CSE 451: Operating Systems
Spring 2017

Module 6
Processes

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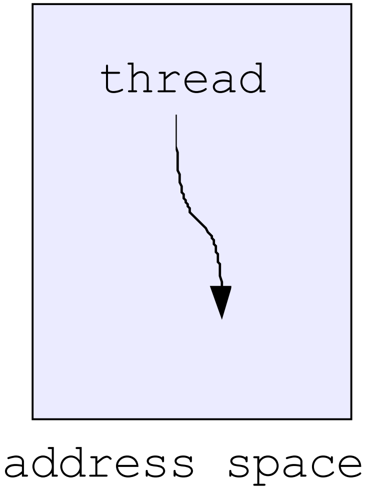
Process management

- This module begins a series of topics on processes, threads, and synchronization
  - this is the most important part of the class
  - there definitely will be several questions on these topics on the midterm
- In this module: processes and process management
  - What is a “process”?
  - What’s the OS’s process namespace?
  - How are processes represented inside the OS?
  - What are the executing states of a process?
  - How are processes created?
  - How can this be made faster?
  - Shells
  - Signals

What is a “process”?

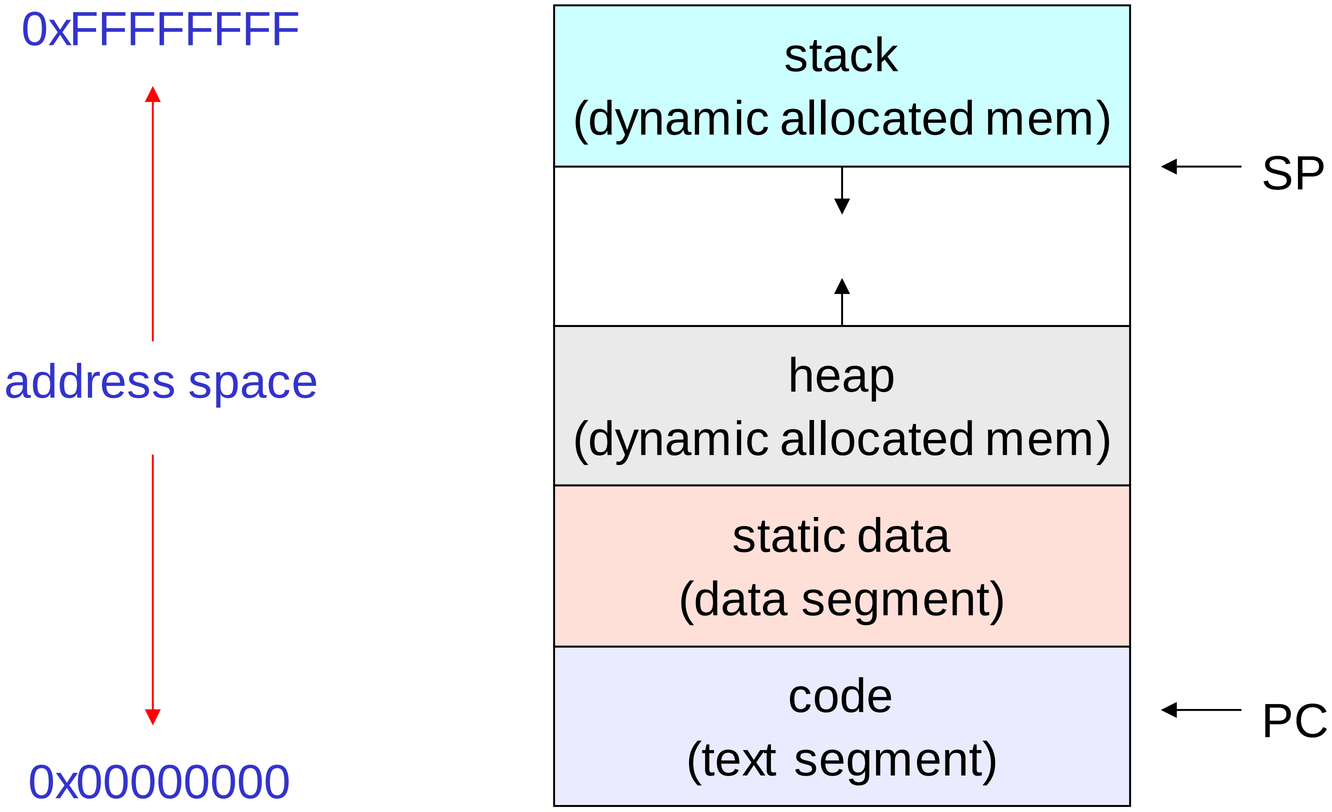
- The process is the OS’s abstraction for execution
  - A process is a program in execution
- Simplest (classic) case: a sequential process
  - An address space (an abstraction of memory)
  - A single thread of execution (an abstraction of the CPU)
- A sequential process is:
  - The unit of execution
  - The unit of scheduling
  - The dynamic (active) execution context
    - vs. the program – static, just a bunch of bytes



What's "in" a process?

- A process consists of (at least):
  - An address space, containing
    - the code (instructions) for the running program
    - the data for the running program (static data, heap data, stack)
  - CPU state, consisting of
    - The program counter (PC), indicating the next instruction
    - The stack pointer
    - Other general purpose register values
  - A set of OS resources
    - open files, network connections, sound channels, …
- In other words, it's all the stuff you need to run the program
  - or to re-start it, if it's interrupted at some point

A process’s address space (idealized)



The OS's process namespace

- (Like most things, the particulars depend on the specific OS, but the principles are general)
- The name for a process is called a process ID (PID)
  - An integer
- The PID namespace is global to the system
  - Only one process at a time has a particular PID
- Operations that create processes return a PID
  - E.g., fork()
- Operations on processes take PIDs as an argument
  - E.g., kill(), wait(), nice()

Representation of processes by the OS

- The OS maintains a data structure to keep track of a process's state
  - Called the process control block (PCB) or process descriptor
  - Identified by the PID

- OS keeps all of a process's execution state in (or linked from) the PCB when the process isn't running
  - PC, SP, registers, etc.
  - when a process is unscheduled, the execution state is transferred out of the hardware registers into the PCB
  - (when a process is running, its state is spread between the PCB and the CPU)

- Note: It's natural to think that there must be some esoteric techniques being used
  - fancy data structures that you'd never think of yourself

  Wrong! It's pretty much just what you'd think of!

The PCB

- The PCB is a data structure with many, many fields:
  - process ID (PID)
  - parent process ID (PPID)
  - execution state
  - program counter, stack pointer, registers
  - address space info
  - UNIX user id (uid), group id (gid)
  - scheduling priority
  - accounting info
  - pointers for state queue
  - …

PCBs and CPU state

- When a process is running, its CPU state is inside the CPU
  - PC, SP, registers
  - CPU contains current values

- When the OS gets control because of a …
  - Trap: Program executes a syscall
  - Exception: Program does something unexpected (e.g., page fault)
  - Interrupt: A hardware device requests service

the OS saves the CPU state of the running process in that process's PCB

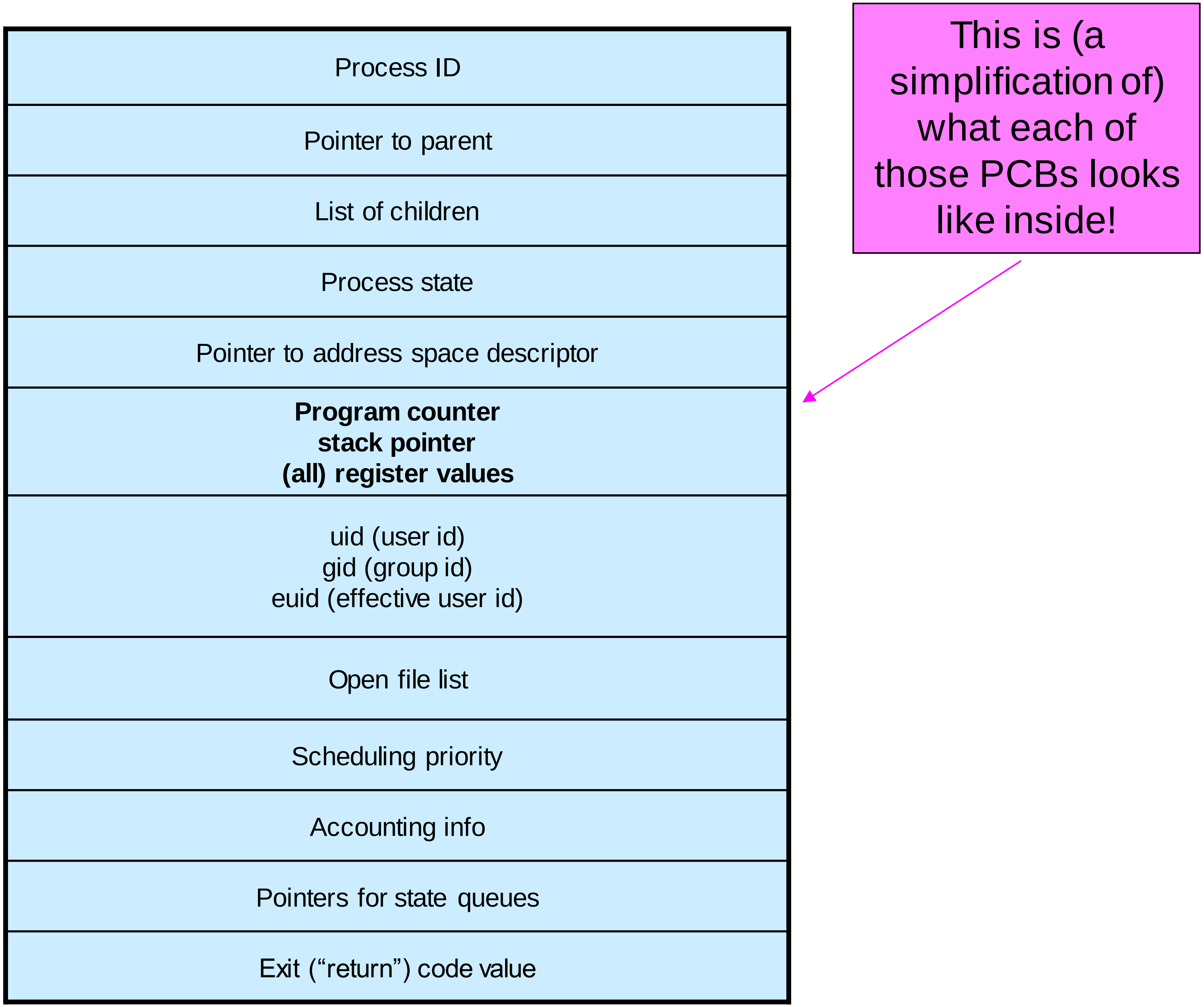
- When the OS returns the process to the running state, it loads the hardware registers with values from that process’s PCB – general purpose registers, stack pointer, instruction pointer

- The act of switching the CPU from one process to another is called a context switch
  - systems may do 100s or 1000s of switches/sec.
  - takes a few microseconds on today’s hardware

- Choosing which process to run next is called scheduling

The OS kernel is not a process

- It’s just a block of code!
- (In a microkernel OS, many things that you normally think of as the operating system execute as user-mode processes. But the OS kernel is just a block of code.)



Process ID

Pointer to parent

List of children

Process state

Pointer to address space descriptor

Program counter
stack pointer
(all) register values

uid (user id)
gid (group id)
euid (effective user id)

Open file list

Scheduling priority

Accounting info

Pointers for state queues

Exit (“return”) code value

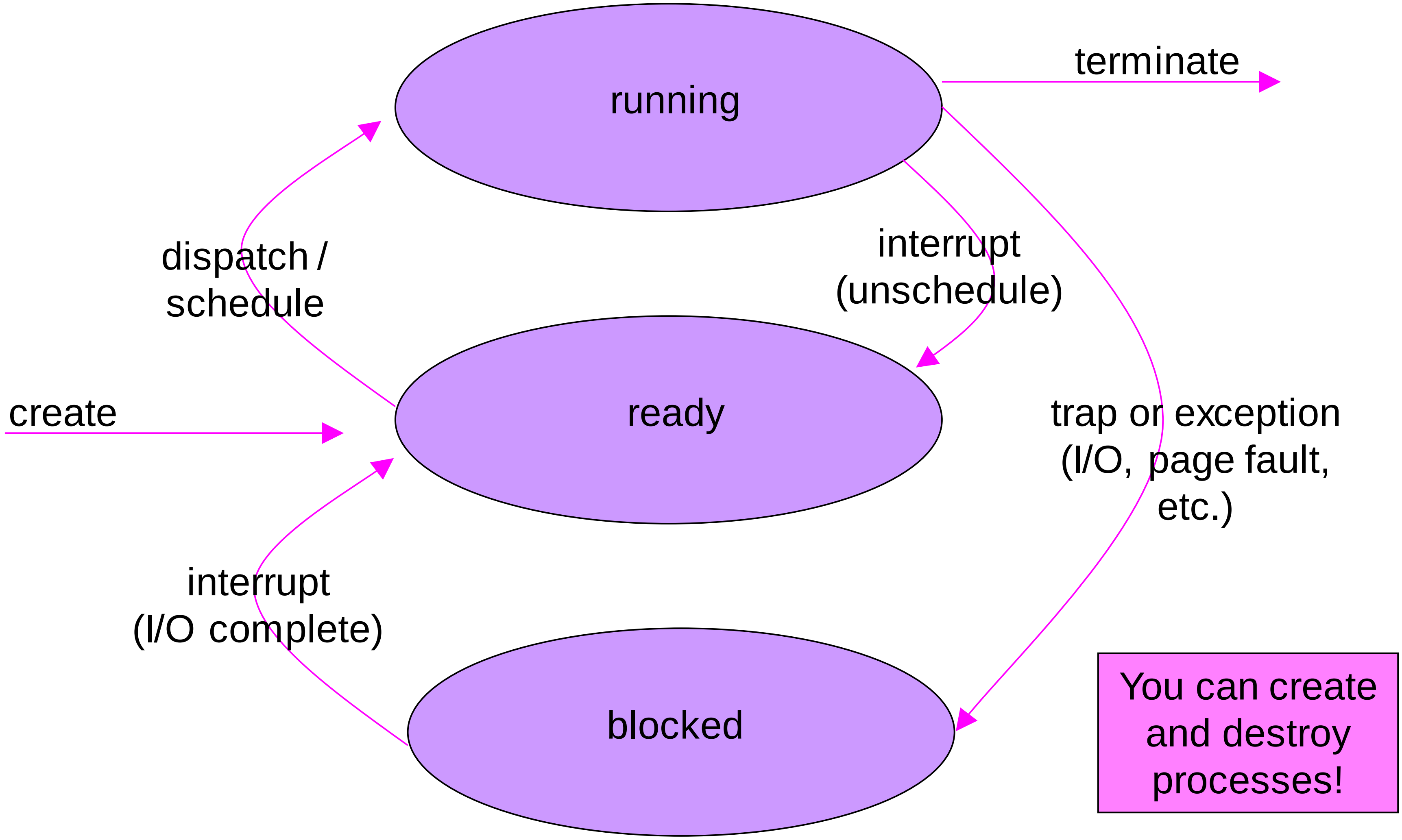
This is (a simplification of) what each of those PCBs looks like inside!

Process execution states

- Each process has an execution state, which indicates what it's currently doing
  - ready: waiting to be assigned to a CPU
    - could run, but another process has the CPU
  - running: executing on a CPU
    - it's the process that currently controls the CPU
  - waiting (aka "blocked"): waiting for an event, e.g., I/O completion, or a message from (or the completion of) another process
    - cannot make progress until the event happens

- As a process executes, it moves from state to state
  - UNIX: run `ps`, STAT column shows current state
  - which state is a process in most of the time?

Process states and state transitions



running

ready

blocked

terminate

dispatch / schedule

interrupt (unschedule)

create

trap or exception (I/O, page fault, etc.)

interrupt (I/O complete)

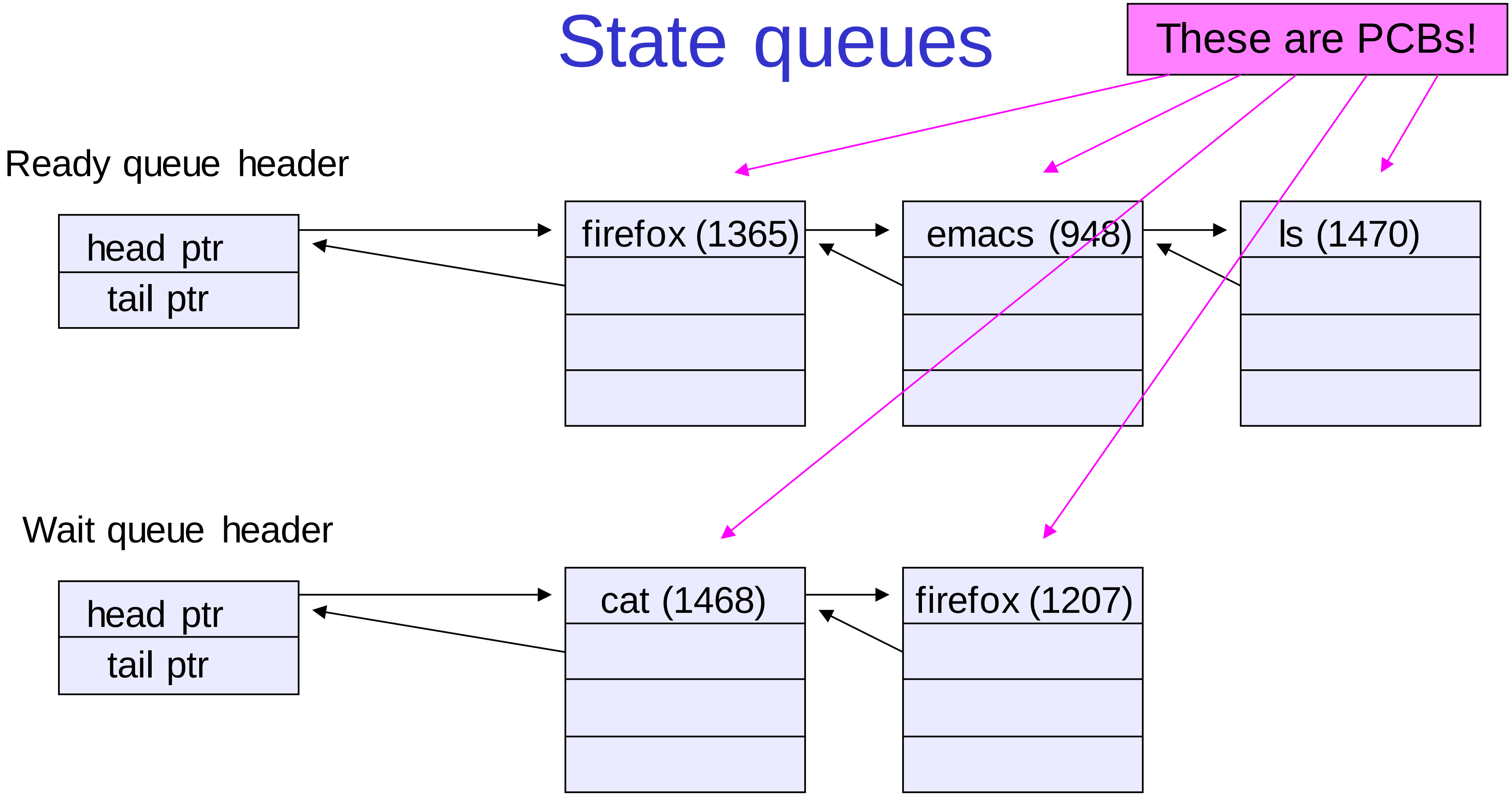
You can create and destroy processes!

State queues

- The OS maintains a collection of queues that represent the state of all processes in the system
  - typically one queue for each state
    - e.g., ready, waiting, …
  - each PCB is queued onto a state queue according to the current state of the process it represents
  - as a process changes state, its PCB is unlinked from one queue, and linked onto another

- Once again, *this is just as straightforward as it sounds!* The PCBs are moved between queues, which are represented as linked lists. *There is no magic!*

State queues



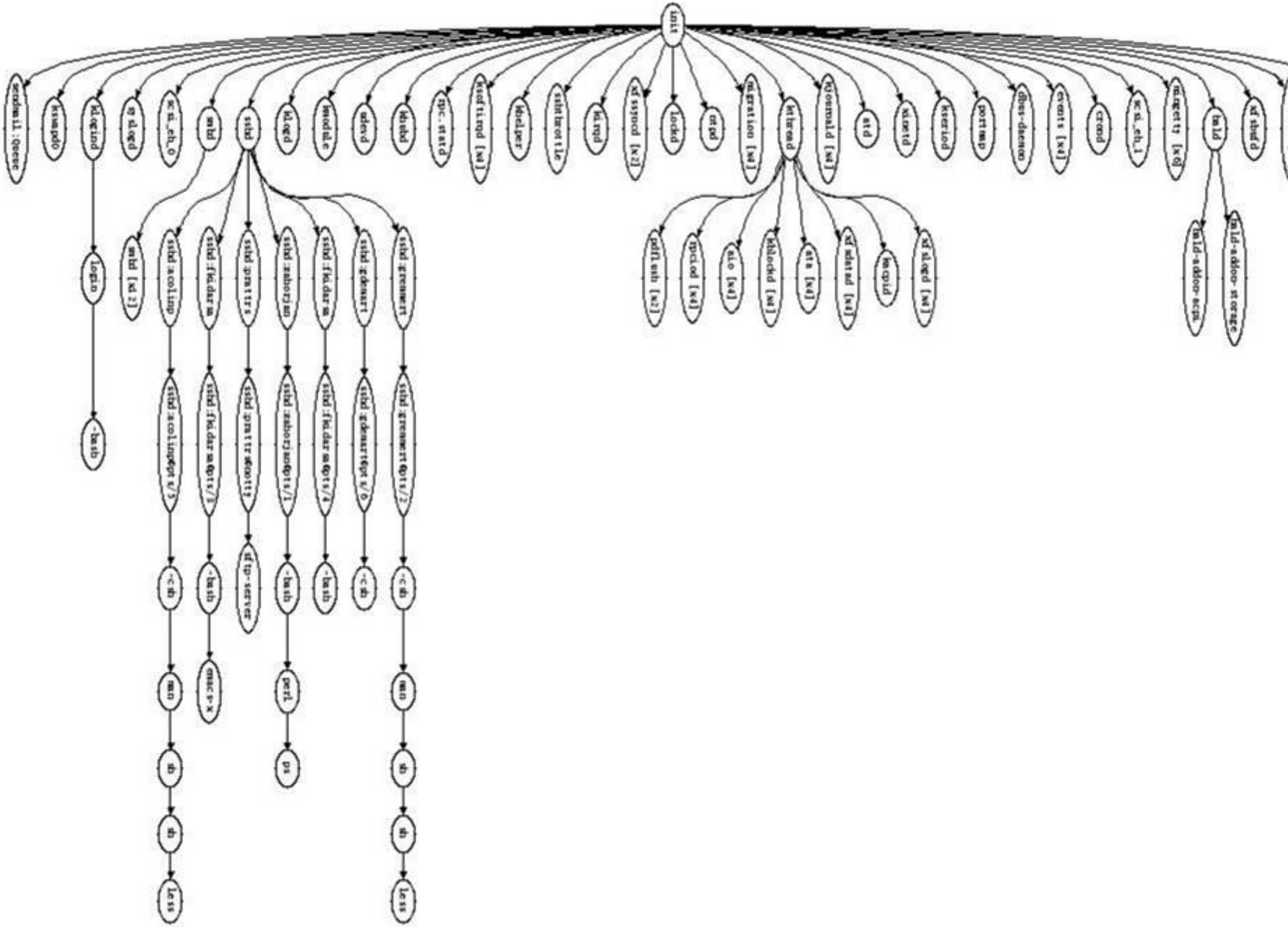
- There may be many wait queues, one for each type of wait (particular device, timer, message, …)

PCBs and state queues

- PCBs are data structures
  - dynamically allocated inside OS memory
- When a process is created:
  - OS allocates a PCB for it
  - OS initializes PCB
  - (OS does other things not related to the PCB)
  - OS puts PCB on the correct queue
- As a process computes:
  - OS moves its PCB from queue to queue
- When a process is terminated:
  - PCB may be retained for a while (to receive signals, etc.)
  - eventually, OS deallocates the PCB

Process creation

- New processes are created by existing processes
  - creator is called the parent
  - created process is called the child
    - UNIX: do **`ps`**, look for PPID field
  - what creates the first process, and when?


init
sendmail: Queue
klogind
syslogd
scsi_eh_0
sshd
klogd
udevd
khubd
rpc.statd
ksoftirqd [x4]
khelper
lockd
ntpd
migration [x4]
kthread
kjournald [x4]
atd
kseriod
portmap
dbus-daemon
events [x4]
crond
scsi_eh_1
mingetty [x6]
hald
xfssyncd [x2]
login
-bash
sftp-server
-csh
man
sh
less
emacs-x
perl
ps
aio [x4]
kblockd [x4]
hald-addon-acpi
hald-addon-storage

Process creation semantics

- (Depending on the OS) child processes inherit certain attributes of the parent
  - Examples:
    - Open file table: implies stdin/stdout/stderr
    - On some systems, resource allocation to parent may be divided among children

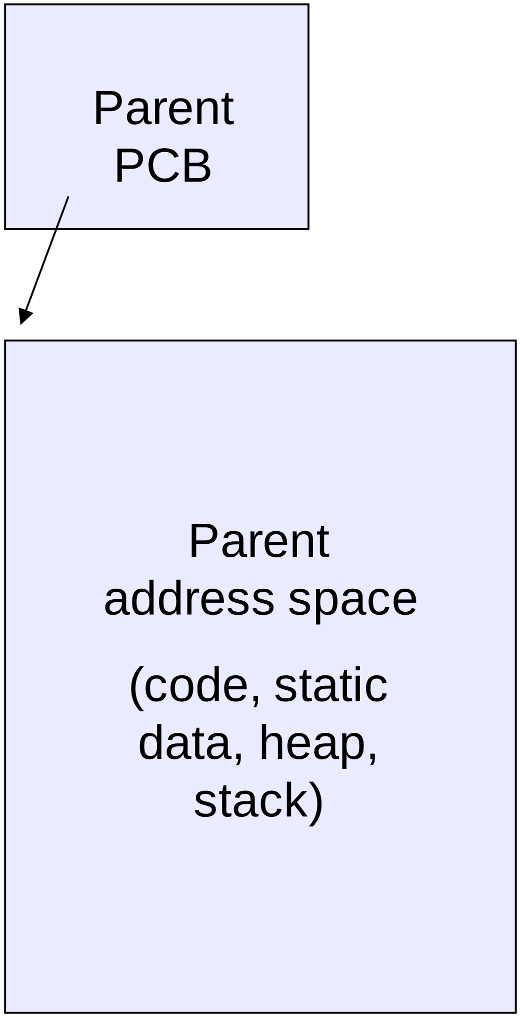
- (In Unix) when a child is created, the parent may either wait for the child to finish, or continue in parallel

UNIX process creation details

- UNIX process creation through **`fork()`** system call
  - creates and initializes a new PCB
    - initializes kernel resources of new process with resources of parent (e.g., open files)
    - initializes PC, SP to be same as parent
  - creates a new address space
    - initializes new address space with a copy of the entire contents of the address space of the parent
  - places new PCB on the ready queue

- the **`fork()`** system call "returns twice"
  - once into the parent, and once into the child
    - returns the child's PID to the parent
    - returns 0 to the child

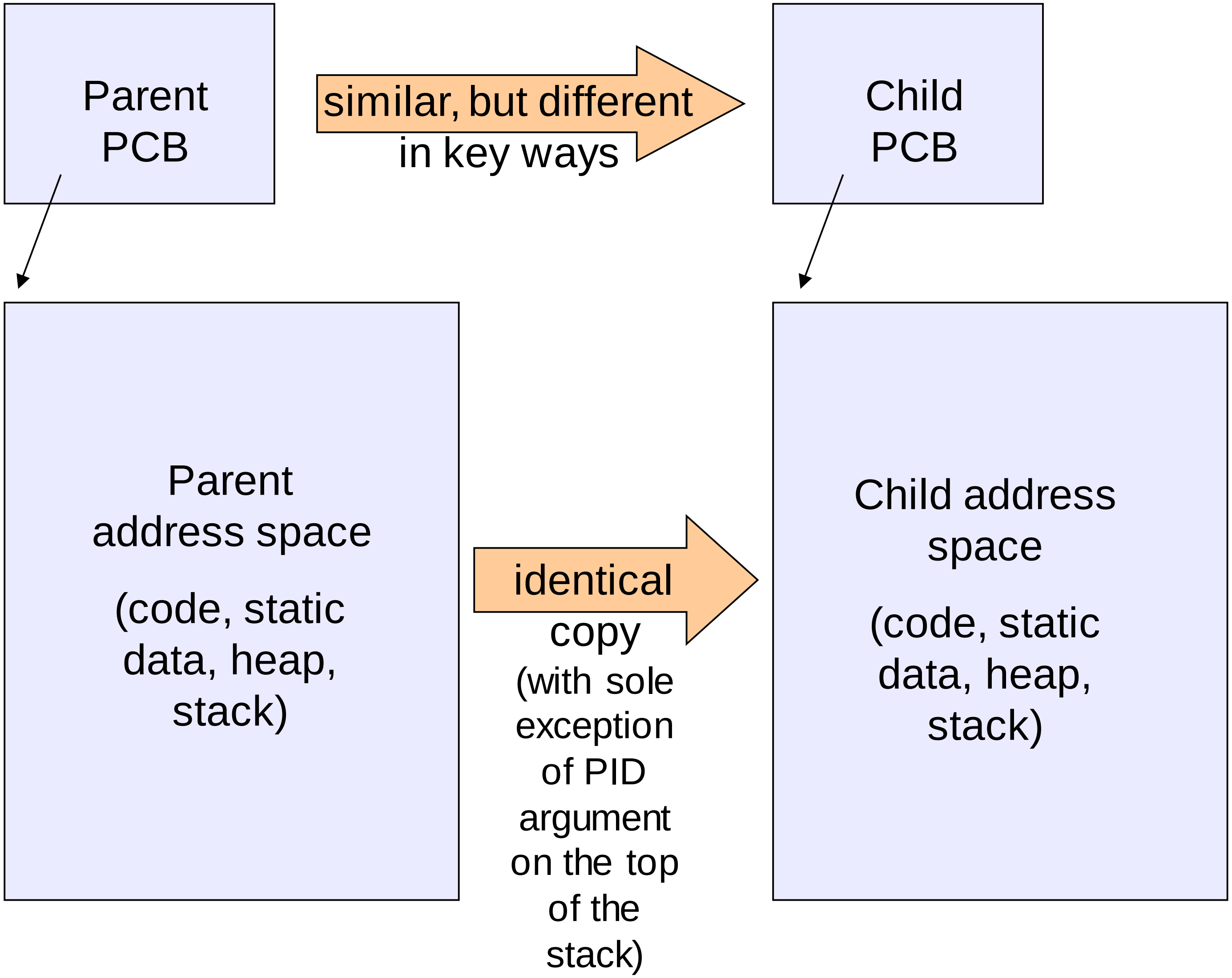
- **`fork()`** = "make a copy of me"



Parent
PCB

Parent
address space

(code, static
data, heap,
stack)



Parent PCB

similar, but different in key ways

Child PCB

Parent address space

(code, static data, heap, stack)

identical copy (with sole exception of PID argument on the top of the stack)

Child address space

(code, static data, heap, stack)

testparent – use of fork( )

```
#include <sys/types.h>
#include <unistd.h>
#include <stdio.h>

int main(int argc, char **argv)
{
  char *name = argv[0];
  int pid = fork();
  if (pid == 0) {
    printf(“Child of %s is %d\n”, name, pid);
    return 0;
  } else {
    printf(“My child is %d\n”, pid);
    return 0;
  }
}
```

testparent output

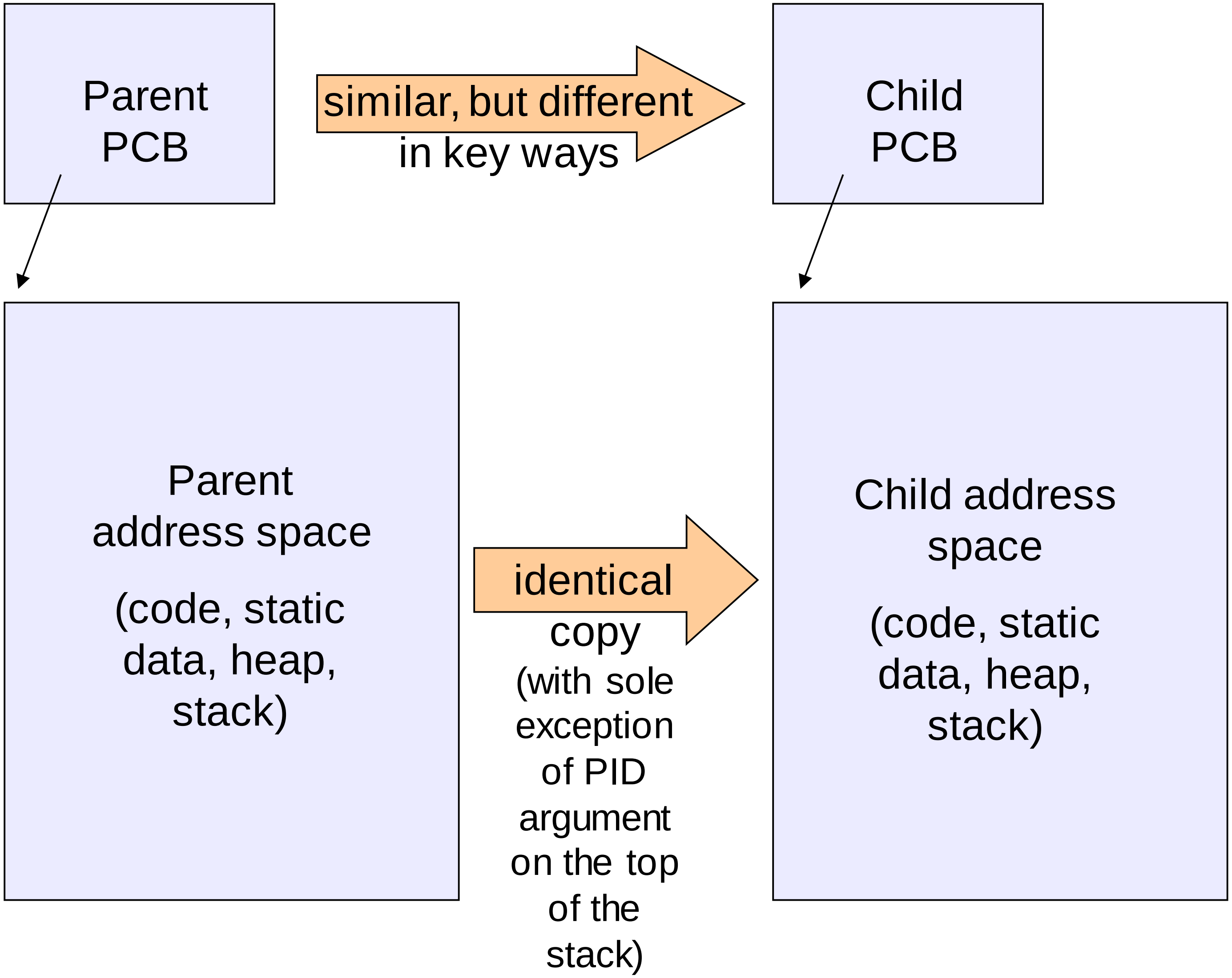
```
spinlock% gcc -o testparent testparent.c
spinlock% ./testparent
My child is 486
Child of testparent is 0
spinlock% ./testparent
Child of testparent is 0
My child is 571
```

exec() vs. fork()

- Q: So how do we start a new program, instead of just forking the old program?
- A: First fork, then exec
  - `int exec(char * prog, char * argv[])`

- **`exec()`**
  - stops the current process
  - loads program ‘prog’ into the address space
    - i.e., over-writes the existing process image
  - initializes hardware context, args for new program
  - places PCB onto ready queue
  - note: *does not create a new process!*

- So, to run a new program:
  - fork()
  - Child process does an exec()
  - Parent either waits for the child to complete, or not



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similar, but different in key ways

Child PCB

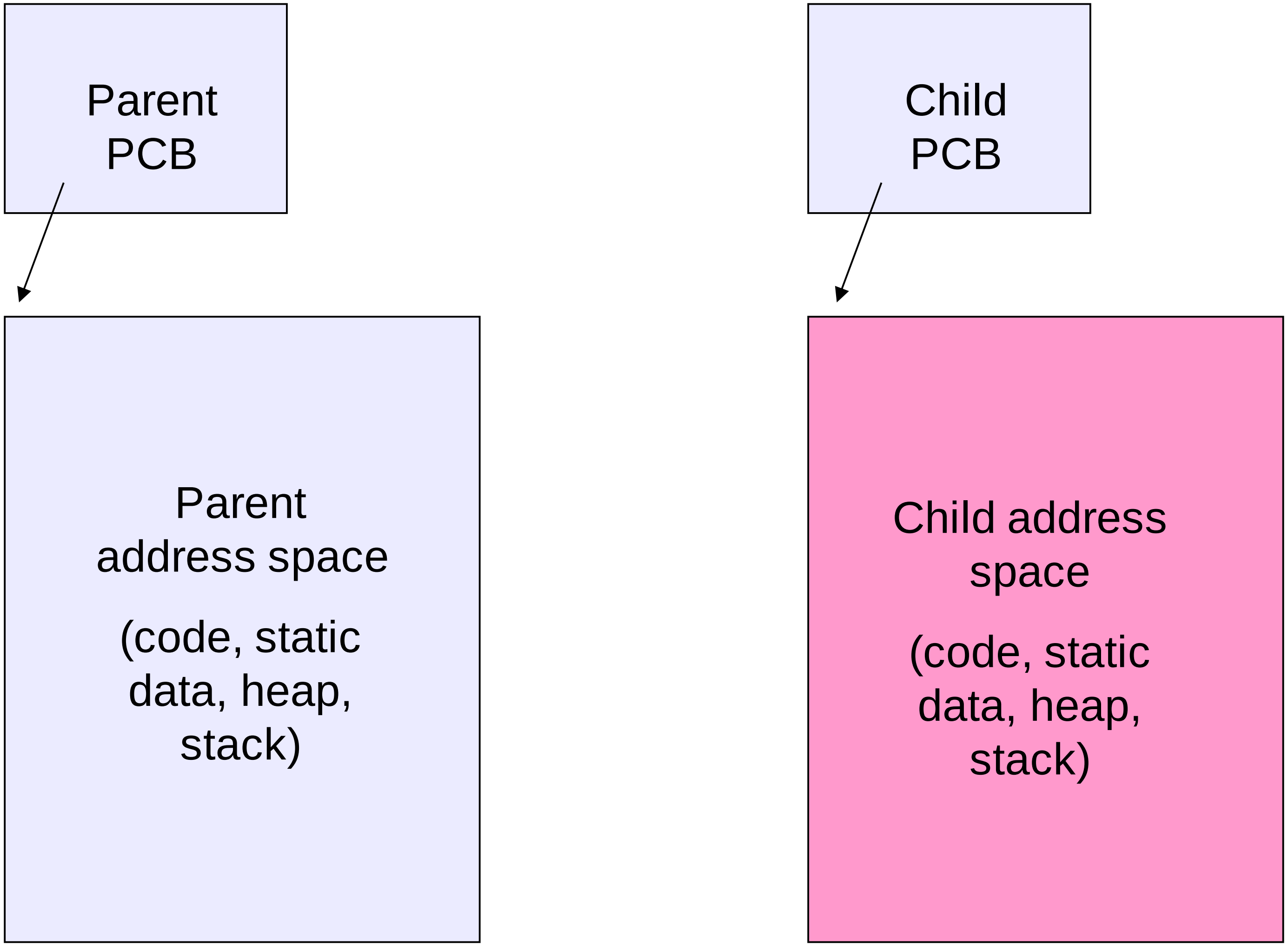
Parent address space

(code, static data, heap, stack)

identical copy (with sole exception of PID argument on the top of the stack)

Child address space

(code, static data, heap, stack)



Parent PCB

Child PCB

Parent address space

(code, static data, heap, stack)

Child address space

(code, static data, heap, stack)

Making process creation faster

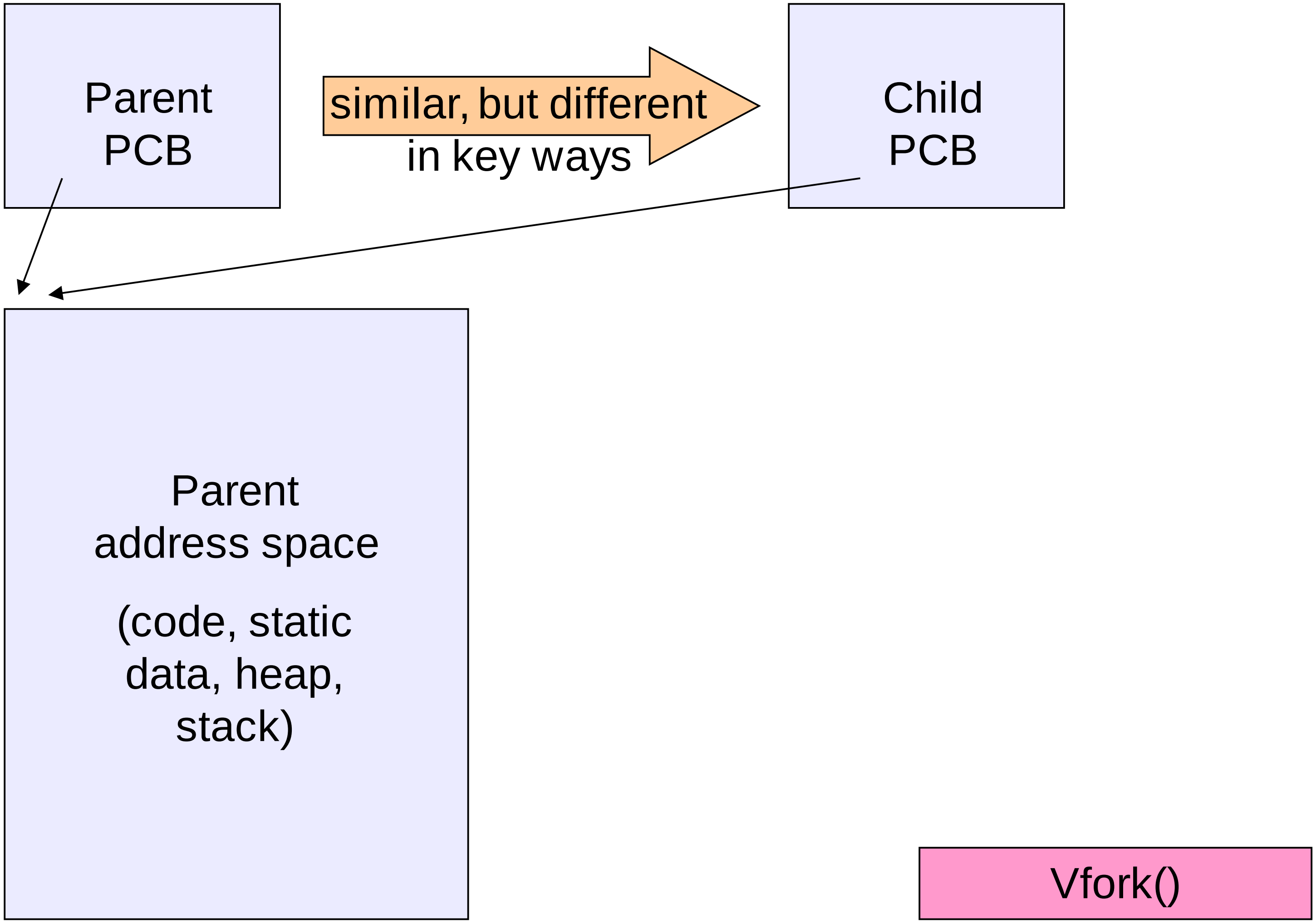
- The semantics of fork() say the child's address space is a copy of the parent's

- Implementing fork() that way is slow
  - Have to allocate physical memory for the new address space
  - Have to set up child's page tables to map new address space
  - Have to copy parent's address space contents into child's address space
    - Which you are likely to immediately blow away with an exec()

Method 1: vfork()

- vfork() is the older (now uncommon) of the two approaches we'll discuss

- Instead of "child's address space is a copy of the parent's," the semantics are "child's address space *is* the parent's"
  - With a "promise" that the child won't modify the address space before doing an execve()
    - Unenforced! You use vfork() at your own peril
  - When execve() is called, a new address space is created and it's loaded with the new executable
  - Parent is blocked until execve() is executed by child
  - Saves wasted effort of duplicating parent's address space, just to blow it away



Parent PCB

similar, but different in key ways

Child PCB

Parent address space

(code, static data, heap, stack)

Vfork()

Method 2: copy-on-write

- Retains the original semantics, but copies "only what is necessary" rather than the entire address space
- On fork():
  - Create a new address space
  - Initialize page tables with same mappings as the parent's (i.e., they both point to the same physical memory)
    - No copying of address space contents have occurred at this point – with the sole exception of the top page of the stack
  - Set both parent and child page tables to make all pages read-only
  - If either parent or child writes to memory, an exception occurs
  - When exception occurs, OS copies the page, adjusts page tables, etc.

Truth in advertising …

- In Linux today, clone is replacing fork (and vfork)
  - clone has additional capabilities/options
- But you need to clearly understand fork as described here
- ./mystrace.sh

Inter-process communication (IPC)

- Processes provide isolation (protection) – great!
- But sometimes you want processes to communicate / cooperate
- How can one process "provide input" to another?
  - command line arguments (argv values)
    - available only to parent process
  - communicate through files
    - one writes and the other reads
  - optimize that: pipes
    - use memory buffers, not files
    - We'll see that this works only if the processes are related (usually siblings)

IPC (cont).

- Additional mechanisms:
  - named pipes
    - like pipes, except that unrelated processes can use them
      - need names…
      - use file system names
    - man 3 mkfifo
  - name shared memory regions
    - shm_open() followed by mmap()
    - “cut out the middle man”
  - **sockets / Internet protocols**
    - robust – prepared to communicate using a heavyweight middle man!
    - optimized when endpoints are on the same machine

IPC: signals

- Processes can register event handlers
  - Feels a lot like event handlers in Java, which ..
  - Feel sort of like catch blocks in Java programs
  - sigaction()
- When the event occurs, process jumps to event handler routine
- Used to catch exceptions
  - signal generated by the OS
  - gives the application a chance to do something other than the default response to the exception
- Also used for inter-process (process-to-process) communication (IPC)
  - signal is generated by another process
  - send signal using kill (man 2 kill)
  - Only argument of the communication is a single int, the signal number

Signals

```
Signal     Value     Action   Comment
---------------------------------------------------------------------
SIGHUP        1       Term    Hangup detected on controlling terminal
                             or death of controlling process
SIGINT        2       Term    Interrupt from keyboard
SIGQUIT       3       Core    Quit from keyboard
SIGILL        4       Core    Illegal Instruction
SIGABRT       6       Core    Abort signal from abort(3)
SIGFPE        8       Core    Floating point exception
SIGKILL       9       Term    Kill signal
SIGSEGV      11       Core    Invalid memory reference
SIGPIPE      13       Term    Broken pipe: write to pipe with no read
SIGALRM      14       Term    Timer signal from alarm(2)
SIGTERM      15       Term    Termination signal
SIGUSR1   30,10,16    Term    User-defined signal 1
SIGUSR2   31,12,17    Term    User-defined signal 2
SIGCHLD   20,17,18    Ign     Child stopped or terminated
SIGCONT   19,18,25            Continue if stopped
SIGSTOP   17,19,23    Stop    Stop process
SIGTSTP   18,20,24    Stop    Stop typed at tty
SIGTTIN   21,21,26    Stop    tty input for background process
SIGTTOU   22,22,27    Stop    tty output for background process
```

Example use

- You're implementing Apache, a web server

- Apache reads a configuration file when it is launched
  - Controls things like what the root directory of the web files is, what permissions there are on pieces of it, etc.

- Suppose you want to change the configuration while Apache is running
  - If you restart the currently running Apache, you drop some unknown number of user connections

- Solution: send the running Apache process a signal
  - It has registered a signal handler that gracefully re-reads the configuration file

Unix Shells

- Shells are just user-level programs
- They're mainly oriented towards launching other programs
  - Using fork() / exec()
- They typically have few "built-in" commands
  - ls, cat, etc. are executables, opaque to the shell
  - (What must be built in?)
- Shells usually offer ways to build "shell scripts"
  - E.g., some looping construct
  - You can view everything you type into a shell as a program that is being simultaneously created and executed

UNIX shells – basic operation

```
int main(int argc, char **argv)
{
  while (1) {
    printf (“$ “);
    char *cmd = get_next_command();
    int pid = fork();
    if (pid == 0) {
       exec(cmd);
       panic(“exec failed!”);
    } else {
       wait(pid);
    }
  }
}
```

Unix Shells: Jobs / Redirection

- Shells usually offer ways to make “jobs” – assemblages of executions
  - ls | grep *.c | less
  - pushd sub && make && popd
  - pushd sub; make; popd

- One way the shell helps you compose jobs is by input-output redirection
  - You can make the output of one program the input of another, without ever writing to a file

Input/output redirection

- $ ./myprog < input.txt > output.txt # UNIX
  - each process has an open file table
  - by (universal) convention:
    - 0: stdin
    - 1: stdout
    - 2: stderr
- A child process inherits the parent's open file table
- Redirection: the shell …
  - copies its current stdin/stdout open file entries
  - opens input.txt as stdin and output.txt as stdout
  - fork …
  - restore original stdin/stdout

Linux Job Control

- A “job” is an assemblage of processes
  - $ cat main.c
  - $ cat main.c | grep –w total | less

- Key concepts:
  - Controlling terminal
    - Follow parent PIDs up to “the top”
    - What is that processes stdin/stdout/stderr connected to?
    - Why does it matter?

  - Session
    - A way to group things that should be terminated if the controlling terminal goes away
    - “Session leader” – process that created the session
    - Sessions are named by integers
      - Use PID of the session leader
    - A forked process inherits the session of its parent
    - A process can set its own session id (setsid)
      - Unless it’s a “process group leader”

Linux Job Control

- Process Group
  - $ myprog | myotherprog | grep B
  - A process inherits the process group of its parent
  - A process can set its process group (setpgid)
  - The “process group leader” is the process that created the group
  - The process group’s name is an integer
    - The PID of the creating process
- Why have process groups?
  - Ctrl-C sends a SIGINT
  - A signal can be sent to a process group
    - Sent to each process in the group

“Demo”

- ./myps.sh