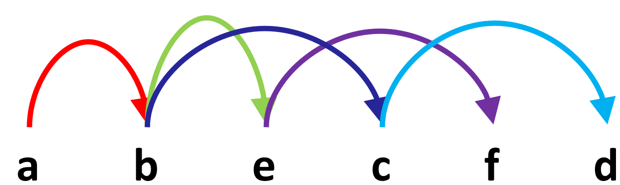
- Original graph:



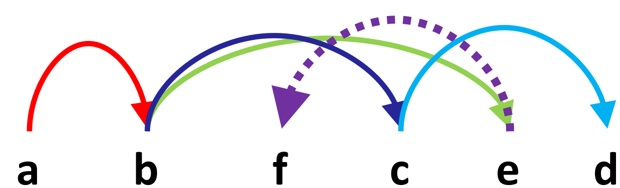
- Relabled graph:



Feasible total ordering:



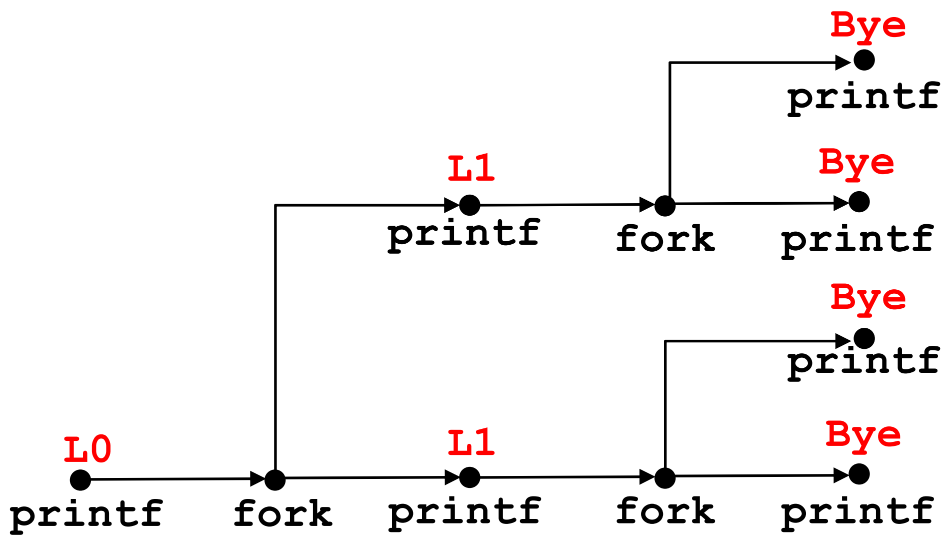
Feasible or Infeasible?



Infeasible: not a topological sort

fork Example: Two consecutive forks

```c
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```
forks.c



Feasible output:

L0
L1
Bye
Bye
L1
Bye
Bye

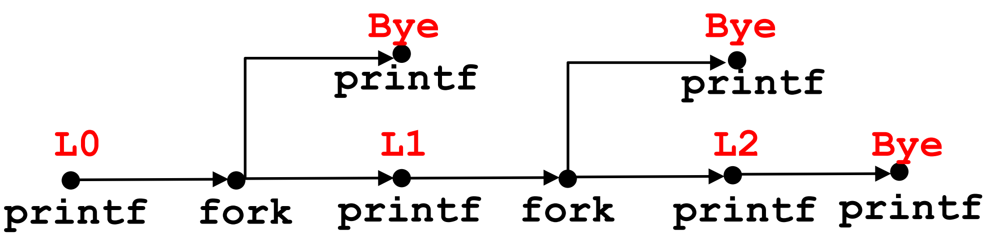
Infeasible output:

L0
Bye
L1
Bye
L1
Bye
Bye

fork Example: Nested forks in parent

```
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
        printf("L1\n");
        if (fork() != 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}
```

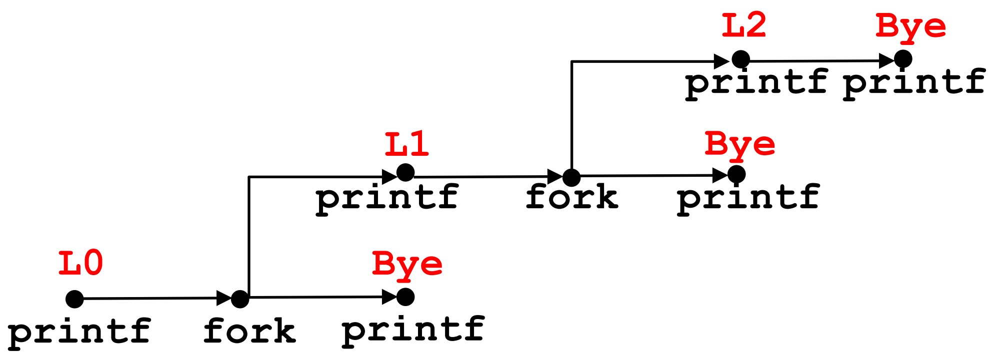
forks.c



Feasible or Infeasible?	Feasible or Infeasible?
L0	L0
Bye	L1
L1	Bye
Bye	Bye
Bye	L2
L2	Bye
Infeasible	Feasible

fork Example: Nested forks in children

```
void fork5()
{
    printf("L0\n");
    if (fork() == 0) {
        printf("L1\n");
        if (fork() == 0) {
            printf("L2\n");
        }
    }
    printf("Bye\n");
}                               forks.c
```



Feasible or Infeasible?	Feasible or Infeasible?
L0	L0
Bye	Bye
L1	L1
Bye	L2
Bye	Bye
L2	Bye
Infeasible	Feasible

Reaping Child Processes

- **Idea**
  - When process terminates, it still consumes system resources
    - Examples: Exit status, various OS tables
  - Called a "zombie"
    - Living corpse, half alive and half dead
- **Reaping**
  - Performed by parent on terminated child (using `wait` or `waitpid`)
  - Parent is given exit status information
  - Kernel then deletes zombie child process
- **What if parent doesn't reap?**
  - If any parent terminates without reaping a child, then the orphaned child should be reaped by **`init`** process (pid == 1)
    - Unless it was **`init`** that terminated! Then need to reboot…
  - So, only need explicit reaping in long-running processes
    - e.g., shells and servers

Zombie Example

```
void fork7() {
    if (fork() == 0) {
        /* Child */
        printf("Terminating Child, PID = %d\n", getpid());
        exit(0);
    } else {
        printf("Running Parent, PID = %d\n", getpid());
        while (1)
            ; /* Infinite loop */
    }
}
```

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

- **`ps`** shows child process as "defunct" (i.e., a zombie)
- Killing parent allows child to be reaped by **`init`**

Non-terminating Child Example

```
void fork8()
{
    if (fork() == 0) {
        /* Child */
        printf("Running Child, PID = %d\n",
               getpid());
        while (1)
            ; /* Infinite loop */
    } else {
        printf("Terminating Parent, PID = %d\n",
               getpid());
        exit(0);
    }
}
```

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

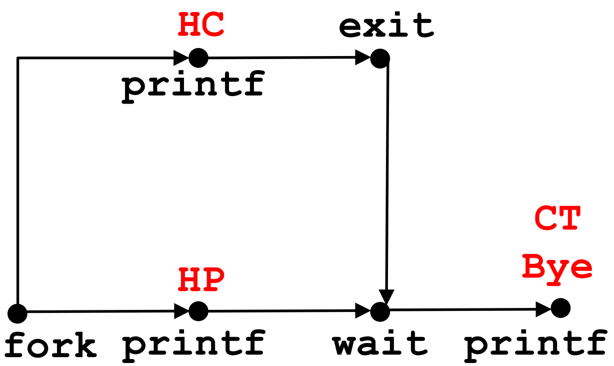
- Child process still active even though parent has terminated
- Must kill child explicitly, or else will keep running indefinitely

`wait`: Synchronizing with Children

- **Parent reaps a child with one of these system calls:**
- **`pid_t wait(int *status)`**
  - Suspends current process until one of its children terminates
  - Returns PID of child, records exit status in **`status`**
- **`pid_t waitpid(pid_t pid, int *status, int options)`**
  - More flexible version of **`wait`**:
  - Can wait for a specific child or group of children
  - Can be told to return immediately if there are no children to reap

wait: Synchronizing with Children

```
void fork9() {
    int child_status;

    if (fork() == 0) {
        printf("HC: hello from child\n");
        exit(0);
    } else {
        printf("HP: hello from parent\n");
        wait(&child_status);
        printf("CT: child has terminated\n");
    }
    printf("Bye\n");
}
```
forks.c



Feasible output(s):

HC	HP
HP	HC
CT	CT
Bye	Bye

Infeasible output:

HP
CT
Bye
HC

wait: Status codes

- Return value of `wait` is the pid of the child process that terminated
- If `status != NULL`, then the integer it points to will be set to a value that indicates the exit status
  - More information than the value passed to `exit`
  - Must be decoded, using macros defined in sys/wait.h
    - WIFEXITED, WEXITSTATUS, WIFSIGNALED, WTERMSIG, WIFSTOPPED, WSTOPSIG, WIFCONTINUED
    - See textbook for details

Another wait Example

- If multiple children completed, will take in arbitrary order
- Can use macros WIFEXITED and WEXITSTATUS to get information about exit status

```
void fork10() {
    pid_t pid[N];
    int i, child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            exit(100+i); /* Child */
        }
    for (i = 0; i < N; i++) { /* Parent */
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminate abnormally\n", wpid);
    }
}
```

forks.c

waitpid: Waiting for a Specific Process

- `pid_t waitpid(pid_t pid, int *status, int options)`
  - Suspends current process until specific process terminates
  - Various options (see textbook)

```
void fork11() {
    pid_t pid[N];
    int i;
    int child_status;

    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    for (i = N-1; i >= 0; i--) {
        pid_t wpid = waitpid(pid[i], &child_status, 0);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminate abnormally\n", wpid);
    }
}
```

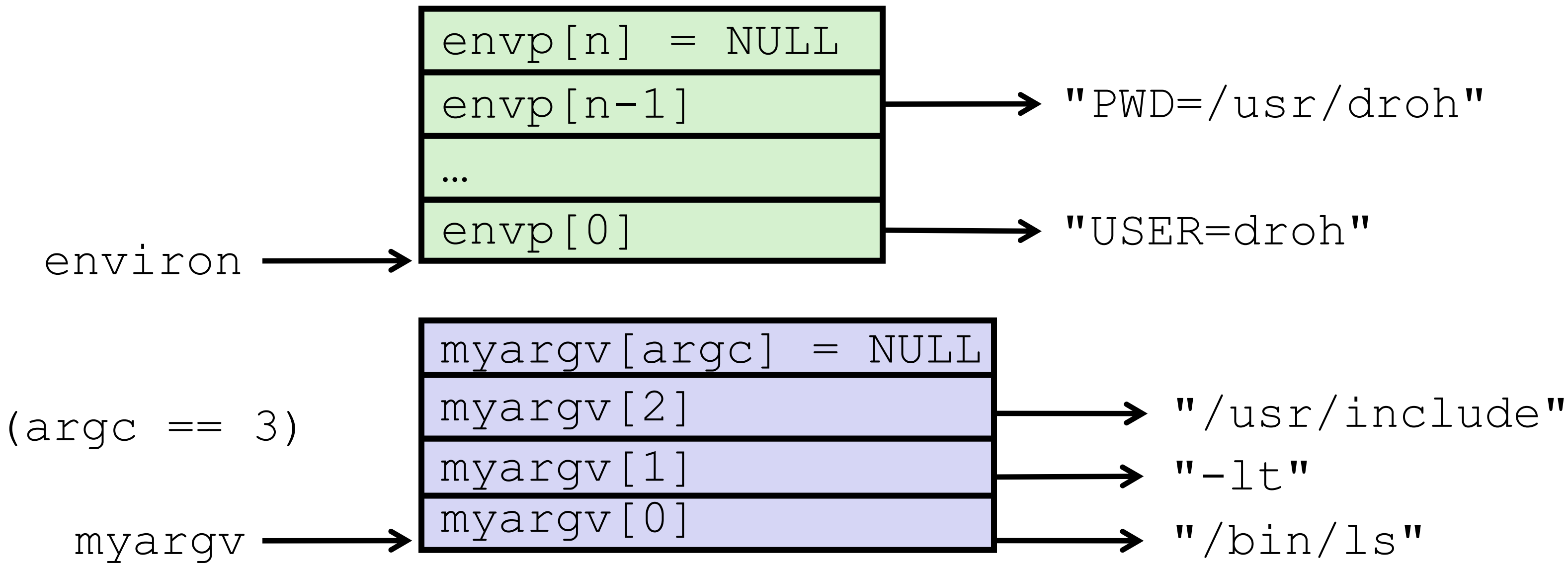
forks.c

`execve`: Loading and Running Programs

- **`int execve(char *filename, char *argv[], char *envp[])`**
- **Loads and runs in the current process:**
  - Executable file **`filename`**
    - Can be object file or script file beginning with `#!interpreter` (e.g., `#!/bin/bash`)
  - …with argument list **`argv`**
    - By convention **`argv[0]==filename`**
  - …and environment variable list **`envp`**
    - "name=value" strings (e.g., `USER=droh`)
    - `getenv, putenv, printenv`
- **Overwrites code, data, and stack**
  - Retains PID, open files and signal context
- **Called once and never returns**
  - …except if there is an error

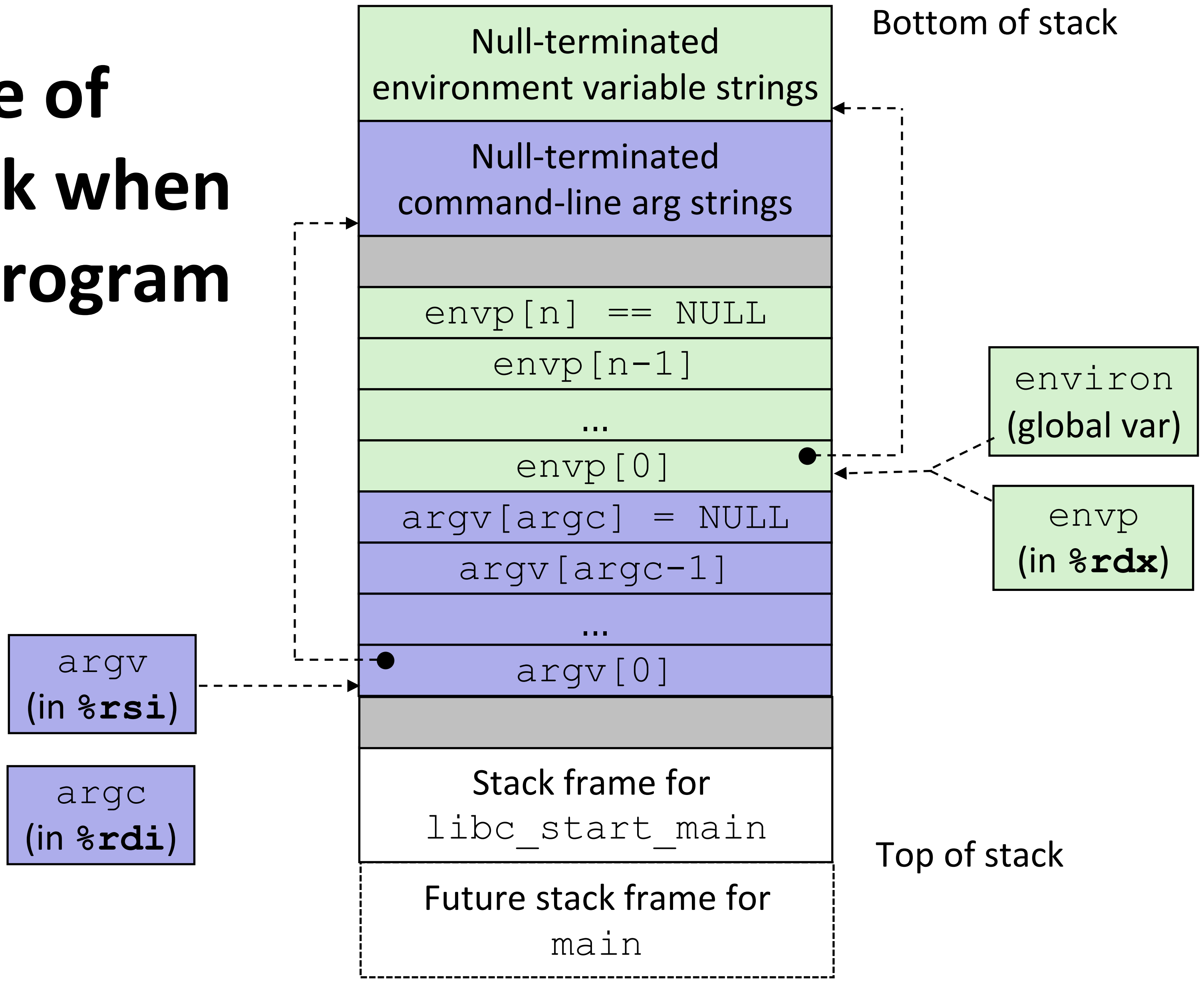
execve Example

- **Execute** `"/bin/ls -lt /usr/include"` **in child process using current environment:**

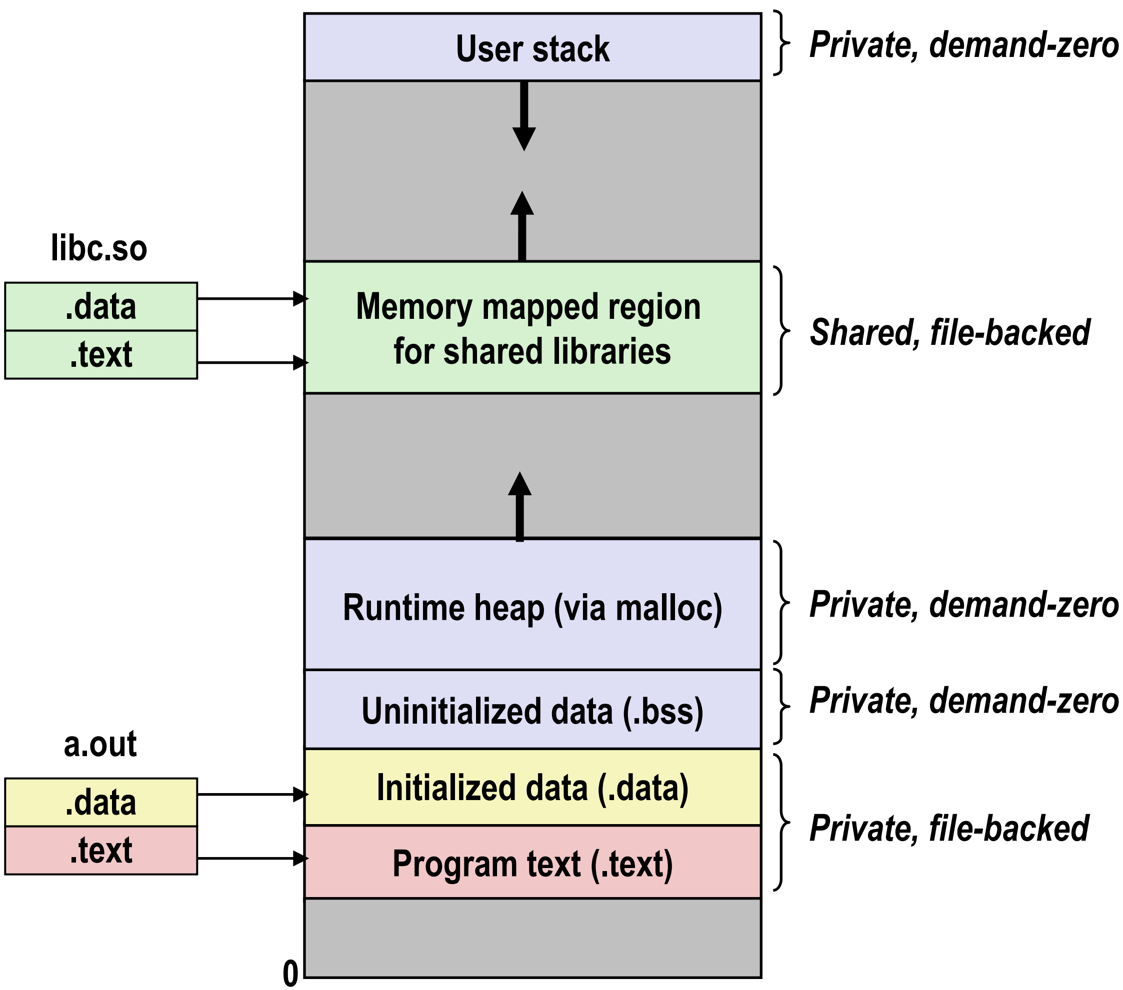



```
if ((pid = Fork()) == 0) {   /* Child runs program */
    if (execve(myargv[0], myargv, environ) < 0) {
        printf("%s: %s\n", myargv[0], strerror(errno));
        exit(1);
    }
}
```

Structure of the stack when a new program starts



execve and process memory layout



- **To load and run a new program `a.out` in the current process using `execve`:**
- **Free `vm_area_struct`'s and page tables for old areas**
- **Create `vm_area_struct`'s and page tables for new areas**
  - Programs and initialized data backed by object files.
  - `.bss` and stack backed by anonymous files.
- **Set PC to entry point in `.text`**
  - Linux will fault in code and data pages as needed.

Discussion

- **Why separate fork() and execve()?**
  - In Windows, these two processes are done by a single system call `CreateProcess()`
- **Sharing system handlers**
  - `ls | grep a.txt`
  - `Step 1: fork() # fork from shell`
  - `Step 2: pipe() # create pipe for IPC`
  - `Step 3: fork() and execve(ls) # create ls`
    - `Then dup2 stdout to read end of pipe`
  - `Step 4: fork() and execve(grep) # create grep`
    - `Then dup2 stdin to write end of pipe`

Summary

- **Processes**
  - At any given time, system has multiple active processes
  - Only one can execute at a time on any single core
  - Each process appears to have total control of processor + private memory space

Summary (cont.)

- **Spawning processes**
  - Call `fork`
  - One call, two returns
- **Process completion**
  - Call `exit`
  - One call, no return
- **Reaping and waiting for processes**
  - Call `wait` or `waitpid`
- **Loading and running programs**
  - Call `execve` (or variant)
  - One call, (normally) no return