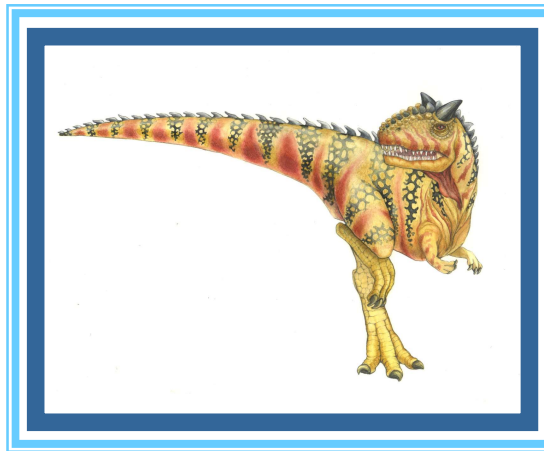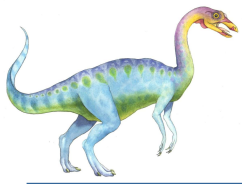# Chapter 3: Processes

# Outline

- Process Concept
- Process Scheduling
- Operations on Processes
- Interprocess Communication
- IPC in Shared-Memory Systems
- IPC in Message-Passing Systems
- Examples of IPC Systems
- Communication in Client-Server 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 interprocess communication using shared memory and message passing.

- Design programs that uses pipes and POSIX shared memory to perform interprocess communication.

- Describe client-server communication using sockets and remote procedure calls.

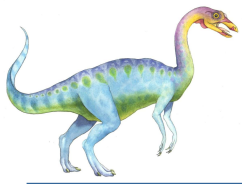- Design kernel modules that interact with the Linux operating system.

# Process Concept

- An operating system executes a variety of programs that run as a process.

- **Process** – a program in execution; process execution must progress in sequential fashion. No parallel execution of instructions of a single process

- Multiple parts

  - The program code, also called **text section**

  - Current activity including **program counter**, processor registers

  - **Stack** containing temporary data

    - Function parameters, return addresses, local variables

  - **Data section** containing global variables

  - **Heap** containing memory dynamically allocated during run time
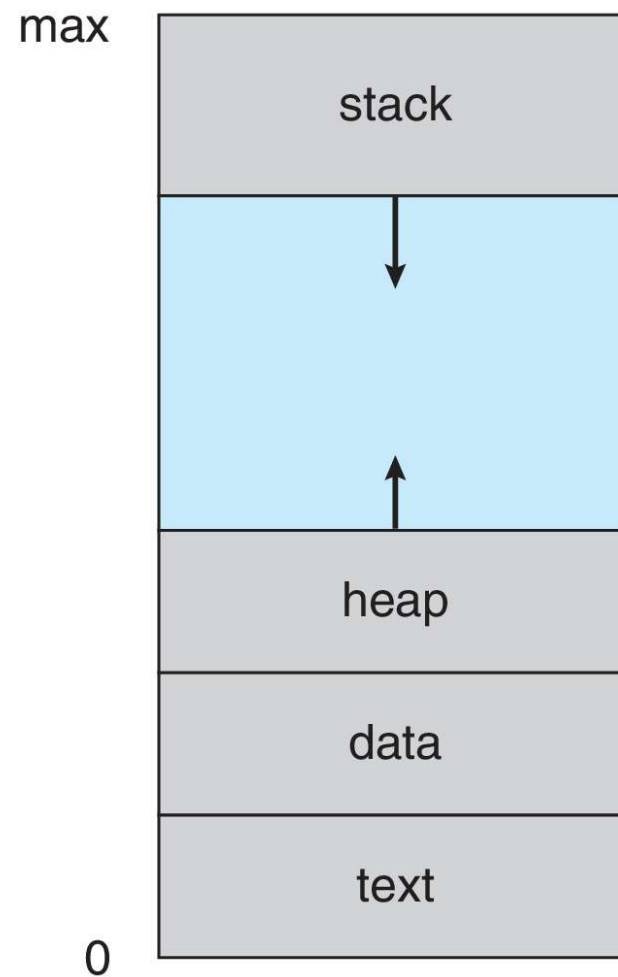
# Process Concept (Cont.)

- Program is **passive** entity stored on disk (**executable file**); process is **active**

  - Program becomes process when an executable file is loaded into memory

- Execution of program started via GUI mouse clicks, command line entry of its name, etc.

- One program can be several processes

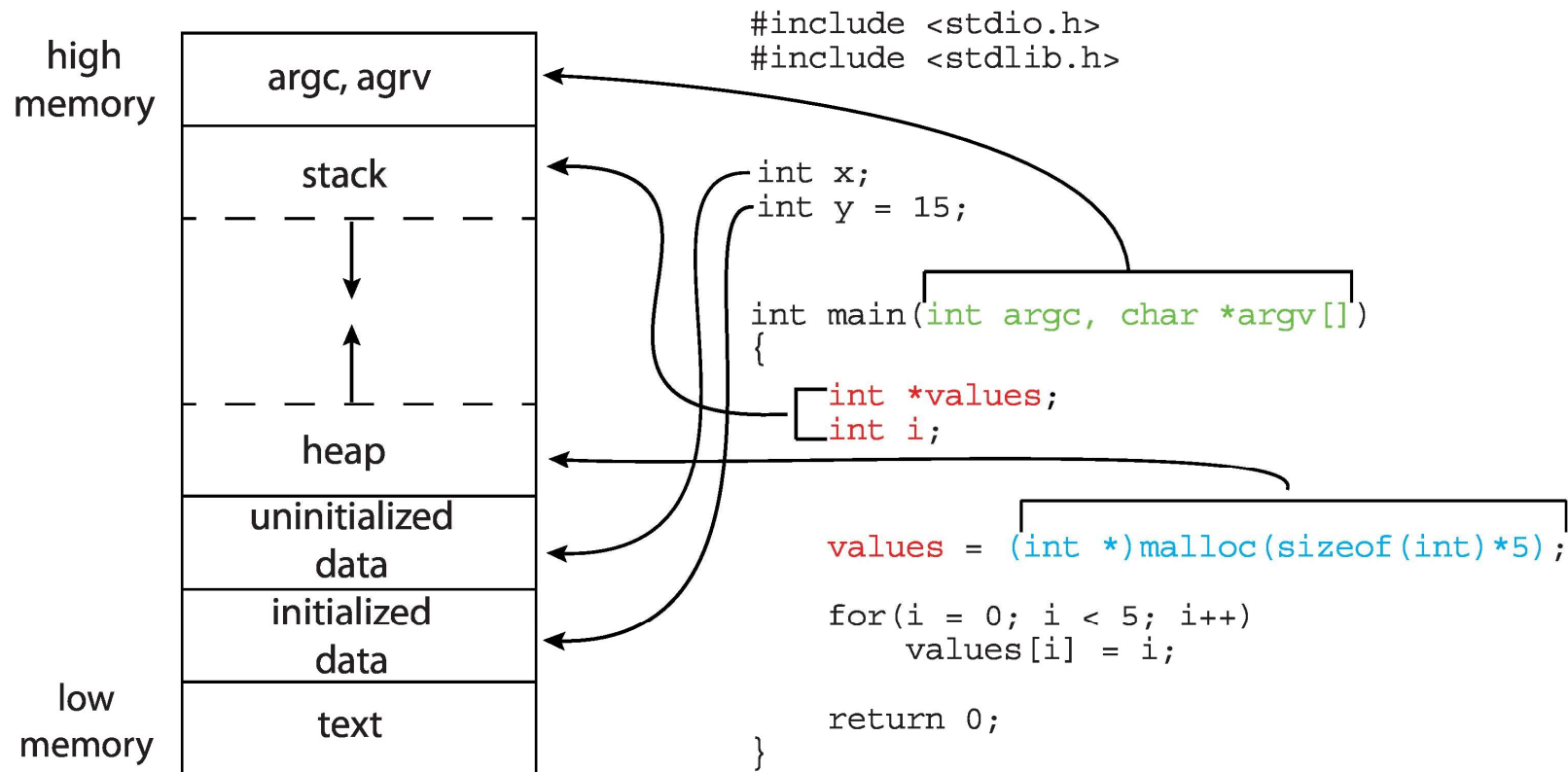  - Consider multiple users executing the same program

# Process in Memory



max

stack

heap

data

text

0

# Memory Layout of a C Program



```
high          ┌─────────────┐
memory        │  argc, agrv │
              ├─────────────┤
              │    stack    │
              │ ┄┄┄┄┄┄┄┄┄ │
              │      ↓      │
              │      ↑      │
              │ ┄┄┄┄┄┄┄┄┄ │
              │    heap     │
              ├─────────────┤
              │uninitialized│
              │    data     │
              ├─────────────┤
              │ initialized │
low           │    data     │
memory        ├─────────────┤
              │    text     │
              └─────────────┘
```

```c
#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;
}
```
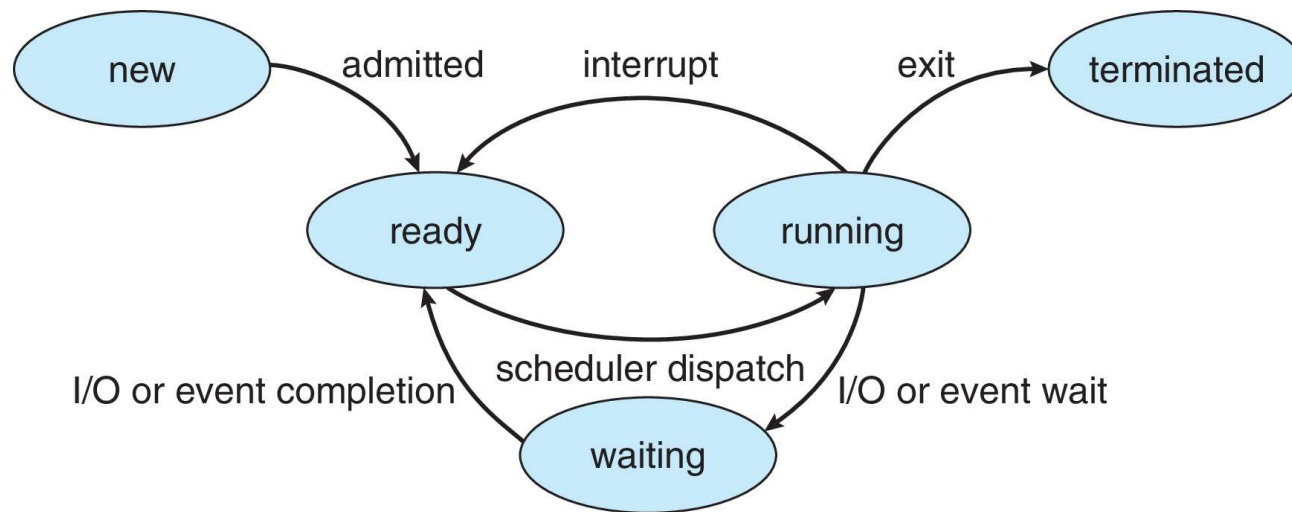
# Process State

- 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

# Diagram of Process State

# 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

| process state |
| --- |
| process number |
| program counter |
| registers |
| memory limits |
| list of open files |
| • • • |

# Threads

- So far, process has a single thread of execution

- Consider having multiple program counters per process

  - Multiple locations can execute at once

    - Multiple threads of control -> **threads**

- Must then have storage for thread details, multiple program counters in PCB

- Explore in detail in Chapter 4
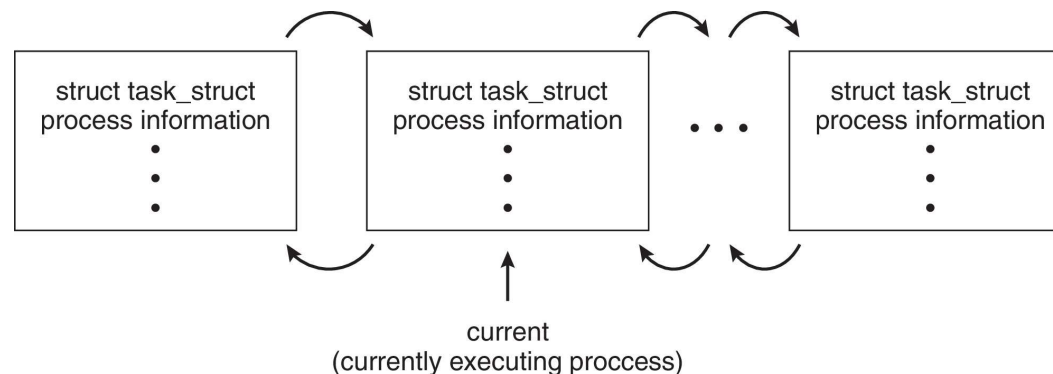
# Process Representation in Linux

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 */
```



```
struct task_struct        struct task_struct              struct task_struct
process information        process information    . . .    process information
        •                         •                                •
        •                         •                                •
        •                         •                                •
```

current
(currently executing proccess)

# Process Scheduling

- **Process scheduler** selects among available processes for next execution on CPU core

- Goal -- Maximize CPU use, 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)
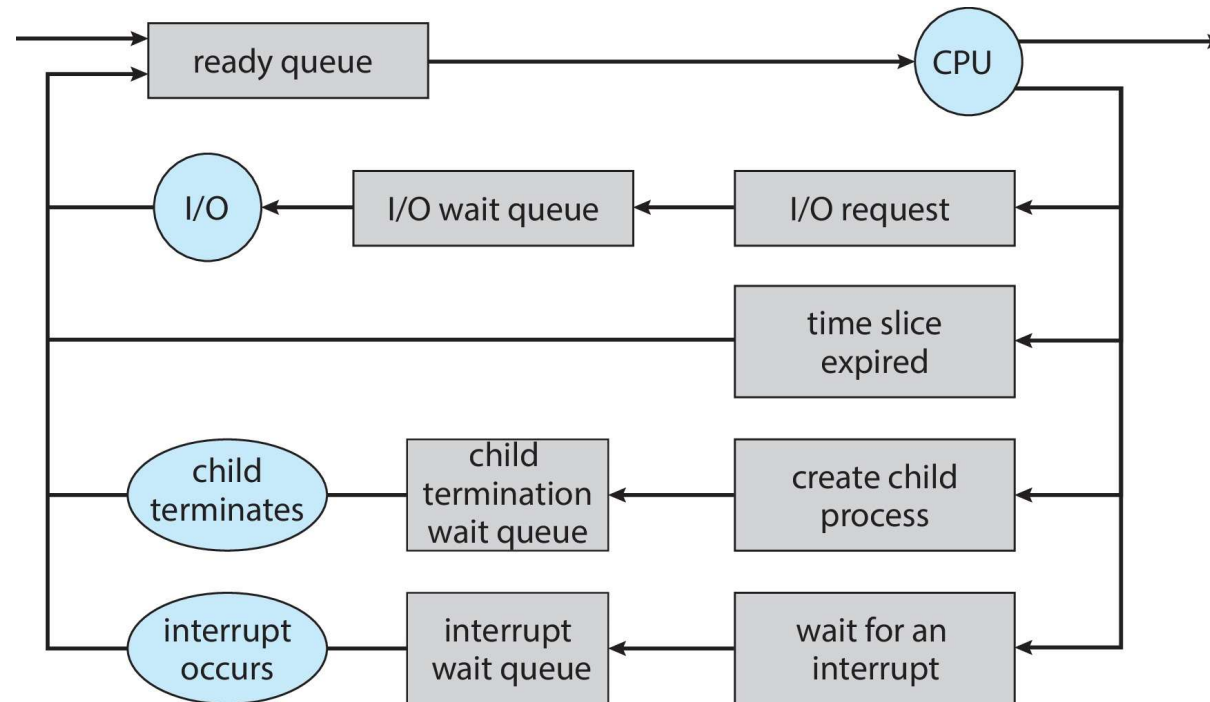
  - Processes migrate among the various queues
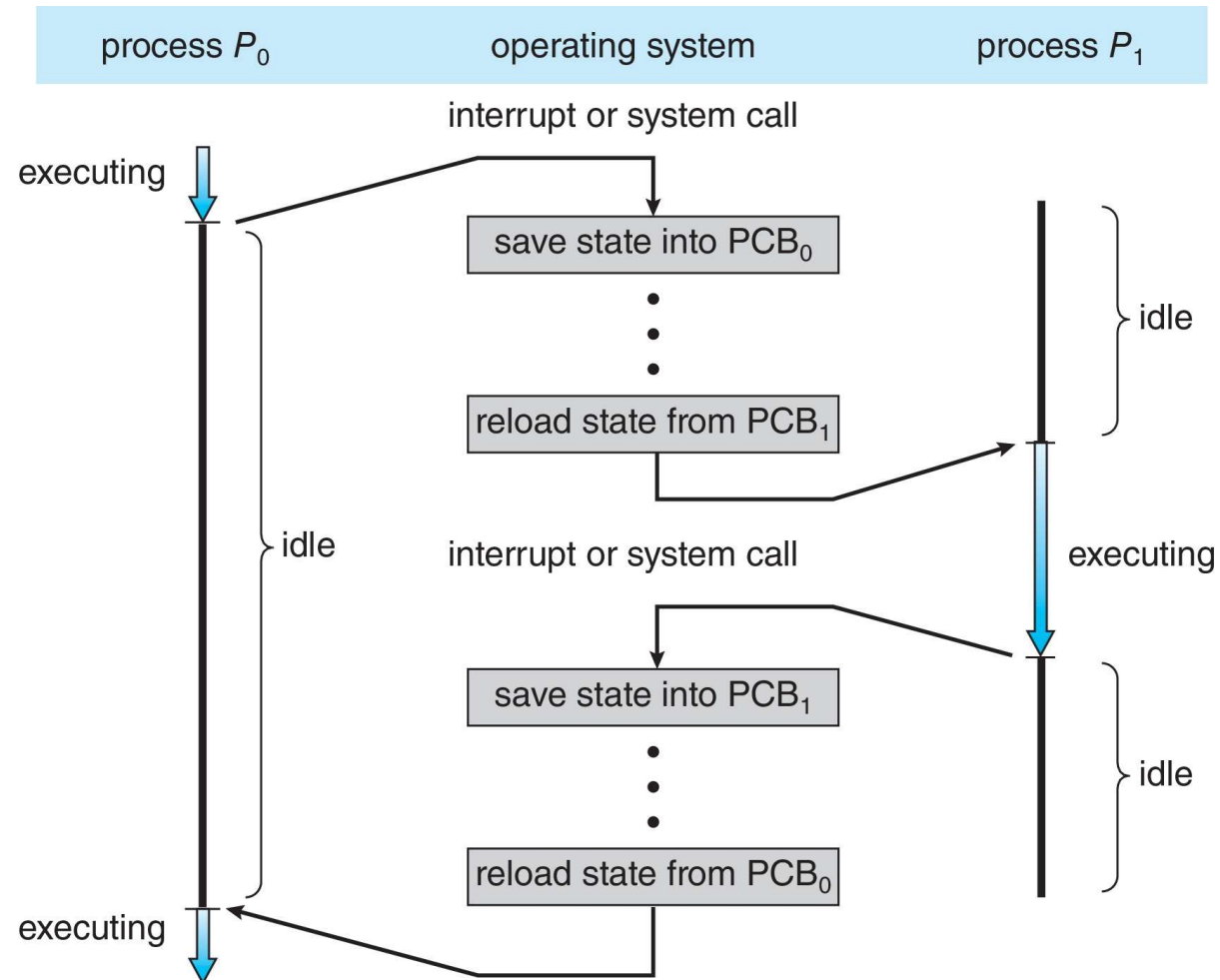
# Ready and Wait Queues
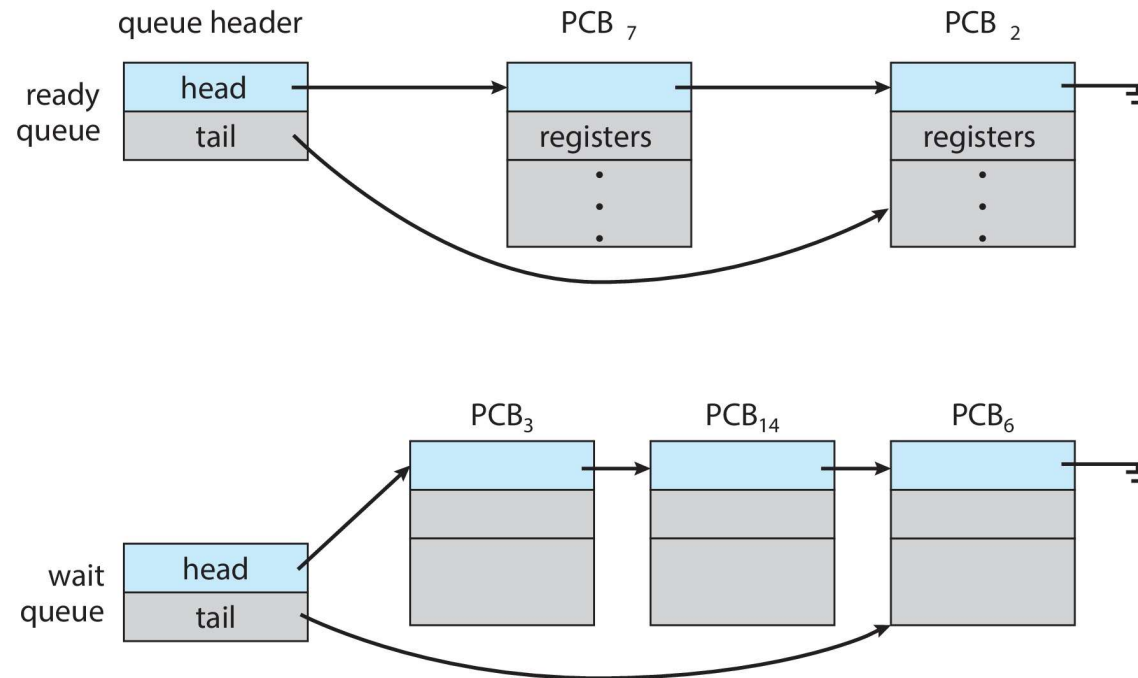
# Representation of Process Scheduling

# CPU Switch From Process to Process

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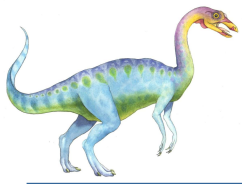
# Context Switch

- 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 pure 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

# Multitasking in Mobile Systems

- Some mobile systems (e.g., early version of iOS) allow only one process to run, others suspended

- Due to screen real estate, user interface limits iOS provides for a

  - 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, with fewer limits

  - Background process uses a **service** to perform tasks

  - Service can keep running even if background process is suspended

  - Service has no user interface, small memory use

# 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

# 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()`** waiting for the child to terminate
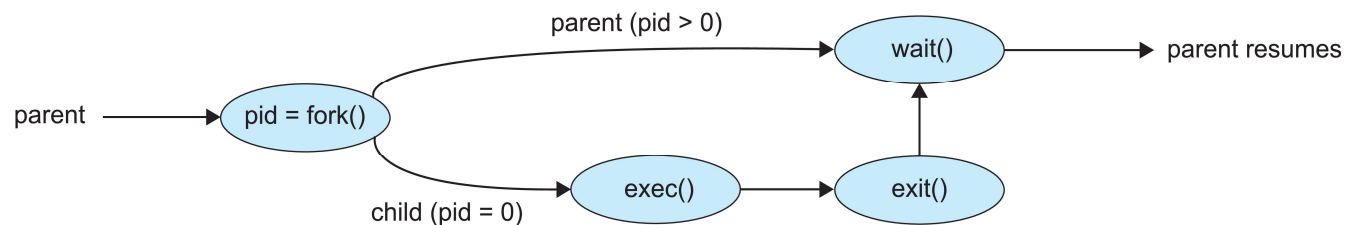
# A Tree of Processes in Linux
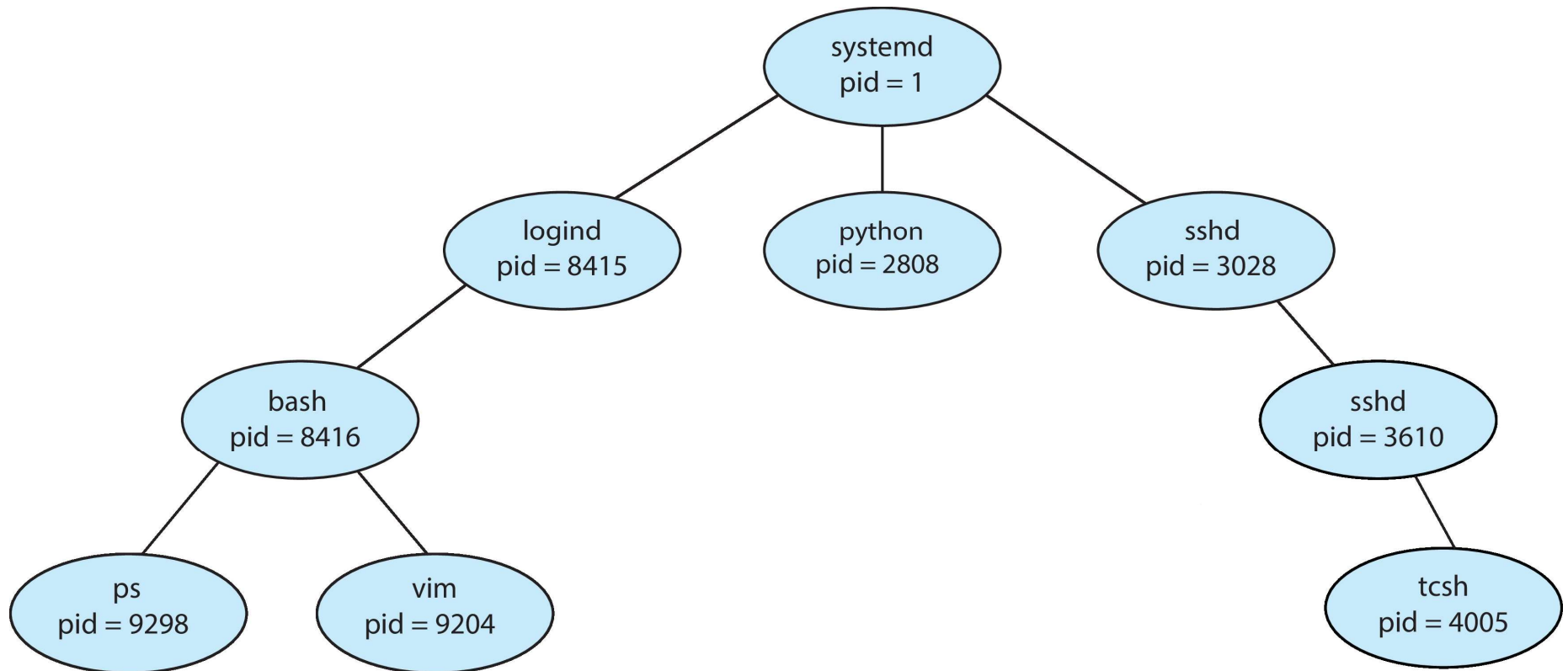
# C Program Forking Separate Process

```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;
}
```

# Creating a Separate Process via Windows API

```c
#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
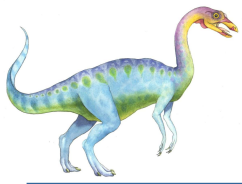
# Process Termination

- 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);
  ```

- 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

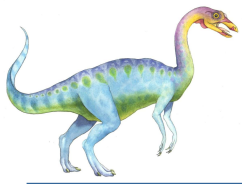- Android will begin terminating processes that are least important.

# Multiprocess Architecture – 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
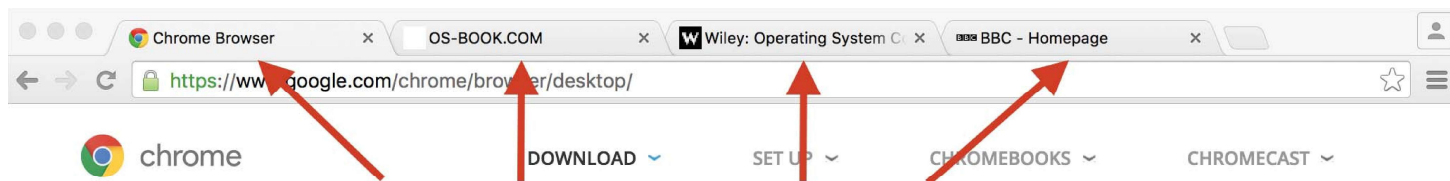


Each tab represents a separate process.

# Interprocess Communication

- 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 **interprocess communication** (**IPC**)

- Two models of IPC
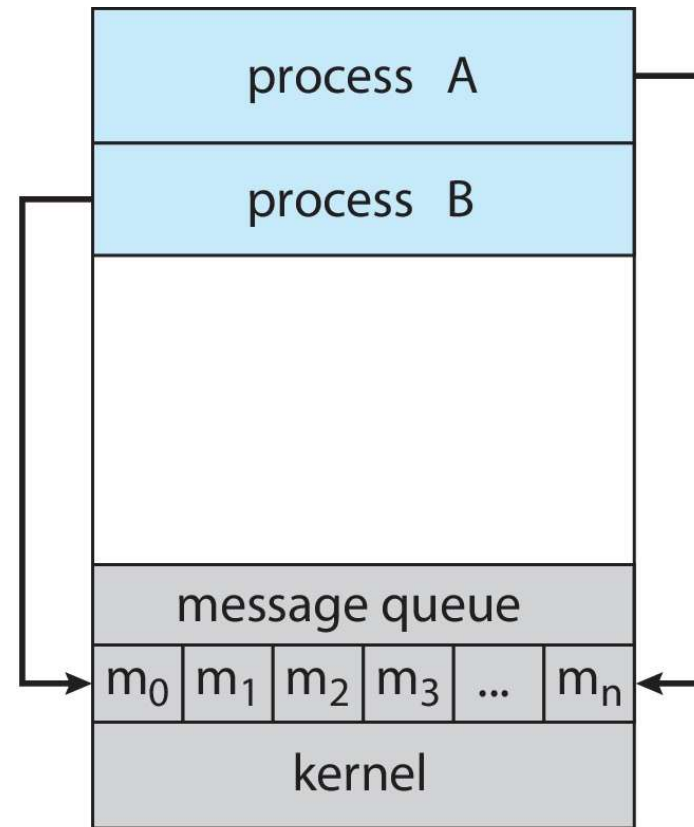
  - **Shared memory**

  - **Message passing**

# Communications Models

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



(a)
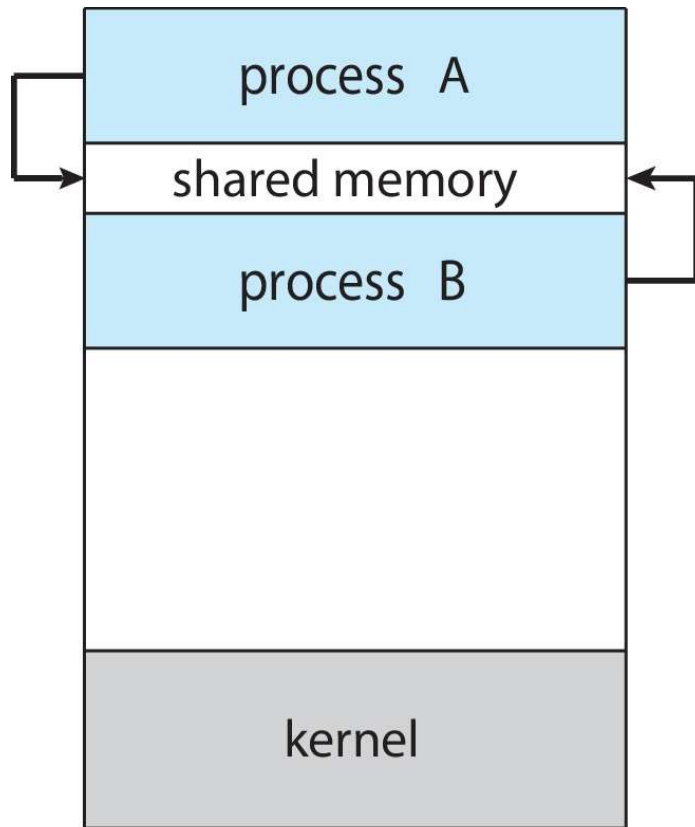


(b)

# Producer-Consumer Problem

- Paradigm for cooperating processes:

  - *producer* process produces information that is consumed by a *consumer* process

- Two variations:

  - **unbounded-buffer** places no practical limit on the size of the buffer:

    - Producer never waits

    - Consumer waits if there is no buffer to consume

  - **bounded-buffer** assumes that there is a fixed buffer size

    - Producer must wait if all buffers are full

    - Consumer waits if there is no buffer to consume

# IPC – 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 Chapters 6 & 7.

# Bounded-Buffer – Shared-Memory Solution

- Shared data

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



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

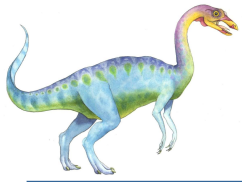- Solution is correct, but can only use `BUFFER_SIZE-1` elements

# 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;
}
```
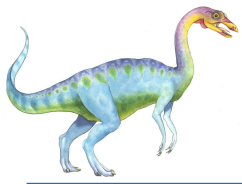
```
item next_consumed;

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

        /* consume the item in next consumed */

}
```

# What about Filling all the Buffers?

- Suppose that we wanted to provide a solution to the consumer-producer problem that fills **all** the buffers.

- We can do so by having an integer `counter` that keeps track of the number of full buffers.

- Initially, `counter` is set to 0.

- The integer `counter` is incremented by the producer after it produces a new buffer.

- The integer `counter` is and is decremented by the consumer after it consumes a buffer.

# Producer

```
while (true) {
        /* produce an item in next produced */

        while (counter == BUFFER_SIZE)
                ; /* do nothing */
        buffer[in] = next_produced;
        in = (in + 1) % BUFFER_SIZE;
        counter++;
}
```

# Consumer

```
while (true) {
        while (counter == 0)
                ; /* do nothing */
        next_consumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        counter--;
        /* consume the item in next consumed */
}
```
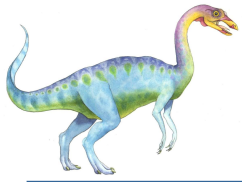
# Race Condition

- **`counter++`** could be implemented as

      register1 = counter
      register1 = register1 + 1
      counter = register1

- **`counter--`** could be implemented as

      register2 = counter
      register2 = register2 - 1
      counter = register2

- Consider this execution interleaving with "count = 5" initially:

      S0: producer execute register1 = counter          {register1 = 5}
      S1: producer execute register1 = register1 + 1     {register1 = 6}
      S2: consumer execute register2 = counter           {register2 = 5}
      S3: consumer execute register2 = register2 – 1     {register2 = 4}
      S4: producer execute counter = register1           {counter = 6 }
      S5: consumer execute counter = register2           {counter = 4}

# Race Condition (Cont.)

- Question – why was there no race condition in the first solution (where at most N – 1) buffers can be filled?

- More in Chapter 6.

# IPC – Message Passing

- Processes communicate with each other without resorting to shared variables

- IPC facility provides two operations:
  - **send**(*message*)
  - **receive**(*message*)

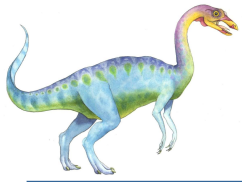- The *message* size is either fixed or variable

# 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?

# 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 (Cont.)

- Operations
  - Create a new mailbox (port)
  - Send and receive messages through mailbox
  - Delete 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 (Cont.)

- 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**
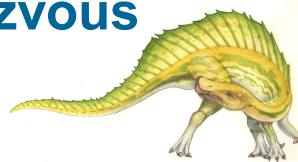
# Producer-Consumer: Message Passing

- Producer

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

   send(next_produced);
 }
```

- Consumer

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

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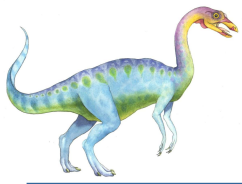
# Buffering

- 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

```c
#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

```c
#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;
}
```
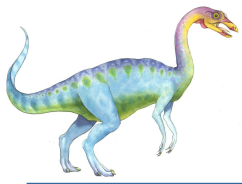
# Examples of IPC Systems - Mach

- 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
);
```

# Examples of IPC Systems – Windows

- Message-passing centric via **advanced local procedure call (LPC)** facility

  - Only works between processes on the same system

  - Uses ports (like mailboxes) to establish and maintain communication channels

  - Communication works as follows:

    - The client opens a handle to the subsystem's **connection port** object.

    - The client sends a connection request.

    - The server creates two private **communication ports** and returns the handle to one of them to the client.

    - The client and server use the corresponding port handle to send messages or callbacks and to listen for replies.

# Local Procedure Calls in Windows
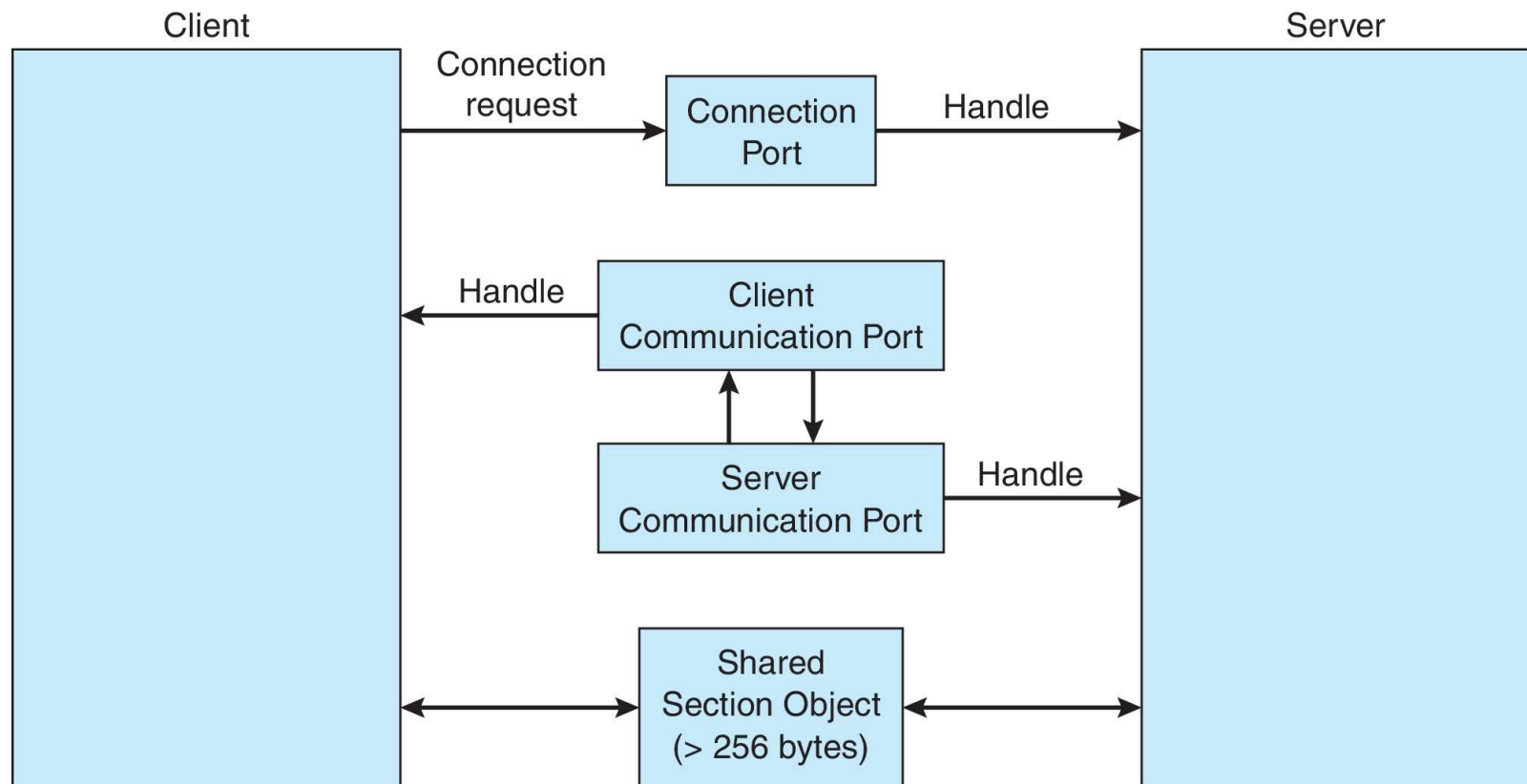
# Pipes

- 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
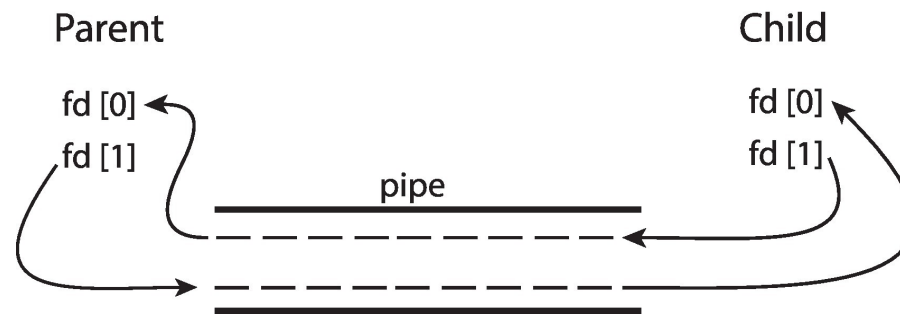


- Windows calls these **anonymous pipes**

# 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



host X
(146.86.5.20)

socket
(146.86.5.20:1625)

web server
(161.25.19.8)
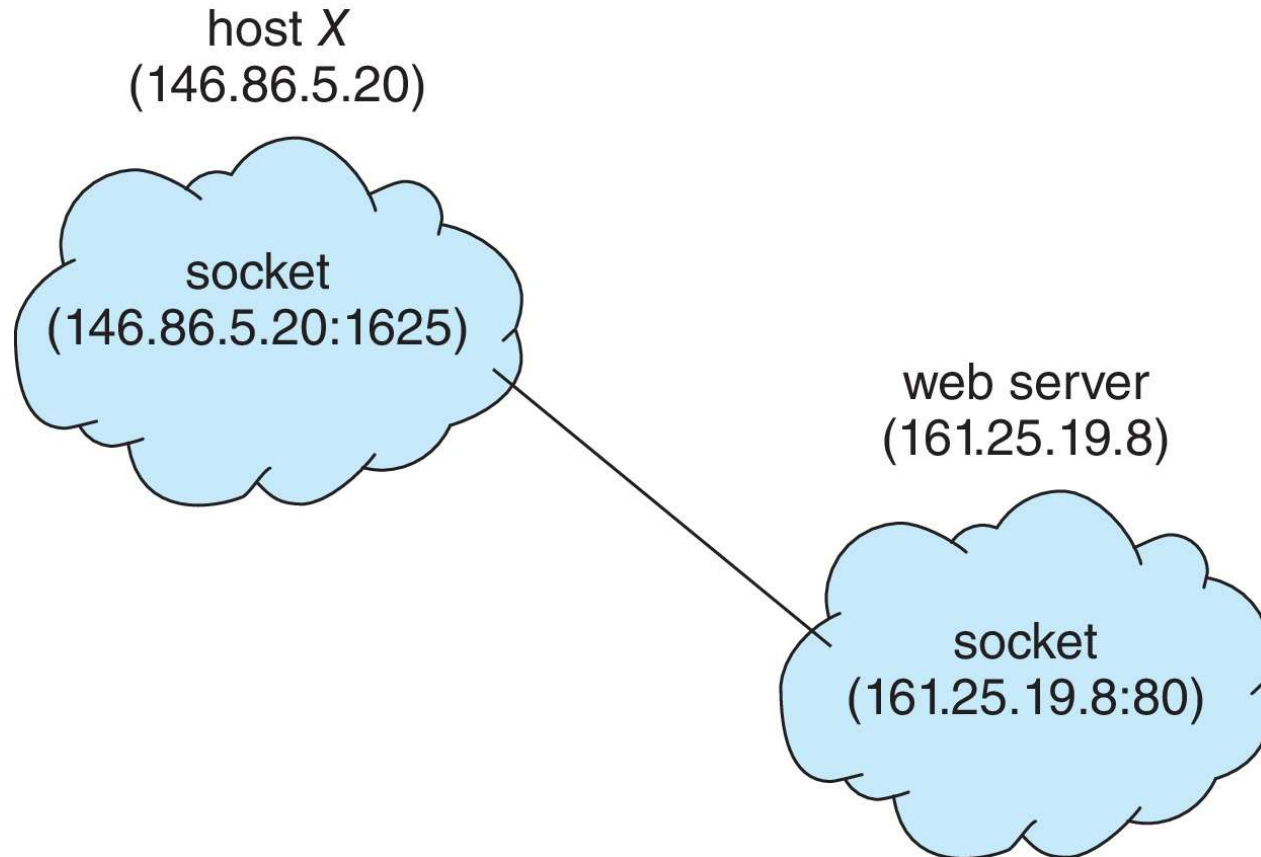
socket
(161.25.19.8:80)

# Sockets in Java

- Three types of sockets

  - **Connection-oriented** (**TCP**)

  - **Connectionless** (**UDP**)

  - `MulticastSocket` class– data can be sent to multiple recipients

- Consider this "Date" server in Java:

```java
import java.net.*;
import java.io.*;

public class DateServer
{
  public static void main(String[] args) {
    try {
      ServerSocket sock = new ServerSocket(6013);

      /* now listen for connections */
      while (true) {
        Socket client = sock.accept();

        PrintWriter pout = new
          PrintWriter(client.getOutputStream(), true);

        /* write the Date to the socket */
        pout.println(new java.util.Date().toString());

        /* close the socket and resume */
        /* listening for connections */
        client.close();
      }
    }
    catch (IOException ioe) {
      System.err.println(ioe);
    }
  }
}
```

# Sockets in Java

The equivalent Date client

```java
import java.net.*;
import java.io.*;

public class DateClient
{
    public static void main(String[] args) {
        try {
            /* make connection to server socket */
            Socket sock = new Socket("127.0.0.1",6013);

            InputStream in = sock.getInputStream();
            BufferedReader bin = new
                BufferedReader(new InputStreamReader(in));

            /* read the date from the socket */
            String line;
            while ( (line = bin.readLine()) != null)
                System.out.println(line);

            /* close the socket connection*/
            sock.close();
        }
        catch (IOException ioe) {
            System.err.println(ioe);
        }
    }
}
```
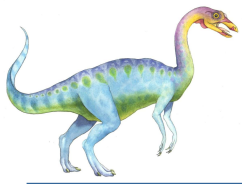
# Remote Procedure Calls

- Remote procedure call (RPC) abstracts procedure calls between processes on networked systems
  - Again uses ports for service differentiation
- **Stubs** – client-side proxy for the actual procedure on the server
- The client-side stub locates the server and **marshalls** the parameters
- The server-side stub receives this message, unpacks the marshalled parameters, and performs the procedure on the server
- On Windows, stub code compile from specification written in **Microsoft Interface Definition Language** (**MIDL**)

# Remote Procedure Calls (Cont.)
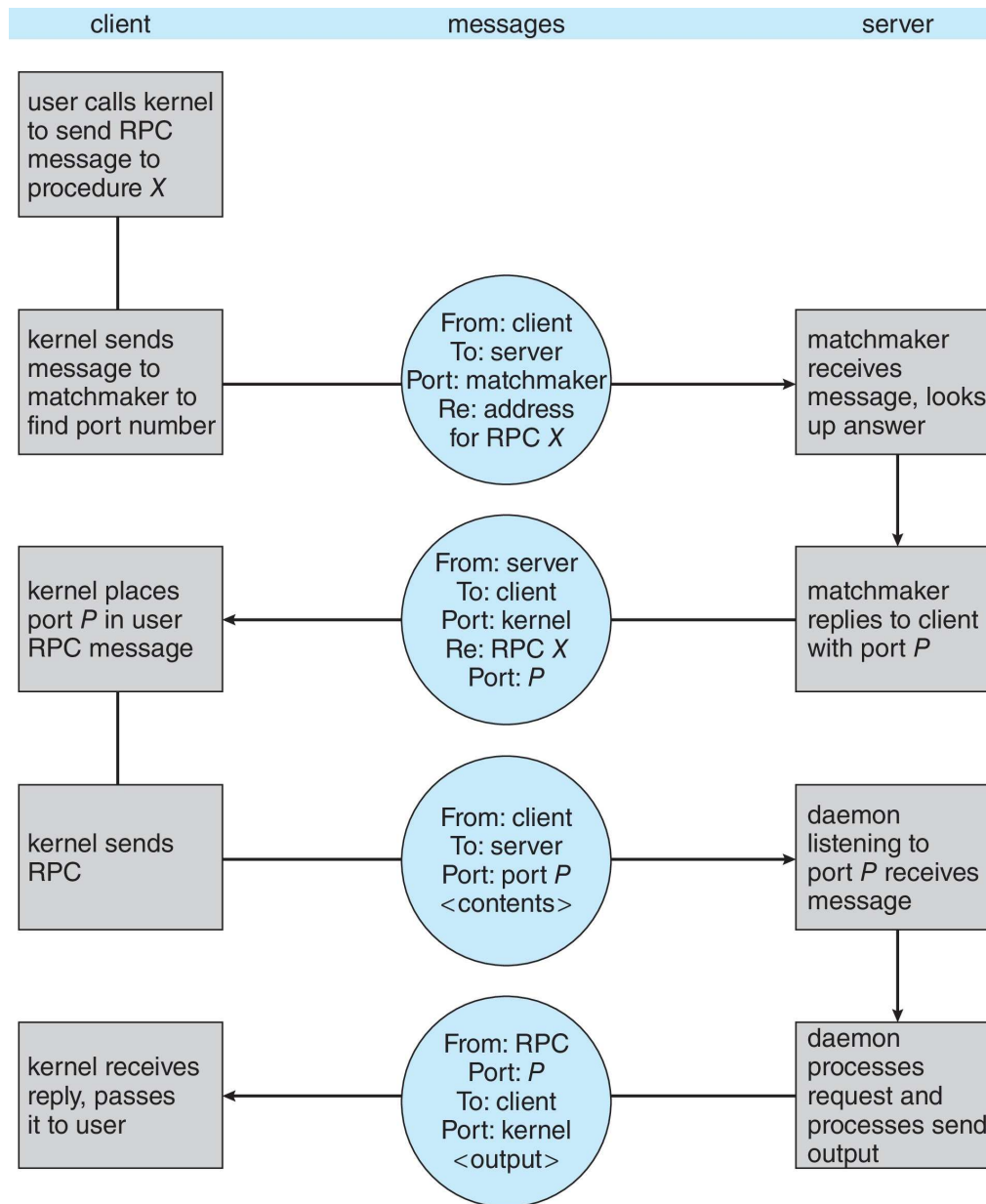
- Data representation handled via **External Data Representation** (**XDL**) format to account for different architectures

  - **Big-endian** and **little-endian**

- Remote communication has more failure scenarios than local

  - Messages can be delivered *exactly once* rather than *at most once*

- OS typically provides a rendezvous (or **matchmaker**) service to connect client and server

# Execution of RPC

| client | messages | server |
|---|---|---|

**user calls kernel to send RPC message to procedure X**

**kernel sends message to matchmaker to find port number**

From: client
To: server
Port: matchmaker
Re: address
for RPC X

**matchmaker receives message, looks up answer**

**kernel places port P in user RPC message**

From: server
To: client
Port: kernel
Re: RPC X
Port: P

**matchmaker replies to client with port P**

**kernel sends RPC**

From: client
To: server
Port: port P
<contents>

**daemon listening to port P receives message**

**kernel receives reply, passes it to user**

From: RPC
Port: P
To: client
Port: kernel

**daemon processes request and processes send output**

# End of Chapter 3