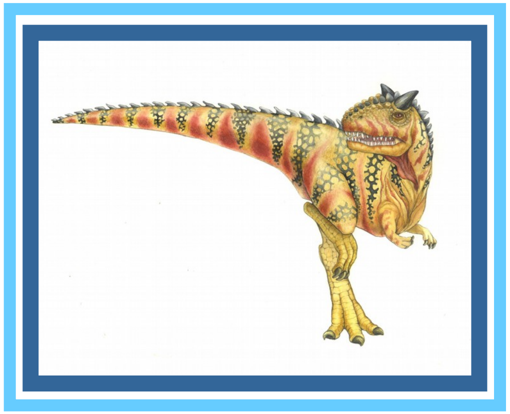
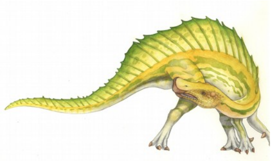
Chapter 3: Processes



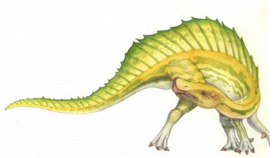
Chapter 3: Processes

- Process Concept
- Process Scheduling
- Operations on Processes
- Interprocess Communication
- IPC in Shared-Memory Systems
- IPC in Message-Passing Systems
- Examples of IPC Systems



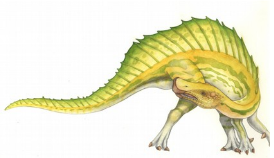
Objectives

- Identify the separate components of a process and illustrate how they are represented and scheduled in an operating system.
- Describe how processes are created and terminated in an operating system, including developing programs using the appropriate system calls that perform these operations.
- Describe and contrast inter-process communication using shared memory and message passing.
- Understand kernel modules that interact with the Linux operating system.



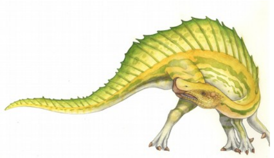
Process Concept

- An operating system executes a variety of programs that run as a ***process***.
- **A process is a program in execution.**
- Multiple parts in a **process image**:
  - The program code, also called **text section**
  - Current processor state, including **program counter**, processor registers, including stack pointer, etc.
  - **Stack contents,** containing temporary data
    - Function parameters, return addresses, local variables
  - **Data section** containing global variables
  - **Heap** containing memory dynamically allocated during run time
  - Other resources such as open files, command-line arguments, environment values, ...

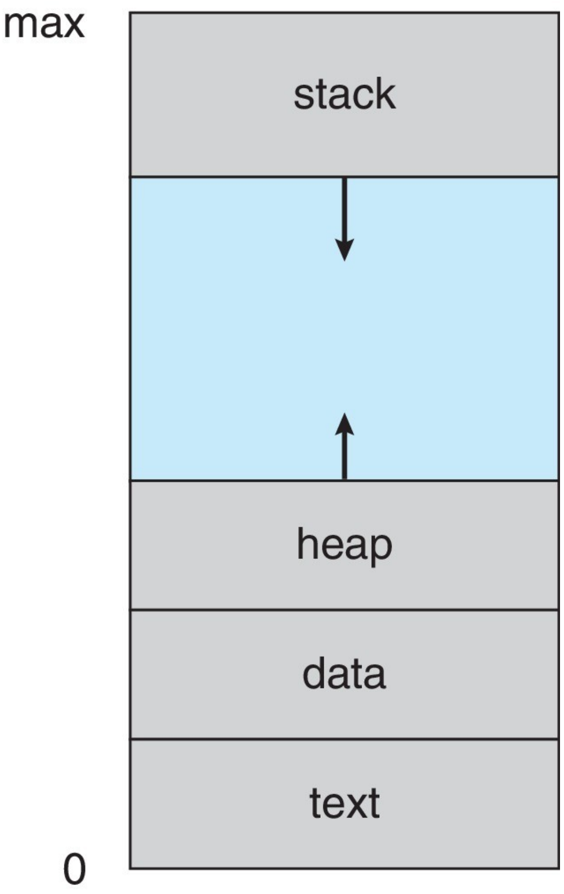


Process Concept (Cont.)

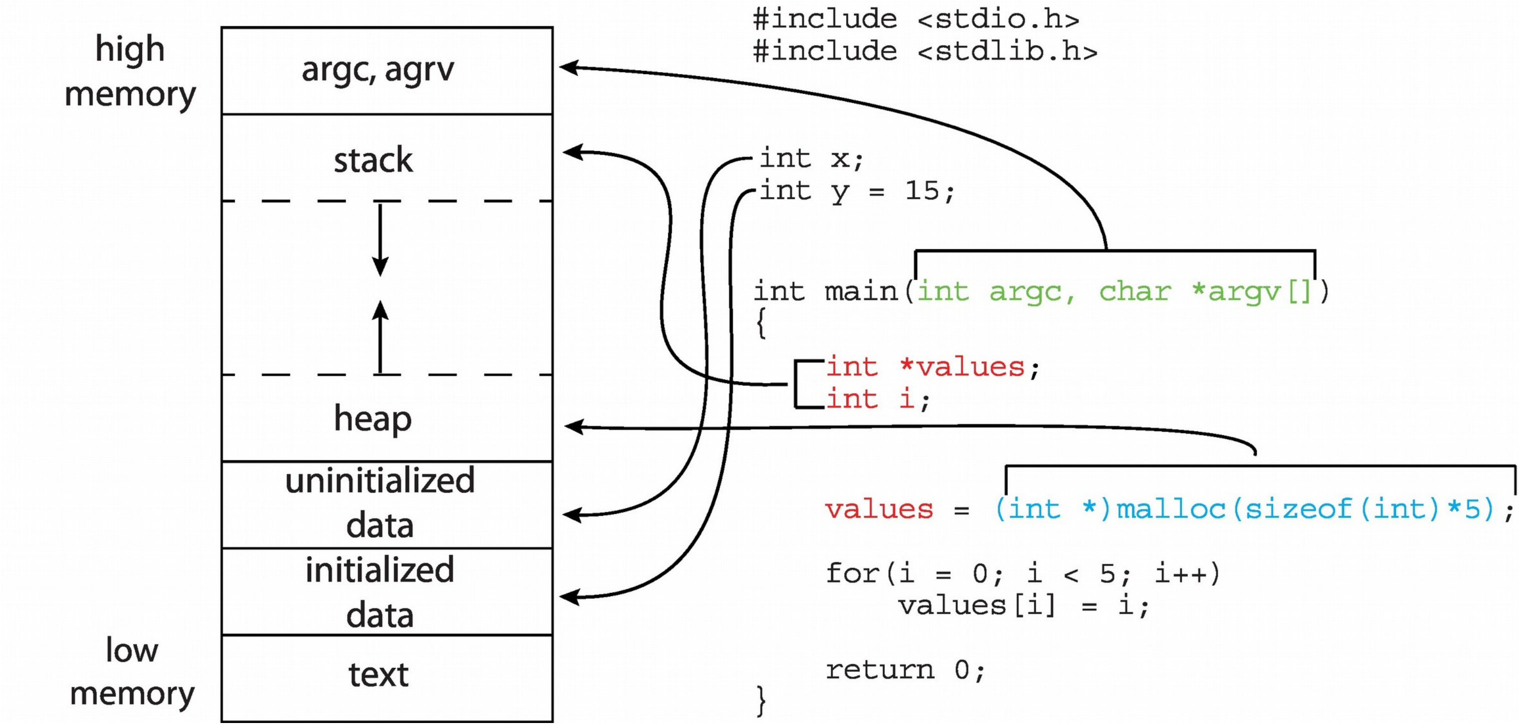
- Program is ***passive*** entity stored on disk (**executable file**); process is ***active*** **-**
  - Program becomes process when executable file loaded into memory
- Execution of program started via GUI mouse clicks, command line entry of its name, etc
- One program can be executed by several processes
  - e.g.: compiler, shell (bash), browser, etc.



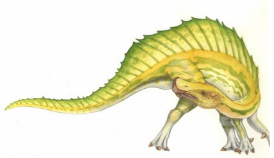
Process in Memory (simplified)



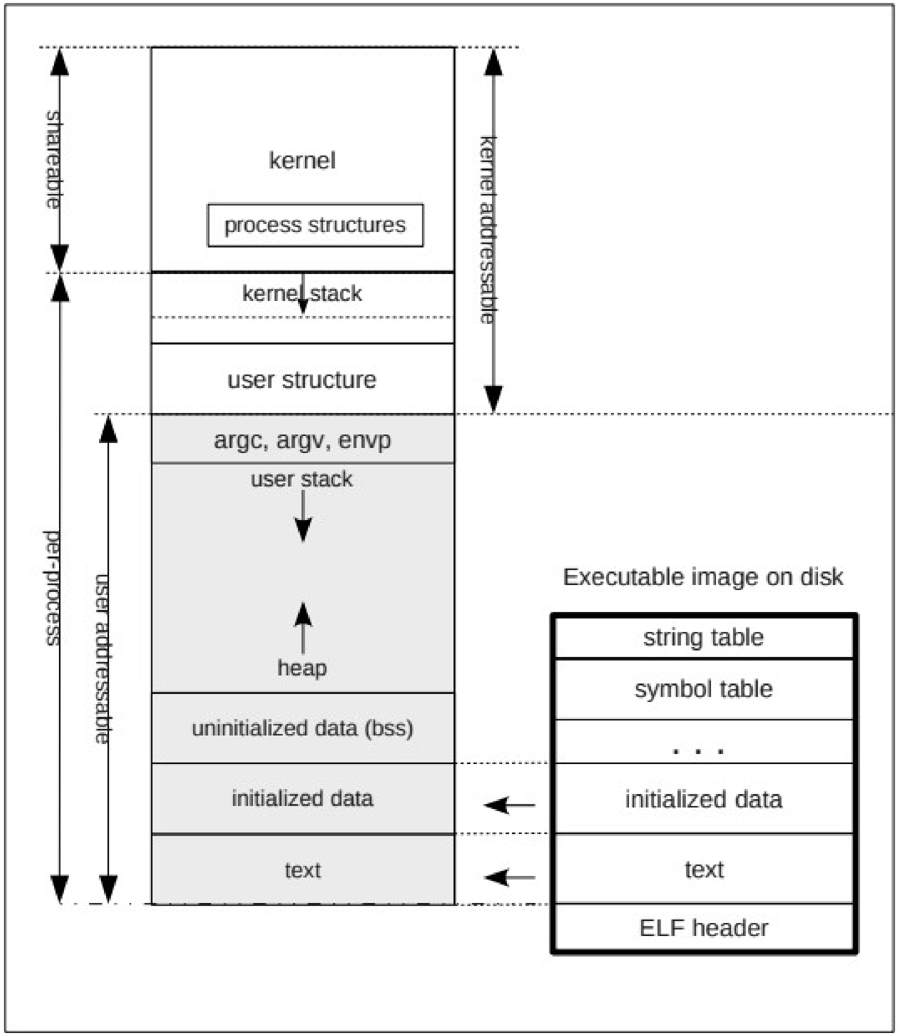
Memory Layout of a C Program



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

int x;
int y = 15;

int main(int argc, char *argv[])
{
   int *values;
   int i;

   values = (int *)malloc(sizeof(int)*5);

   for(i = 0; i < 5; i++)
      values[i] = i;

   return 0;
}
```

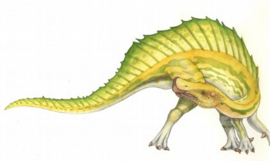


Detailed ELF Memory Layout

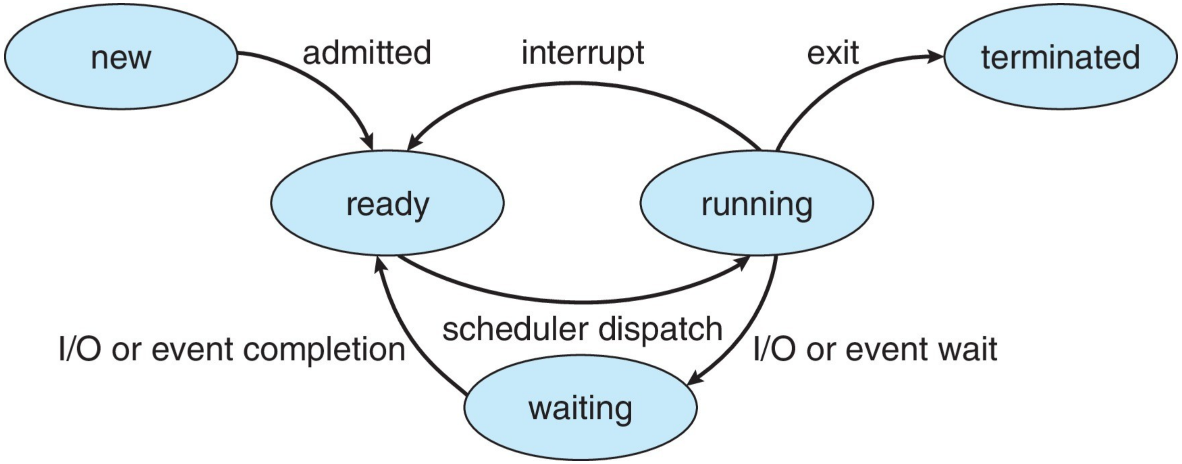


Process State

- As a process executes, it changes **state**
  - **New**: The process was just created
  - **Ready**: The process is ready to run but is waiting to be assigned to a processor
  - **Running: Instructions are being executed**
  - **Waiting: The process is waiting for some event to occur and is not able to use the processor**
  - **Terminated**: The process has finished execution



Process State Transition Diagram



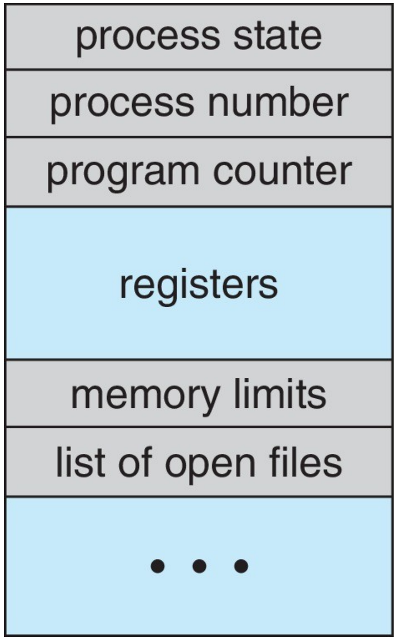
- Edges are transitions.

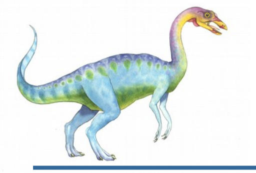
- Their labels are the actions or events that cause these transitions.

Process Control Block (PCB)

Information associated with each process (also called **task control block**)

- 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

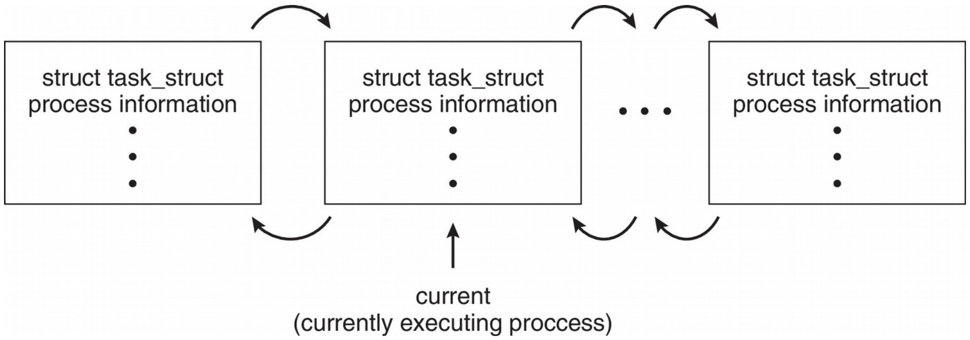


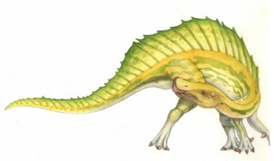


PCB Representation in Linux

Represented by the C structure `task_struct,` part of which is

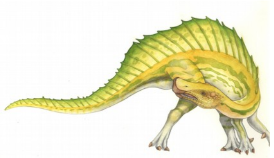
```
pid t_pid;                      /* process identifier */
long state;                     /* state of the process */
unsigned int time_slice         /* scheduling information */
struct task_struct *parent;/* this process’s parent */
struct list_head children; /* this process’s children */
struct files_struct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





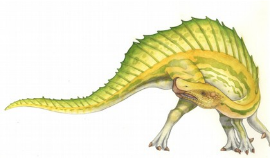
Scheduling

- There are three levels of scheduling:
  - **long-term scheduling**: decision about which processes are admitted into system (usually just in batch systems)
  - **medium-term scheduling**: decision about which processes are memory resident
  - **short-term scheduling**: decision about which memory resident process gets the CPU next
- **Short-term scheduler** is also called **process scheduler**

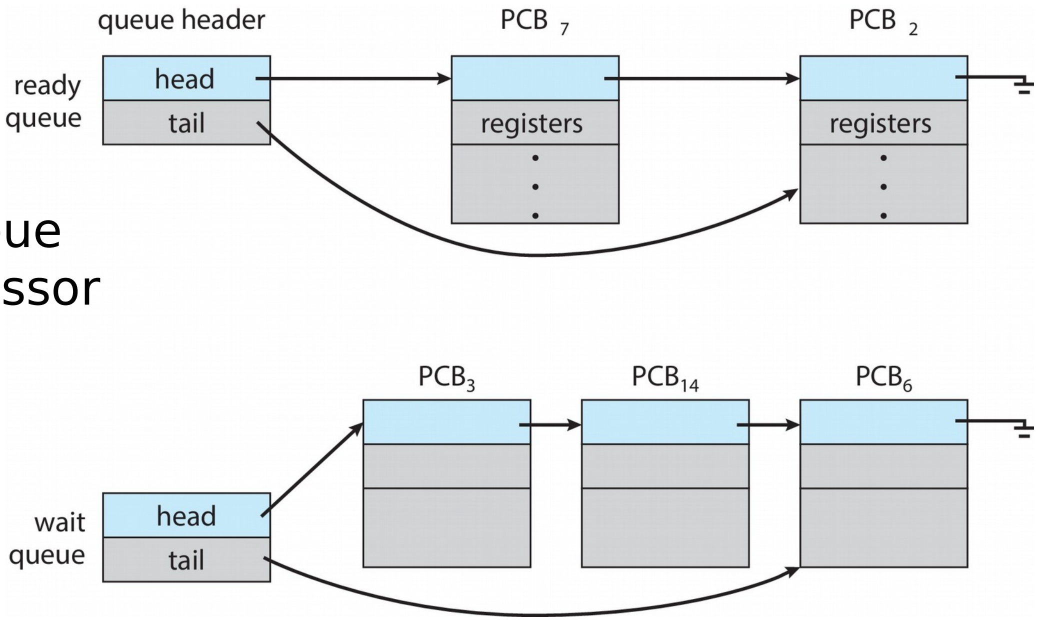


Process Scheduler

- Objective: Maximize CPU utilization, quickly switch processes onto CPU core
- Maintains **scheduling queues** of processes
  - **Ready queue** – set of all processes residing in main memory, ready and waiting to execute
  - **Wait queues** – set of processes waiting for an event (i.e. I/O)
  - Processes migrate among the various queues
- Scheduler runs most frequently, so it must be very fast



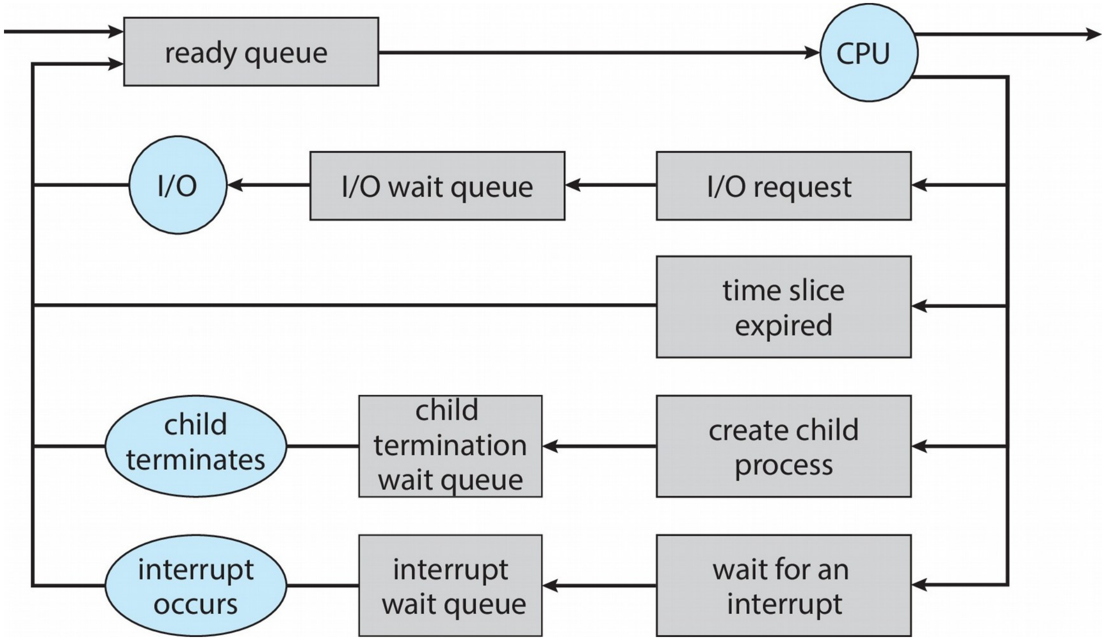
Ready and Wait Queues

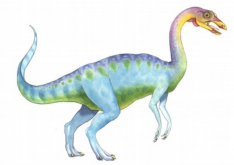


One ready queue for each processor

One wait queue for each device

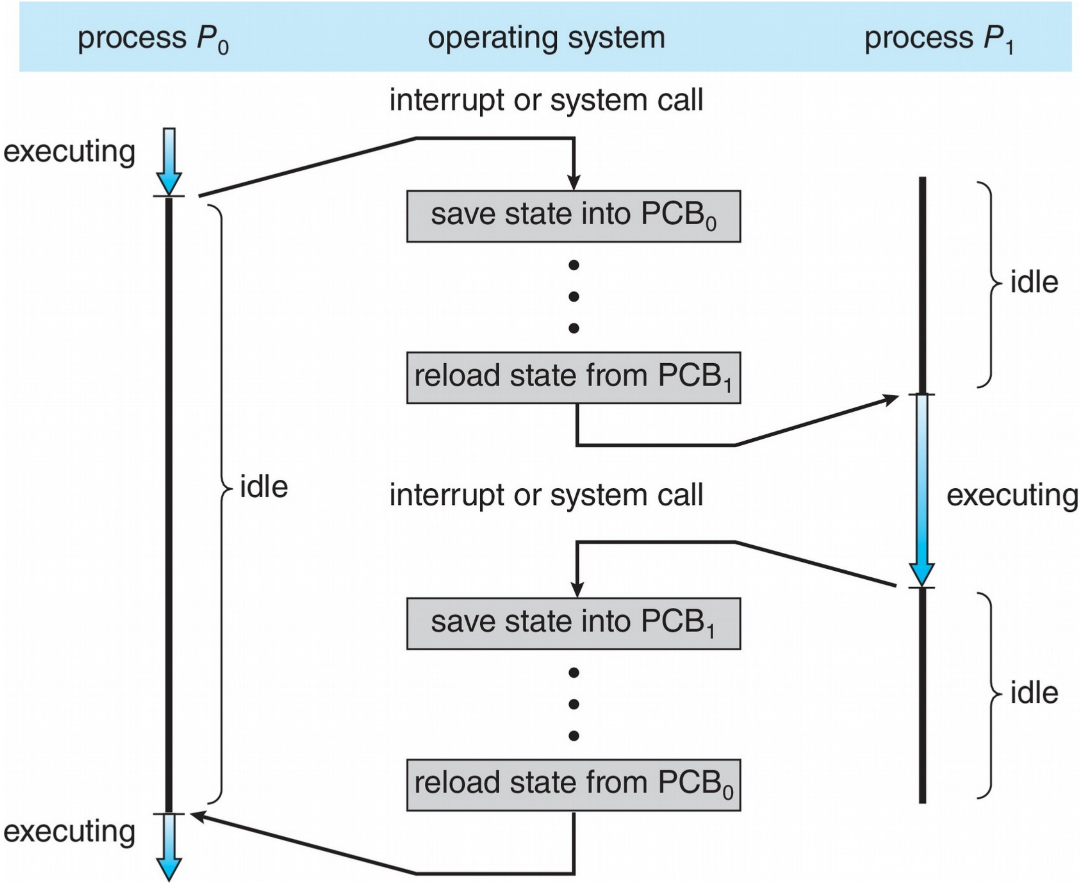
Transitions in Process Scheduling





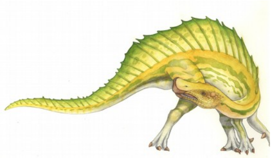
CPU Switch From Process to Process

A **context switch** occurs when the CPU switches from one process to another.



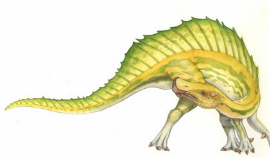
process P_0
operating system
process P_1

interrupt or system call
executing
save state into PCB$_0$
idle
reload state from PCB$_1$
idle
interrupt or system call
executing
save state into PCB$_1$
idle
reload state from PCB$_0$
executing



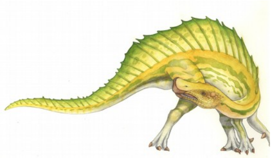
Context Switch

- 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



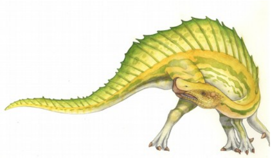
Operations on Processes

- System must provide mechanisms for:
  - process creation
  - process termination

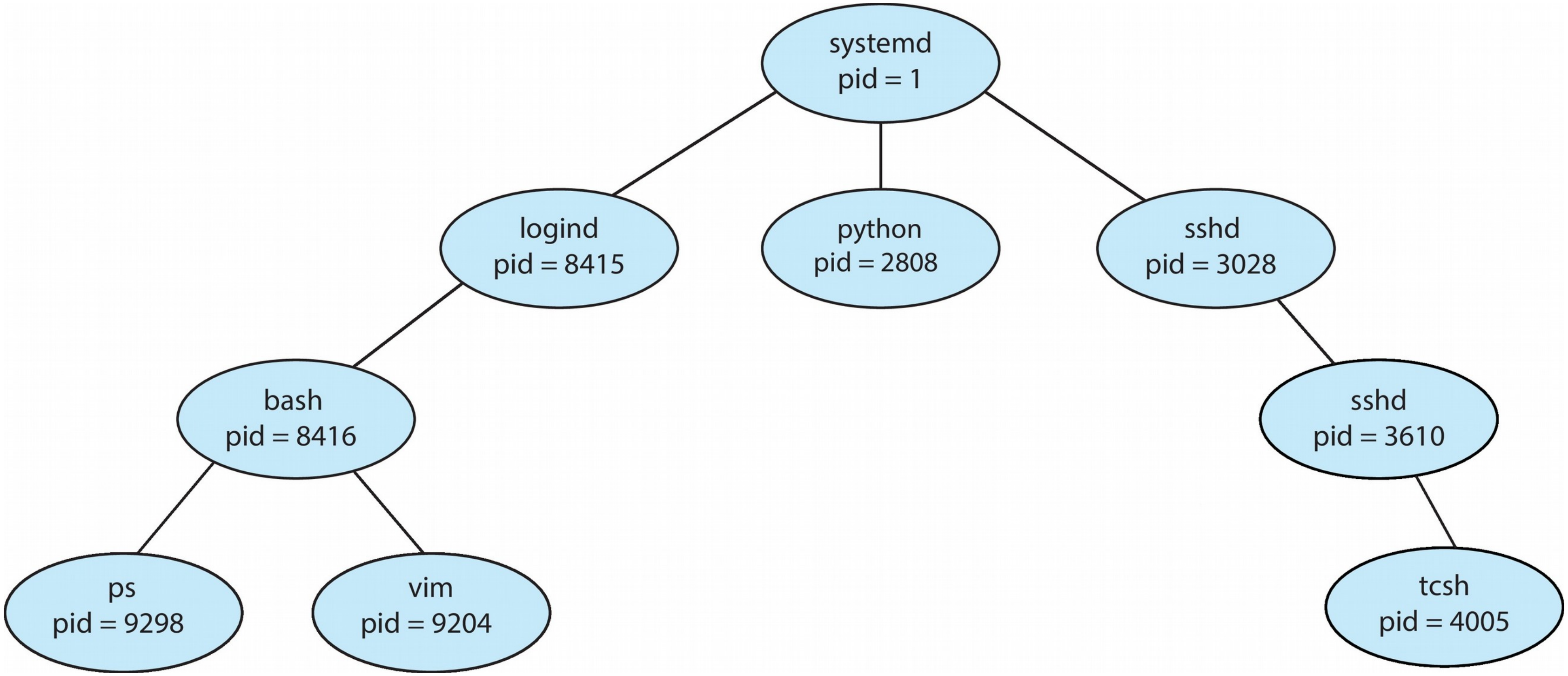


Process Creation

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

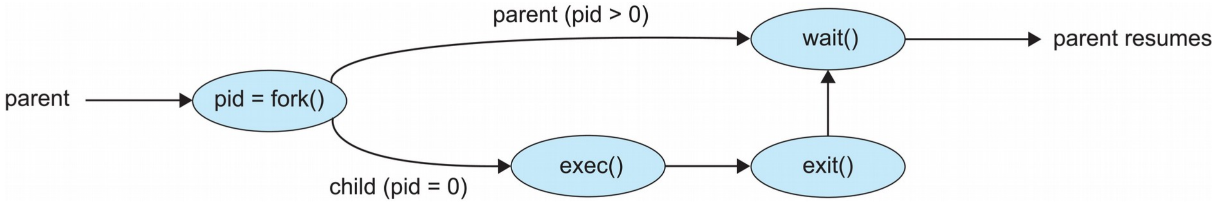


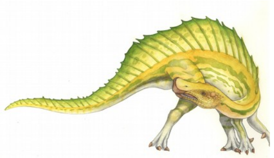
A Tree of Processes in Linux



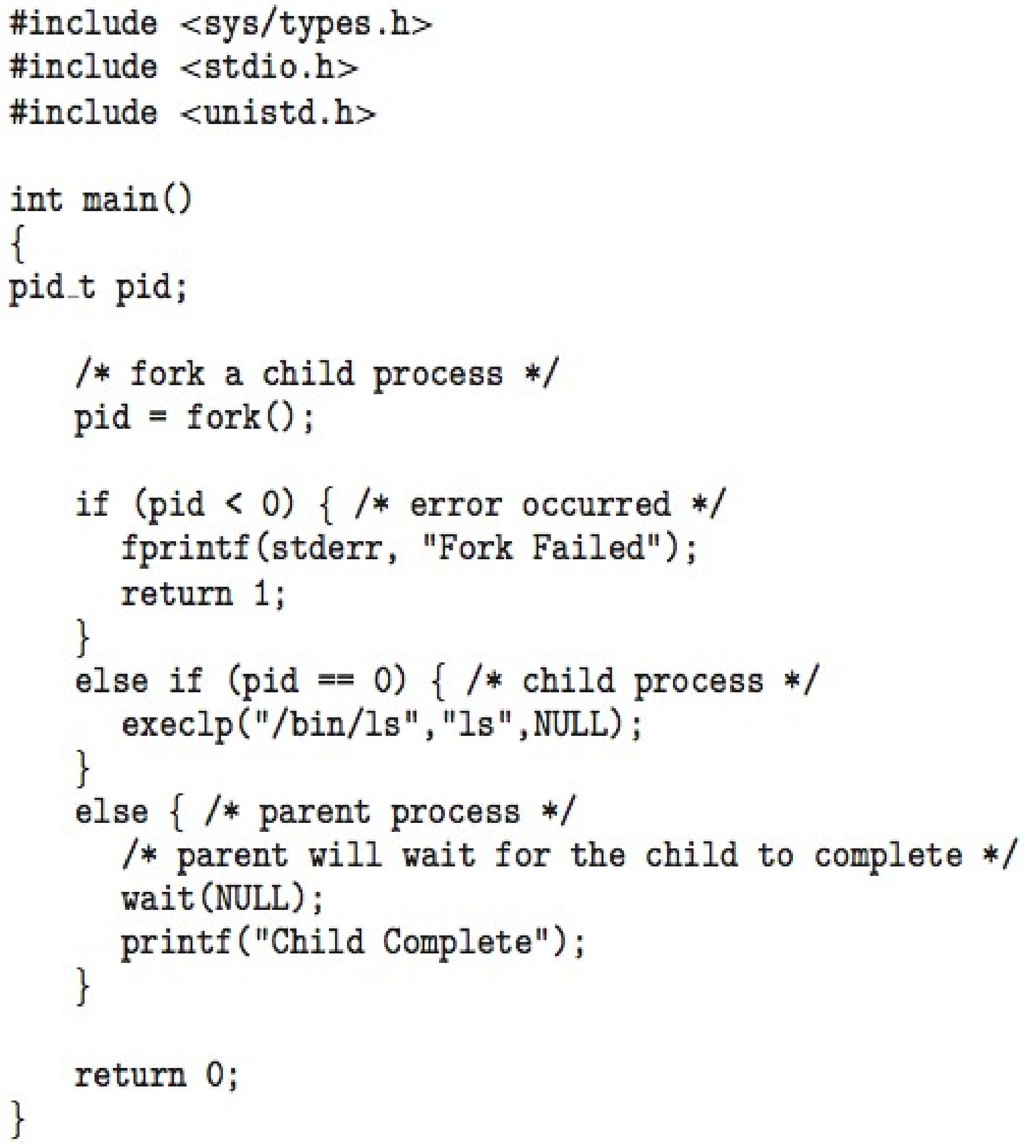
Process Creation (Cont.)

- 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
  - Parent process calls **`wait()`** for the child to terminate



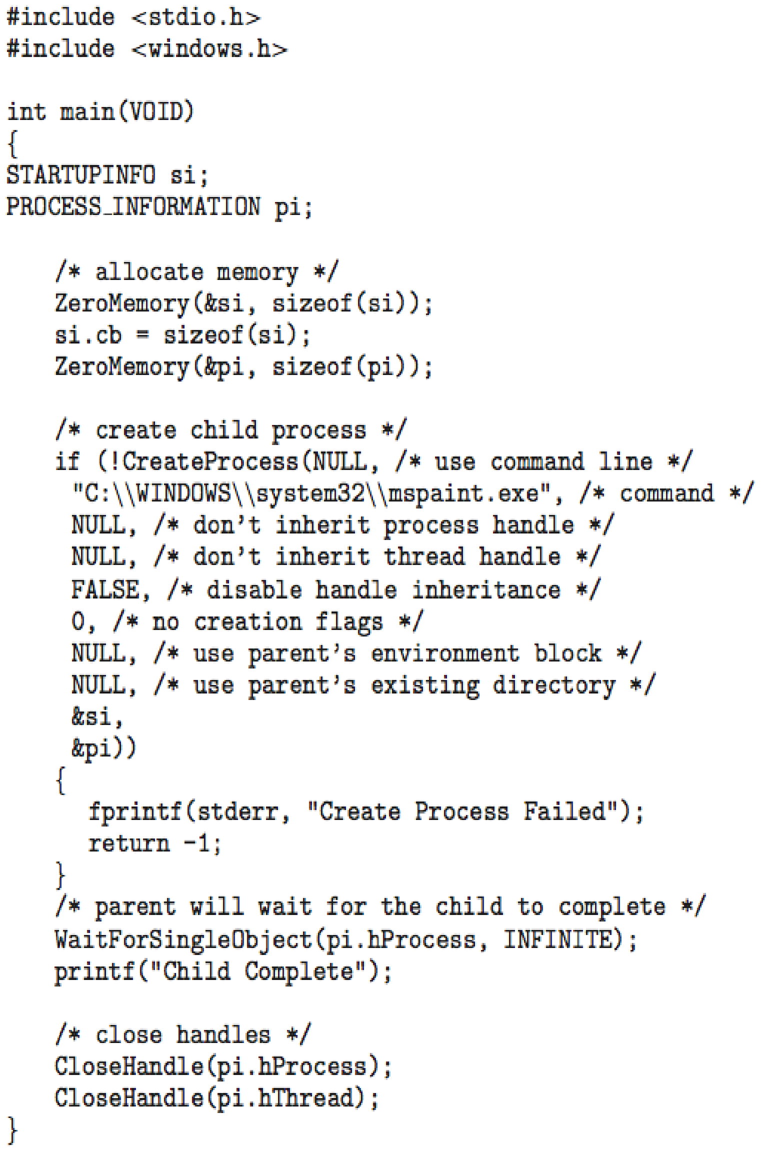


C Program Forking Separate Process



```
#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;
}
```

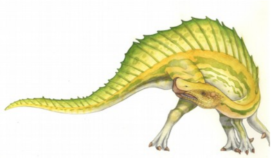
Creating a Separate Process via Windows API



```
#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 signals. 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

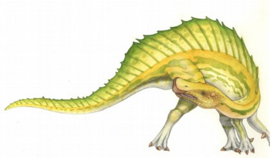


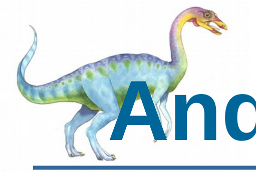
Process Termination 2

- 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);
```

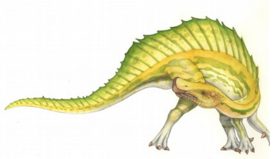
- If no parent waiting (did not invoke `wait()`) process is a **zombie**
- If parent terminated without invoking `wait` , process is an **orphan**





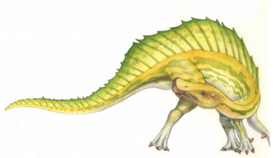
Android Process Importance Hierarchy

- Mobile operating systems often have to terminate processes to reclaim system resources such as memory. From **most** to **least** important:
  - Foreground process
  - Visible process
  - Service process
  - Background process
  - Empty process
- Android will begin terminating processes that are least important.



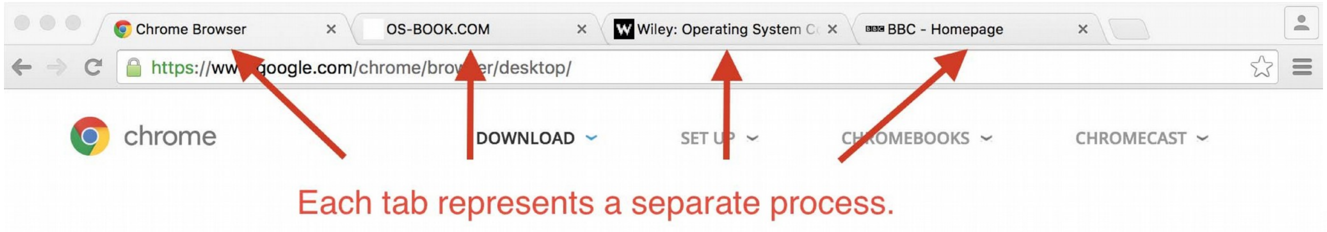
Cooperating Processes

- Two processes can be either ***independent*** or ***cooperating with respect to each other*****.**
- They are ***independent*** if neither can affect or be affected by the execution of the other process
- They are ***cooperating*** if either can affect or be affected by the execution of the other process.
- Various reasons for processes to cooperate:
  - To share information sharing
  - To speed up a computation
  - To increase modularity of an application



Example: Chrome Browser

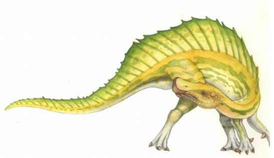
- Many web browsers ran as single process (some still do)
  - If one web site causes trouble, entire browser can hang or crash
- Google Chrome Browser is multiprocess with 3 different types of processes:
  - **Browser** process manages user interface, disk and network I/O
  - **Renderer** process renders 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



Each tab represents a separate process.

Interprocess Communication

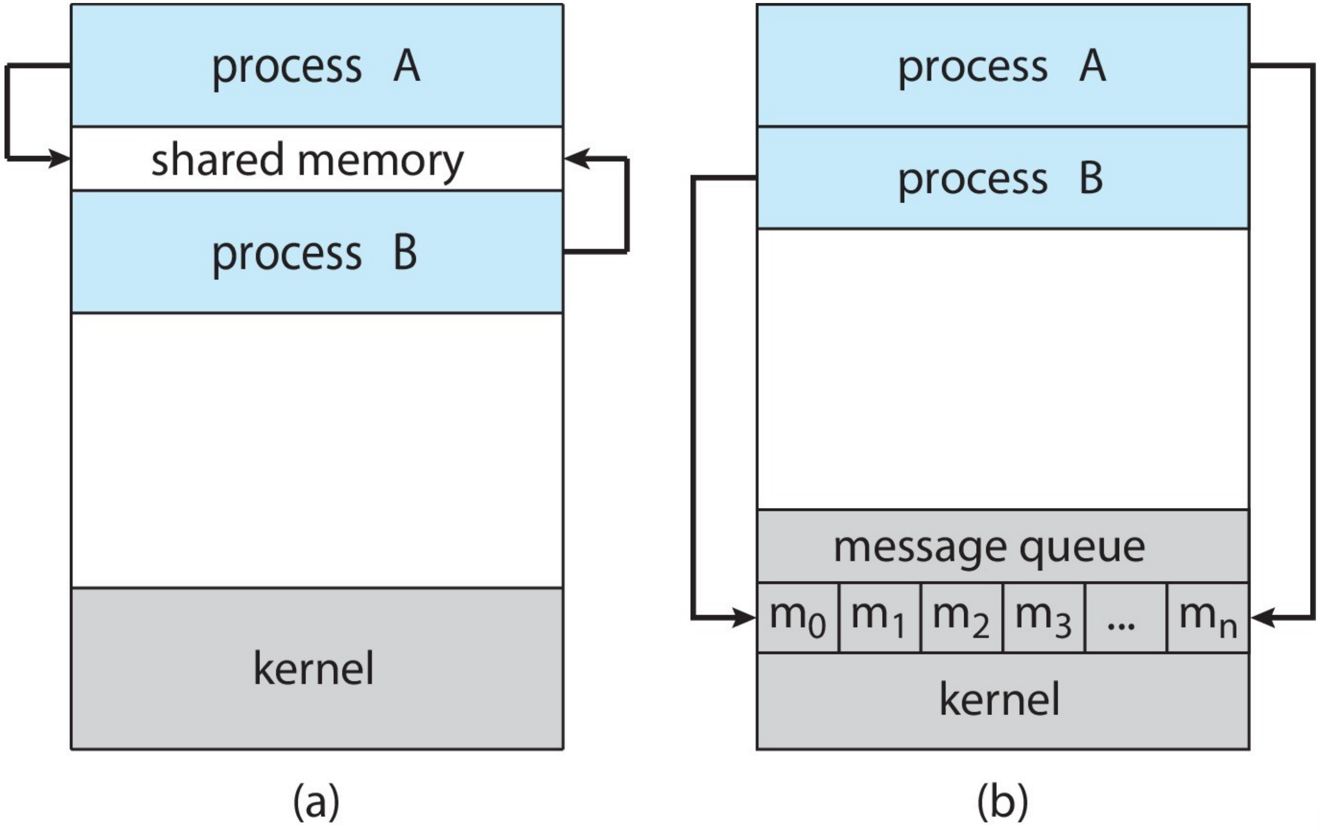
- Cooperating processes need **interprocess communication** (**IPC**), a mechanism that allows them to exchange data.
- Two models of IPC:
  - **Shared memory**
  - **Message passing**



Communications Models

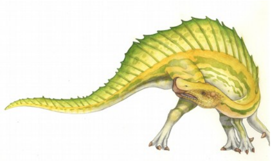
(a) Shared memory.

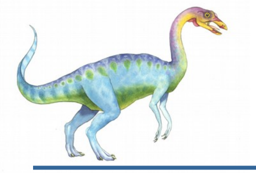
(b) Message passing.



Interprocess Communication – Shared Memory

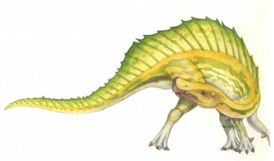
- An area of memory shared among the processes that wish to communicate
- With threads (discussed later) sharing memory is easy.
- The communication is under the control of the user processes, not the operating system.
- Processes do not have access to same memory, so operating system must provide mechanism to allow them to create a shared memory region.
- When processes share memory to communicate – **grave danger**! They must synchronize otherwise they risk lots of bad problems (addressed in Chapters 6 and 7).





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
- No buffer means they run in lockstep; as buffer size increases, less need for synchronizing.
- Examples:
  - printer is consumer; word processor is producer
  - compiler produces assembler code; assembler consumes it, producing machine code.
  - pipeline:
    - `grep expr file | sort | uniq`
    - command to left is producer for command to right of pipe

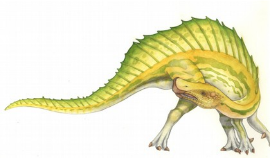


Bounded-Buffer – Shared-Memory Solution

- Shared data

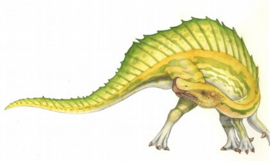
```
#define BUFFER_SIZE 10
typedef struct {
  . . .
} item;

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

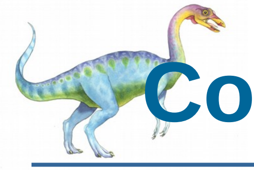
- Assumes processes somehow access shared **`buffer`** and shared variables **`in`** and **`out`**
- This solution uses **`BUFFER_SIZE-1`** elements: treats buffer as a circular queue.
- **`in == out`** *iff* **`buffer`** is empty
- **`(in +1) % BUFFER_SIZE == out`** iff **`buffer`** is full



Producer Process – Shared Memory

```
item next_produced; /* local var in producer */

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





Consumer Process – Shared Memory

```
item next_consumed; /* local var in consumer */

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

       /* consume the item in next_consumed */
}
```

- Why is this correct?
- What does “correct” mean?
  - No data produced is lost before consumed
  - No data produced is consumed more than once
  - What else?

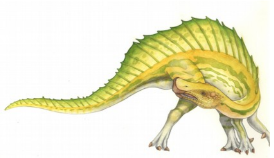
Interprocess Communication – Message Passing

- Mechanism for processes to communicate and to synchronize their actions

- Message system – processes communicate with each other without resorting to shared variables

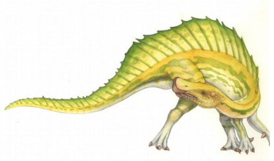
- IPC facility provides two operations:
  - **`send`**([destination,] *message*)
  - **`receive`**([source,] *message*)

- The *message* size is either fixed or variable
- Usually a destination is required by send and usually a source is required by receive.
- Can be used by processes on remote hosts or on same host, so is very general.



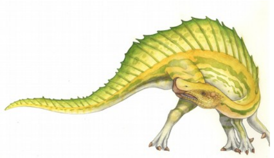
Message Passing (Cont.)

- 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?
  - Do links have buffering?
  - Is the size of a message that the link can accommodate fixed or variable?
  - Is a link unidirectional or bi-directional? (Do we need two separate links for messages from P to Q and from Q to P?)



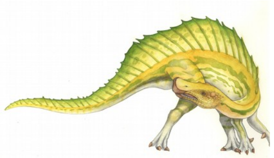
Message Passing (Cont.)

- Implementation of communication link
  - Physical:
    - Shared memory
    - Hardware bus
    - Network
  - Logical:
    - Direct or indirect naming of links
    - Blocking or non-blocking transmission (defined soon)
    - Symmetric or asymmetric communication (e.g., send is non-blocking but receive is blocking)
    - Automatic or explicit buffering of link



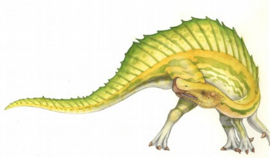
Direct Communication

- Processes must name each other explicitly:
  - **`send`** (*P, message*) – send a message to process P
  - **`receive`**(*Q, message*) – receive a message from process Q
- Names are bound at compile time
- 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
  - Easy to implement
  - Cannot be used for client/server architectures
  - Compile-time binding is very limiting



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
  - **`send`** (A, *message*) – send a message to mailbox A
  - **`receive`**(A, *message*) – receive a message from mailbox A
- Mailboxes might be owned and managed by OS, or by processes.
- 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

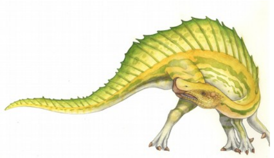
- Operations
  - create a new mailbox (port)
  - send and receive messages through mailbox
  - destroy a mailbox
- Primitives are defined as:

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

  `receive`(*A, message*) – receive a message from mailbox A
- If process creates mailbox, it owns it.
- If process creates child processes they can access sometimes:
  - P creates A
  - P creates child Q
  - Q can receive from or send to A

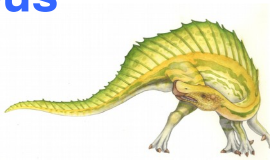
Indirect Communication

- 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.
- Many unanswered questions, such as lost messages, faulty communications, process terminations, scrambled messages, etc



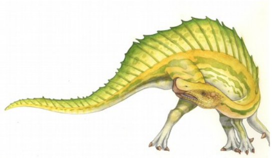
Synchronization

- 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 continues without waiting
  - **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**



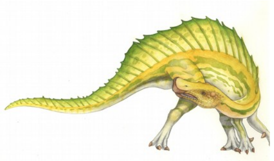
Producer – Message Passing

```
message next_produced;

while (true) {
      /* produce an item in next_produced */

       send(next_produced);
}
```



Consumer– Message Passing

```
message next_consumed;

while (true) {
        receive(next_consumed)

        /* consume the item in next_consumed */
 }
```

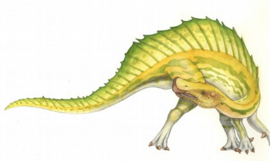


Buffering

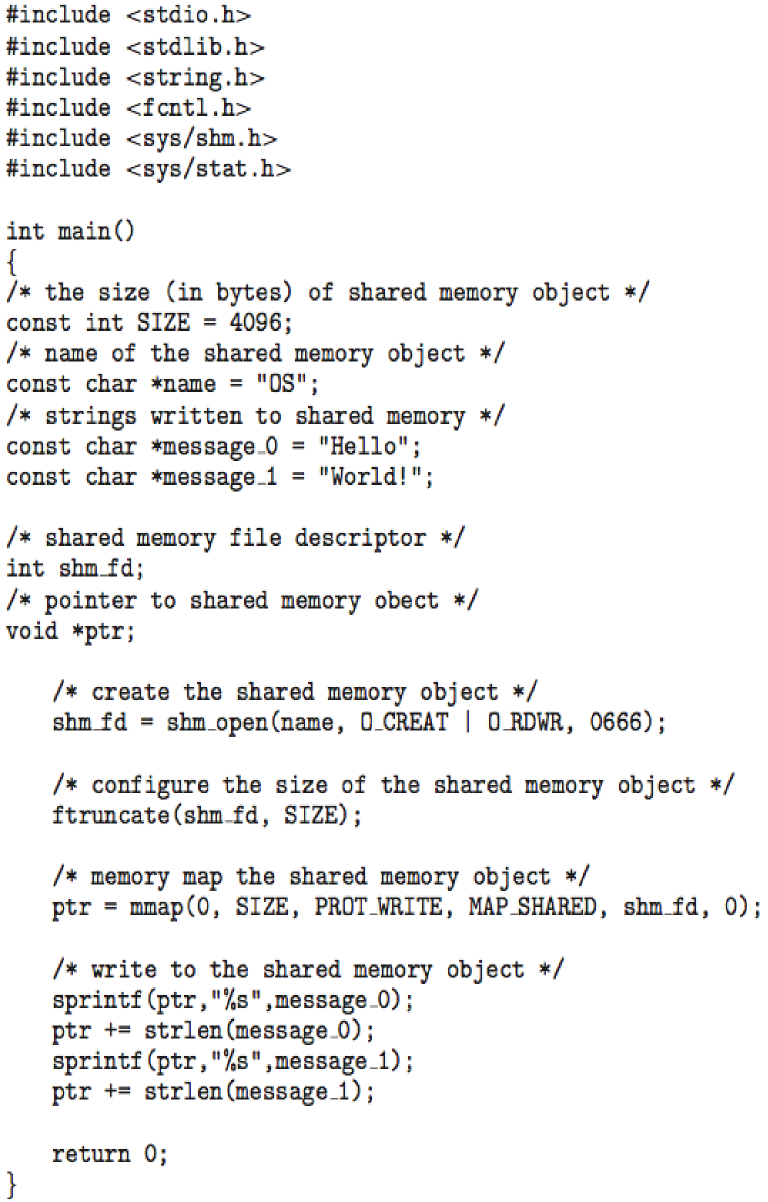
- Queue of messages attached to the link.
- Implemented in one of three ways
  1. Zero capacity – no messages are queued on a link.
     Sender must wait for receiver (rendezvous)
  2. Bounded capacity – finite length of *n* messages
     Sender must wait if link full
  3. Unbounded capacity – infinite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

Examples of IPC Systems - POSIX

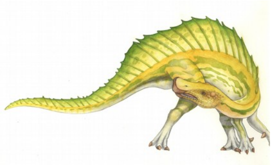
- POSIX Shared Memory
  - Process first creates shared memory segment
    ```
    shm_fd = shm_open(name, O_CREAT | O_RDWR, 0666);
    ```
  - Also used to open an existing segment
  - Set the size of the object
    ```
    ftruncate(shm_fd, 4096);
    ```
  - Use **`mmap()`** to memory-map a file pointer to the shared memory object
  - Reading and writing to shared memory is done by using the pointer returned by **`mmap()`**.



IPC POSIX 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;
}
```

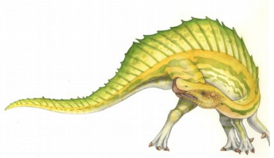


IPC POSIX Consumer

```
#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;
}
```

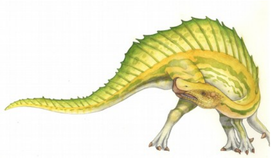
Examples of IPC Systems - Mach

- Mach communication is message based
  - Even system calls are messages
  - Each task gets two ports at creation- Kernel and Notify
  - Messages are sent and received using the **`mach_msg()`** function
  - Ports needed for communication, created via **`mach_port_allocate()`**
  - Send and receive are flexible, for example four options if mailbox full:
    - Wait indefinitely
    - Wait at most n milliseconds
    - Return immediately
    - Temporarily cache a message

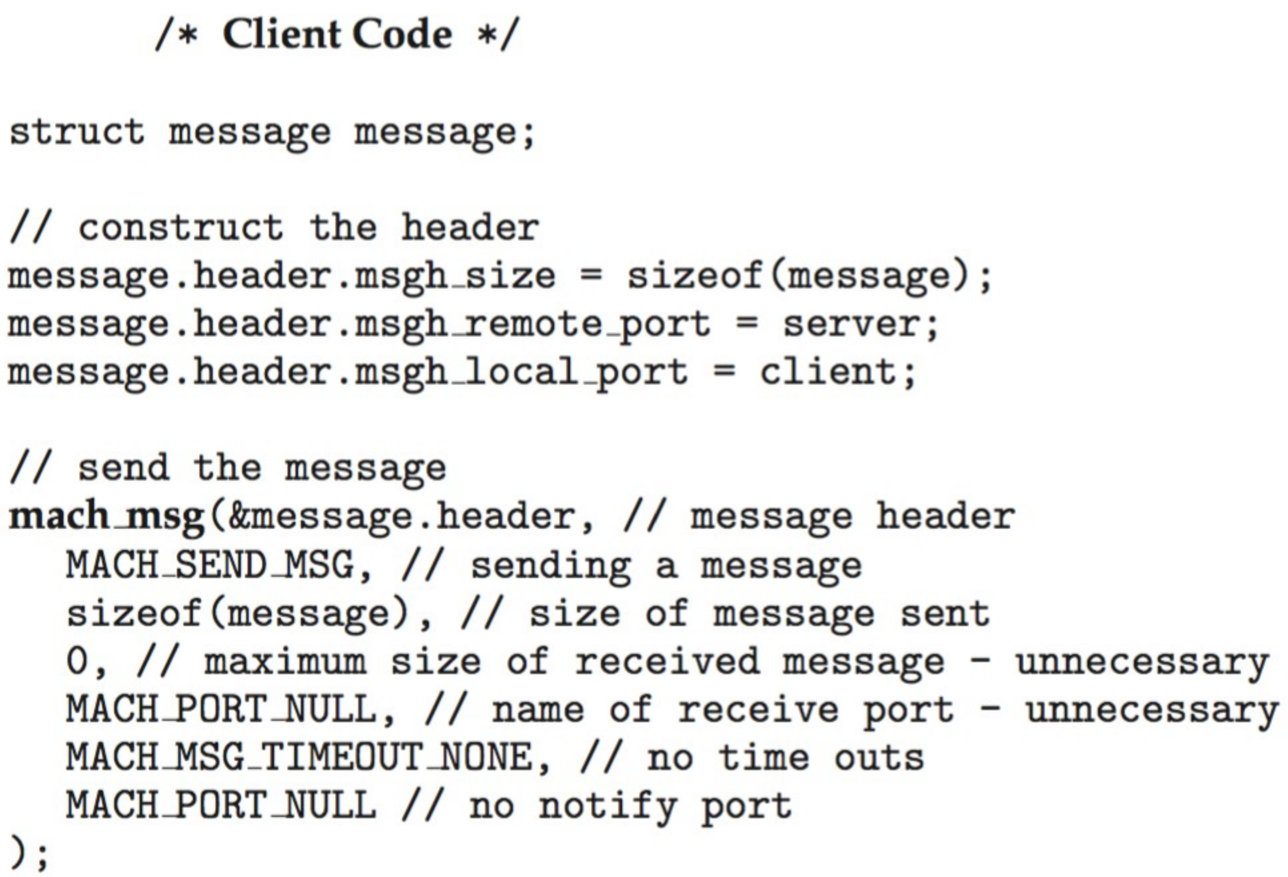


Mach Messages

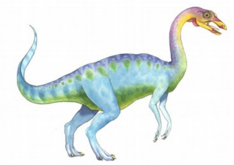
```
#include<mach/mach.h>

struct message {
      mach_msg_header_t header;
      int data;
};

mach port t client;
mach port t server;
```



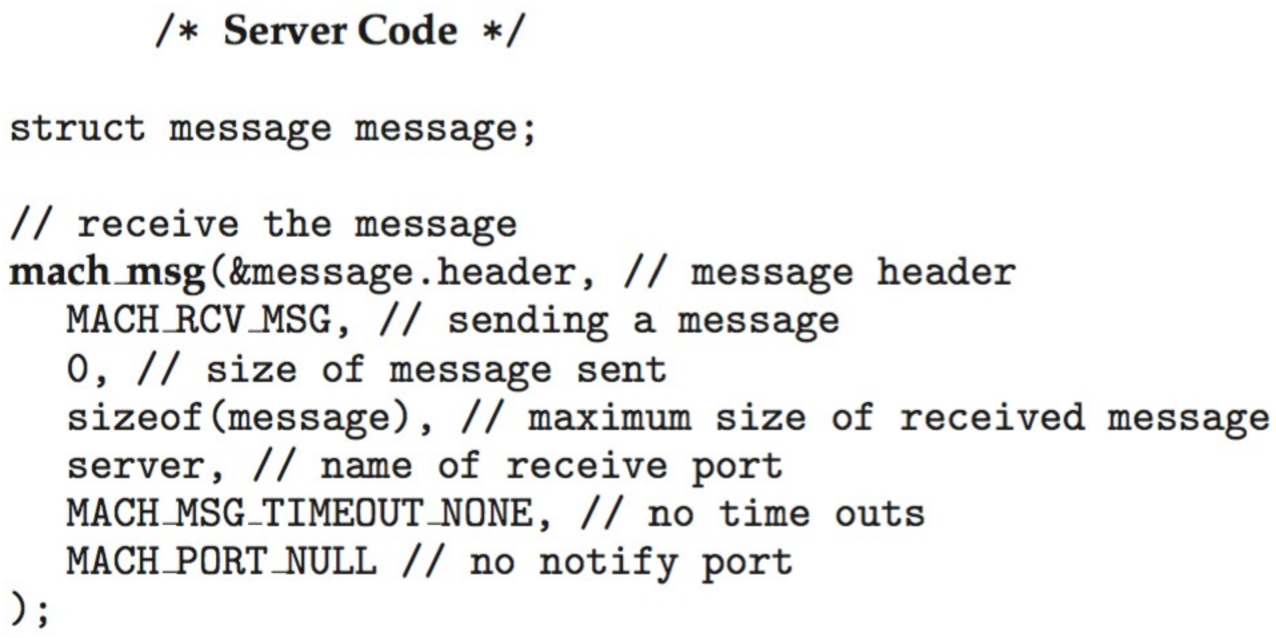
Mach Message Passing - Client



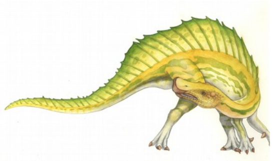
```
        /* Client Code */

struct message message;

// construct the header
message.header.msgh_size = sizeof(message);
message.header.msgh_remote_port = server;
message.header.msgh_local_port = client;

// send the message
mach_msg(&message.header, // message header
   MACH_SEND_MSG, // sending a message
   sizeof(message), // size of message sent
   0, // maximum size of received message - unnecessary
   MACH_PORT_NULL, // name of receive port - unnecessary
   MACH_MSG_TIMEOUT_NONE, // no time outs
   MACH_PORT_NULL // no notify port
);
```



Mach Message Passing - Server

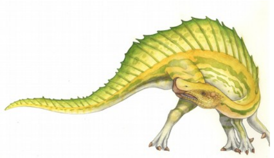


```
/* Server Code */

struct message message;

// receive the message
mach_msg(&message.header, // message header
   MACH_RCV_MSG, // sending a message
   0, // size of message sent
   sizeof(message), // maximum size of received message
   server, // name of receive port
   MACH_MSG_TIMEOUT_NONE, // no time outs
   MACH_PORT_NULL // no notify port
);
```



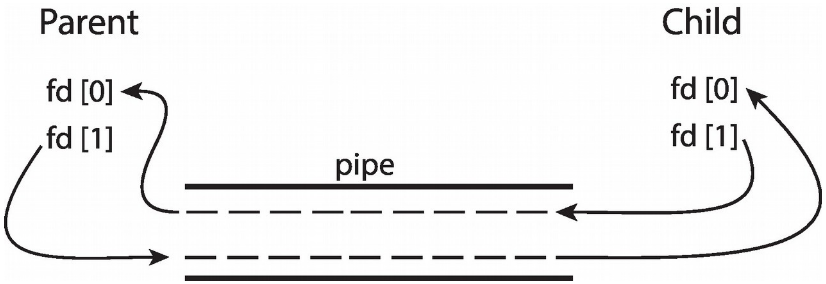
Pipes

- A **pipe** acts as a conduit allowing two processes 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?
- **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.

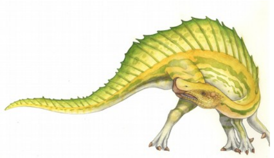


Ordinary Pipes

- ***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
- Require parent-child relationship between communicating processes

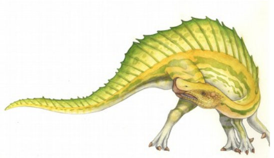


- Windows calls these **anonymous pipes**



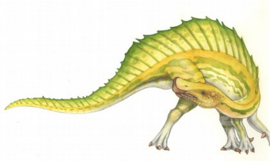
Named Pipes

- ***Named Pipes*** are more powerful than ordinary pipes
- Communication is 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



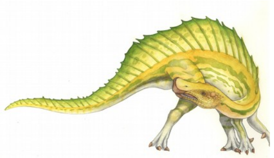
Communications in Client-Server Systems

- Sockets
- Remote Procedure Calls

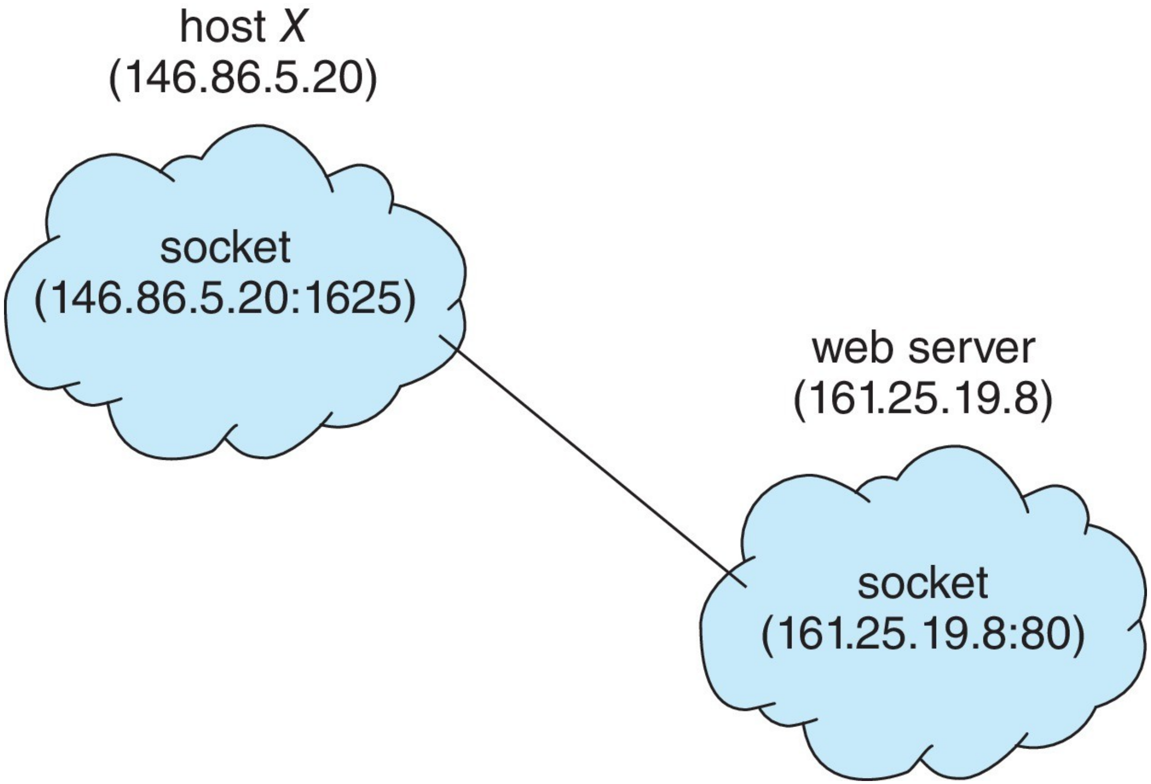


Sockets

- A **socket** is defined as an endpoint for communication
- 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**
- Communication consists between a pair of sockets
- All ports below 1024 are ***well known***, used for standard services
- Special IP address 127.0.0.1 (**loopback**) to refer to system on which process is running



Socket Communication



End of Chapter 3