

# Chapter 3: Processes

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# Outline

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- 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

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- 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

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- 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.)

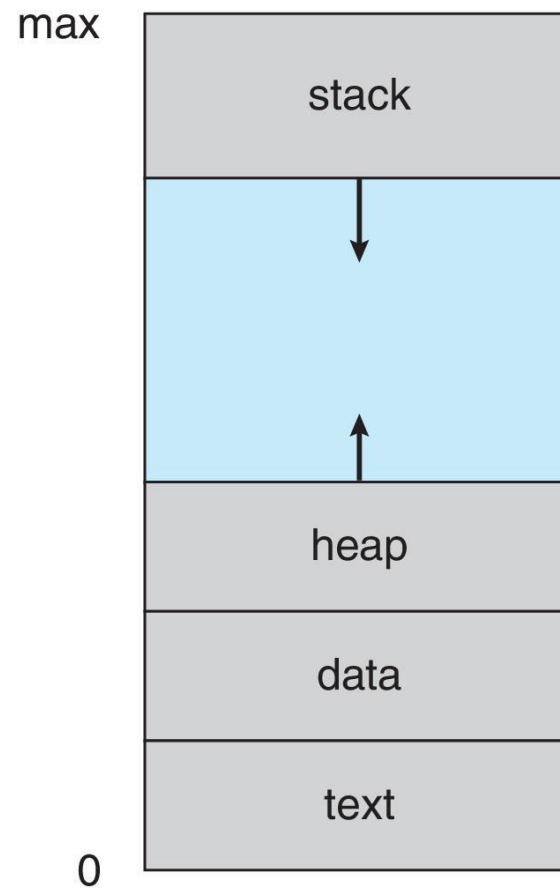
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- Program is **passive** entity stored on disk (**executable file**); process is **active**
  - Program becomes process when an executable file is loaded into memory
- Execution of program started via GUI mouse clicks, command line entry of its name,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



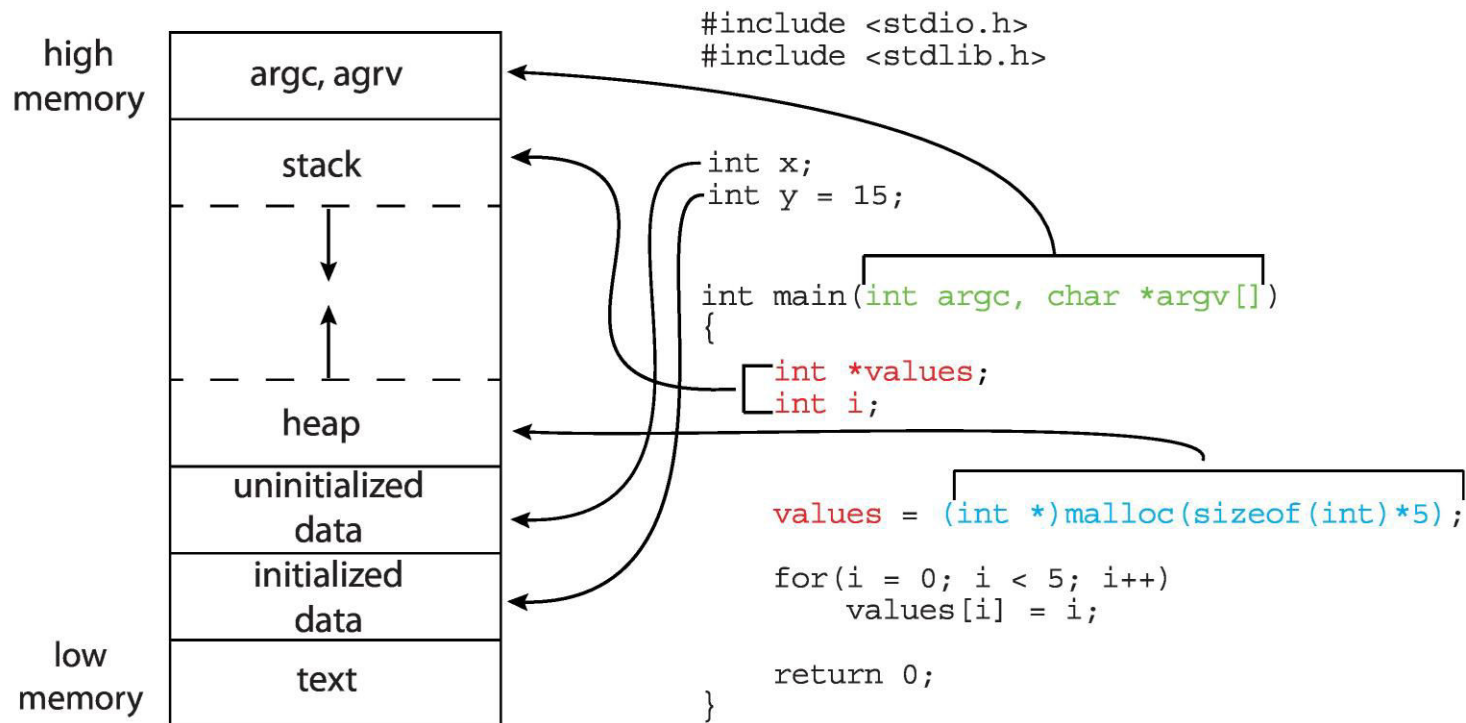


# Process in Memory





# Memory Layout of a C Program





# Process State

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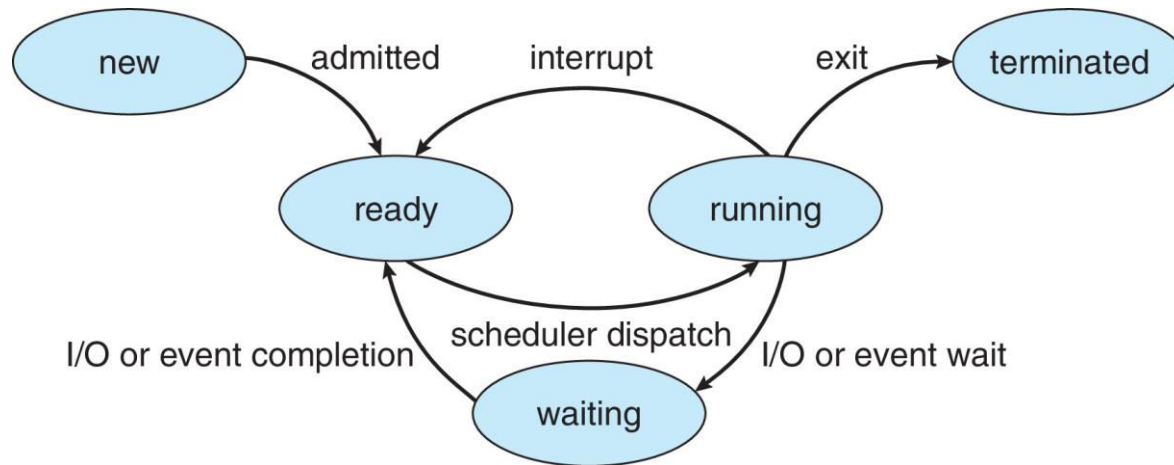
- As a process executes, it changes **state**
  - **New**: The process is being created
  - **Running**: Instructions are being executed
  - **Waiting**: The process is waiting for some event to occur
  - **Ready**: The process is waiting to be assigned to a processor
  - **Terminated**: The process 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

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- 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

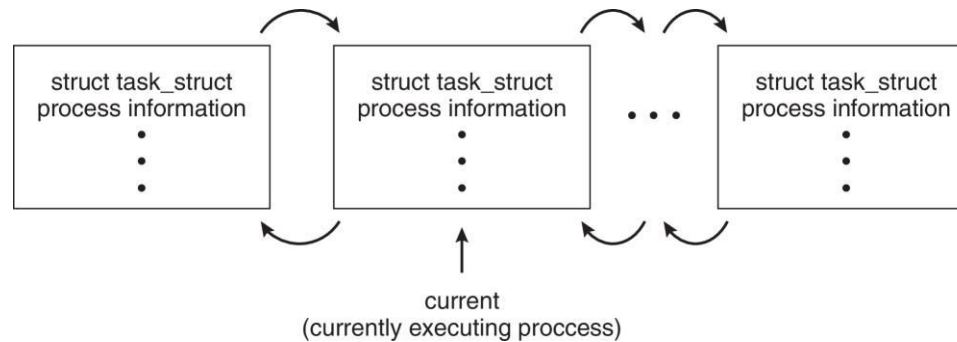




# Process Representation in Linux

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 */
```





# Process Scheduling

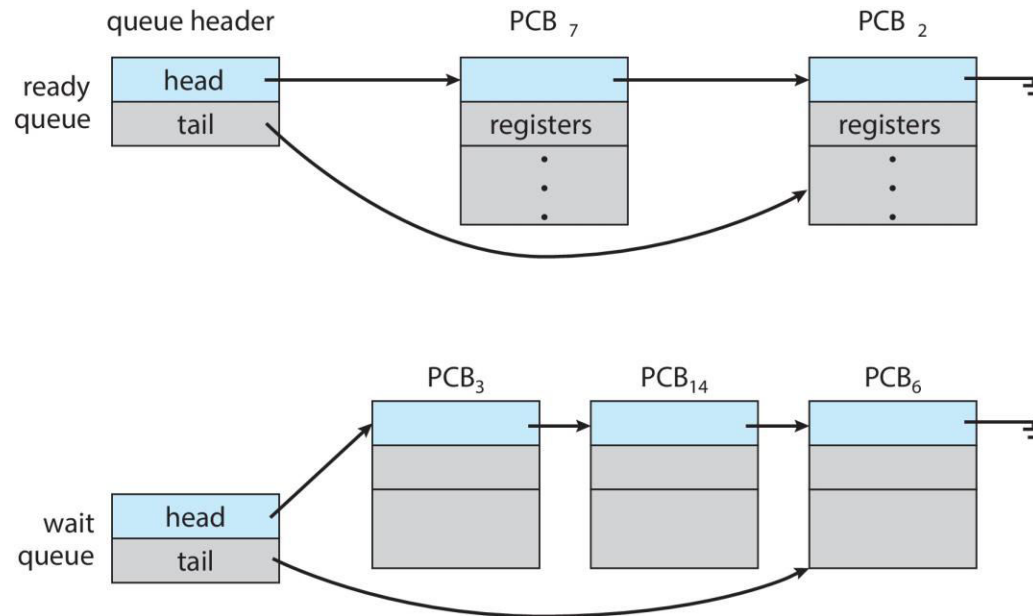
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- **Process scheduler** selects among available processes for next execution on CPU core
- Goal -- Maximize CPU use, quickly switch processes onto CPU core
- Maintains **scheduling queues** of processes
  - **Ready queue** – set of all processes residing 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



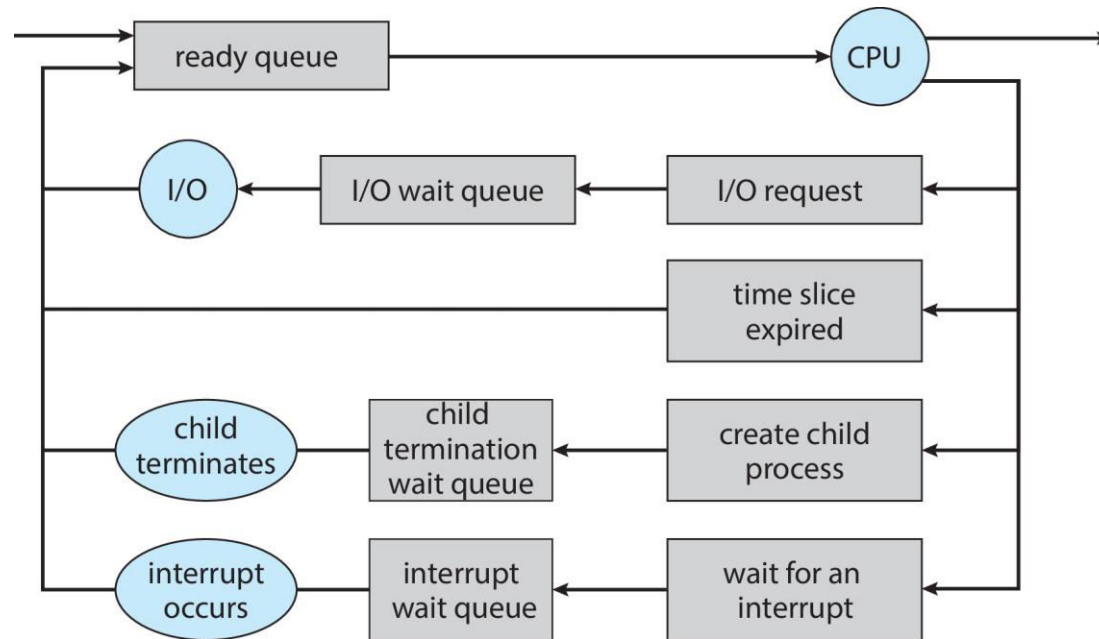


# Ready and Wait Queues





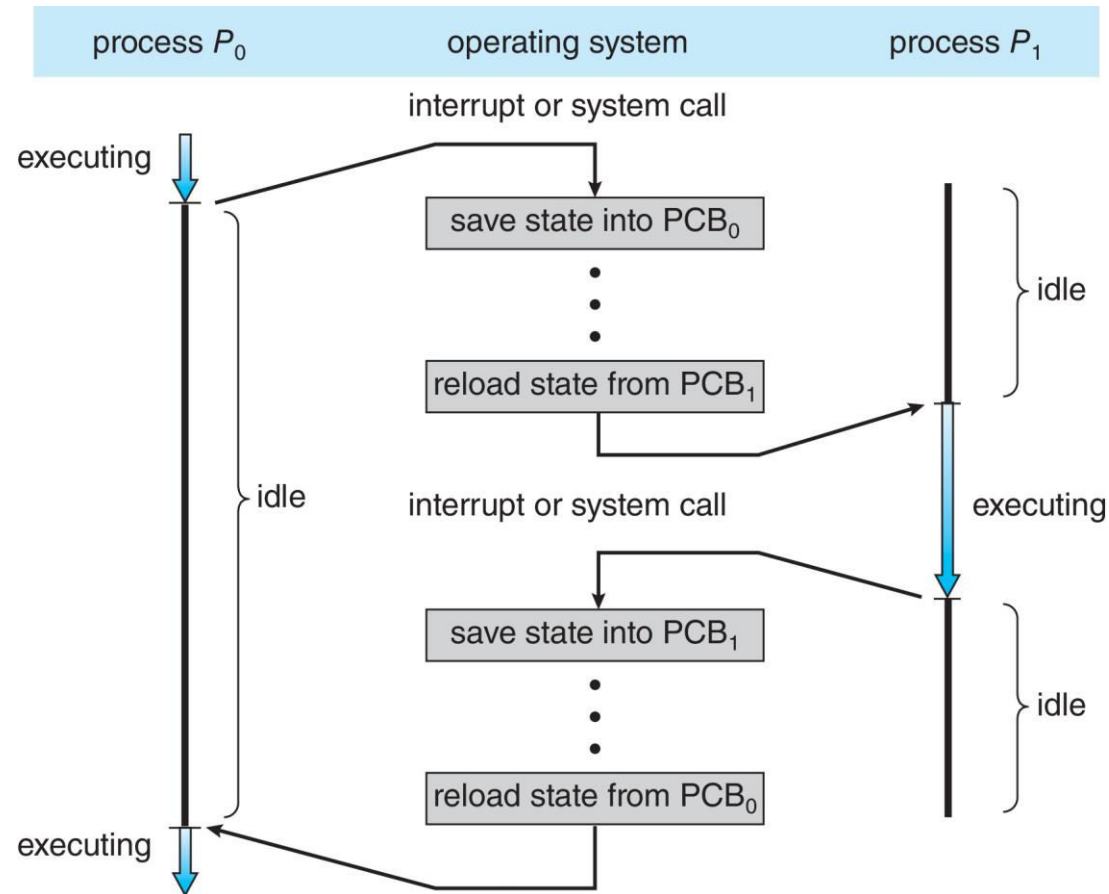
# Representation of Process Scheduling





# CPU Switch From Process to Process

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







# Context Switch

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- 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

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





# Process Creation

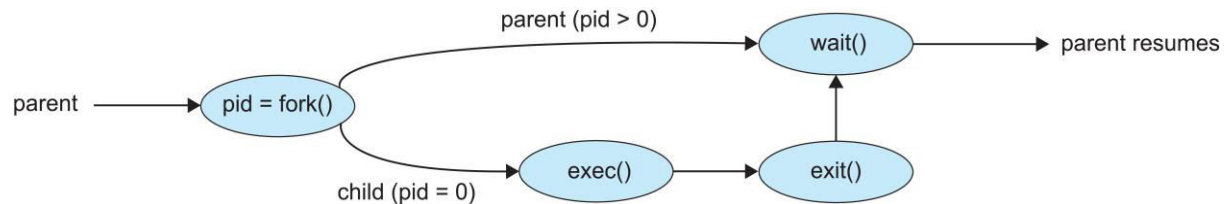
- **Parent** process create **children** processes, which, in turn create other processes, forming a **tree** of processes
- Generally, process identified and managed via a **process identifier (pid)**
- Resource sharing options
  - Parent and children share all resources
  - Children share subset of parent's resources
  - Parent and child share no resources
- Execution options
  - Parent and children execute concurrently
  - Parent waits until children terminate





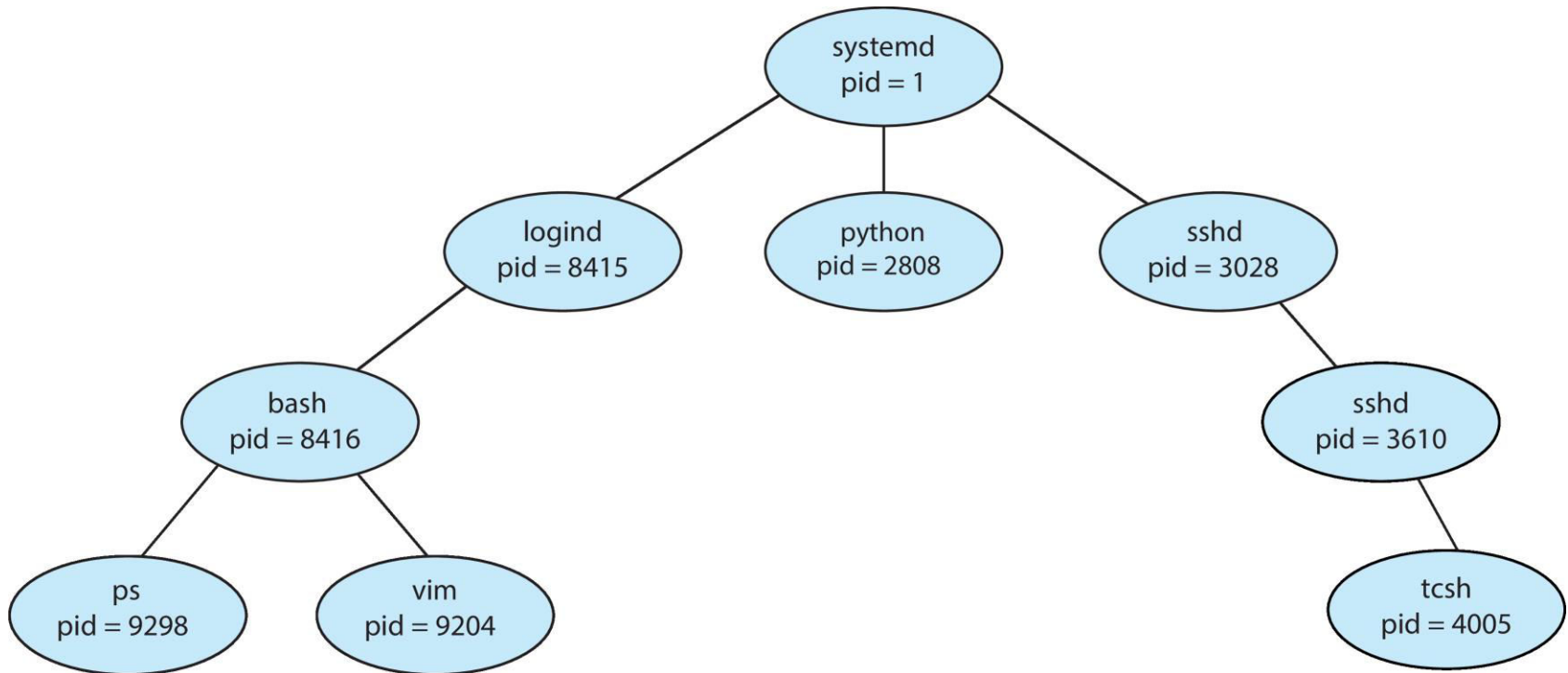
# Process Creation (Cont.)

- 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

```
#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

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- 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 exist 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

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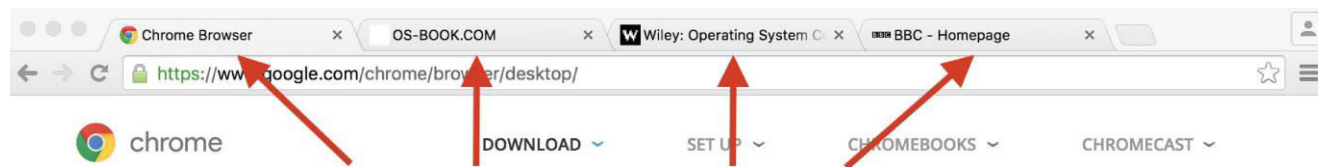
- Mobile operating systems often have to terminate processes to reclaim system resources such as memory. From **most** to **least** important:
  - Foreground process
  - Visible process
  - Service process
  - Background process
  - Empty process
- Android will begin terminating processes that are least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





# Multiprocess Architecture – Chrome Browser

- Many web browsers run 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

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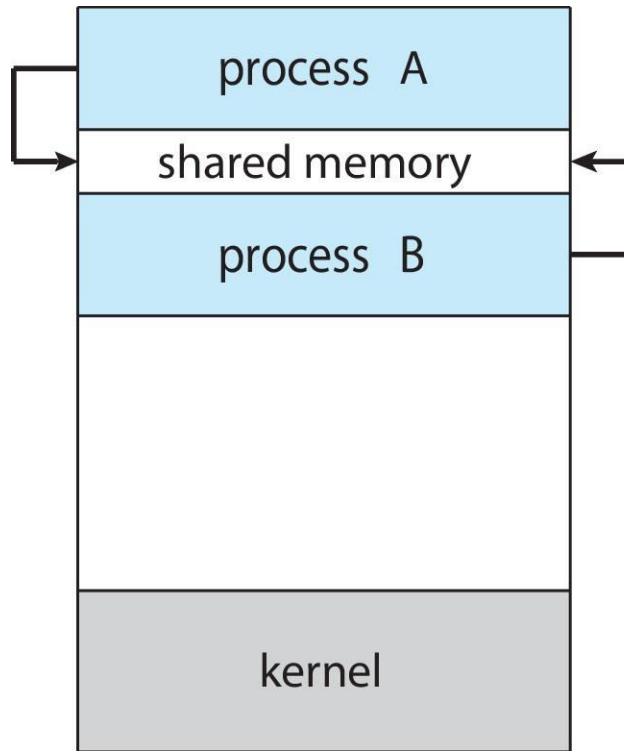
- Processes within a system may be *independent* or *cooperating*
- Cooperating process can affect or be affected by other processes, including sharing data
- Reasons for cooperating processes:
  - Information sharing
  - Computation speedup
  - Modularity
  - Convenience
- Cooperating processes need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





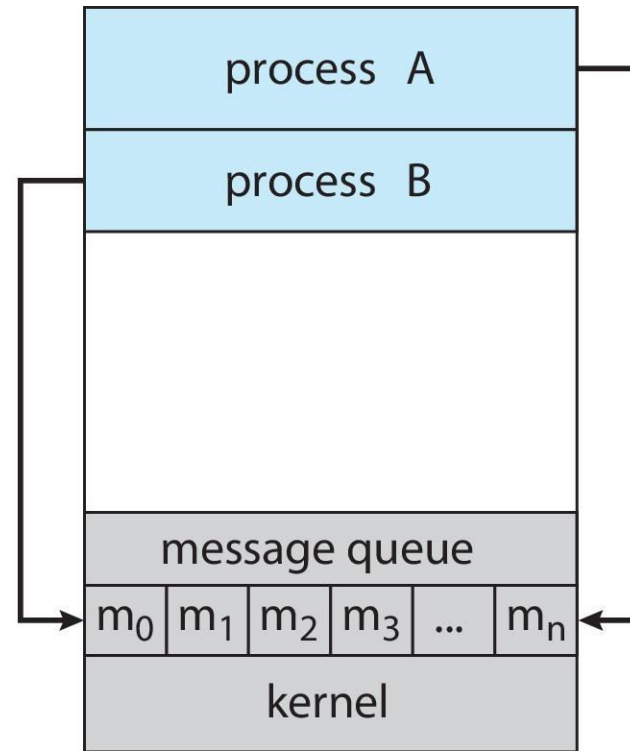
# Communications Models

(a) Shared memory.



(a)

(b) Message passing.



(b)





# Producer-Consumer Problem

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- 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

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- 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;
}
```





# 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 */
}
```





# 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++;  
}
```

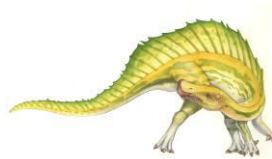




# Consumer

---

```
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	<b>register1 = counter</b>	{register1 = 5}
S1: producer execute	<b>register1 = register1 + 1</b>	{register1 = 6}
S2: consumer execute	<b>register2 = counter</b>	{register2 = 5}
S3: consumer execute	<b>register2 = register2 - 1</b>	{register2 = 4}
S4: producer execute	<b>counter = register1</b>	{counter = 6}
S5: consumer execute	<b>counter = register2</b>	{counter = 4}





# Race Condition (Cont.)

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- 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

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- 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.)

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- 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

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





# Direct Communication

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- 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

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- 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.)

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- 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.

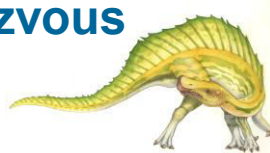




# Synchronization

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

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- 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

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## ■ 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 object */
    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 object */
    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

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- 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

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```
/* 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
);
```





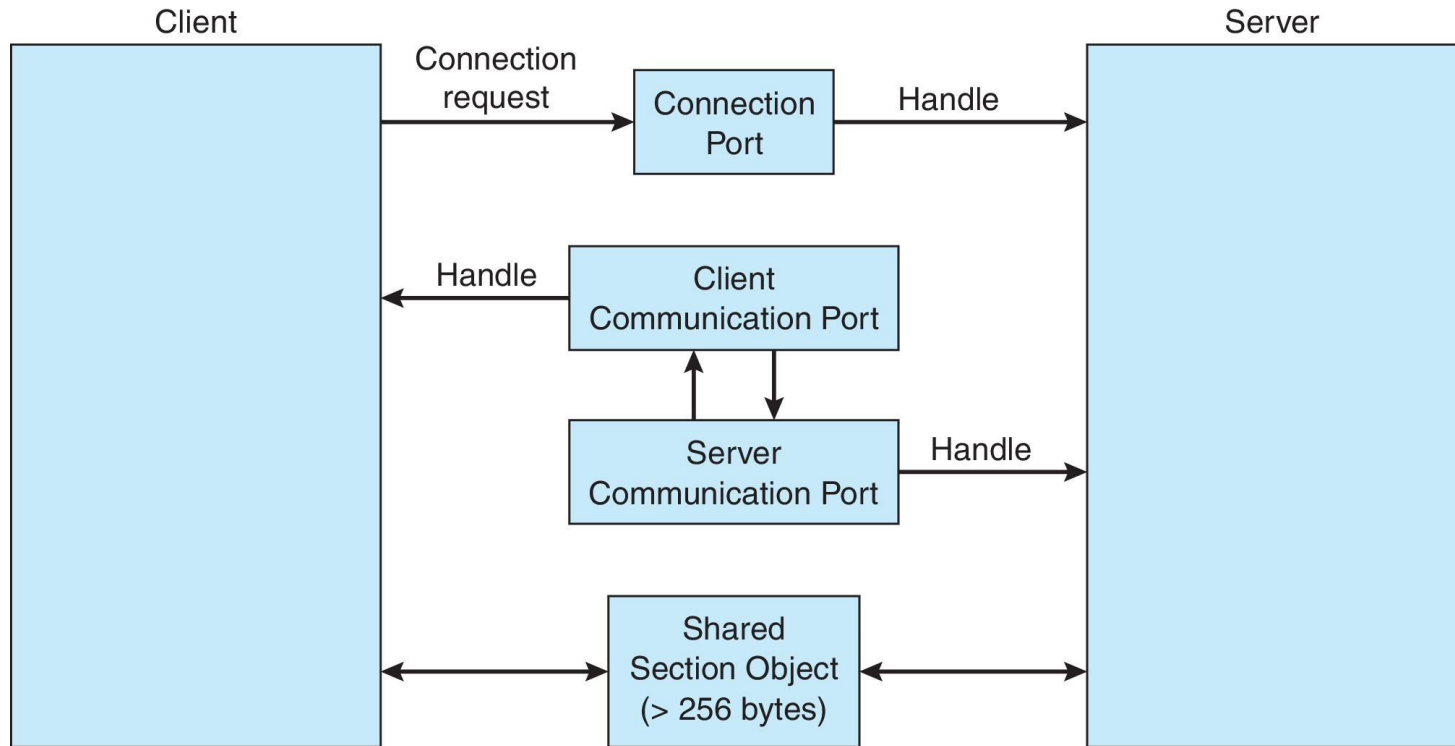
# Examples of IPC Systems – Windows

- 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

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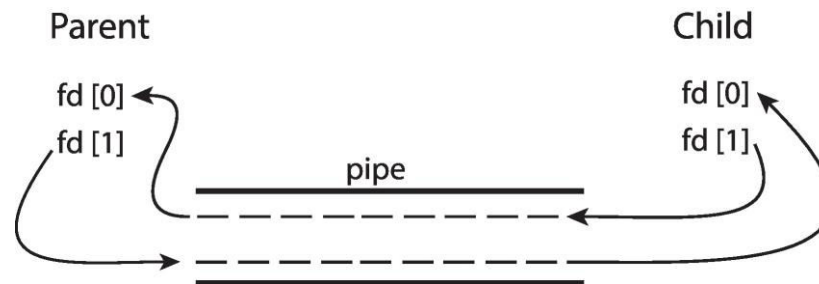
- Acts as a conduit allowing two processes to communicate
- Issues:
  - Is communication unidirectional or bidirectional?
  - In the case of two-way communication, is it half or full-duplex?
  - Must there exist a relationship (i.e., **parent-child**) between the communicating processes?
  - Can the 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

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- 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

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- Sockets
- Remote Procedure Calls





# Sockets

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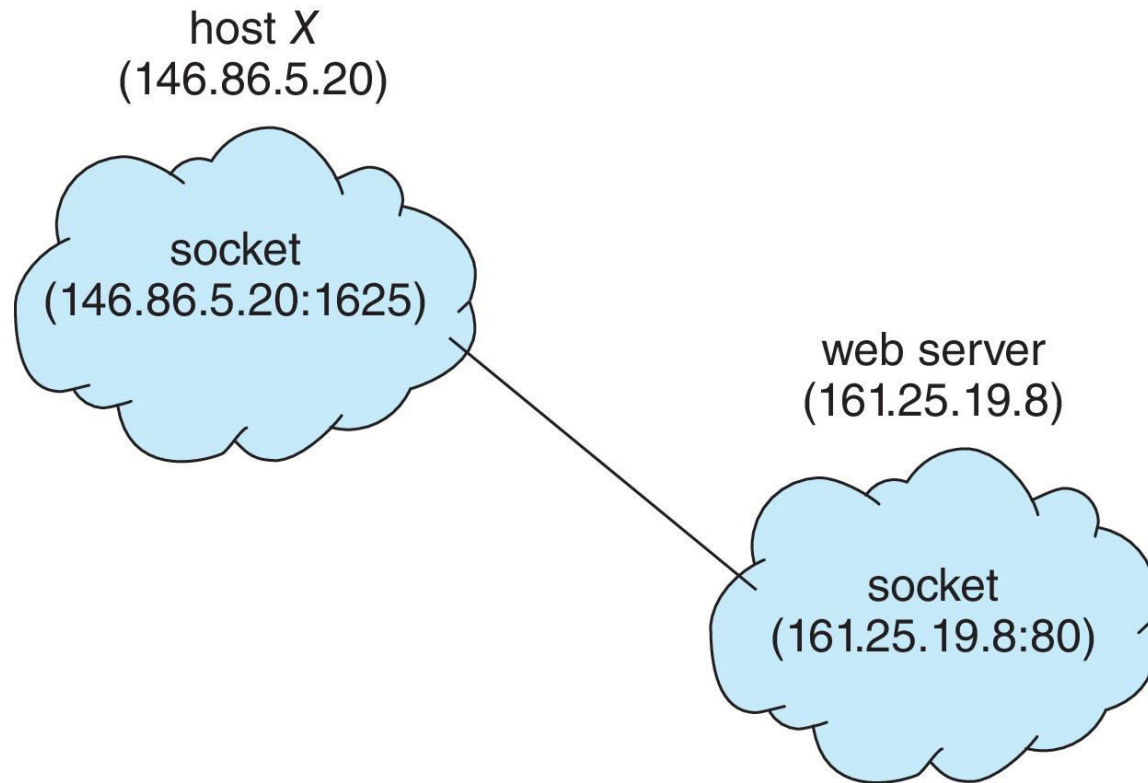
- A **socket** is defined as an endpoint for communication
- Concatenation of IP address and **port** – a number included at start of message packet to differentiate network services on a host
- The socket **161.25.19.8:1625** refers to port **1625** on host **161.25.19.8**
- Communication consists between 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





# 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:

```
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

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## The equivalent Date client

```
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

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- 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.)

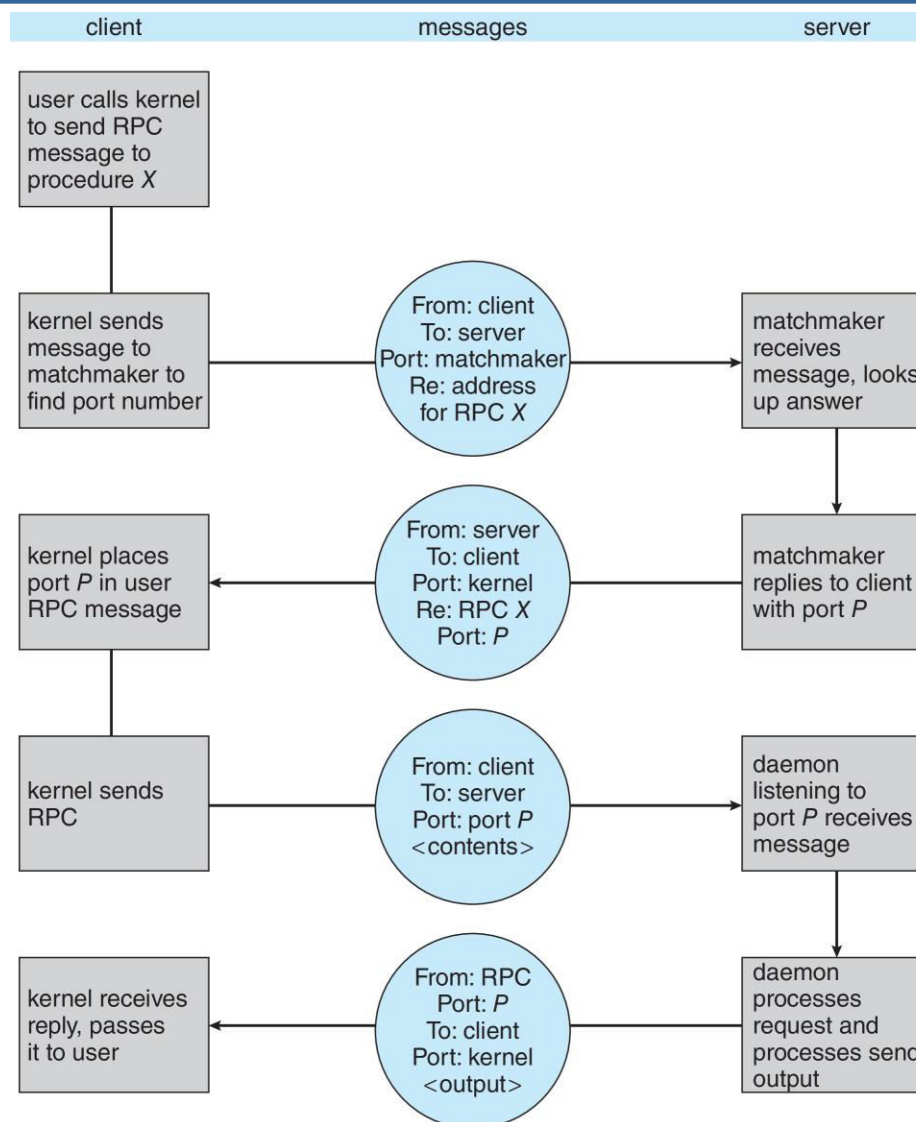
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- Data representation handled via **External Data Representation (XDL)** format to account for different architectures
  - **Big-endian** and **little-endian**
- Remote communication has more failure scenarios than local
  - Messages can be delivered ***exactly once*** rather than ***at most once***
- OS typically provides a rendezvous (or **matchmaker**) service to connect client and server





# Execution of RPC



# End of Chapter 3

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