Processes

CS 3113

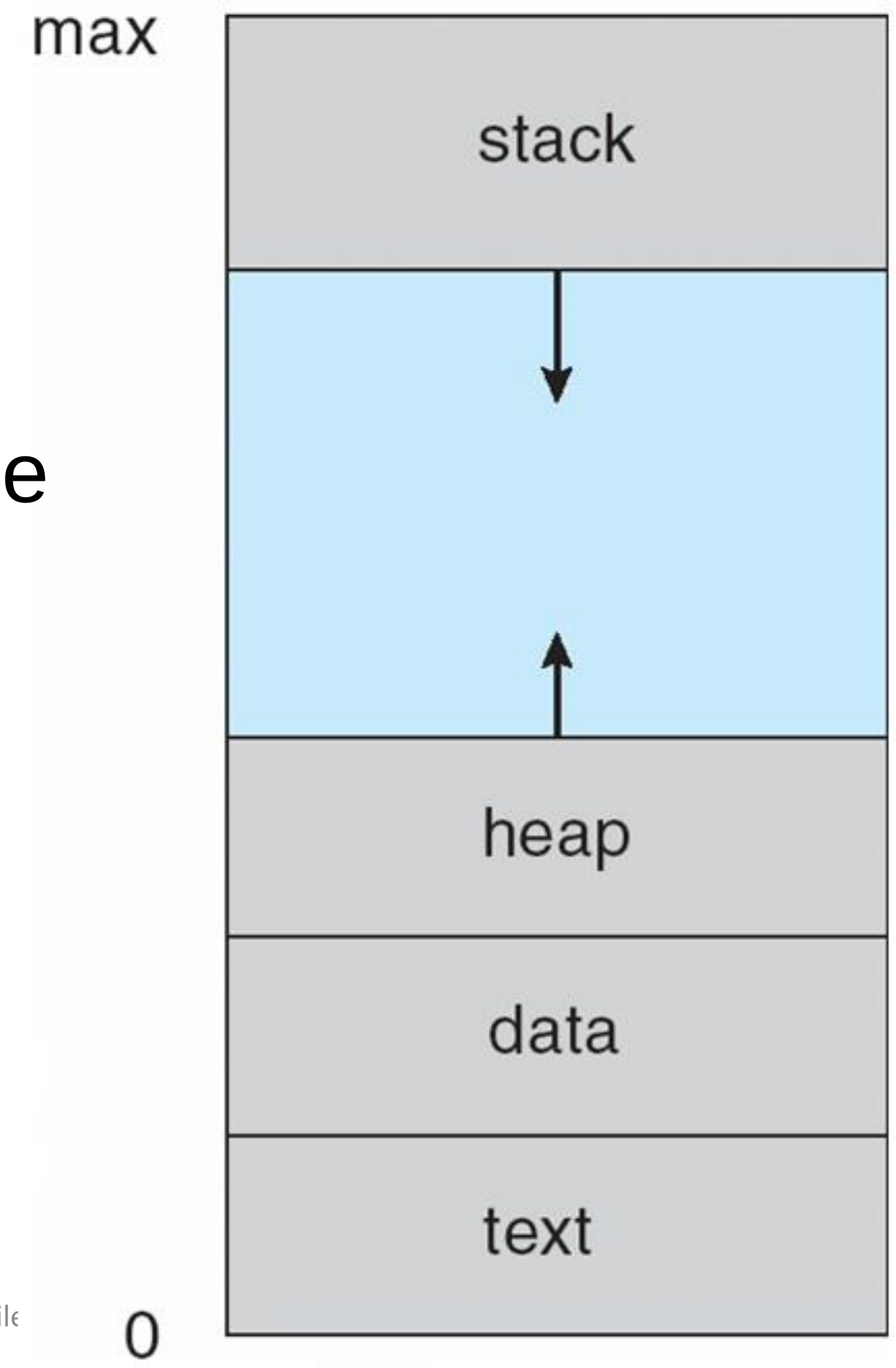
Processes

- Program is ***passive*** entity stored on disk (**executable file**), process is ***active***
  - Program becomes process when executable file loaded into memory
- Execution of program started via GUI mouse clicks, command line entry of its name, etc
- One program can be several processes
  - Consider multiple users executing the same program

Processes and Memory

On process creation, the process is effectively given its own memory space

- Text: storage of code
- Data: global variables (preallocated space)
- Heap: dynamically allocated space
- Stack: local variable storage



Stack and Heap

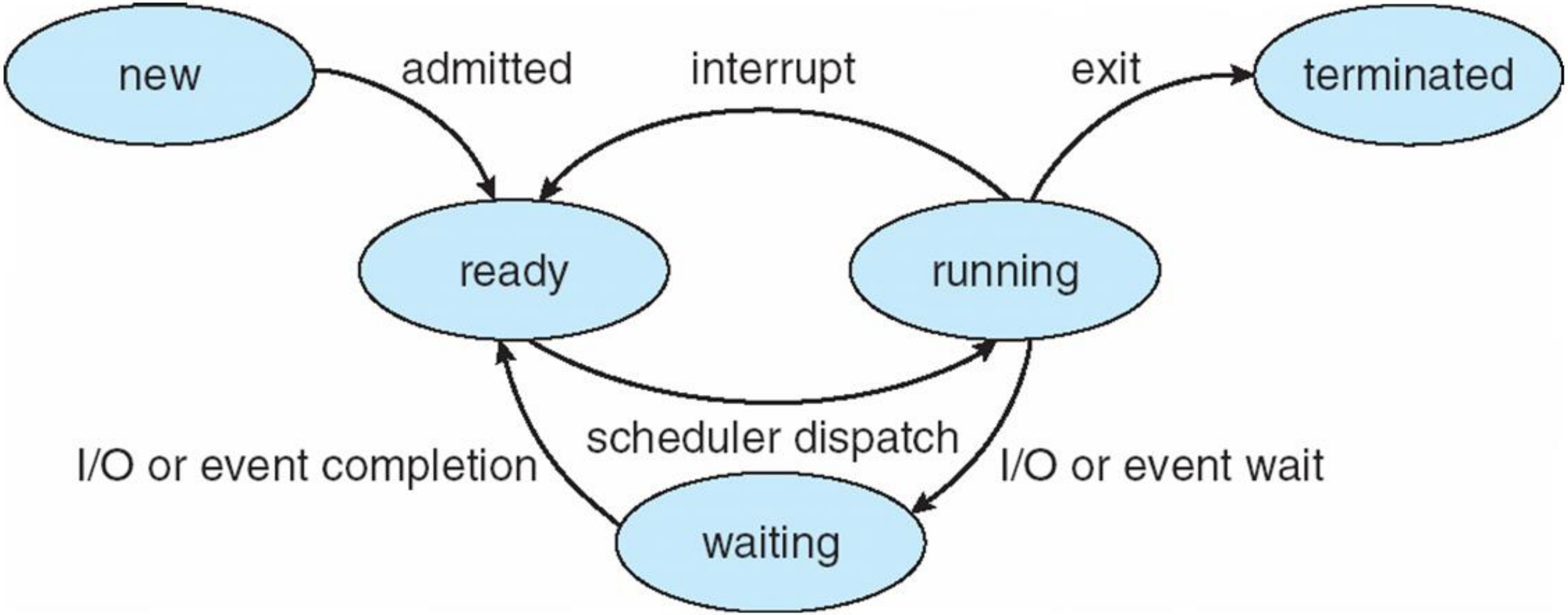
- Stack grows downward with each nested function call
  - Local variables, register state, return memory address
- Heap
  - Storage of dynamically allocated items that must be persistent across function calls (and returns from function calls)
  - OOP languages: object instantiation is done in the heap

Process State

A process is in exactly one state at any instant in time:

- **new**: The process is being created
- **running**: Instructions are being executed by the CPU
- **waiting**: The process is waiting for some event to occur
- **ready**: The process is waiting to be assigned to a processor
- **terminated**: The process has finished execution

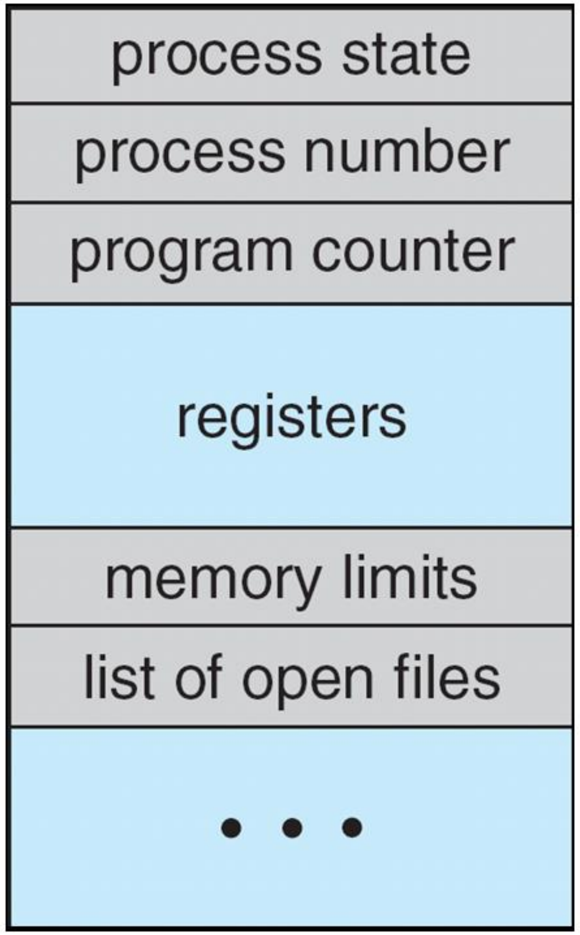
Process State



Kernel Data Structure: Process Control Block

Stores information about the running process:

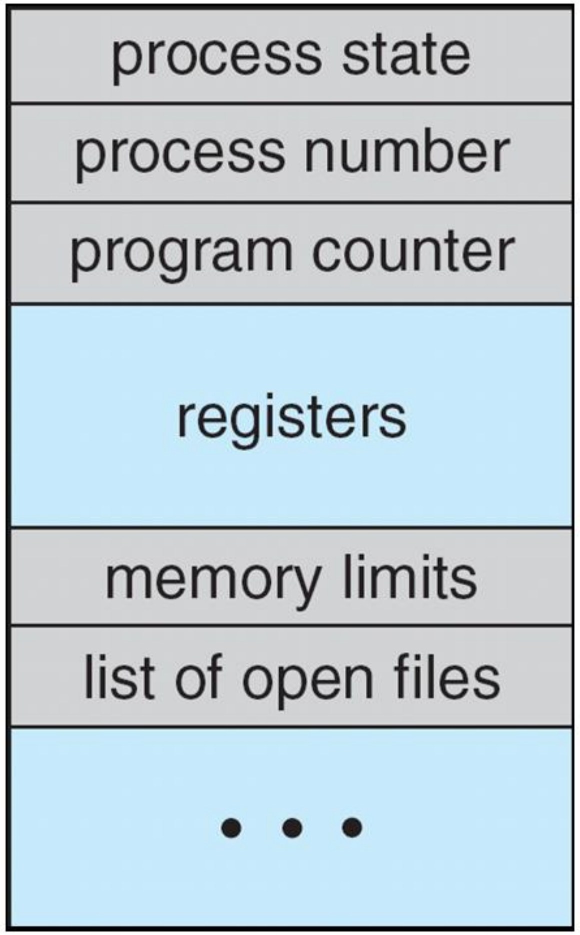
- Process state – running, waiting, etc
- *Program counter – location of instruction to next execute
- *CPU registers – contents of all process-centric registers
- CPU scheduling information- priorities, scheduling queue pointers



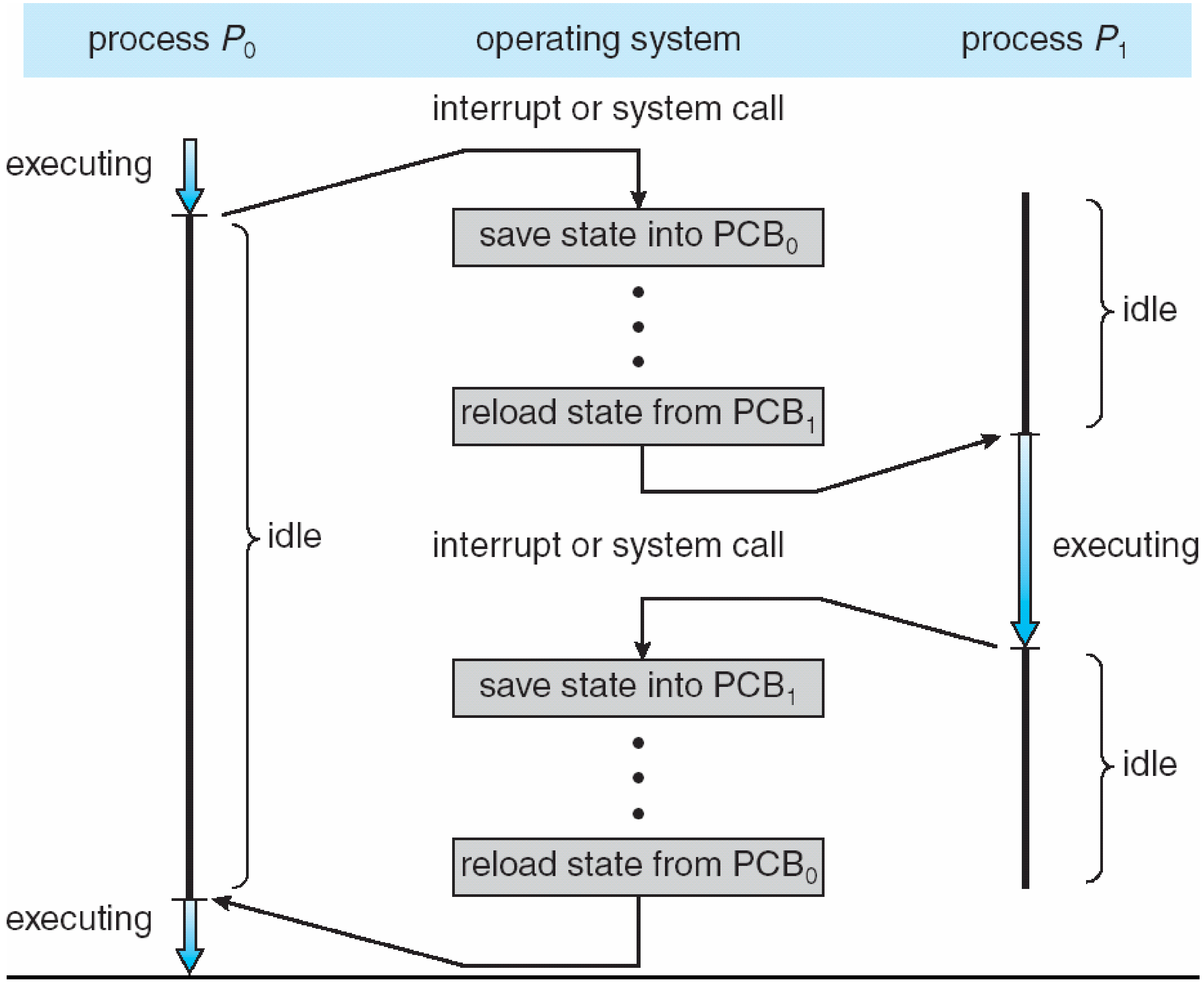
Kernel Data Structure: Process Control Block

continued:

- Memory-management information – memory allocated to the process
- Accounting information – CPU used, clock time elapsed since start, time limits
- I/O status information – I/O devices allocated to process, list of open files



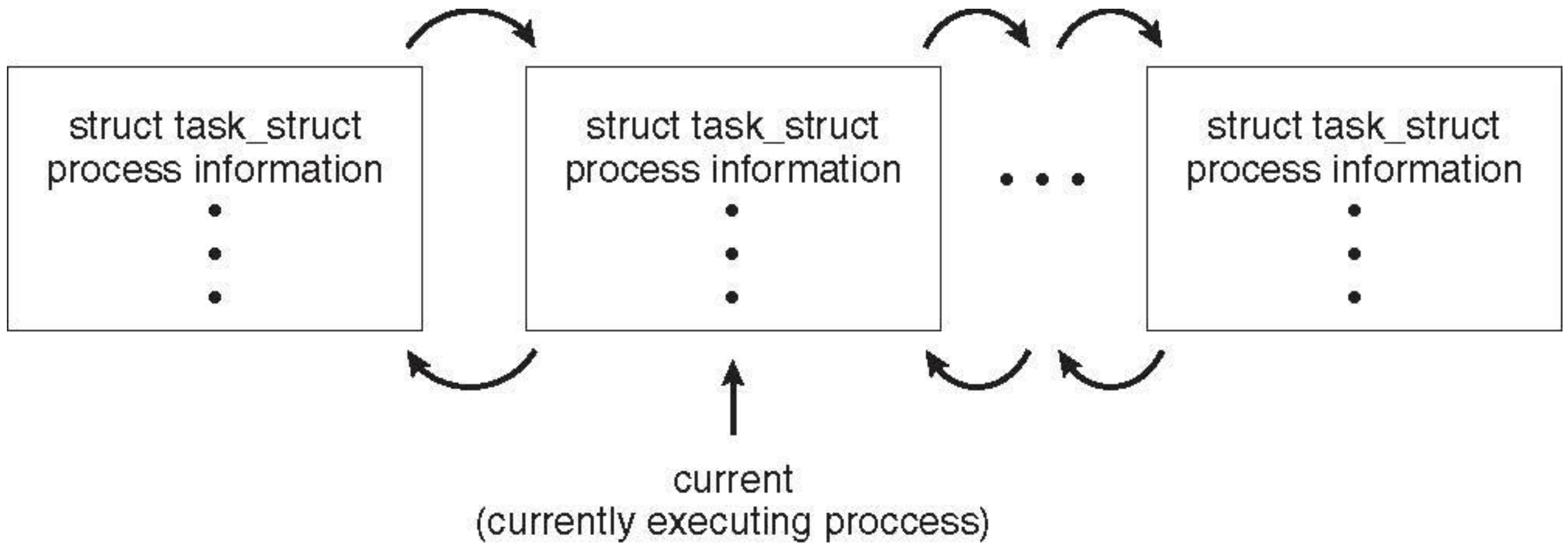
CPU Switching from One Process to Another



Process Representation in Linux

Represented by the C structure `task_struct`

```
pid t_pid; /* process identifier */
long state; /* state of the process */
unsigned int time_slice /* scheduling information */
struct task_struct *parent; /* this process's parent */
struct list_head children; /* this process's children */
struct files_struct *files; /* list of open files */
struct mm_struct *mm; /* address space of this process */
```



Process Scheduling

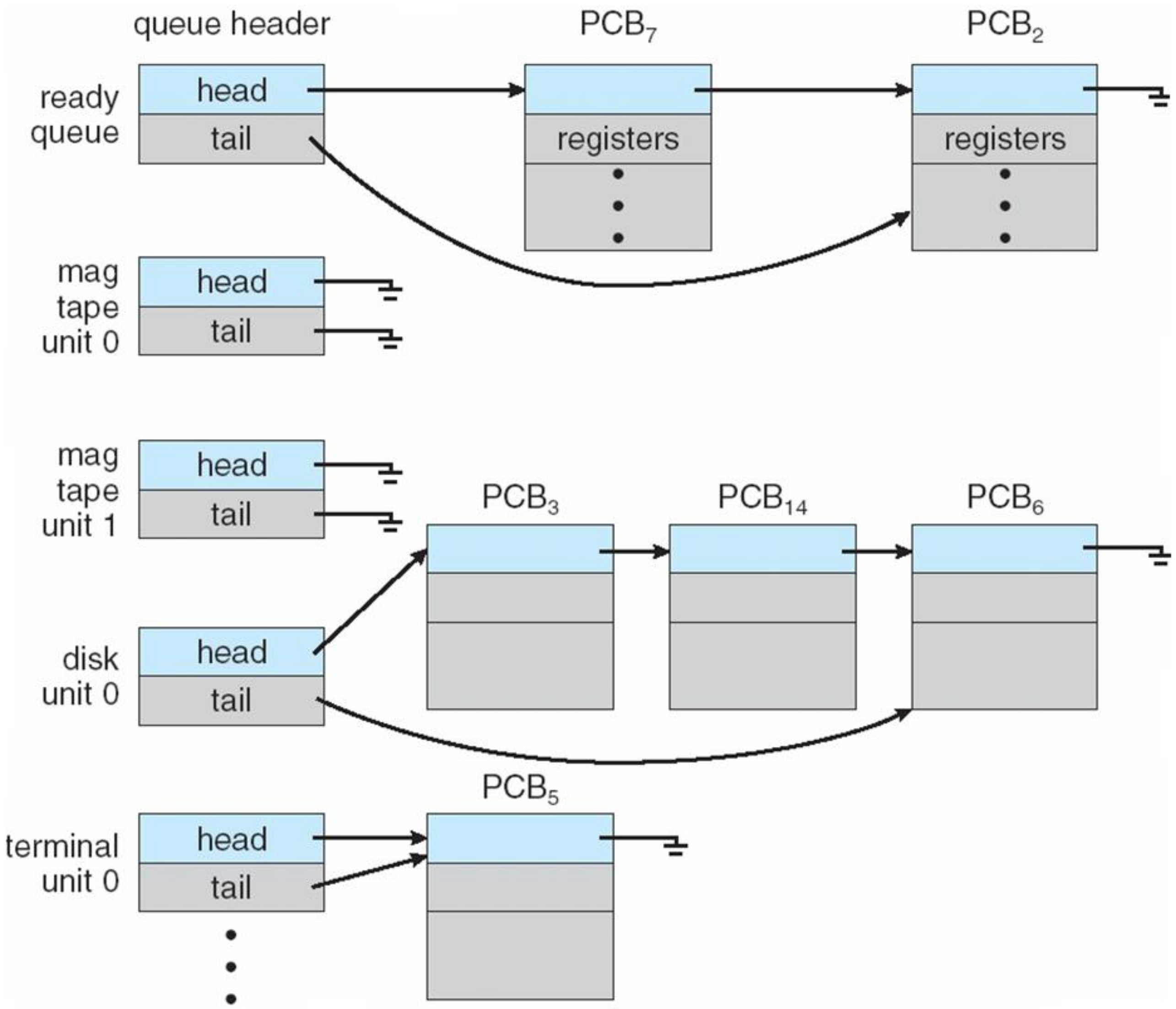
- Our goals are to:
  - Maximize CPU use
  - Give processes the CPU time that they need
- **Process scheduler** selects among available processes for next execution on CPU

Process Scheduler

Maintains **scheduling queues** of processes

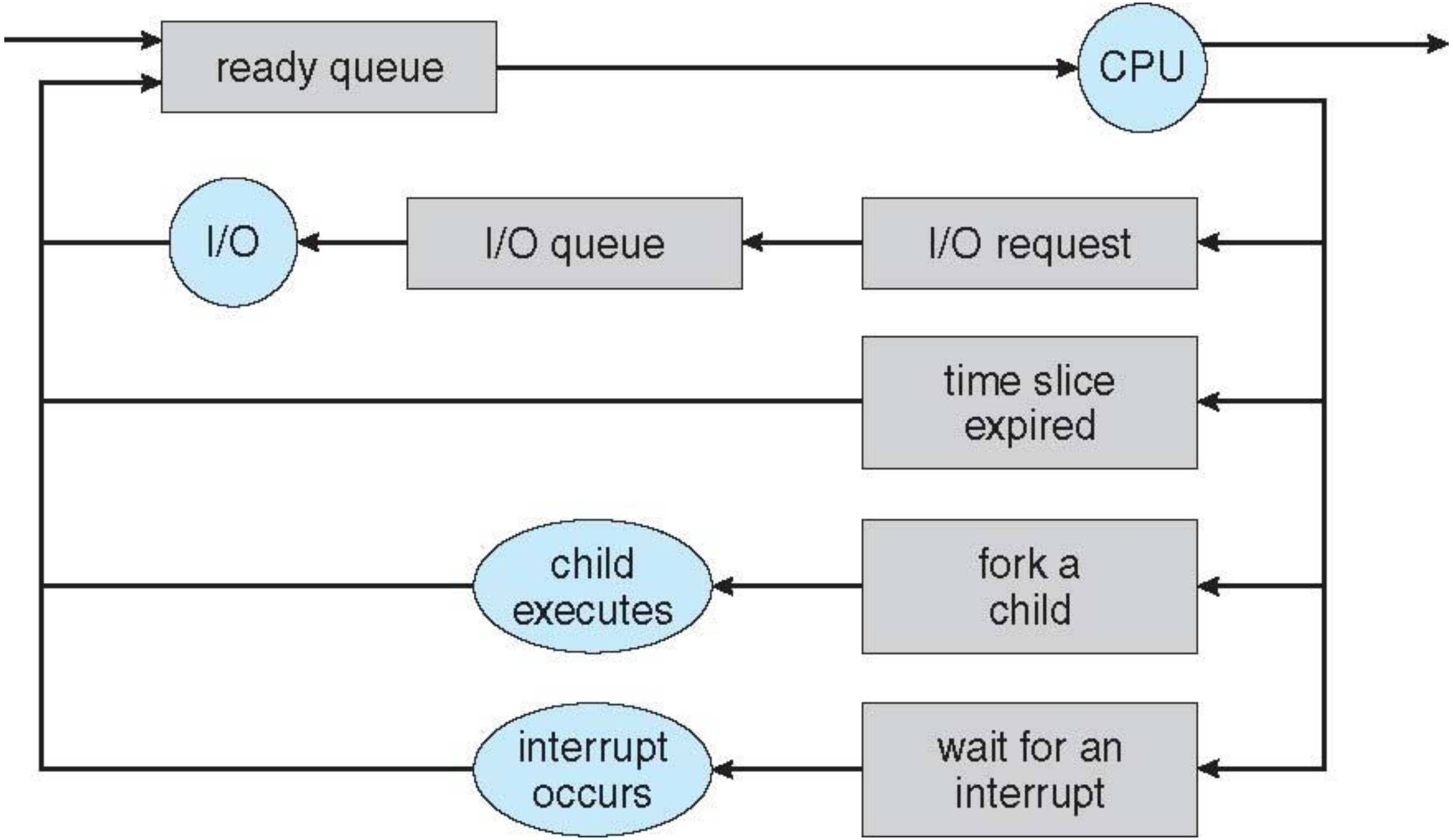
- **Job queue:** set of all processes in the system
- **Ready queue:** set of all processes residing in main memory, ready and waiting to execute
- **Device queues:** set of processes waiting for an I/O device
- Processes migrate among the various queues, depending (in part) on their state

Ready Queue And Various I/O Device Queues



Process Scheduling

Queueing diagram represents queues, resources, flows



Scheduler Components

Short-term scheduler (or CPU scheduler) – selects which process should be executed next and allocates CPU

- Sometimes the only scheduler in a system
- Short-term scheduler is invoked frequently (milliseconds), so it must be fast

Scheduler Components

Long-term scheduler (or job scheduler) – selects which processes should be brought into the ready queue

- Long-term scheduler is invoked infrequently (seconds, minutes), so it may respond slowly
- The long-term scheduler controls the degree of multiprogramming
- Most important in (older) resource-bound systems

Scheduler Components

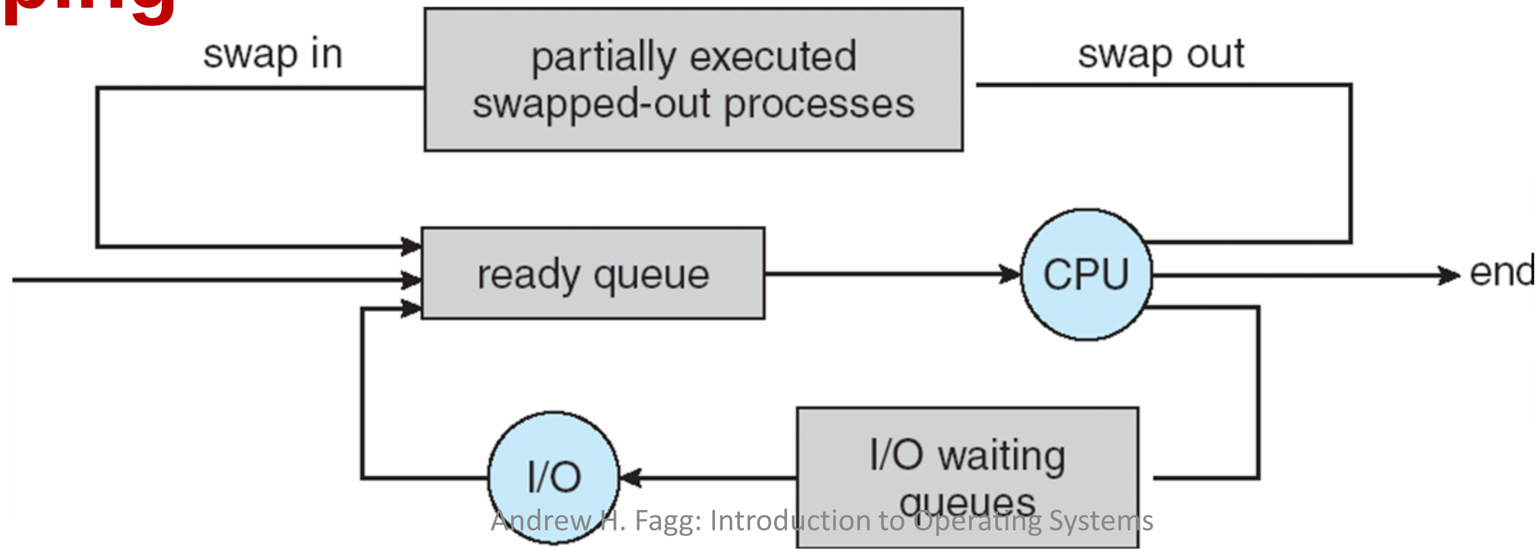
Processes can be described as either:

- **I/O-bound**: spends more time doing I/O than computations, many short CPU bursts
- **CPU-bound**: spends more time doing computations; few very long CPU bursts
- Long-term scheduler strives for good process mix
  - Goal: keep both I/O and CPU resources as busy as possible

Medium Term Scheduling

Medium-term scheduler can be added if degree of multiple programming needs to decrease

- Remove process temporarily from memory, store on disk, bring back in from disk to continue execution: **swapping**



Multitasking in Mobile Systems

- Some mobile systems (e.g., early version of iOS) allow only one process to run; others are suspended
- Due to screen real estate and user interface limits, iOS provides for:
  - Single foreground process: controlled via user interface
  - Multiple background processes: in memory, running, but not on the display, and with limits
  - Limits include single, short task, receiving notification of events, specific long-running tasks like audio playback
- Android runs foreground and background processes, with fewer limits

Context Switching

- When CPU switches to another process, the system must save the state of the old process and load the saved state for the new process via a context switch
- **Context** of a process represented in the PCB
- Context-switch time is overhead; the system does no useful work while switching
  - The more complex the OS and the PCB, the longer the context switch
  - Time is dependent on hardware support
  - Some hardware provides multiple sets of registers per CPU
    - Allows multiple contexts to be loaded at once

Operations on Processes

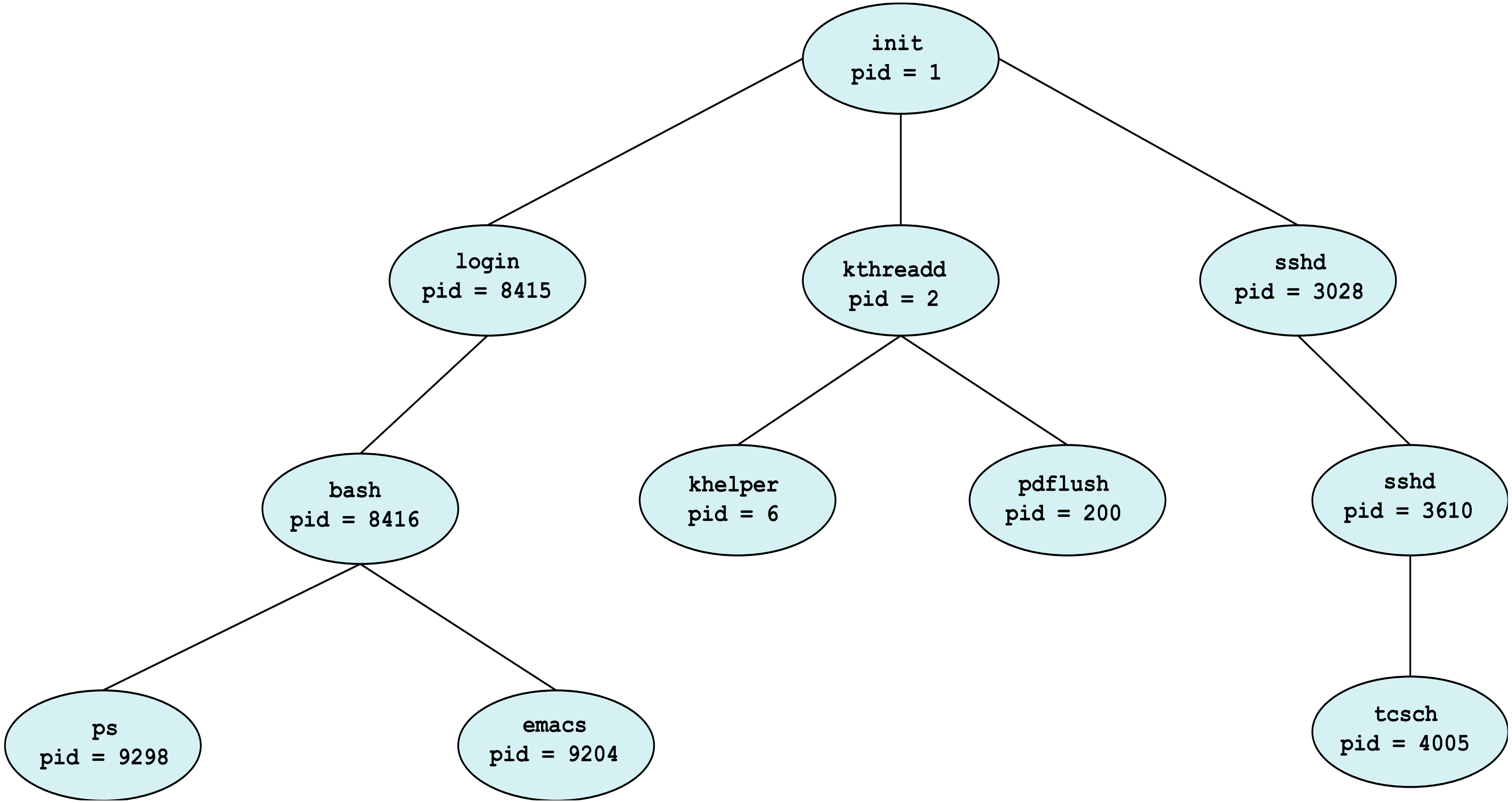
Process Creation

- **Parent** process creates **child** processes, which, in turn create other processes, forming a **tree** of processes
- Generally, process identified and managed via a **process identifier** (**pid**)

Process Creation

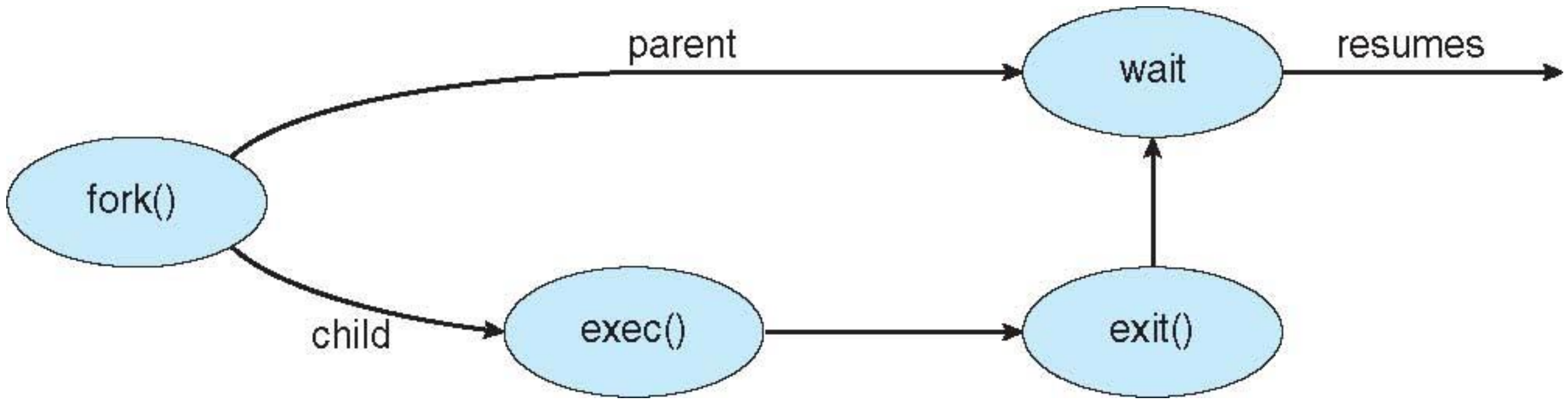
- Resource sharing options
  - Parent and children share all resources
  - Children share subset of parent’s resources
  - Parent and child share no resources
- Execution options
  - Parent and children execute concurrently
  - Parent waits until children terminate

Process Tree



Process Creation (Cont.)

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

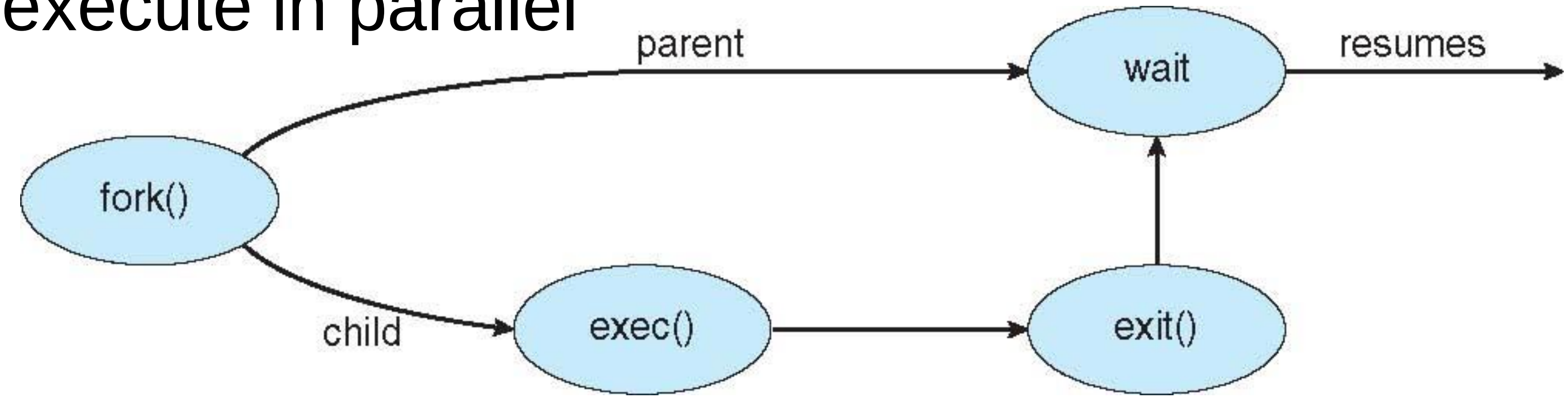


fork live demo

fork()

fork() creates an identical process to the one that called fork()

- Same program
- Same state, including open file descriptors
- Exception: fork() returns 0 to the child; and a positive integer to the parent
- Processes execute in parallel



C Program Forking a Child Process

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

int main()
{
pid_t pid;

    /* fork a child process */
    pid = fork();

    if (pid < 0) { /* error occurred */
      fprintf(stderr, "Fork Failed");
      return 1;
    }
    else if (pid == 0) { /* child process */
      execlp("/bin/ls","ls",NULL);
    }
    else { /* parent process */
      /* parent will wait for the child to complete */
      wait(NULL);
      printf("Child Complete");
    }

    return 0;
}
```

Live execlp() demo

execlp

```
execlp(char *command, char *argv0, char *argv1, … NULL)
```

- Replaces the currently executing program with a new program & begins execution
- command is a string that references an executable file
  - Can be absolute or relative path
  - Relative path: use the **path** environment variable to find the executable
- argv0, argv1, … are arguments to be passed to the executable
  - Don’t forget the NULL at the end!

execlp

```
execlp(char *command, char *argv0, char *argv1, … NULL)
```

- If this function is successful in finding the specified executable, it does not return!

system()

`system(char *command)`

- Command specifies the executable and arguments in one string
- Relative path: looks up the executable in the path environment variable
- First calls fork(), then execlp()
- Always returns
  - Return value is the exit code from the specified command

Live system() demonstration

Process Termination

Process executes last statement and then asks the operating system to delete it using the exit() system call.

- exit(-1): -1 is the exit code returned by the process
- Status data from child can be passed to the parent
  - `pid = wait(&status);`
  - status contains information about the reason for termination
- Process' resources are deallocated by operating system

Process Termination

Some operating systems do not allow child processes to exist if its parent has terminated (including Linux). If a process terminates, then all its children must also be terminated.

- If parent is executing, but not waiting (did not invoke `wait()`) and the child process ends, then the child process is a **zombie**
- If parent terminated without invoking `wait`(), the child process is an **orphan**
  - Orphans become children of the **init** process

Cooperating Processes

- ***Independent*** process cannot affect or be affected by the execution of another process
- ***Cooperating*** process can affect or be affected by the execution of another process
- Advantages of process cooperation
  - Information sharing
  - Computation speed-up
  - Modularity
  - Convenience

Multiprocess Architecture – Chrome Browser

Many web browsers used to run as single process (some still do)

- If one web site causes trouble, the entire browser can hang or crash

Multiprocess Architecture – Chrome Browser

Google Chrome Browser is multiprocess with 3 different types of processes:

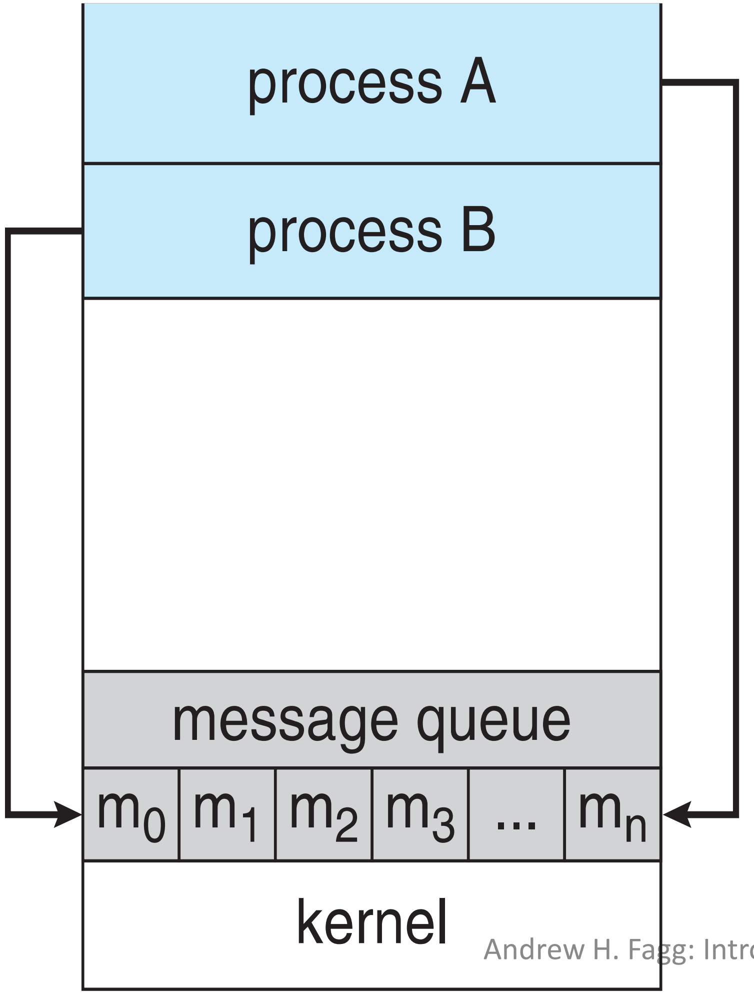
- **Browser** process manages user interface, disk and network I/O
- **Renderer** process renders web pages, deals with HTML, Javascript. A new renderer created for each website opened
  - Runs in **sandbox** restricting disk and network I/O, minimizing effect of security exploits
- **Plug-in** process for each type of plug-in

Interprocess Communication

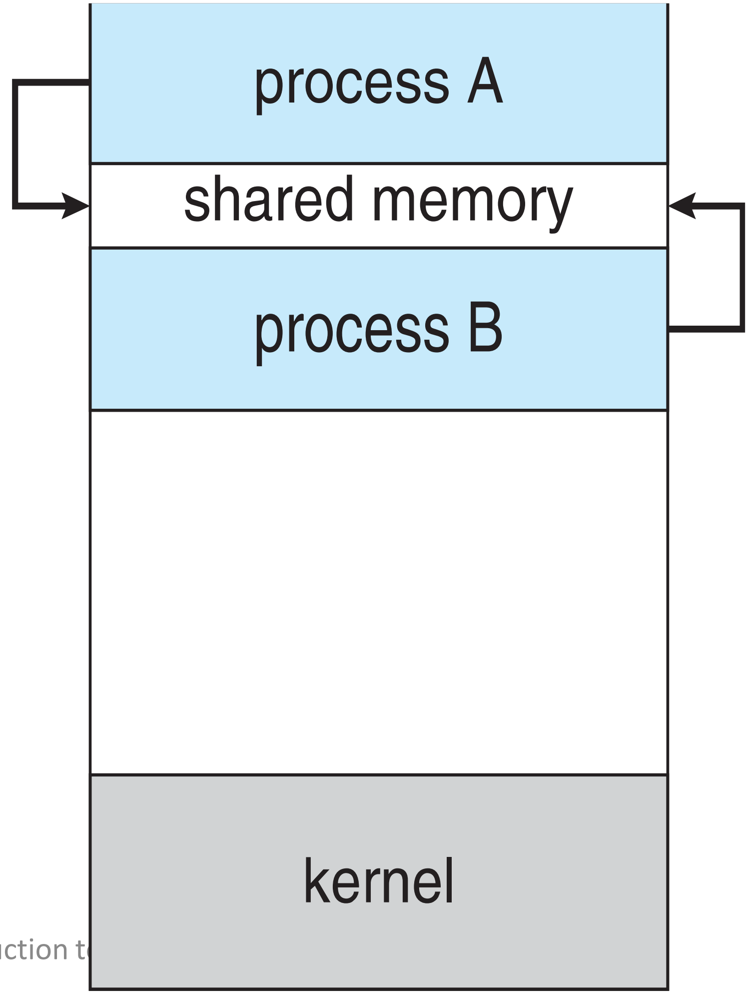
- Cooperating processes need **interprocess communication** (**IPC**)
- Two models of IPC
  - **Shared memory**
  - **Message passing**

Communication Models

Message Passing



Shared Memory



Producer-Consumer Problem

- Producer: process generates data through some mechanism
- Consumer: process uses data generated by another

Producer-Consumer Problem

Typical approach: implement a data buffer from the producer to the consumer

- **unbounded-buffer** places no practical limit on the size of the buffer
- **bounded-buffer** assumes that there is a fixed buffer size

Circular/Shared Buffer of Items

- Items are instances of type **item**

```
#define BUFFER_SIZE 10
typedef struct {
  . . .
} item;

item buffer[BUFFER_SIZE];
int in = 0;
int out = 0;
```

- in = the next location to place a new item
- out = the next location to remove an item from
- Both the producer and consumer processes have access to this buffer

Circular/Shared Buffer of Items

- in == out: no items in the buffer
- (in+1)%BUFFER_SIZE = out: buffer is full

Circular Buffer: Producer

```
item next_produced;
while (true) {
    // Generate new item
    next_produced = …

    // Wait for there to be space in the buffer
    while (((in + 1) % BUFFER_SIZE) == out)
        ; /* do nothing */

    // Place item in the buffer
    buffer[in] = next_produced;
    in = (in + 1) % BUFFER_SIZE;
}
```

Circular Buffer: Consumer

```
item next_consumed;
while (true) {
    // Wait for item to be available
    while (in == out)
        ; /* do nothing */

    // Get the next item
    next_consumed = buffer[out];
    out = (out + 1) % BUFFER_SIZE;

    // Do something with the item
}
```

Shared Memory

- Shared memory: an area of memory shared among the processes that wish to communicate
- The communication is entirely under the control of the users processes & not the operating system
  - Good for efficiency (no system calls to update memory)
  - Lots of opportunities for bugs
- Major issues is to provide mechanism that will allow the user processes to synchronize their actions when they access the shared memory

Interprocess Communication: Message Passing

Mechanism for processes to communicate and to synchronize their actions

- Message system: processes communicate with each other without resorting to shared variables
- IPC facility provides two generic operations:
  - send(message)
  - receive(message)
- The message size can be either fixed or variable

Message Passing

- If processes *P* and *Q* wish to communicate, they need to:
  - Establish a ***communication link*** between them
  - Exchange messages via send/receive
- Implementation issues:
  - How are links established?
  - Can a link be associated with more than two processes?
  - How many links can there be between every pair of communicating processes?
  - What is the capacity of a link? (buffer)
  - Is the size of a message that the link can accommodate fixed or variable?
  - Is a link unidirectional or bi-directional?

Message Passing

Implementation of a communication link

- Physical choices:
  - Shared memory
  - Hardware bus
  - Network
- Logical choices:
  - Direct or indirect
  - Synchronous or asynchronous
  - Automatic or explicit buffering

Synchronization

- Message passing may be either blocking or non-blocking
- Blocking is considered synchronous
    - Blocking send: the sender is blocked until the message is received
    - Blocking receive: the receiver is blocked until a message is available

Synchronization

- Non-blocking is considered asynchronous
  - Non-blocking send: the sender sends the message and continues
    - The message is placed into a temporary buffer
  - Non-blocking receive: the receiver receives:
    - A valid message, or
    - Null message (nothing to receive)
- Different combinations possible
  - If both send and receive are blocking, we have a **rendezvous**

Synchronization with Rendezvous

Producer-consumer becomes trivial

```
message next_produced;
while (true) {
      /* produce an item in next produced */
      send(next_produced);
}
```

```
message next_consumed;
while (true) {
   receive(next_consumed);

   /* consume the item in next consumed */
}
```

Buffering

- Queue of messages attached to the link
- Implemented in one of three ways:
  - Zero capacity: no messages are queued on a link.
    Sender must wait for receiver (rendezvous)
  - Bounded capacity: finite length of n messages
    Sender must wait if link full
    - This is our circular buffer example!
  - Unbounded capacity: infinite length
    Sender never waits

Shared Memory in POSIX (includes Linux)

- Process first creates shared memory segment (or opens an existing one):

```
shm_fd = shm_open(name, O CREAT | O RDWR, 0666);
```

- Set the size of the object:

```
ftruncate(shm_fd, 4096);
```

- Create a pointer to the shared memory:

```
shared_memory = mmap(shm_fd, 0, 4096 PROT_WRITE,
                      MAP_SHARED, shm_fd, 0);
```

- Now the process can write to the shared memory

```
sprintf(shared_memory, "Writing to shared memory");
```

Shared Memory Producer

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <fcntl.h>
#include <sys/shm.h>
#include <sys/stat.h>

int main()
{
/* the size (in bytes) of shared memory object */
const int SIZE = 4096;
/* name of the shared memory object */
const char *name = "OS";
/* strings written to shared memory */
const char *message_0 = "Hello";
const char *message_1 = "World!";

/* shared memory file descriptor */
int shm_fd;
/* pointer to shared memory obect */
void *ptr;

   /* create the shared memory object */
   shm_fd = shm_open(name, O_CREAT | O_RDWR, 0666);

   /* configure the size of the shared memory object */
   ftruncate(shm_fd, SIZE);

   /* memory map the shared memory object */
   ptr = mmap(0, SIZE, PROT_WRITE, MAP_SHARED, shm_fd, 0);

   /* write to the shared memory object */
   sprintf(ptr,"%s",message_0);
   ptr += strlen(message_0);
   sprintf(ptr,"%s",message_1);
   ptr += strlen(message_1);

   return 0;
}
```

Shared Memory Consumer

```
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <sys/shm.h>
#include <sys/stat.h>

int main()
{
/* the size (in bytes) of shared memory object */
const int SIZE = 4096;
/* name of the shared memory object */
const char *name = "OS";
/* shared memory file descriptor */
int shm_fd;
/* pointer to shared memory obect */
void *ptr;

   /* open the shared memory object */
   shm_fd = shm_open(name, O_RDONLY, 0666);

   /* memory map the shared memory object */
   ptr = mmap(0, SIZE, PROT_READ, MAP_SHARED, shm_fd, 0);

   /* read from the shared memory object */
   printf("%s",(char *)ptr);

   /* remove the shared memory object */
   shm_unlink(name);

   return 0;
}
```

Client-Server Model of Communication

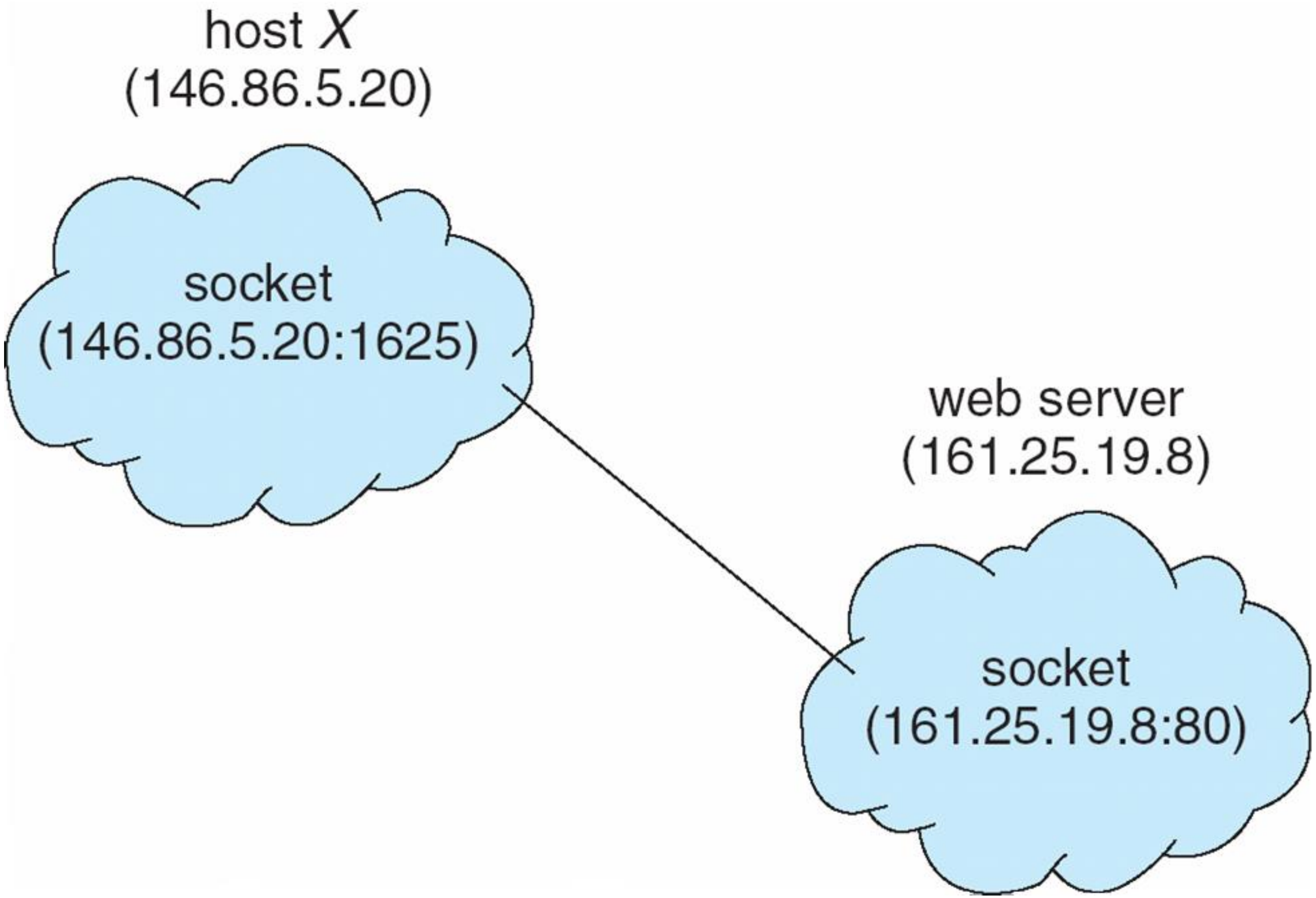
- Built on top of Producer/Consumer concept
- Server: provides some service (data, computation)
- Client: requests actions on the part of the server
- Implementation choices include:
  - Sockets
  - Pipes
  - Remote Procedure Calls
  - Remote Method Invocation (Java)

Sockets

A socket is defined as an endpoint for communication

- Identified by a concatenation of IP address and port: a number included at start of message packet to differentiate network services on a host
- The socket 161.25.19.8:1625 refers to port 1625 on host 161.25.19.8
- All communication is done between a pair of sockets (one for client; the other for server)
- All ports below 1024 are well known and are used for standard services
- Special IP address 127.0.0.1 (loopback) to refer to system on which process is running

Socket Communication



Remote Procedure Calls

- From the programmer’s perspective, they appear as functions/methods that take arguments and return a value
- Under the hood, this function call:
  - Contacts a server
  - Sends the arguments to the server
  - Server does the work and sends the result back
  - Return the return value back to the client

Pipes

- Act as a conduit allowing two processes on the same computer to communicate
- Issues:
  - Is communication unidirectional or bidirectional?
  - In the case of two-way communication, is it half or full-duplex?
  - Must there exist a relationship (i.e., parent-child) between the communicating processes?
  - Can the pipes be used over a network?

Pipes

- Ordinary pipes: cannot be accessed from outside the process that created it.
  - Typically, a parent process creates a pipe and uses it to communicate with a child process that it created.
- Named pipes: can be accessed without a parent-child relationship.

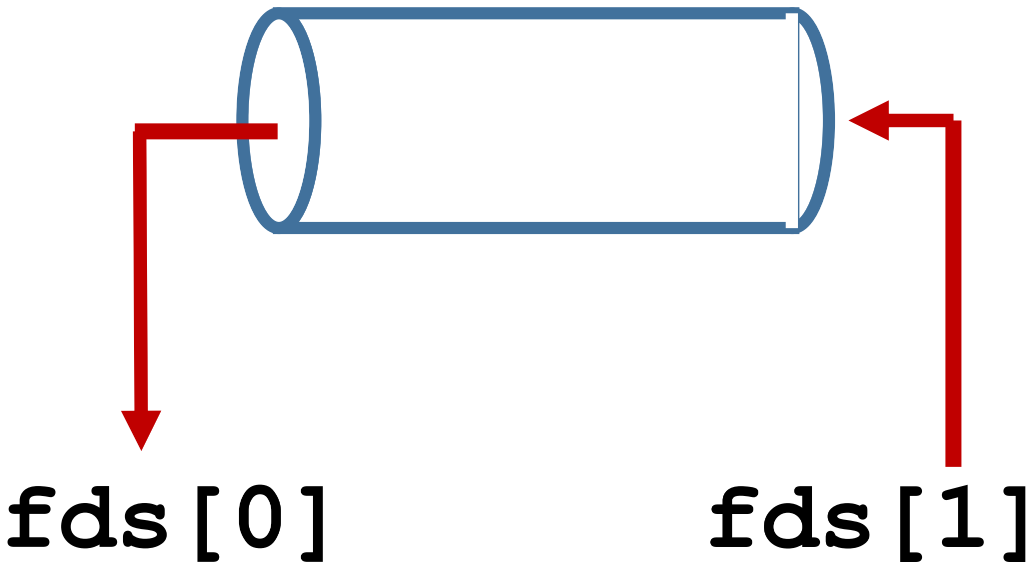
Ordinary Pipes

Ordinary Pipes allow communication in standard producer-consumer style

- Producer writes to one end (the write-end of the pipe)
- Consumer reads from the other end (the read-end of the pipe)
- Ordinary pipes are therefore unidirectional

Ordinary Pipe

```
int fds[2];
int ret = pipe(fds);
if(ret < 0) exit(-1);
// Now use the pipe
```



- fds[0]: output from pipe
- fds[1]: input to pipe

Ordinary Pipes for Communication

- The pipe is implemented inside the kernel (so, it does not exist within the process)
- However, the process maintains this pair of file descriptors, which allow it to reference the pipe

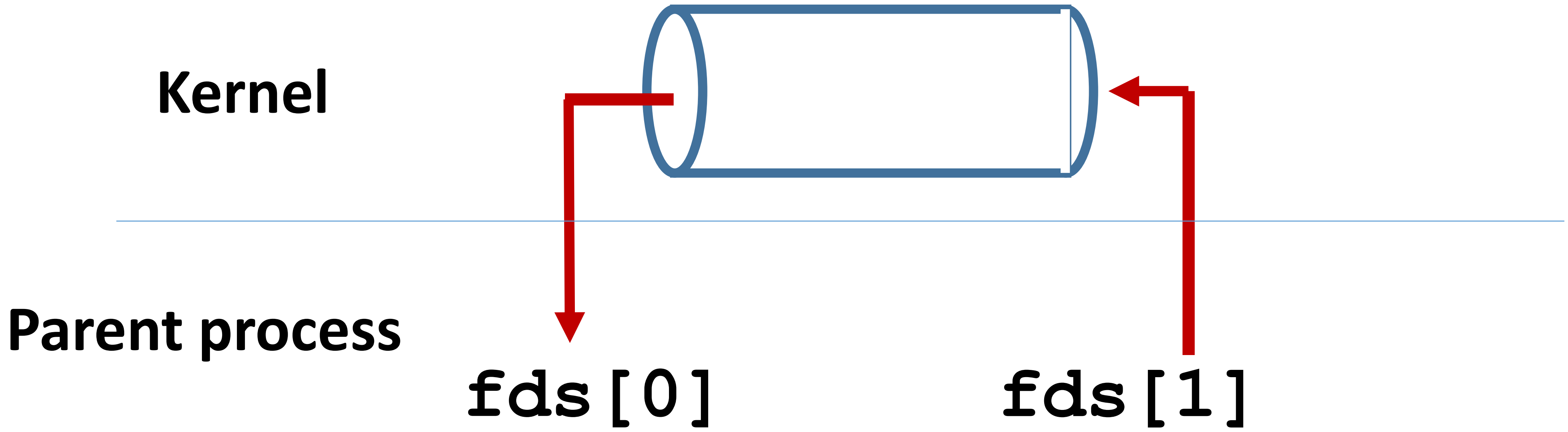
Ordinary Pipes for Communication

- The file descriptors cannot be shared outside of the process
- But: if the process forks(), then both the parent and child will have copies of the file descriptors!
  - And these reference the same pipe

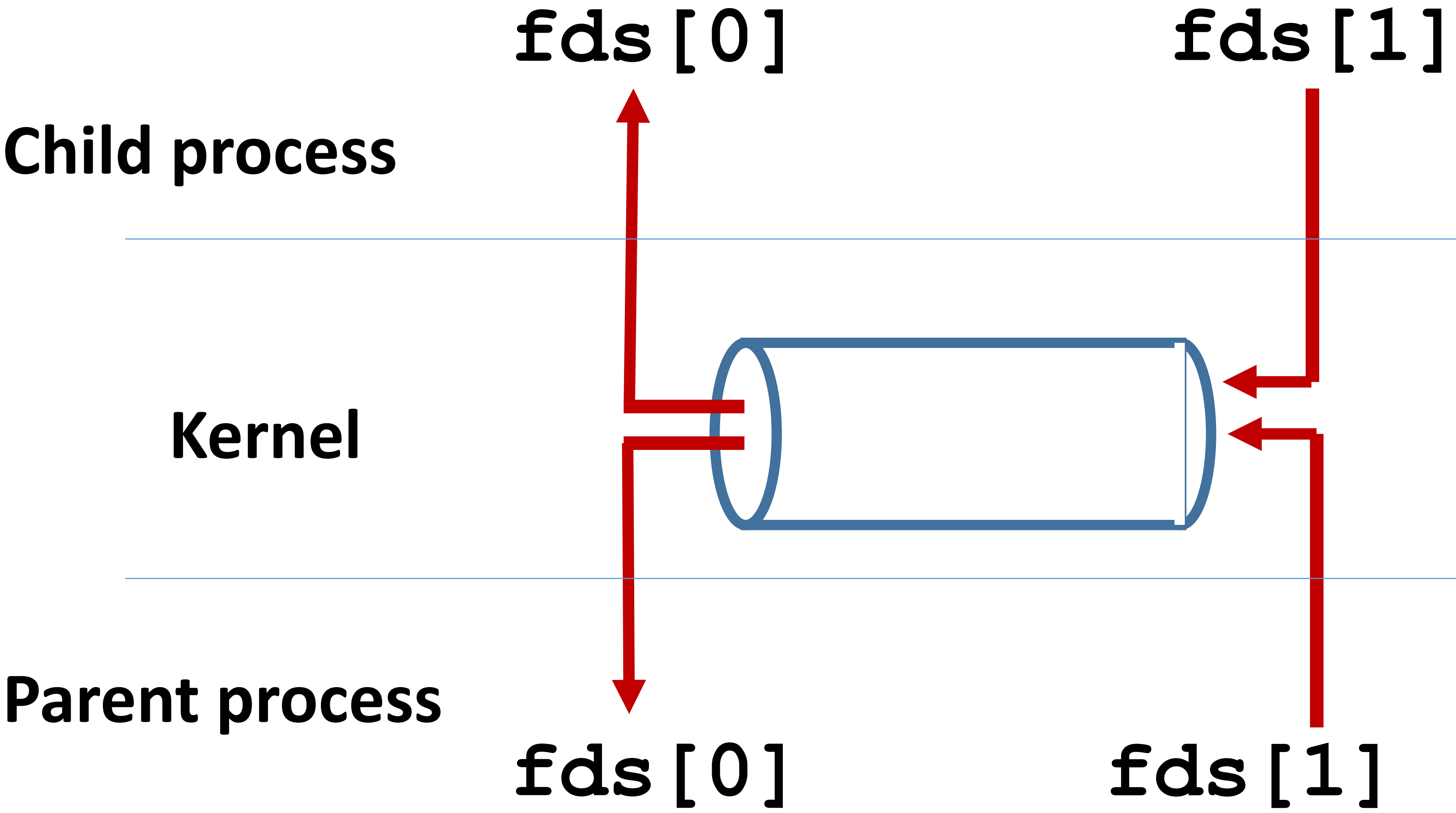
Ordinary Pipe with Fork()

```
int fds[2];
int ret = pipe(fds);
if(ret < 0) exit(-1);
// Now use the pipe
int pid = fork()
if(pid > 0) {          // Note: leaving off error case
    // parent code
}else {
    // child code
}
```

Before Fork



After Fork

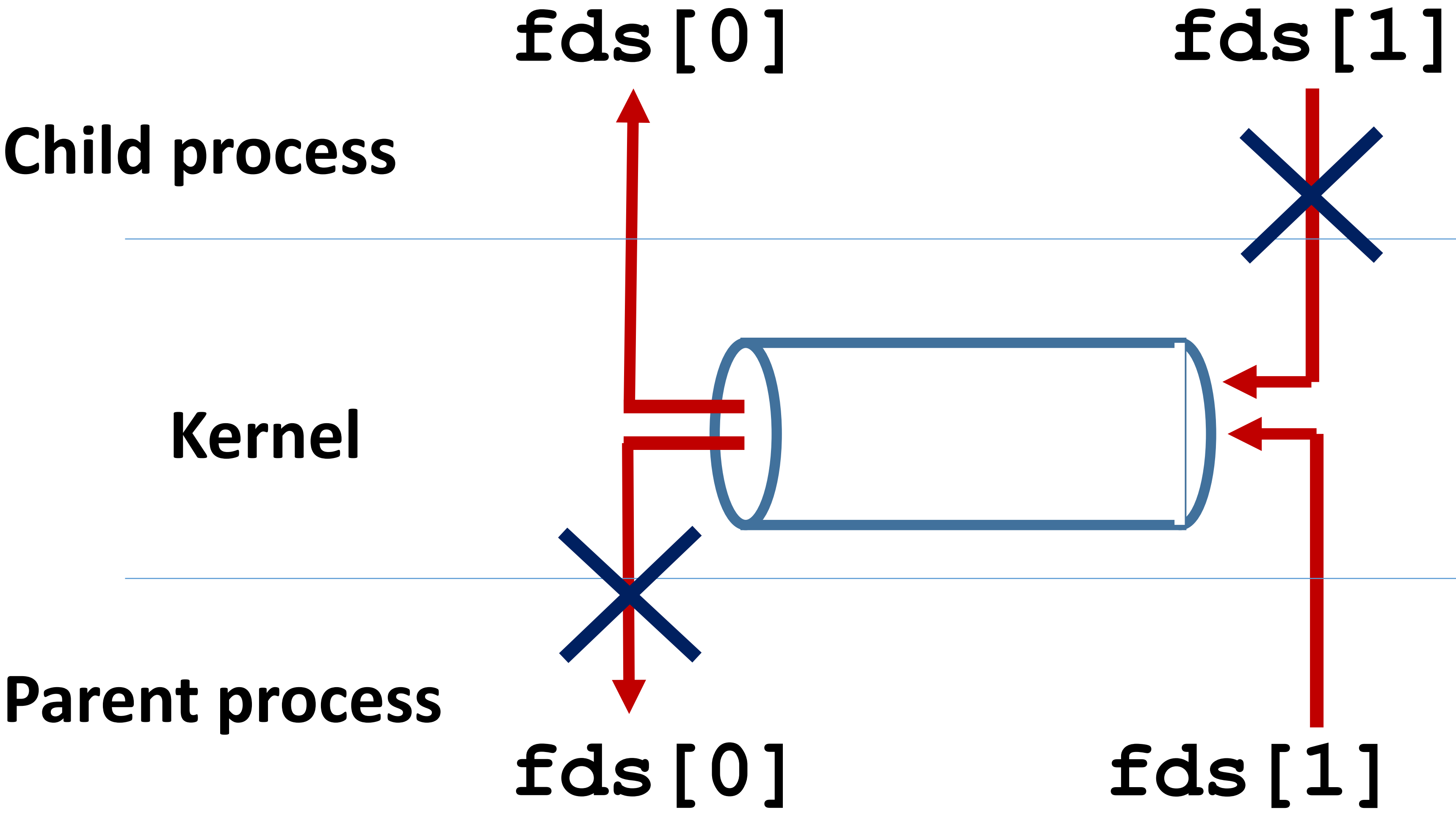


Pipes

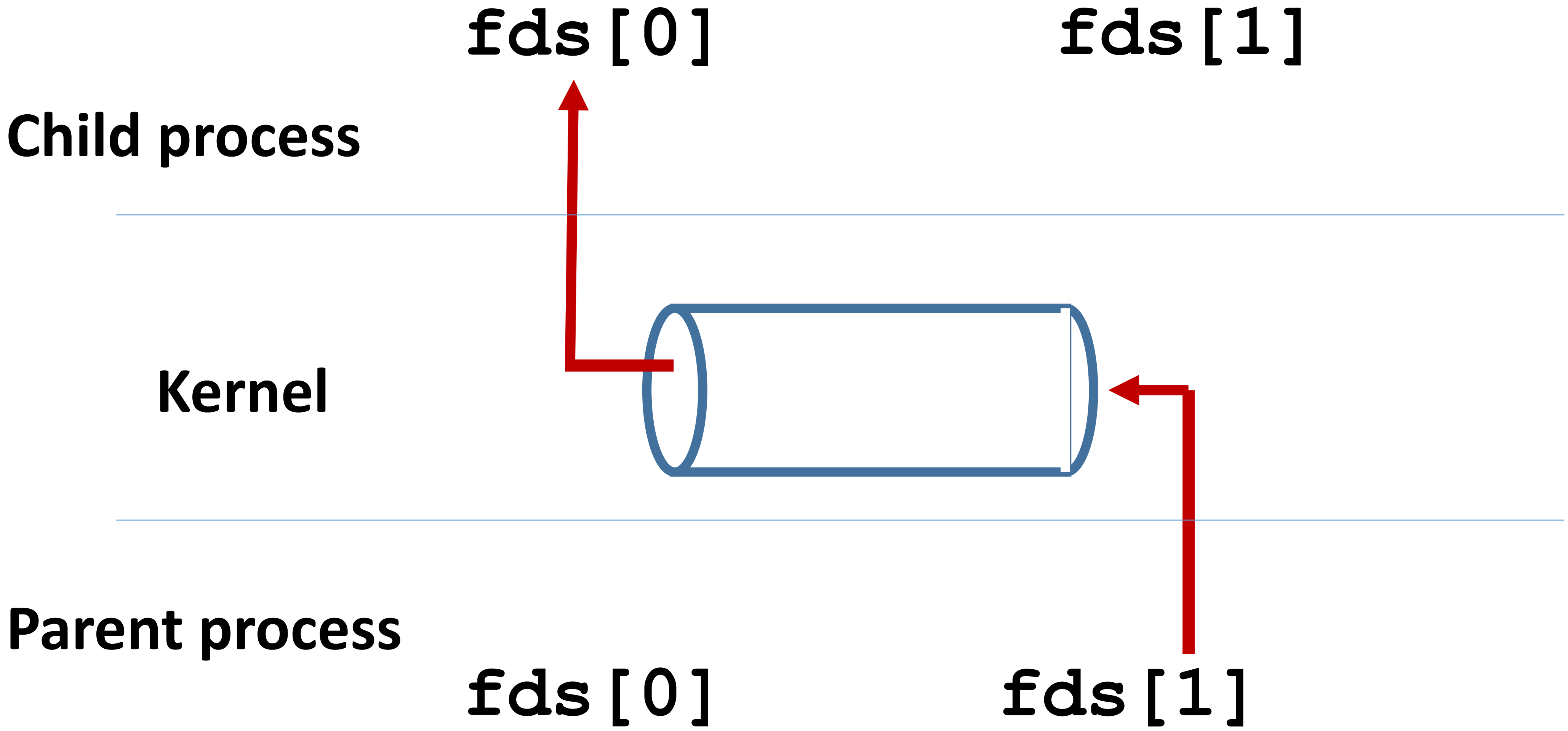
For our purposes, we will assume:

- Pipes will only work properly with one reader and one writer (this is the typical use case)
- This means, after the fork, each of the parent and child will close one of the two file descriptors

After Fork: Parent is the Producer



After Fork: Parent is the Producer



After Fork: Parent is the Producer

```
// Now use the pipe
int pid = fork()
if(pid > 0) {          // Note: leaving off error case
    // parent code
    close(fds[0])
        :
}else {
    // child code
    close(fds[1])
        :
}
```

After Fork: Parent is the Producer

After fork and closing:

- Parent can write bytes to fds[1]
- Child can read these bytes from fds[0]

After Fork: Parent is the Producer

- The pipe has a buffer: it will hold written bytes until they are read
- If the writer closes the pipe, then
  - The reader gets to read the remaining bytes
  - But then will see an EOF
- Windows calls ordinary pipes ***anonymous pipes***

Pipe demos

Named Pipes

Named Pipes are more powerful than ordinary pipes

- Communication ***can*** be bidirectional
- No parent-child relationship is necessary between the communicating processes
- Several processes can use the named pipe for communication
- Provided on both UNIX and Windows systems

Named Pipes in Unix

- Access points exist in the file system
  - Open them just as you would a file!
  - Use read()/write() to receive/send data
- Can have multiple readers/writers
  - A message is delivered to one randomly selected reader
  - So, effectively, they are bidirectional
  - **However, we will use them as unidirectional pipes**
- Create at the command line (or programmatically):

```
mkfifo [NAME]
```