Processes

Slides adapted from: Randy Bryant of Carnegie Mellon University

A program is the static executable, and is different from a process. Do not use “program” to talk about a “process”!

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:**
  - Logical control flow
    - Each program seems to have exclusive use of the CPU
  - Private virtual address space
    - Each program seems to have exclusive use of main memory

- **How are these illusions maintained?**
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system

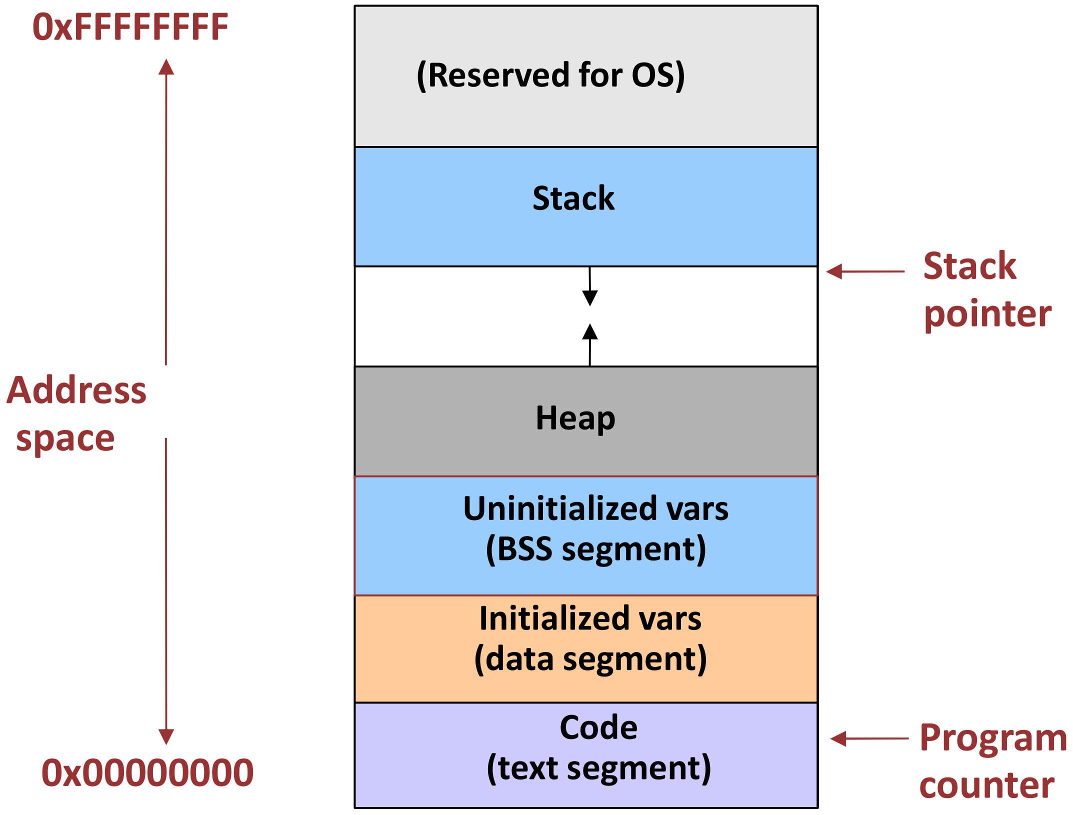
What is a process?

- **A process is the OS's abstraction for execution**
  - A process represents a single running application on the system
- **Process has three main components:**
  1. **Address space**
     - The memory that the process can access
     - Consists of various pieces: the program code, static variables, heap, stack, etc.
  2. **Processor state**
     - The CPU registers associated with the running process
     - Includes general purpose registers, program counter, stack pointer, etc.
  3. **OS resources**
     - Various OS state associated with the process
     - Examples: open files, network sockets, etc.

CPU state • **%rax,….** • **%rsp, %rip** • **CC**
Address space • **Code** • **Vars** • **Heap** • **Libraries** • **Stack**
OS resources • **Open file info** • **Network sockets** • **..**

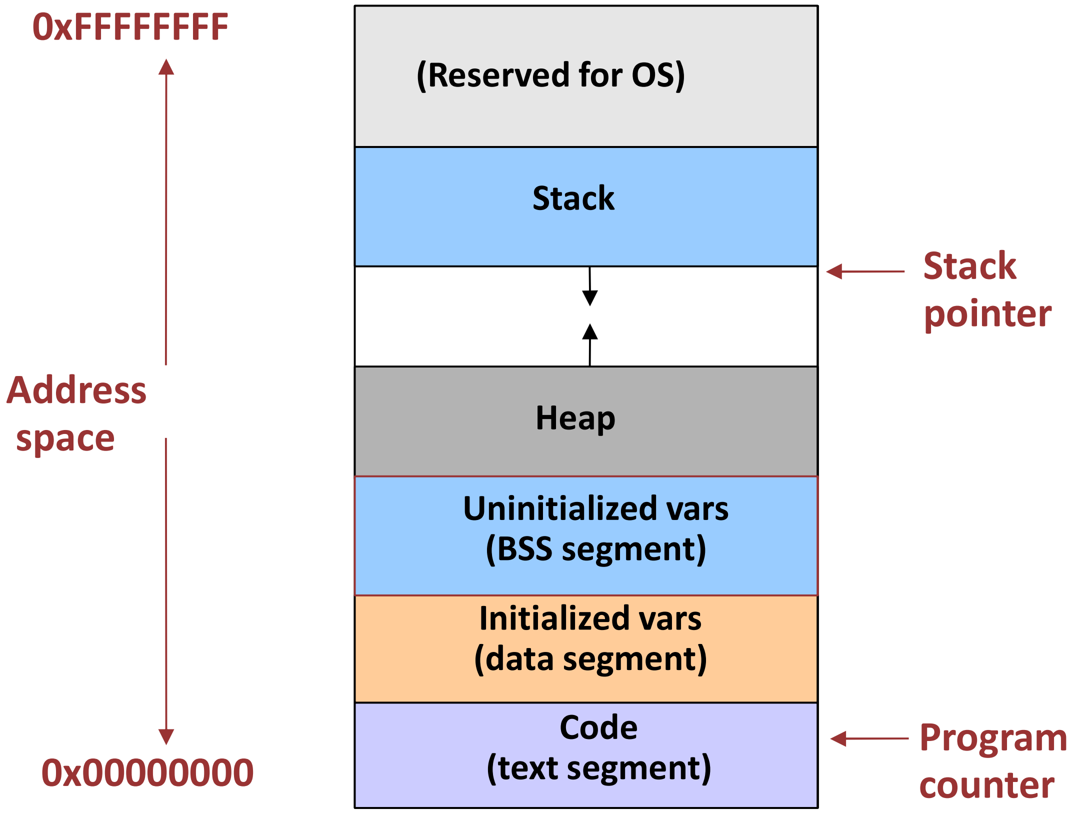
Process Address Space

- **Virtual memory of a process includes**
  - the code of the running program
  - the data of the running program (static variables and heap)
  - the execution stack storing local variables and saved registers for each procedure call



Process Address Space

- **This is the process's own view of the address space**
  - physical memory may not be laid out this way at all.
  - The virtual memory system provides this illusion to each process.

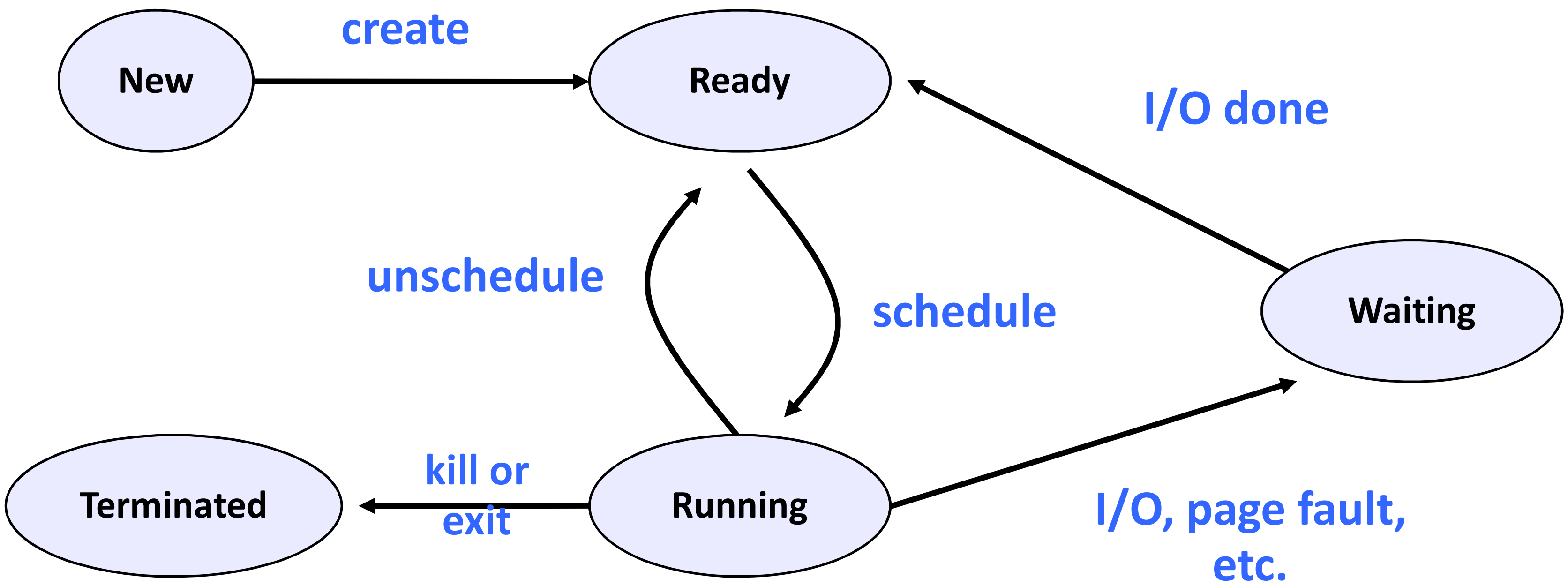


Execution State (context) of a Process

- **Each process has an execution state (context)**
  - Indicates what the process is currently doing
- **Running:**
  - Process is currently using the CPU
- **Ready:**
  - Currently waiting to be assigned to a CPU
  - That is, the process could be running, but another process is using the CPU
- **Waiting (or sleeping):**
  - Process is waiting for an event
  - Such as completion of an I/O, a timer to go off, etc.
  - Why is this different than “ready” ?
- **As the process executes, it moves between these states**
  - What state is the process in most of the time?

Process State (Context) Transitions

- What causes schedule and unschedule transitions?



Process Control Block

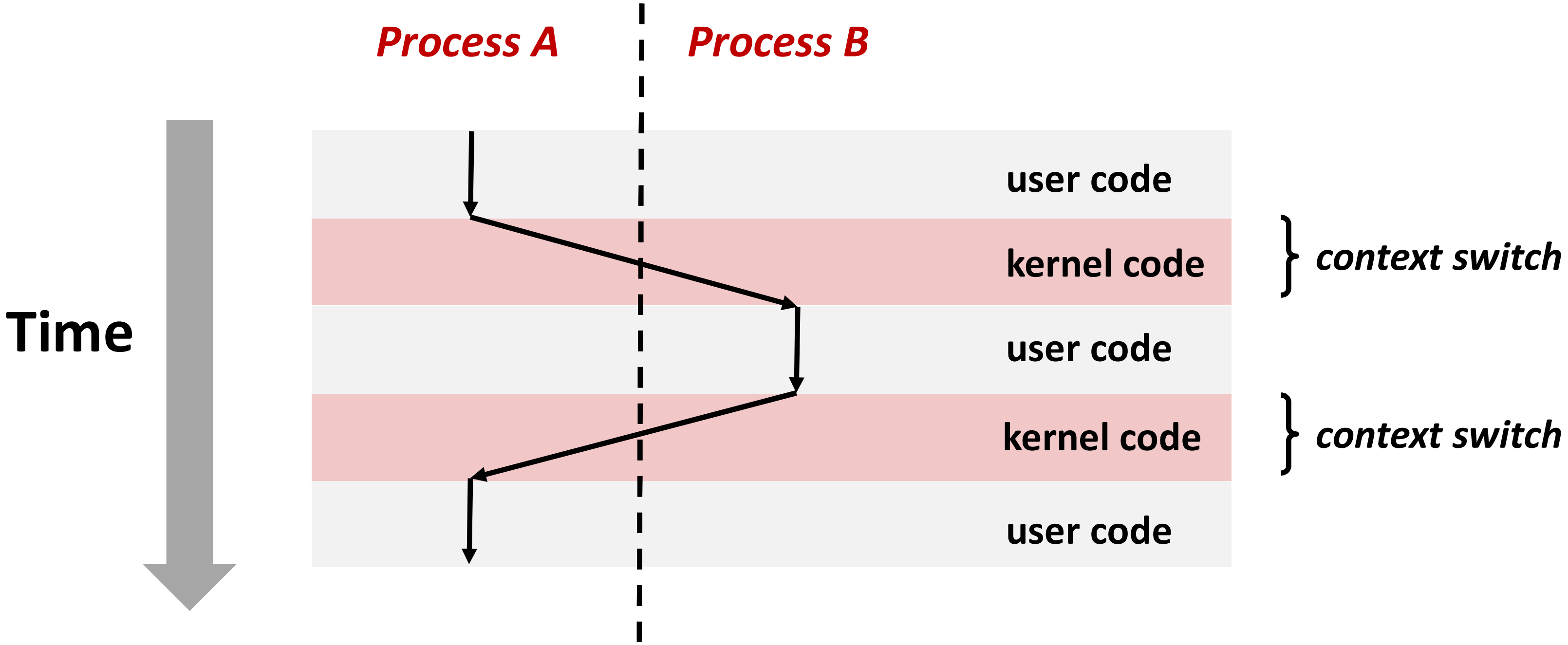
- **OS maintains a Process Control Block (PCB) for each process**
- **The PCB is a big data structure with many fields:**
  - Process ID
  - User ID
  - Execution state
    - ready, running, or waiting
  - Saved CPU state
    - CPU registers saved the last time the process was suspended.
  - OS resources
    - Open files, network sockets, etc.
  - Memory management info
  - Scheduling priority
    - Give some processes higher priority than others
  - Accounting information
    - Total CPU time, memory usage, etc.

```
struct task_struct {/* these are hardcoded - don't touch */
 volatile long          state;          /* -1 unrunnable, 0 runnable, >0 stopped */
 long                   counter;
 long                   priority;
 unsigned long          signal;
 unsigned long          blocked;   /* bitmap of masked signals */
 unsigned long          flags;     /* per process flags, defined below */
 int errno;
 long                   debugreg[8];    /* Hardware debugging registers */
 struct exec_domain     *exec_domain;
 /* various fields */
 struct linux_binfmt    *binfmt;
 struct task_struct     *next_task, *prev_task;
 struct task_struct     *next_run,  *prev_run;
 unsigned long          saved_kernel_stack;
 unsigned long          kernel_stack_page;
 int                    exit_code, exit_signal;
 /*…................. */
 int                    pid;
 struct wait_queue      *wait_chldexit;
 unsigned short         uid,euid,suid,fsuid;
 unsigned short         gid,egid,sgid,fsgid;
 unsigned long          timeout, policy, rt_priority;
 /* file system info */
 int                    link_count;
 struct tty_struct      *tty;           /* NULL if no tty */
 /* ipc stuff */
 struct sem_undo        *semundo;
 struct sem_queue       *semsleeping;/* ldt for this task - used by Wine.  If NULL, default_ldt is used */
 /*…................. */
 struct desc_struct *ldt;/* tss for this task */
 struct thread_struct tss;/* filesystem information */
 struct fs_struct       *fs;/* open file information */
 struct files_struct    *files;/* memory management info */
 struct mm_struct       *mm;/* signal handlers */
 struct signal_struct *sig;
/*…................. */
}
```

- PCB in Linux
- Each **task_struct** dat a structure describes a process or task in the system.

Context Switching

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



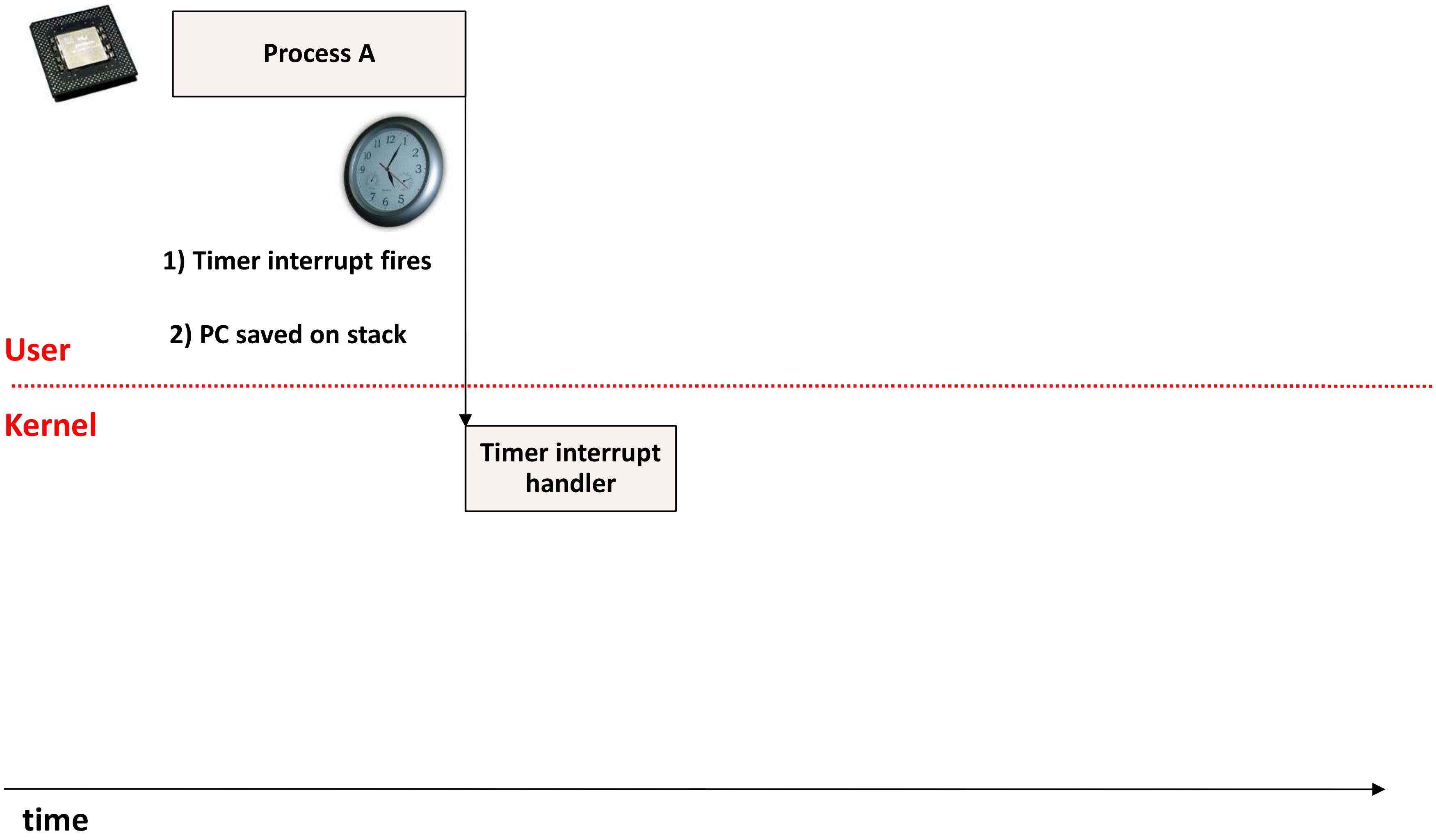
Context Switching in Linux

Process A

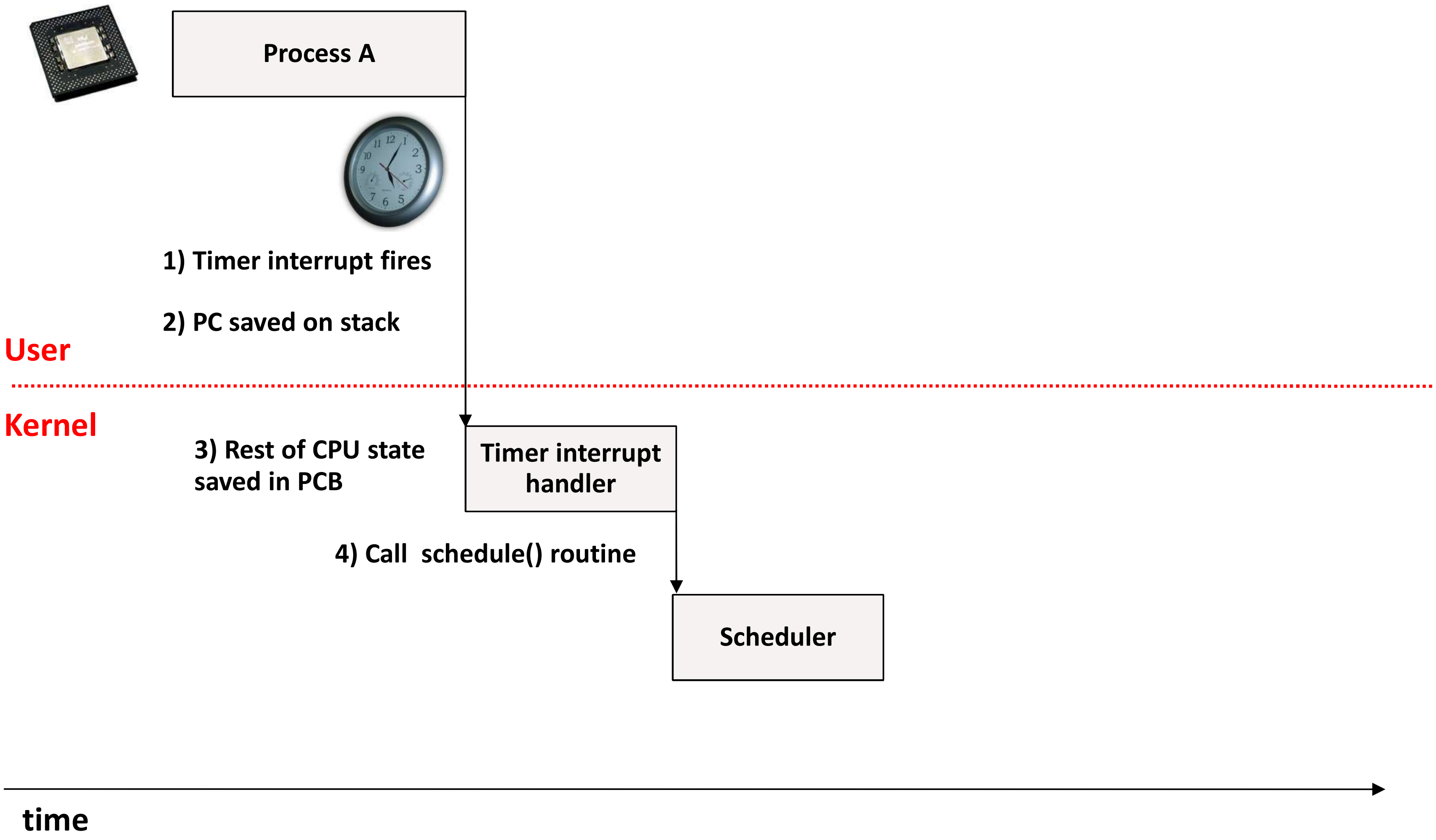
Process A is happily running along...

time

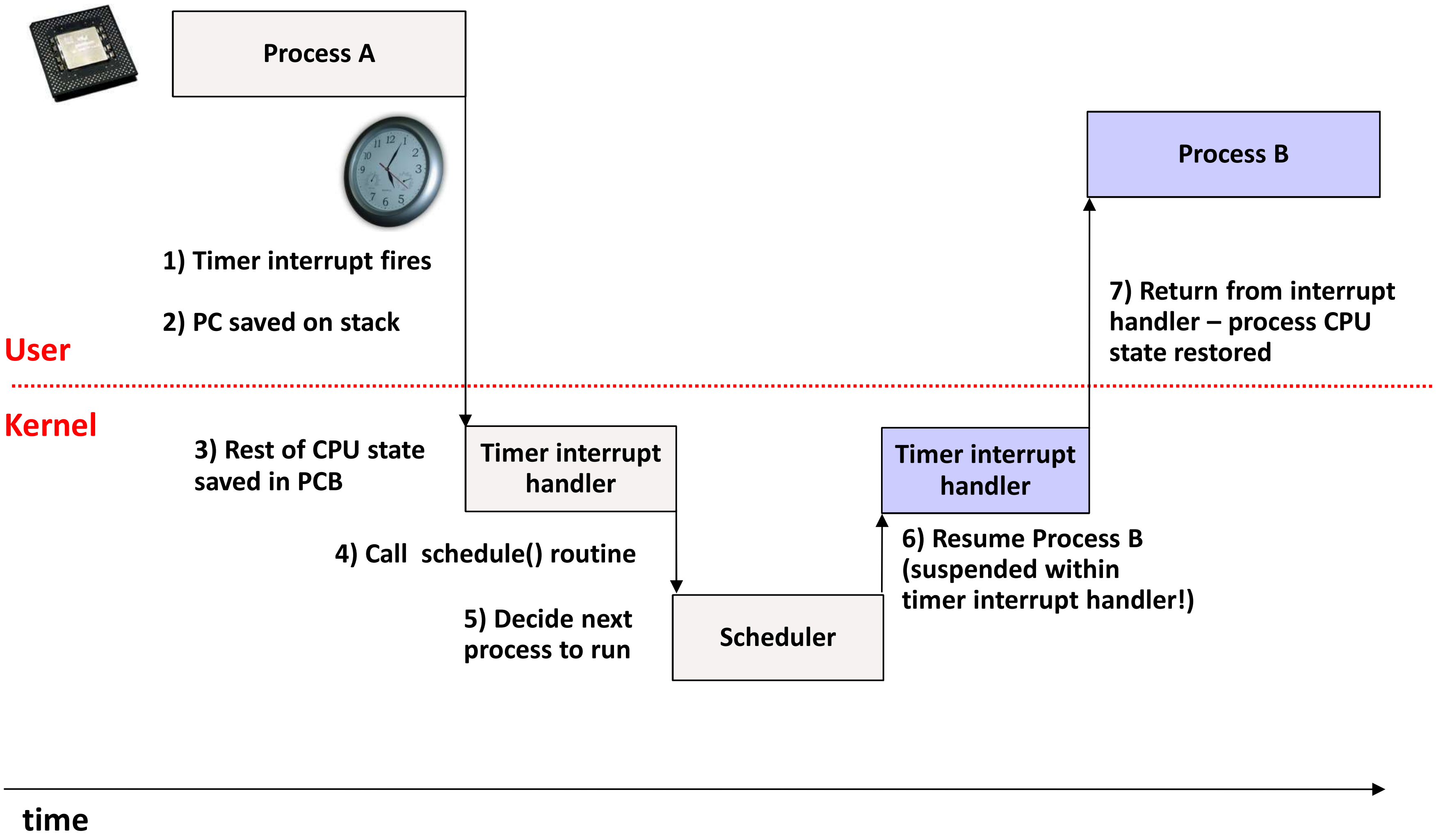
Context Switching in Linux



Context Switching in Linux



Context Switching in Linux

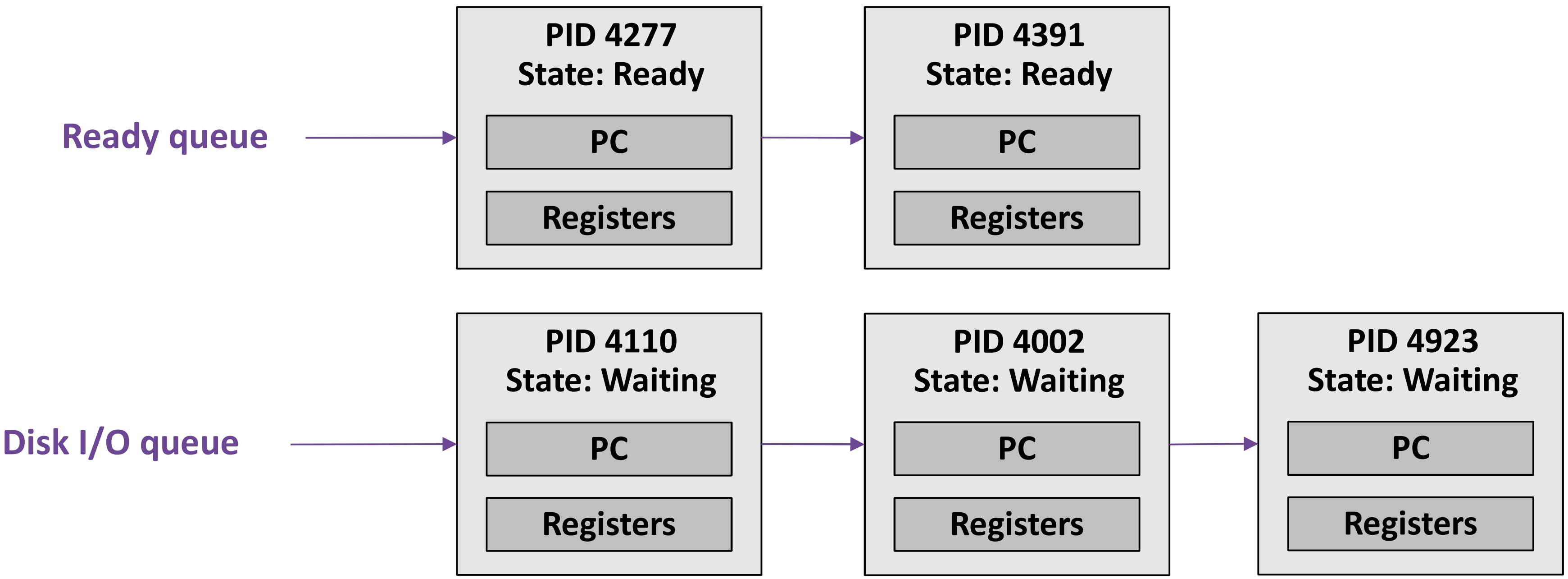


Context Switch Overhead

- **Context switches are not cheap**
  - Generally have a lot of CPU state to save and restore
  - Also must update various flags in the PCB
  - Picking the next process to run – scheduling – is also expensive
- **Context switch overhead in Linux**
  - About 5-7 usec (u: micro)
  - This is equivalent to about 10,000 CPU cycles!

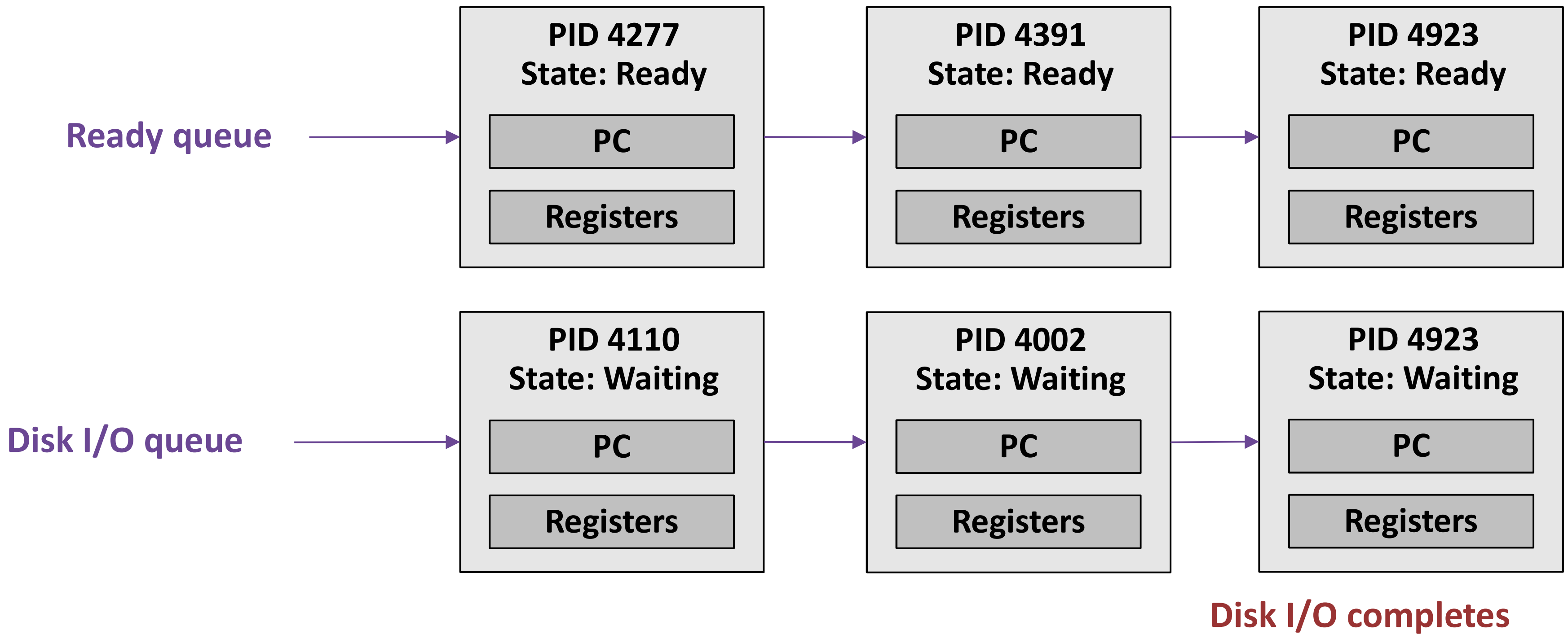
State Queues

- **The OS maintains a set of state queues for each process state**
  - Separate queues for ready and waiting states
  - Generally separate queues for each kind of waiting process
    - One queue for processes waiting for disk I/O, another for network I/O, etc.



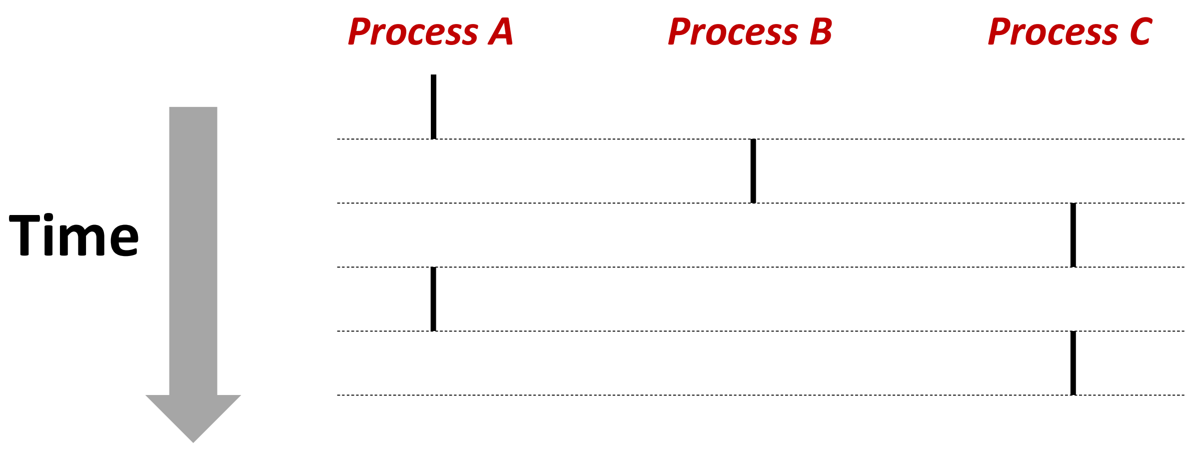
State Queue Transitions

- **PCBs move between these queues as their state changes**
  - When scheduling a process, pop the head off of the ready queue
  - When I/O has completed, move PCB from waiting queue to ready queue



Concurrent Processes

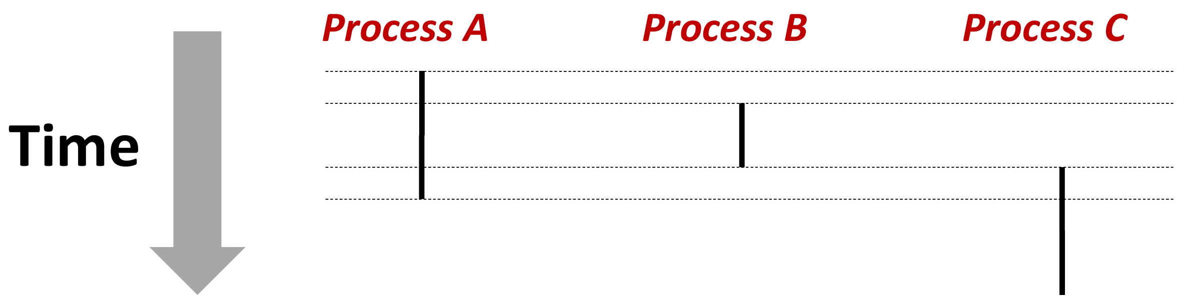
- **Each process is a logical control flow.**
- **Two processes *run* *concurrently* (*are concurrent)* if their flows overlap in time**
- **Otherwise, they are *sequential***
- **Examples (running on single core):**
  - Concurrent: A & B, A & C
  - Sequential: B & C



User View of Concurrent Processes

- Control flows for concurrent processes are physically disjoint in time

- However, we can think of concurrent processes as running in parallel with each other



Creating Processes

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

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***

https://www.cdn.geeksforgeeks.org/fork-system-call/

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
```

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

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

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);
        printf("child : x=%d\n", ++x);
        return 0;
    }

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

```
linux> ./fork
parent: x=0
child : x=2
parent: x=-1
child : x=3
```

- 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

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

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

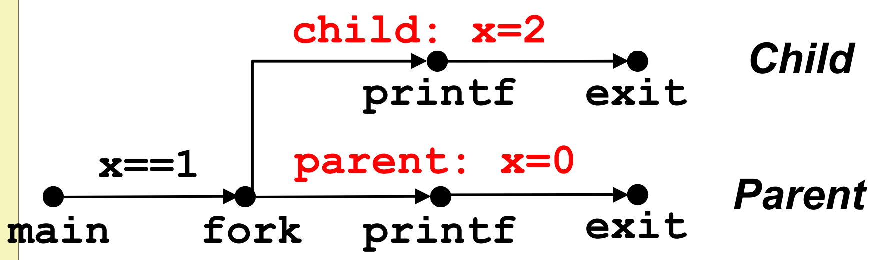
Modeling `fork` with Process Graphs

- **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 in-edges
- **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

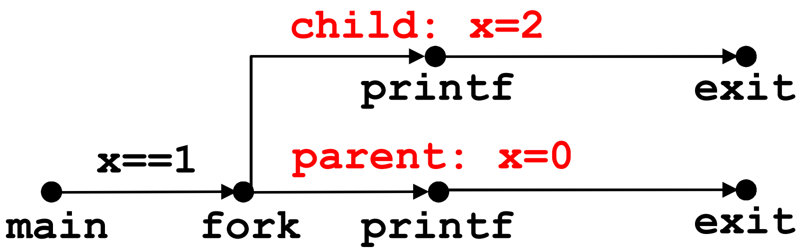
```c
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    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

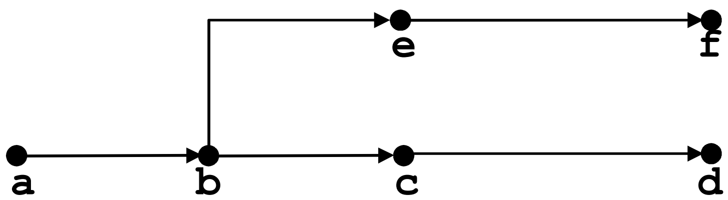


Interpreting Process Graphs

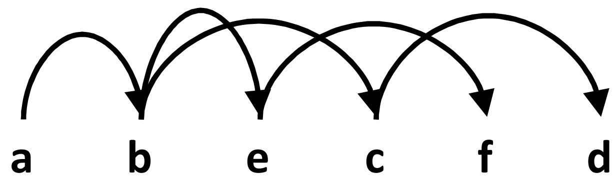
- **Original graph:**



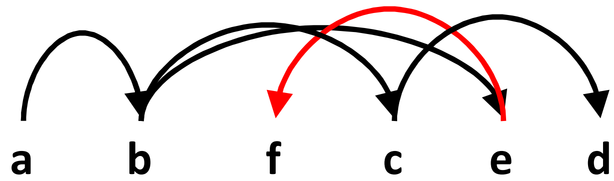
- **Relabeled graph:**



Feasible total ordering:



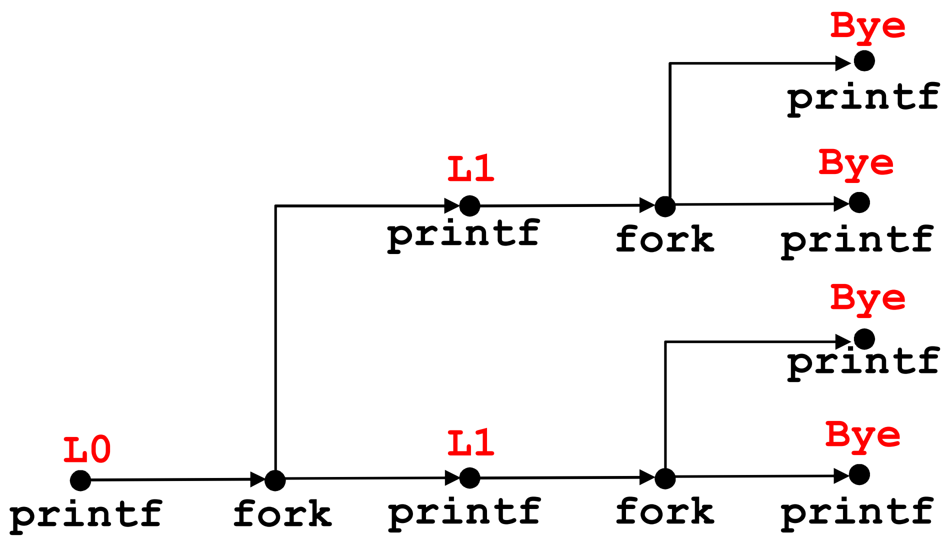
Infeasible total ordering:



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
```

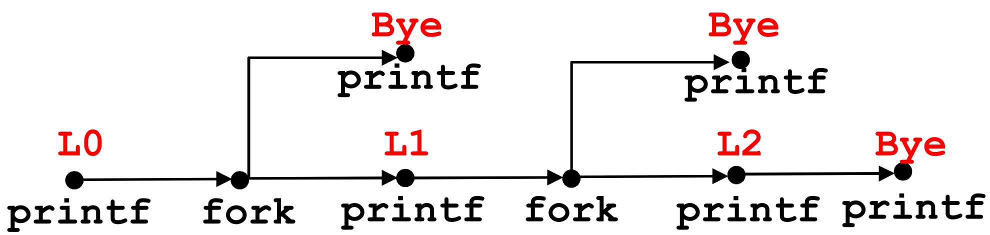
Infeasible output:

```
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 output:

L0
L1
Bye
Bye
L2
Bye

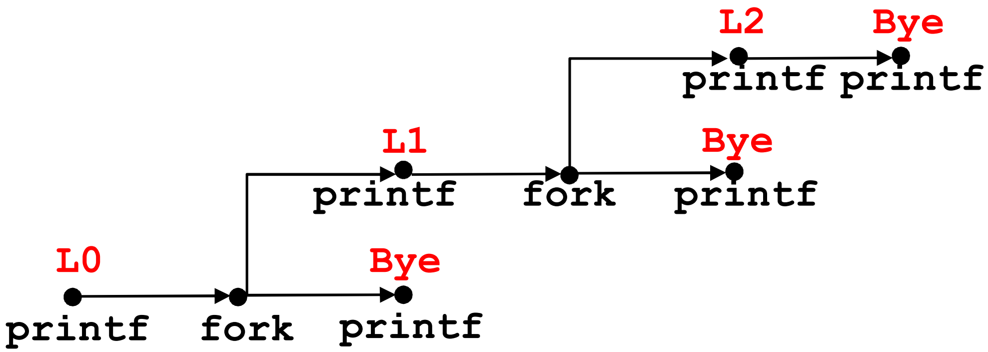
Infeasible output:

L0
Bye
L1
Bye
Bye
L2

fork Example: Nested forks in children

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

forks.c



Feasible output:
L0
Bye
L1
L2
Bye
Bye

Infeasible output:
L0
Bye
L1
Bye
Bye
L2

Why have fork() at all?

- **Why make a copy of the parent process?**
- **Don't you usually want to start a new program instead?**
- **Where might "cloning" the parent be useful?**
  - Web server – make a copy for each incoming connection
  - Parallel processing – set up initial state, fork off multiple copies to do work
- **UNIX philosophy: System calls should be minimal.**
  - Don't overload system calls with extra functionality if it is not always needed.
  - Better to provide a flexible set of simple primitives and let programmers combine them in useful ways.

What if `fork`'ing gets out of control?

```
void forkbomb() {
    while (1)
        fork();
}
```

Memory concerns

- **OS aggressively tries to share memory between processes.**
  - Especially processes that are **`fork()`**'d copies of each other
- **Copies of a parent process do not actually get a private copy of the address space...**
  - ... though that is the illusion that each process gets.
  - Instead, they share the same physical memory, until one of them makes a change.
- **The virtual memory system is behind these tricks.**
  - We will discuss this in much detail later in the course

Terminating Processes

- **Process becomes terminated for one of three reasons:**
  - Receiving a signal whose default action is to terminate (more later)
  - 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.**

`atexit()` registers functions to be executed upon exit

```
void cleanup(void) {
   printf("cleaning up\n");
}

void fork() {
   atexit(cleanup);
   fork();
   exit(0);
}
```

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 will be reaped by `init` process (pid == 1)
  - 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);
    }
}
```

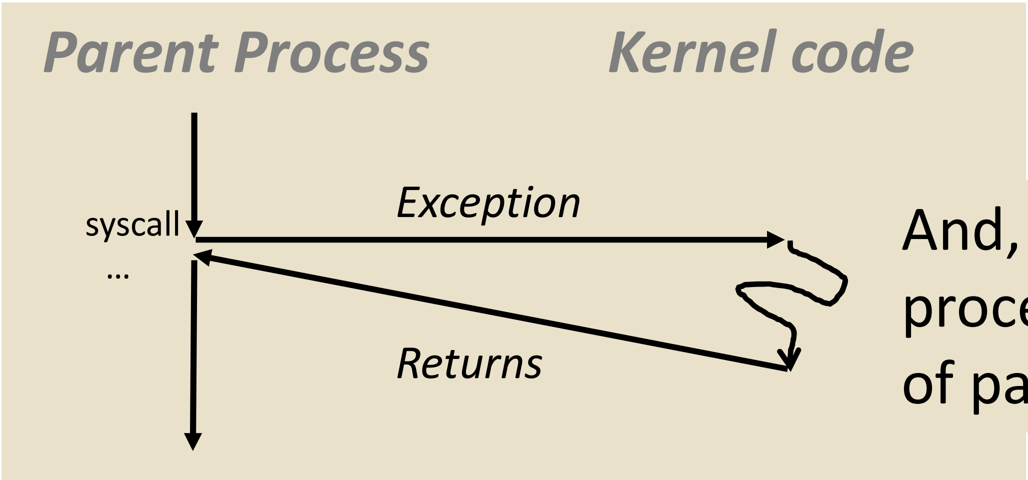
```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9   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

- **`int wait(int *child_status)`**
  - Suspends current process until <u>one of its children</u> terminates



And, potentially other user processes, including a child of parent

`wait`: Synchronizing with Children

- **Parent reaps a child by calling the `wait` function**

- **`int wait(int *child_status)`**
  - Suspends current process until one of its children terminates
  - Return value is the **`pid`** of the child process that terminated
  - If **`child_status != NULL`**, then the integer it points to will be set to a value that indicates reason the child terminated and the exit status:
    - Checked using macros defined in **`wait.h`**
      - **`WIFEXITED`, `WEXITSTATUS`, `WIFSIGNALED`, `WTERMSIG`, `WIFSTOPPED`, `WSTOPSIG`, `WIFCONTINUED`**
      - See man pages for details

Process completion status

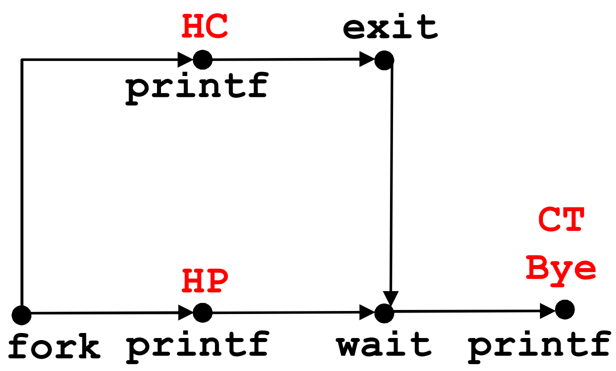
- `int WIFEXITED (int status)`
  - returns a nonzero value if the child process terminated normally with exit or _exit.
- `int WEXITSTATUS (int status)`
  - If WIFEXITED is true of *status*, this macro returns the low-order 8 bits of the exit status value from the child process.
- `int WIFSIGNALED (int status)`
  - returns a nonzero value if the child process terminated because it received a signal that was not handled
- `int WTERMSIG (int status)`
  - If WIFSIGNALED is true of *status*, this macro returns the signal number of the signal that terminated the child process.
- `int WCOREDUMP (int status)`
  - Returns a nonzero value if the child process terminated and produced a core dump.
- `int WIFSTOPPED (int status)`
  - returns a nonzero value if the child process is stopped.
- `int WSTOPSIG (int status)`
  - If WIFSTOPPED is true of *status*, this macro returns the signal number of the signal that caused the child process to stop.

http://www.gnu.org/software/libc/manual/html_node/Process-Completion-Status.html

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

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 man page)

```
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

`fork()` and **`execve()`**

- **`execve()` does not fork a new process!**
  - Rather, it replaces the address space and CPU state of the current process
  - Loads the new address space from the executable file and starts it from **`main()`**
  - So, to start a new program, use **`fork()`** followed by **`execve()`**

`execl` and `exec` Family

- `int execl(char *path, char *arg0, char *arg1, …, 0)`
- **Loads and runs executable at `path` with args `arg0`, `arg1`, …**
  - `path` is the complete path of an executable object file
  - By convention, `arg0` is the name of the executable object file
  - "Real" arguments to the program start with `arg1`, etc.
  - List of `args` is terminated by a `(char *)0` argument
  - Environment taken from `char **environ`, which points to an array of "name=value" strings:
    - `USER=ganger`
    - `LOGNAME=ganger`
    - `HOME=/afs/cs.cmu.edu/user/ganger`
- **Returns −1 if error, *otherwise doesn't return*!**
- **Family of functions includes `execv`, `execve` (base function), `execvp`, `execl`, `execle`, and `execlp`**

`exec`: Using fork followed by exec

```
int main(int argc, char **argv) {
    int rv;
    if (fork()) {    /* Parent process */
        wait(&rv);
    } else {         /* Child process */
        char *newargs[3];
        printf("Hello, I am the child process.\n");
        newargs[0] = "/bin/echo";    /* Convention! Not required!! */
        newargs[1] = "some random string";
        newargs[2] = NULL;           /* Indicate end of args array */
        if (execv("/bin/echo", newargs)) {
            printf("warning: execve returned an error.\n"); exit(-1);
        }
        printf("Child process should never get here\n");
        exit(42);
    }
}
```

exec() function family

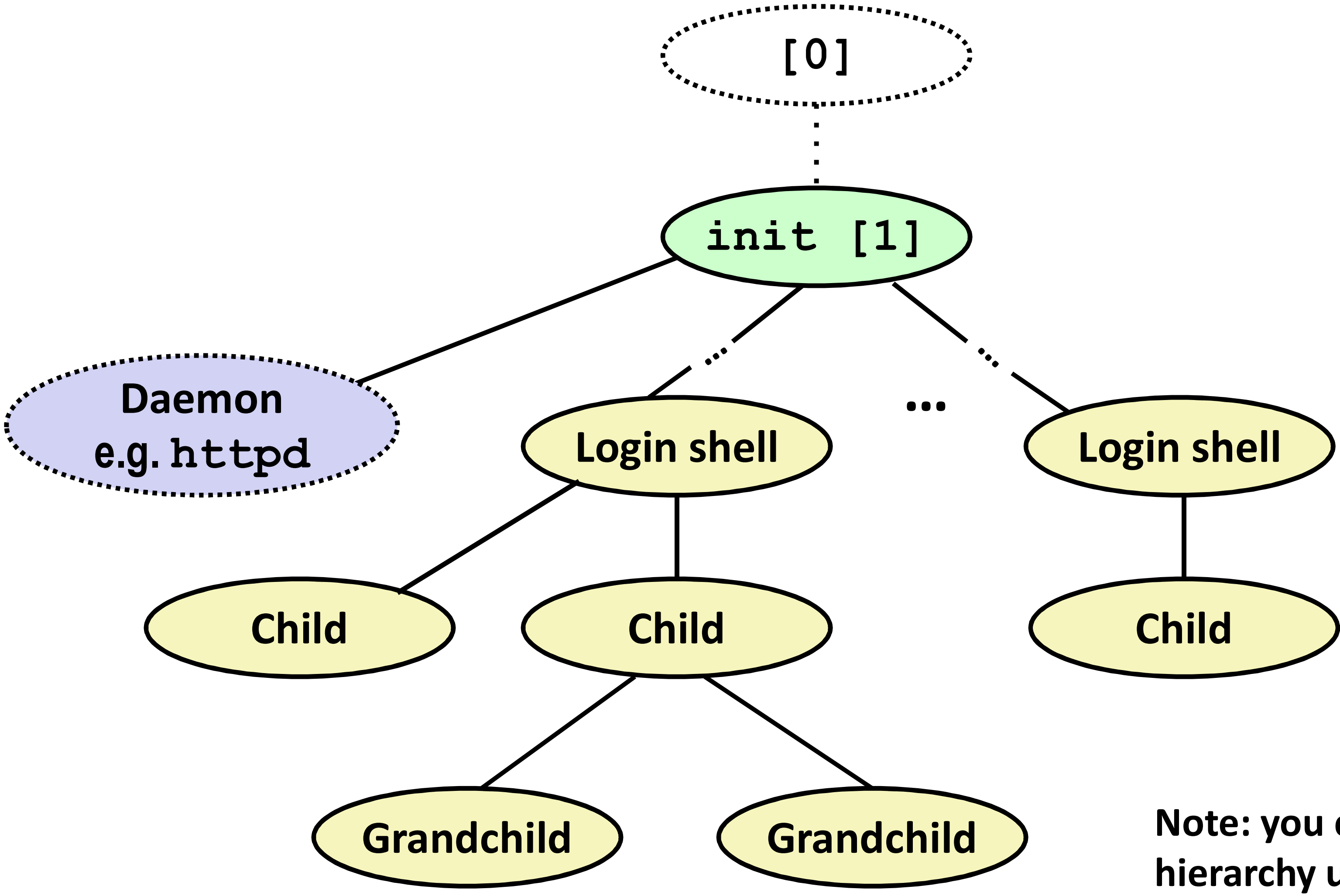
- The suffix's determine the arguments
  - **l** : arguments are passed as a list of strings to the main()
  - **v** : arguments are passed as an array of strings to the main()
  - **p** : path/s to search for the new running program
  - **e** : the environment can be specified by the caller
- One can mix them with different combinations
  - `int execl(const char *path, const char *arg, ...);`
  - `int execlp(const char *file, const char *arg, ...);`
  - `int execle(const char *path, const char *arg, ..., char * const envp[]);`
  - `int execv(const char *path, char *const argv[]);`
  - `int execve(const char *path, char *const argv[], char *const envp[]);`
  - `int execvp(const char *file, char *const argv[]);`
  - `int execvpe(const char *file, char *const argv[], char *const envp[]);`
- The initial argument is always the name of a file to be executed.

Environment variables

- An **environment variable** is a dynamic-named value that can affect the way running processes will behave on a computer.
- They are part of the environment in which a process runs. For example,
  - a running process can query the value of the TEMP environment variable to discover a suitable location to store temporary files,
  - or the HOME or USERPROFILE variable to find the directory structure owned by the user running the process
- In Unix, use `printenv` in your shell to get the full list.

https://en.wikipedia.org/wiki/Environment_variable

Linux Process Hierarchy



Note: you can view the hierarchy using the Linux `pstree` **command**

Summary

- **Process**
  - is an instance of program in execution
  - At any given time, a system has multiple active processes
  - Only one can execute at a time, though
  - Each process appears to have total control of processor + private memory space
- **Spawning processes**
  - Call to **`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 **`execl`** (or variant)
  - One call, (normally) no return