Session Plan

- Process Concept
- Process States and Scheduling
- Operations on Processes
- Inter-process Communication

Process Concept

program vs. process

program: passive, on disk

process: active, in memory, one of several states

- Process – a program in execution
  - process execution must progress in sequential fashion

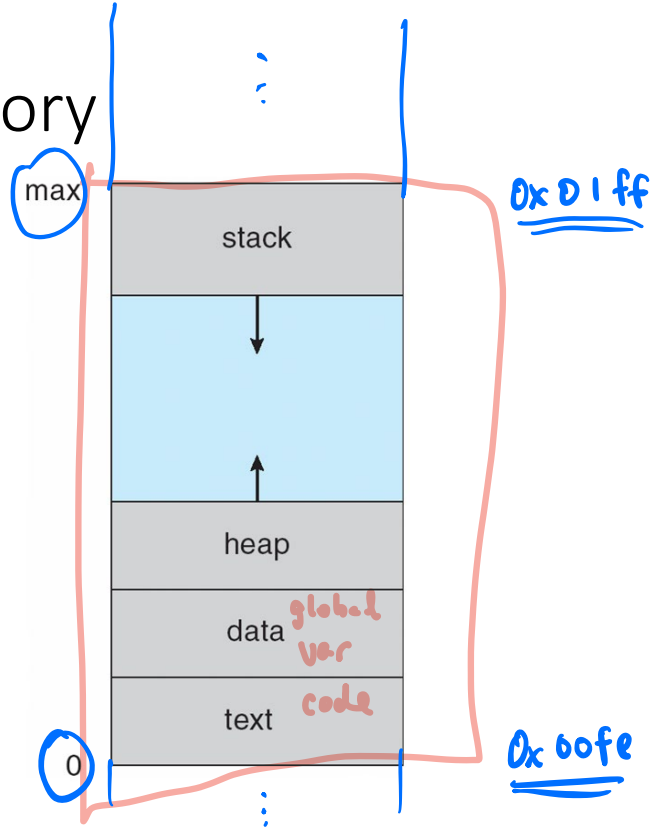
a program can be executed by multiple processes

- A *program* is a *passive* entity, whereas a process is an *active* entity with a program counter and a set of associated resources
- Each process has its own address space
  - The program code, also called text section
  - Stack containing temporary data
    - function parameters, return addresses, local variables
  - Data section containing global variables
  - Heap containing memory dynamically allocated during run time

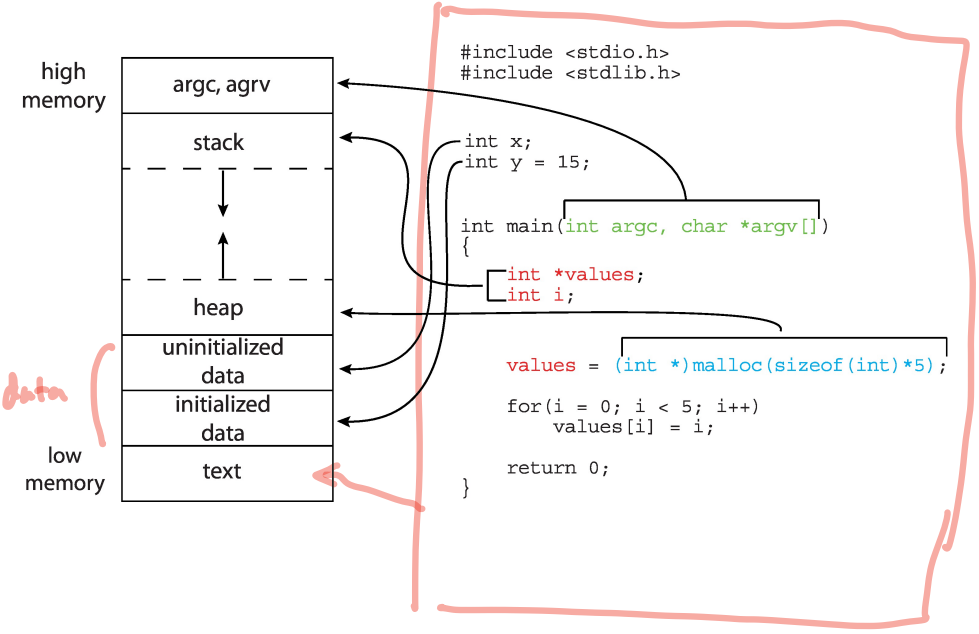
malloc( )
free( )

- Program counter and CPU registers are part of the process context

Process in Memory



Memory Layout of a C Program



Peeking Inside

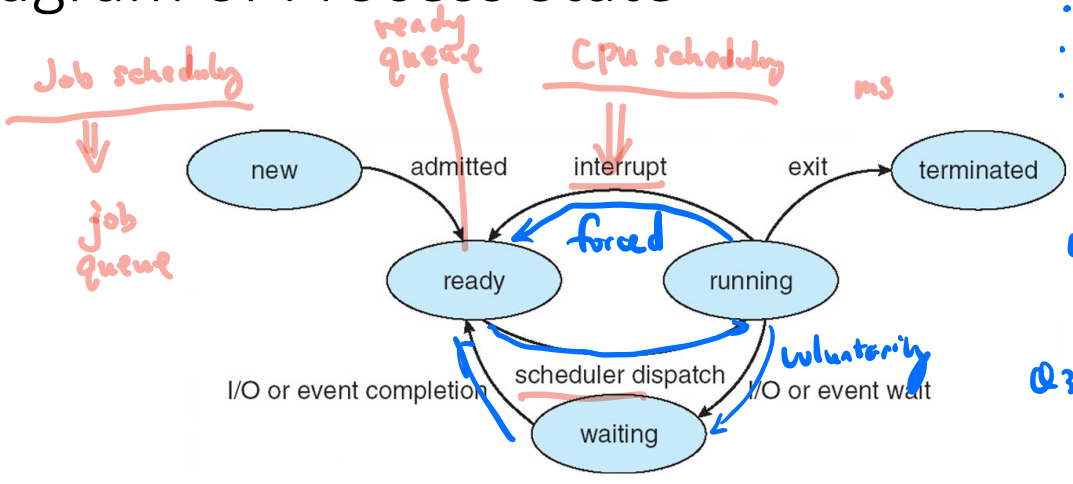
- Processes share code, but each has its own “context”
- CPU
  - Instruction pointer (Program Counter)
  - Stack pointer
- Memory
  - Set of memory addresses (“address space”)
  - `cat /proc/<PID>/maps`
- Disk
  - Set of file descriptors
  - `cat /proc/<PID>/fdinfo/*`

Process State

- As a process executes, it changes state
  - **new**: The process is being created
  - **running**: Instructions are being executed
  - **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

waiting time

Diagram of Process State



- As the program executes, it moves from state to state, as a result of the program actions (e.g., system calls), OS actions (scheduling), and external actions (interrupts).

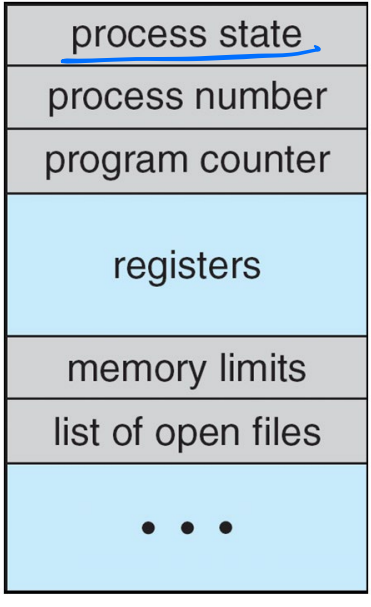
Process Control Block

PCB: OS data structures to keep track of all processes

- The PCB tracks the execution state and location of each process
- The OS allocates a new PCB on the creation of each process and places it on a state queue
- The OS deallocates the PCB when the process terminates

The PCB contains:

- 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
- 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



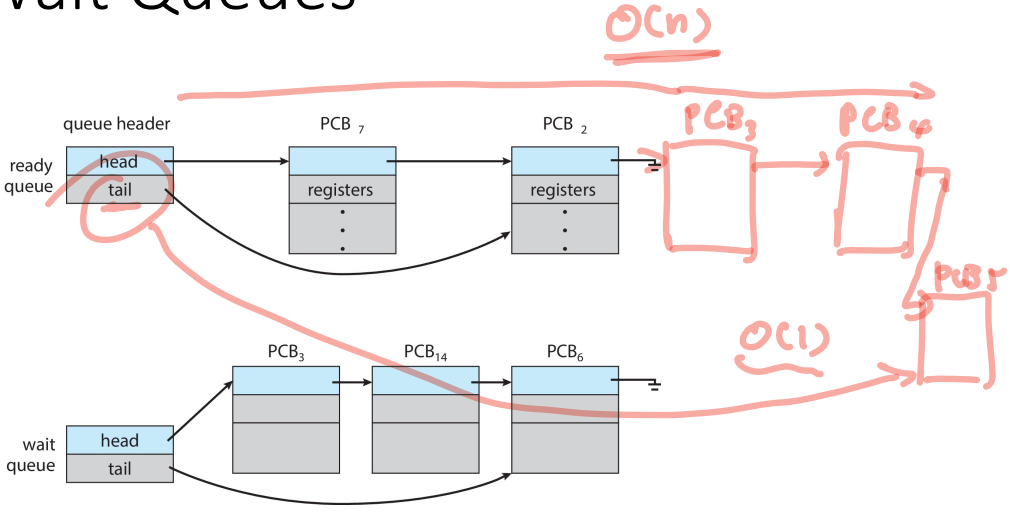
Process Scheduling

- The operating system is responsible for managing the scheduling activities
  - A uniprocessor system can have only one running process at a time
  - The main memory cannot always accommodate all processes at runtime for multi-programmed OS
  - The operating system will need to decide on which process to execute next (CPU scheduling), and which processes will be brought to the main memory (job scheduling)

Process Scheduling

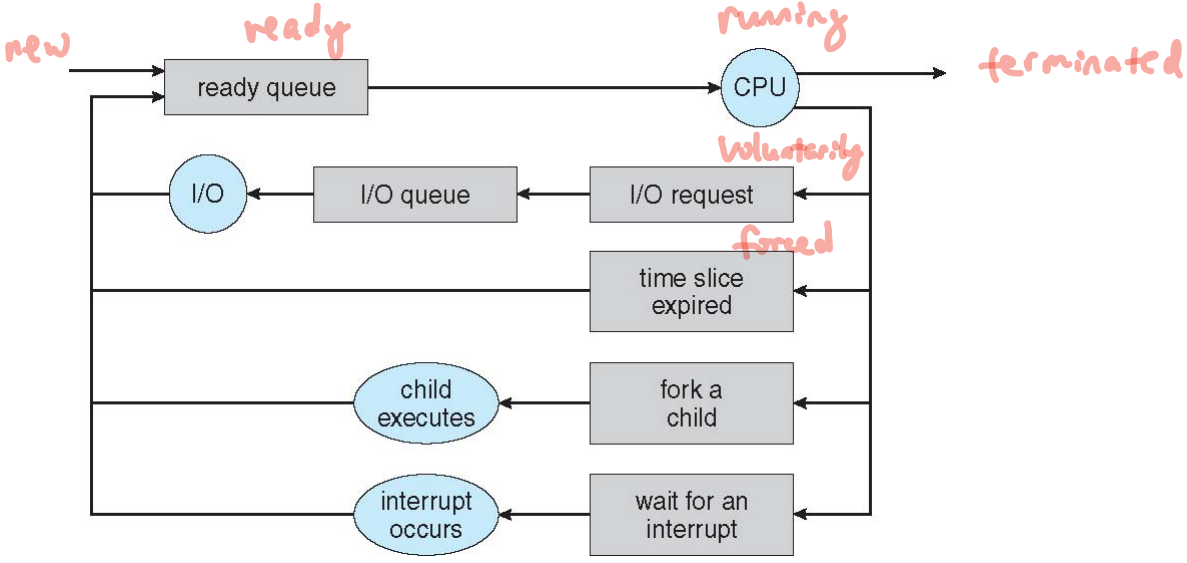
- Maximize CPU use, quickly switch processes onto CPU for time sharing
- Process scheduler selects among available processes for next execution on CPU
- Maintains scheduling queues of processes
  - Job queue – set of all processes in the system
  - Ready queue – set of all processes residing in main memory, ready and waiting to execute
  - Wait queues – set of processes waiting for an event (e.g., I/O)
  - Processes migrate among the various queues

Ready and Wait Queues



Representation of Process Scheduling

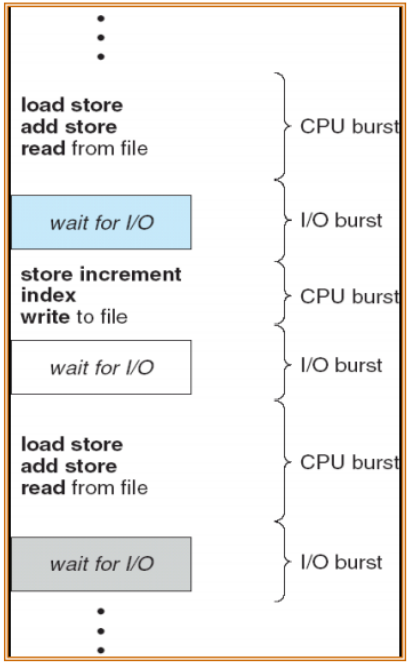
- Queueing diagram represents queues, resources, flows



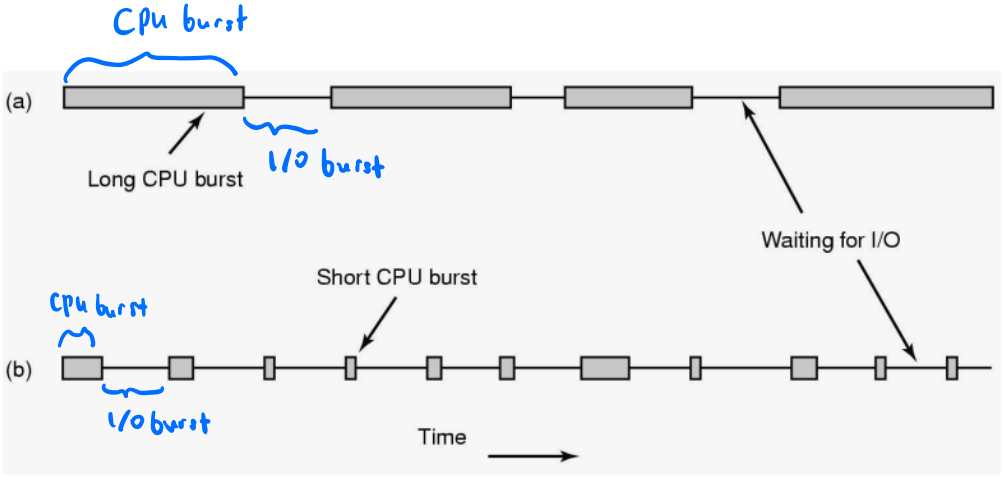
Schedulers

- 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) ⇒ (must be fast)
- Long-term scheduler (or job scheduler) – selects which processes should be brought into the ready queue
  - Long-term scheduler is invoked infrequently (seconds, minutes) ⇒ (may be slow)
  - The long-term scheduler controls the degree of multiprogramming
- Processes can be described as either:
  - I/O-bound process – spends more time doing I/O than computations, many short CPU bursts
  - CPU-bound process – spends more time doing computations; few very long CPU bursts
- Long-term scheduler strives for good ***process mix***

CPU and I/O Bursts



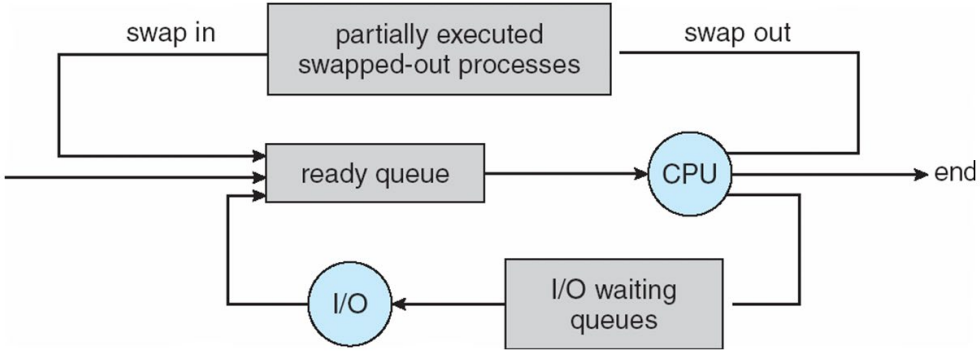
CPU-bound vs. I/O-bound Processes



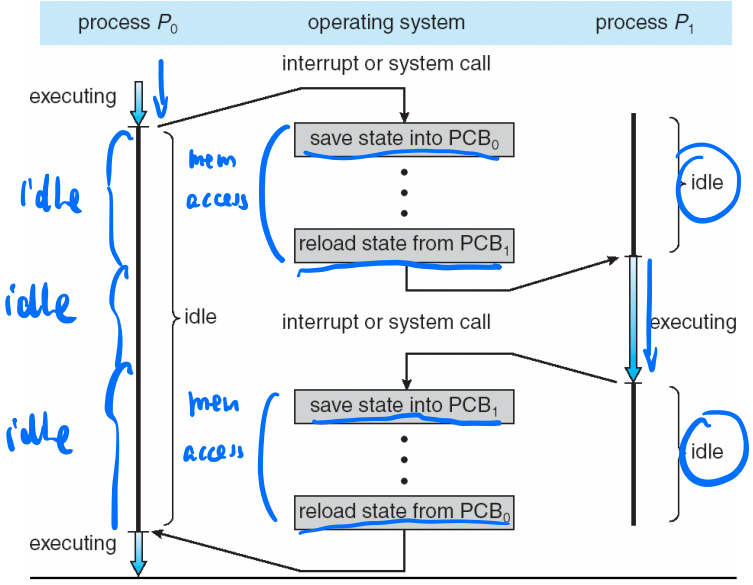
- (a) A CPU-bound process
- (b) An I/O-bound process

Addition of Medium-Term Scheduling

- Medium-term scheduler can be added if degree of multiple programming needs to decrease
  - Remove process from memory, store on disk, bring back in from disk to continue execution: swapping



CPU Switch from Process to Process



Context Switch

- 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 dependent on hardware support
  - Some hardware provides multiple sets of registers per CPU ➔ multiple contexts loaded at once

SW

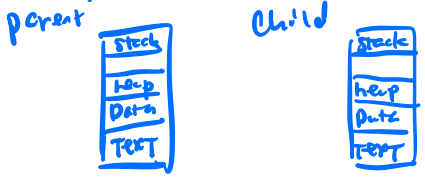
HW

Operations on Processes

- System must provide mechanisms for:
  - process creation,
  - process termination,
  - and so on

Process Creation

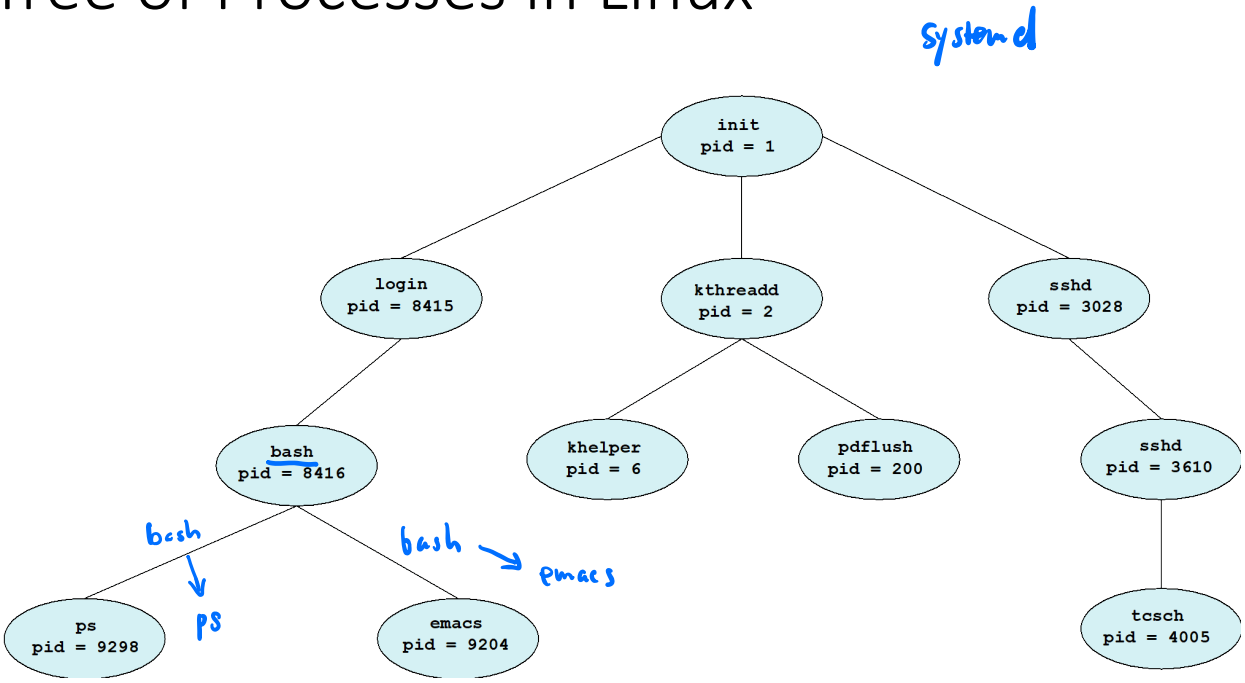
- Parent process create children processes, which, in turn create other processes, forming a tree (hierarchy) of processes
- Generally, process identified and managed via a process identifier (pid)
- Issues
  - Will the parent and child execute concurrently?
  - How will the address space of the child be related to that of the parent?
  - Will the parent and child share some resources?



Process Creation (cont.)

- 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

A Tree of Processes in Linux

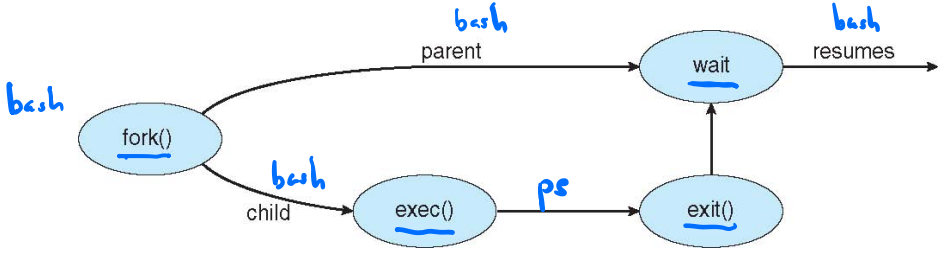


How to View Process Tree in Linux

- `% ps auxf`
  - `f` is the option to show the process tree
- `% pstree`

Process Creation (cont.)

- Address space
  - Child duplicate of parent
  - Child 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

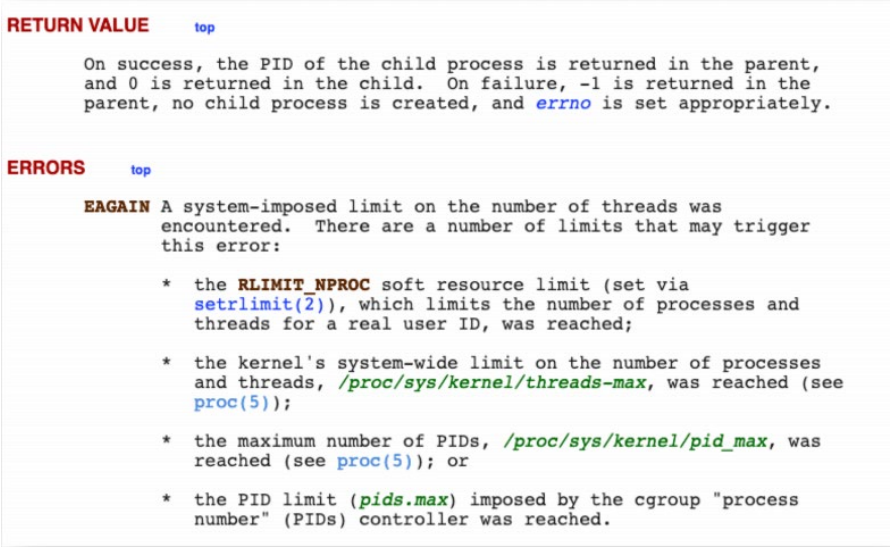


Process Creation in Linux

- Each process has a process identifier (pid)
- The parent executes `fork()` system call to spawn a child
- The child process has a separate copy of the parent's address space
- Both the parent and the child continue execution at the instruction following the `fork()` system call
- The return value for the `fork()` system call is
  - Zero value for the new (child) process
  - Non-zero pid for the parent process → Child's pid
- Typically, a process can execute a system call like `exec()` to load a binary file into memory

man page of `fork()`

- http://man7.org/linux/man-pages/man2/fork.2.html



RETURN VALUE top

On success, the PID of the child process is returned in the parent, and 0 is returned in the child. On failure, -1 is returned in the parent, no child process is created, and *errno* is set appropriately.

ERRORS top

EAGAIN A system-imposed limit on the number of threads was encountered. There are a number of limits that may trigger this error:

* the **RLIMIT_NPROC** soft resource limit (set via setrlimit(2)), which limits the number of processes and threads for a real user ID, was reached;
* the kernel's system-wide limit on the number of processes and threads, */proc/sys/kernel/threads-max*, was reached (see proc(5));
* the maximum number of PIDs, */proc/sys/kernel/pid_max*, was reached (see proc(5)); or
* the PID limit (*pids.max*) imposed by the cgroup "process number" (PIDs) controller was reached.

C Program Forking Separate Process

```
#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;
}
```

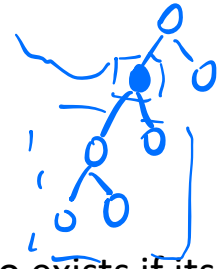
Creating a Separate Process via Windows API

```
#include <stdio.h>
#include <windows.h>

int main(VOID)
{
STARTUPINFO si;
PROCESS_INFORMATION pi;

   /* allocate memory */
   ZeroMemory(&si, sizeof(si));
   si.cb = sizeof(si);
   ZeroMemory(&pi, sizeof(pi));

   /* create child process */
   if (!CreateProcess(NULL, /* use command line */
    "C:\\WINDOWS\\system32\\mspaint.exe", /* command */
    NULL, /* don't inherit process handle */
    NULL, /* don't inherit thread handle */
    FALSE, /* disable handle inheritance */
    0, /* no creation flags */
    NULL, /* use parent's environment block */
    NULL, /* use parent's existing directory */
    &si,
    &pi))
   {
     fprintf(stderr, "Create Process Failed");
     return -1;
   }
   /* parent will wait for the child to complete */
   WaitForSingleObject(pi.hProcess, INFINITE);
   printf("Child Complete");

   /* close handles */
   CloseHandle(pi.hProcess);
   CloseHandle(pi.hThread);
}
```

Process Termination

- Process executes last statement and then asks the operating system to delete it using the **`exit()`** system call.
  - Returns status data from child to parent (via **`wait()`**)
  - Process' resources are deallocated by operating system
- Parent may terminate the execution of children processes using the **`abort()`** system call. Some reasons for doing so:
  - Child has exceeded allocated resources
  - Task assigned to child is no longer required
  - The parent is exiting and the operating systems does not allow a child to continue if its parent terminates

Process Termination



- Some operating systems do not allow child to exists if its parent has terminated. If a process terminates, then all its children must also be terminated.
  - **cascading termination.** All children, grandchildren, etc. are terminated.
  - The termination is initiated by the operating system.
- The parent process may wait for termination of a child process by using the **`wait()`** system call. The call returns status information and the pid of the terminated process

```
pid = wait(&status);
```

to be terminated

- If no parent waiting (did not invoke **`wait()`**) process is a zombie
- If parent terminated without invoking **`wait`**, process is an orphan

its parent was terminated

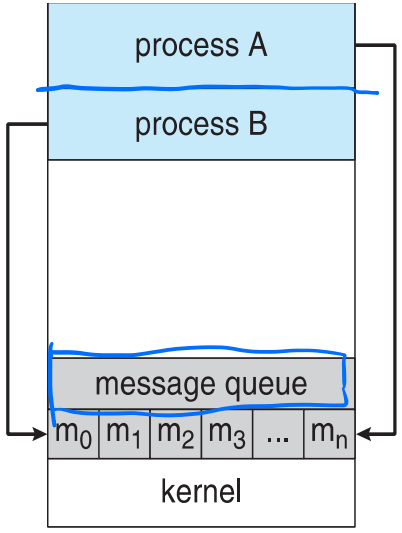
Inter-process Communication

- Processes within a system may be ***independent*** or ***cooperating***
- Cooperating process can affect or be affected by other processes, including sharing data
- Reasons for cooperating processes:
  - Information sharing
  - Computation speedup
  - Modularity
  - Convenience
- Cooperating processes need inter-process communication (IPC)
- Two models of IPC
  - Shared memory
  - Message passing

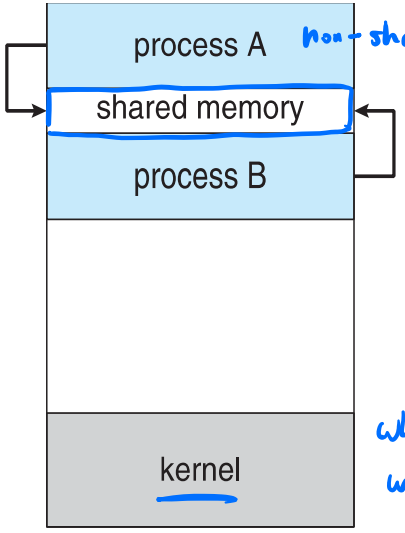
Communications Models

1. ft the restriction

(a) Message passing. (b) Shared memory.



(a)



(b)

non-shareable

when the shared region was created

send (...)
receive (...)

⊖ slower
more expensive

⊕ a small amount of data distributed

⊕ faster
cheaper

Producer-Consumer Problem

- Paradigm for cooperating processes, *producer* process produces information that is consumed by a *consumer* process
  - unbounded-buffer places no practical limit on the size of the buffer
  - bounded-buffer assumes that there is a fixed buffer size

Inter-process Communication – Shared Memory

- An area of memory shared among the processes that wish to communicate
- The communication is under the control of the users processes not the operating system.
- Major issues is to provide mechanism that will allow the user processes to synchronize their actions when they access shared memory.
- Synchronization is discussed in great details in Chapter 6 & 7.

Bounded-Buffer – Shared-Memory Solution

- Shared data

10 slots

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

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

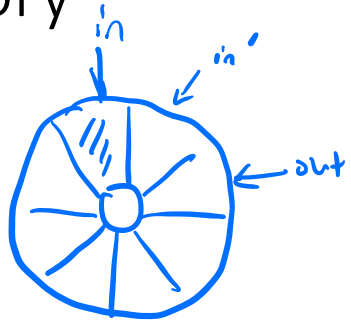
- Solution is correct, but can only use BUFFER_SIZE-1 elements

9 elements

90%

Producer Process – Shared Memory

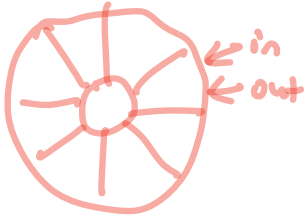
```
item next_produced;
while (true) {
      /* produce an item in next produced */
      while (((in + 1) % BUFFER_SIZE) == out)
            ; /* do nothing */
      buffer[in] = next_produced;
      in = (in + 1) % BUFFER_SIZE;
}
```

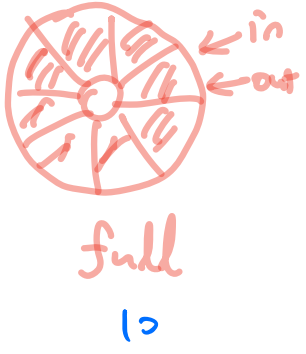


Consumer Process – Shared Memory

```
item next_consumed;

while (true) {
      while (in == out)
            ; /* do nothing */
      next_consumed = buffer[out];
      out = (out + 1) % BUFFER_SIZE;

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

Ambiguity





Counter

Inter-process 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 operations:
  - **`send`**(*message*)
  - **`receive`**(*message*)
- The *message* size is either fixed or variable

Message Passing (cont.)

- 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?
  - Is the size of a message that the link can accommodate fixed or variable?
  - Is a link unidirectional or bi-directional?

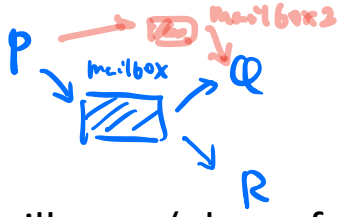
Message Passing (cont.)

- Implementation of communication link
  - Physical:
    - Shared memory
    - Hardware bus
    - Network
  - Logical:
    - Direct or indirect
    - Synchronous or asynchronous
    - Automatic or explicit buffering

Direct Communication

- Processes must name each other explicitly:
  - **`send`** (*P, message*) – send a message to process P
  - **`receive`**(*Q, message*) – receive a message from process Q
- Properties of communication link
  - Links are established automatically
  - A link is associated with exactly one pair of communicating processes
  - Between each pair there exists exactly one link
  - The link may be unidirectional, but is usually bi-directional

Indirect Communication



- Messages are directed and received from mailboxes (also referred to as ports)
  - Each mailbox has a unique id
  - Processes can communicate only if they share a mailbox
- Properties of communication link
  - Link established only if processes share a common mailbox
  - A link may be associated with many processes
  - Each pair of processes may share several communication links
  - Link may be unidirectional or bi-directional

Indirect Communication

- Operations
  - create a new mailbox (port)
  - send and receive messages through mailbox
  - destroy a mailbox
- Primitives are defined as:

  `send`(*A, message*) – send a message to mailbox A

  `receive`(*A, message*) – receive a message from mailbox A

Indirect Communication

- Mailbox sharing
  - P_1, P_2, and P_3 share mailbox A
  - P_1, sends; P_2 and P_3 receive
  - Who gets the message?
- Solutions
  - Allow a link to be associated with at most two processes
  - Allow only one process at a time to execute a receive operation
  - Allow the system to select arbitrarily the receiver. Sender is notified who the receiver was.

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
- Non-blocking is considered asynchronous
  - **Non-blocking send** -- the sender sends the message and continue
  - **Non-blocking receive** -- the receiver receives:
    - A valid message, or
    - Null message
- Different combinations possible
  - If both send and receive are blocking, we have a rendezvous

Synchronization (cont.)

- 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 */
}
```

buffer vs. cache

Buffering

- Queue of messages attached to the link.
- Implemented in one of three ways
    1. Zero capacity – no messages are queued on a link.
    Sender must wait for receiver (rendezvous)
    2. Bounded capacity – finite length of *n* messages
    Sender must wait if link full
    3. Unbounded capacity – infinite length
    Sender never waits

Exit Slips

- Take 1-2 minutes to reflect on this lecture
- On a sheet of paper write:
  - One thing you learned in this lecture
  - One thing you didn't understand