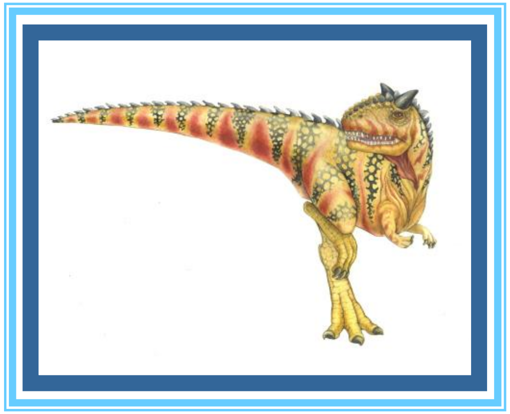
Chapter 3: Processes



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 using system calls.
- 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

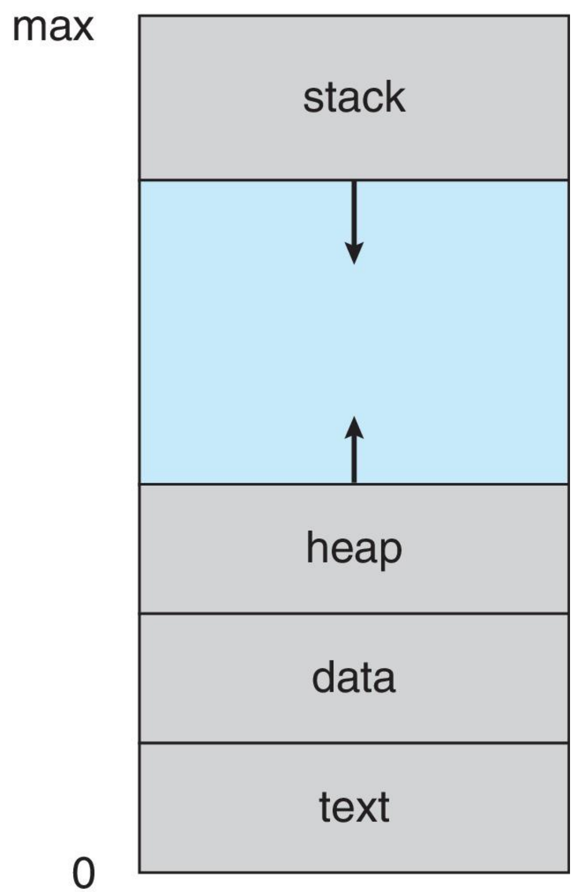
- An operating system executes a variety of programs that run as a process.
- Multiple processes can execute concurrently, with the CPU (or CPUs) multiplexed among them.
- **Process** – a program in execution; process execution must progress in sequential fashion. No parallel execution of instructions of a single process
- Multiple parts
  - The executable 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.)

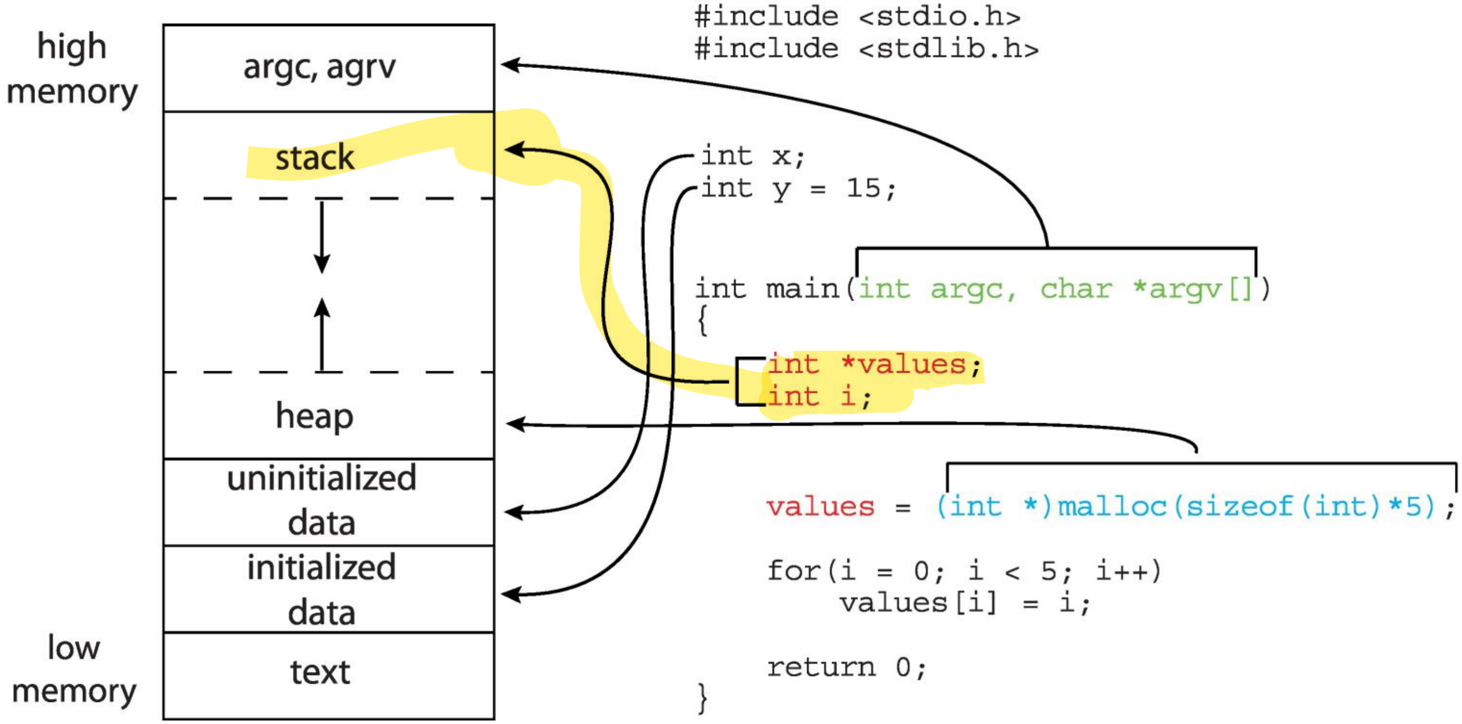
- Program is **passive** entity stored on disk (**executable file**); process is **active**
  - Program becomes process when an executable file is loaded into memory
- Execution of program started via GUI mouse clicks, command line entry of its name, etc.
- One program can be associated with several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

Process in Memory

- Sizes of the text and data sections are fixed (Why??)
- Operating system must ensure they do not ***overlap*** one another



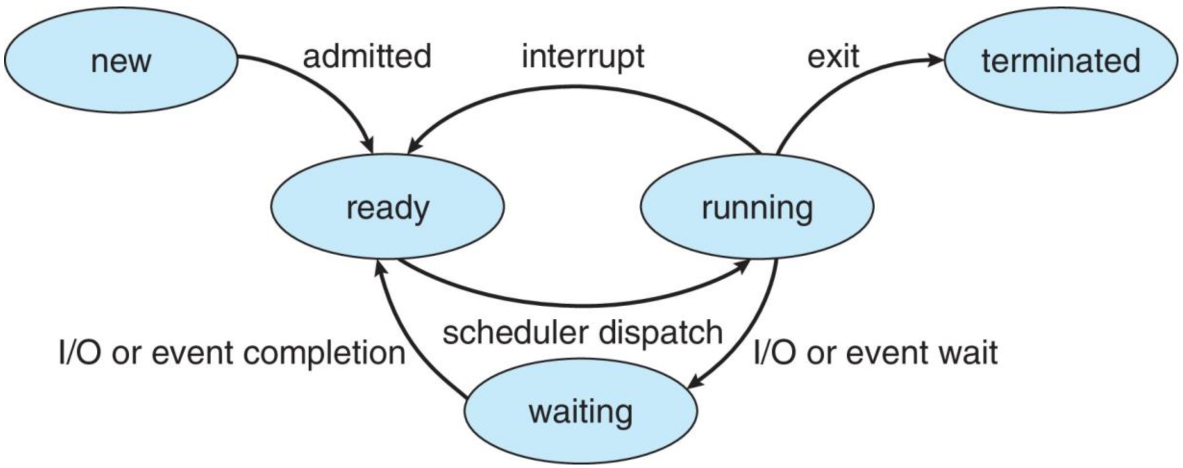
Memory Layout of a C Program



Process State

- As a process executes, it changes **state**
  - **New**: The process is being created
  - **Running**: Instructions are being executed
    - only one process can be running on any processor core at any instant
  - **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 e.g., accumulators, stack pointers, etc
- 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
• • •

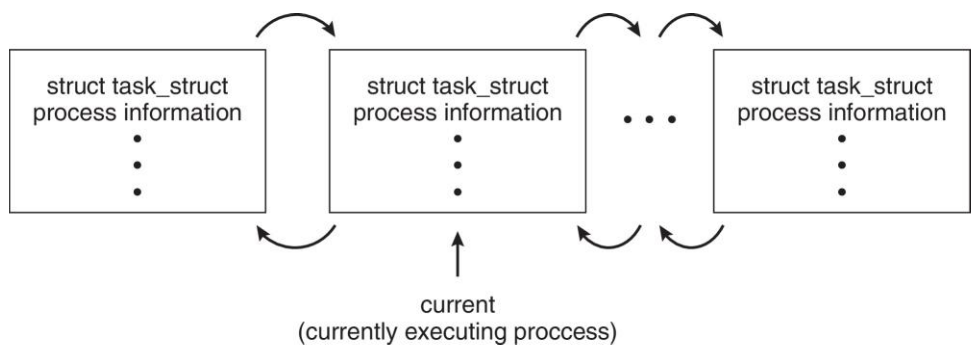
Threads

- 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**
- PCB must have storage for thread details, multiple program counters
- Example: A multithreaded word processor could, for example, assign one thread to manage user input while another thread runs the spell checker.

Process Representation in Linux

Represented by the C structure `task_struct` in <include/linux/sched.h>

```
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 */
```

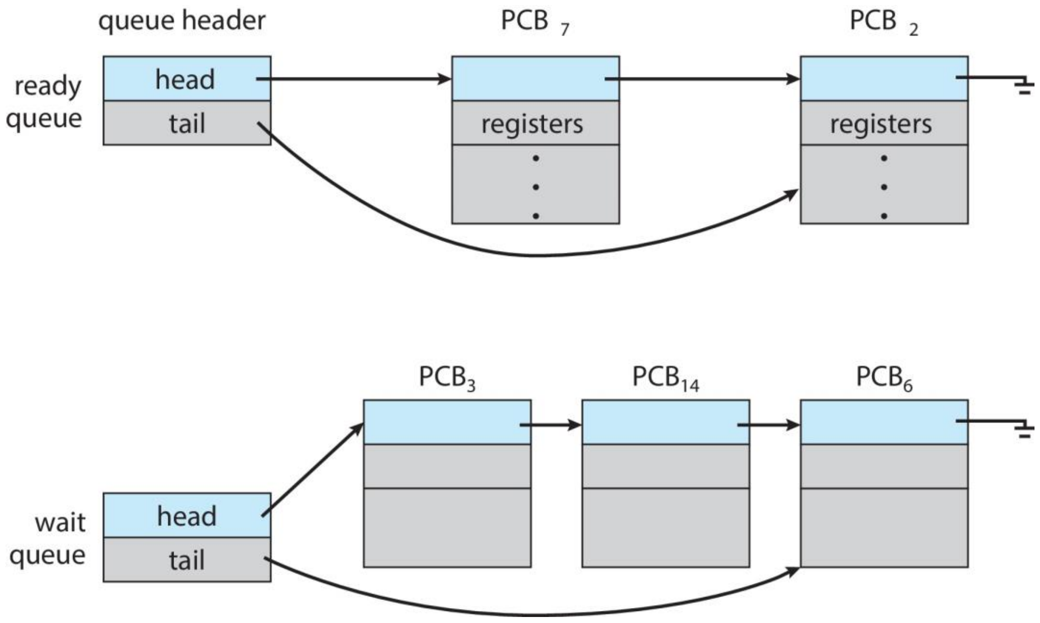


- Within the Linux kernel, all active processes are represented using a doubly linked list of `task_struct`

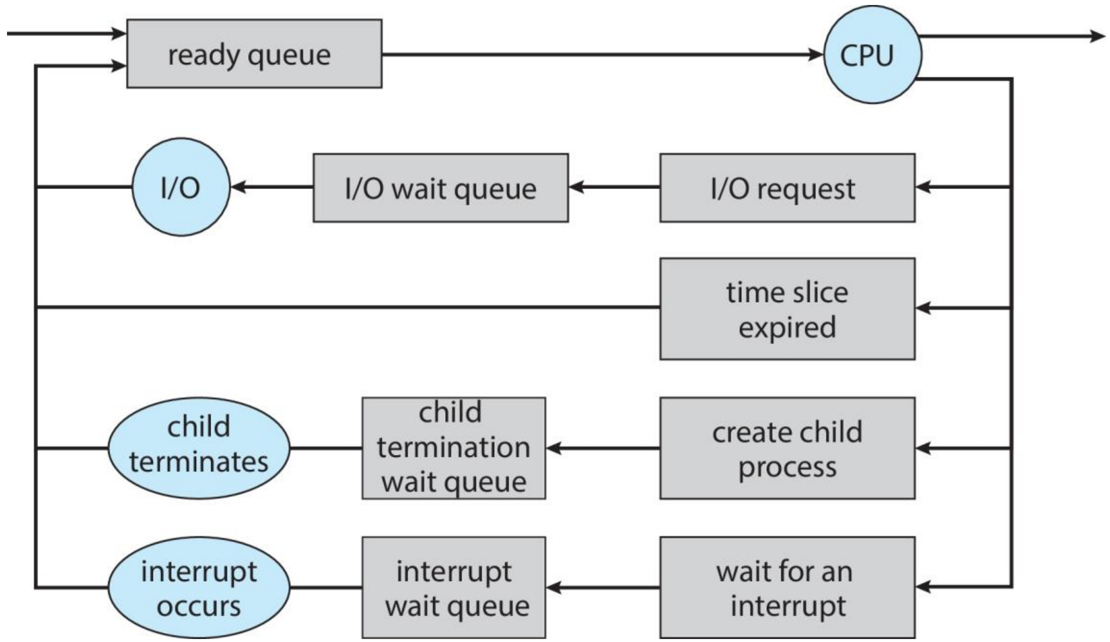
Process Scheduling

- For a system with a single CPU core, there will never be more than one process running at a time.
- In case more processes than cores, excess processes will have to wait until a core is free.
- The number of processes currently in memory is known as the **degree of multiprogramming**.
- **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 (state diagram!!)

Ready and Wait Queues



Representation of Process Scheduling

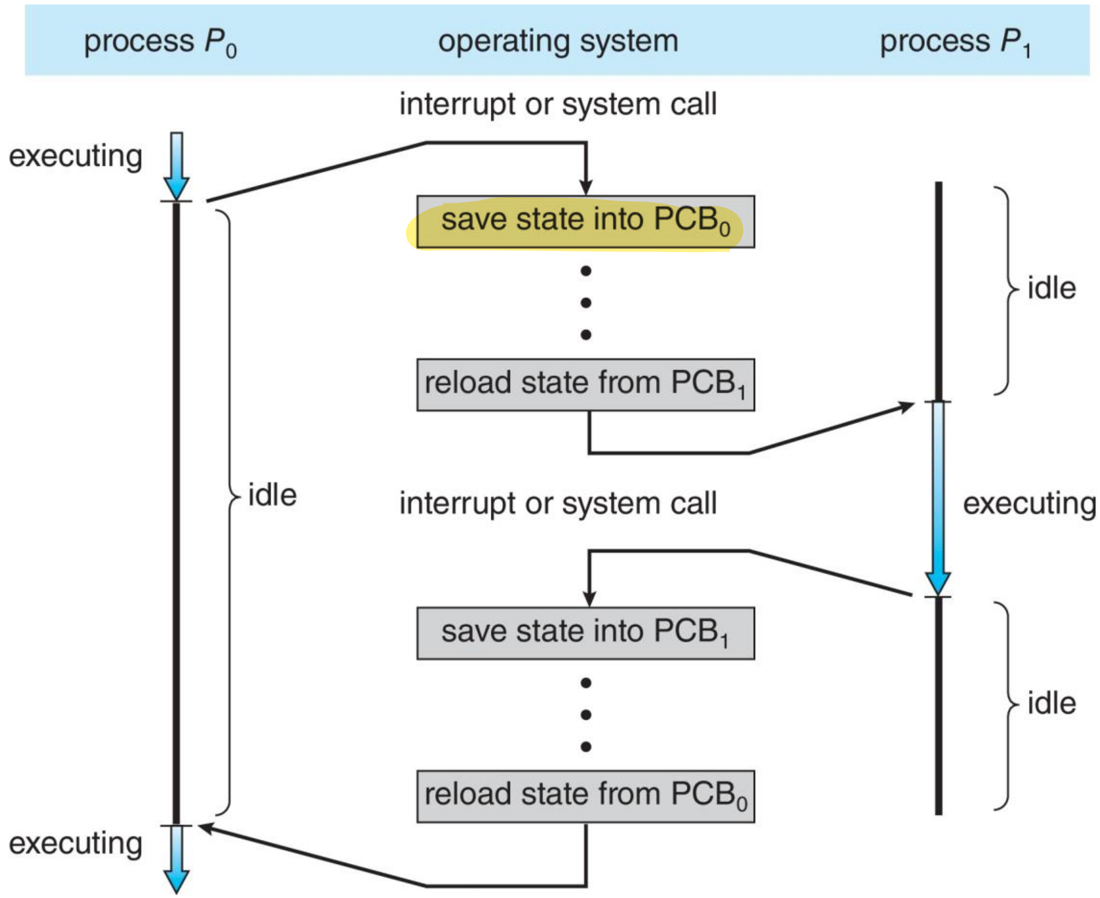


Context Switch

- 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 ➔ A context switch here simply requires changing the pointer to the current register set.

CPU Switch From Process to Process

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



Multitasking in Mobile Systems

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

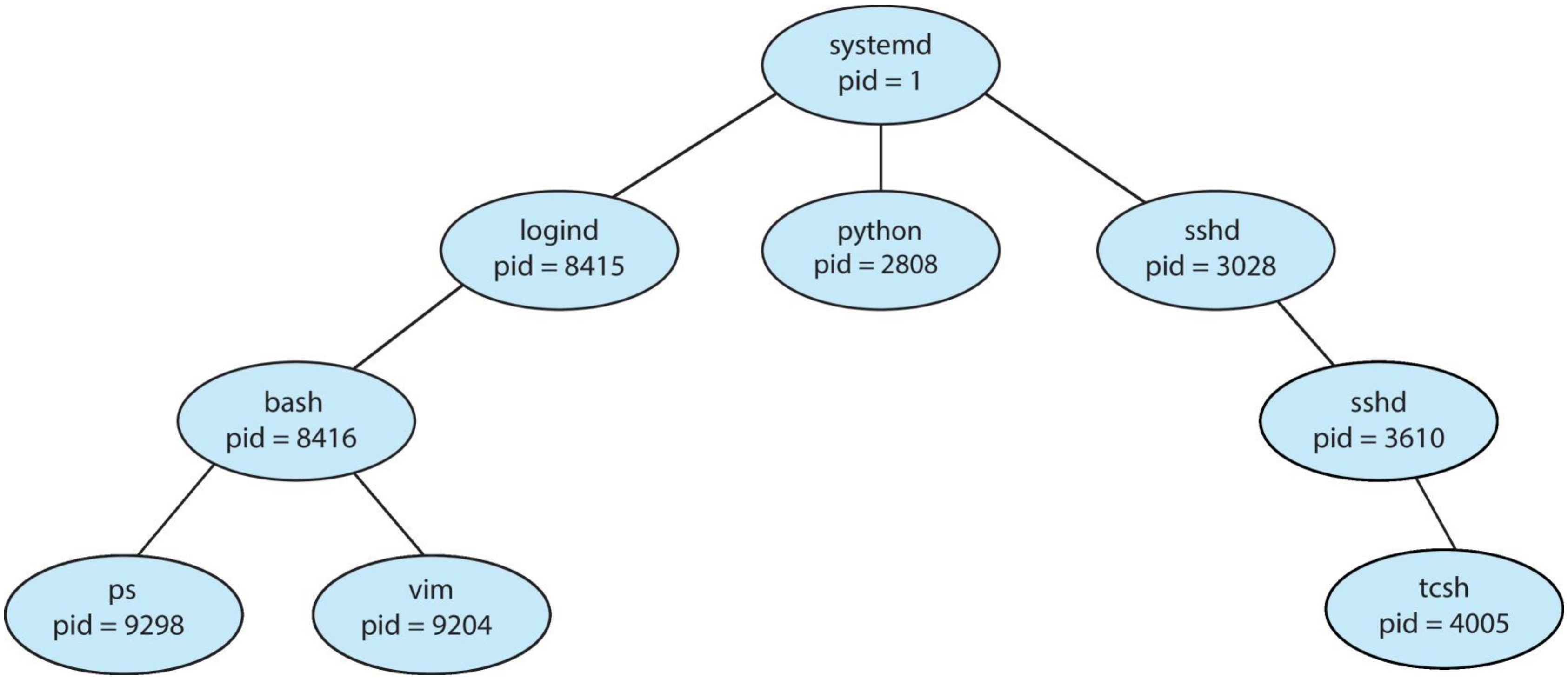
Process Creation

- **Parent** process create **children** processes, which, in turn create other processes, forming a **tree** of processes
- **pstree** command displays a tree of all processes in Linux
- 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



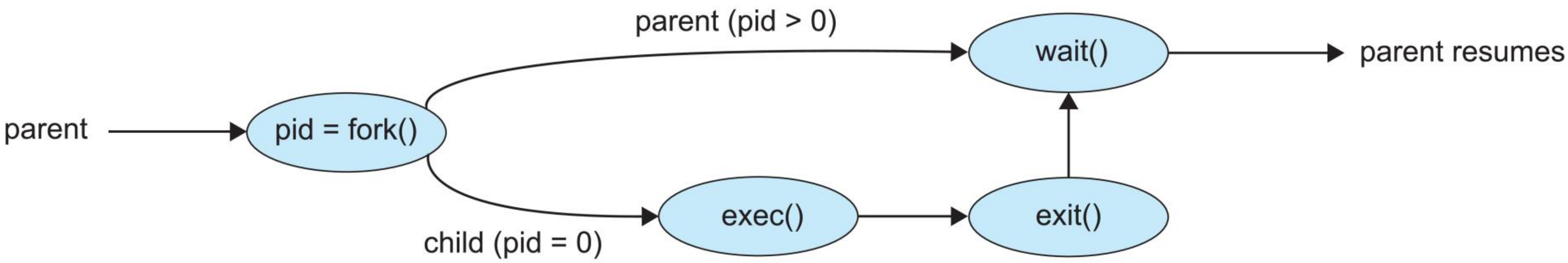
C Program Forking Separate Process

```
#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;
}
```

Process Creation (Cont.)

- After fork(), one of the two processes typically uses the exec() to replace the process's memory space with a new program.
- execlp() is a version of the exec() through which child process overlays its address space with the UNIX command /bin/ls
- The parent waits for the child process to complete with the wait()
  - When the child process completes, by either implicitly or explicitly, invoking exit() the parent process resumes from the call to wait()

The execlp() function in C (part of the POSIX standard) is used to replace the current running process with a new process. It is a variant of the exec family of functions, which are used to execute a program.



Creating a Separate Process via Windows API

- Read by yourself

Steps to Create a Separate Process:

1. Define a STARTUPINFO structure, which contains information about how the new process should be started.

2. Define a PROCESS_INFORMATION structure, which will receive information about the newly created process.

3. Call CreateProcess to create the new process.

```
#include <windows.h>
#include <stdio.h>
int main() {

    STARTUPINFO si;
    PROCESS_INFORMATION pi;
    BOOL result;

    // Initialize the structures
    ZeroMemory(&si, sizeof(si));
    si.cb = sizeof(si);
    ZeroMemory(&pi, sizeof(pi));

    // Create the new process
    result = CreateProcess(
        "C:\\Windows\\System32\\notepad.exe",  // Path to the executable
        NULL,          // Command line arguments (can be NULL)
        NULL,          // Process handle not inheritable
        NULL,          // Thread handle not inheritable
        FALSE,         // Set handle inheritance to FALSE
        0,             // No creation flags
        NULL,          // Use parent's environment block
        NULL,          // Use parent's starting directory
        &si,           // Pointer to STARTUPINFO structure
        &pi            // Pointer to PROCESS_INFORMATION structure
    );

    // Check if the process was created successfully
    if (result) {
        printf("Process created successfully!\n");
        printf("Process ID: %lu\n", pi.dwProcessId);
        // Wait until the new process exits
        WaitForSingleObject(pi.hProcess, INFINITE);
        // Close process and thread handles
        CloseHandle(pi.hProcess);
        CloseHandle(pi.hThread);
    } else {
        printf("Failed to create process. Error: %lu\n", GetLastError());
    }

    return 0;
}
```

Process Termination

>>> Once the exit is called all the resources allocated to the process are freed

- 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 (**cascading termination**)
    - Normally initiated by the operating system

>>> Child process is existing, and its parent gets terminated then the child process is also terminated

Process Termination

- 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);`

- When a process terminates, its resources are deallocated
  - However, its entry in the process table must remain there until the parent calls wait(), because it contains the process's exit status
  - All processes transition to this state when they terminate
- If no parent waiting (did not invoke **`wait()`**) process is a **zombie**
- If parent terminated without invoking **`wait()`**, process is an **orphan**

Most of the resources used by the process, such as memory, file descriptors, and CPU scheduling information, are deallocated upon termination. However, the process's entry in the process table remains. This entry contains crucial information, particularly the exit status of the process.

Zombie State :

After a process terminates but before its exit status is collected by the parent process, it enters the zombie state. A zombie process is no longer running, but it still has an entry in the process table, which allows the parent process to retrieve its termination status.

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 (allow concurrent access to such information)
  - Computation speedup (we must break it into subtasks)
  - Modularity
- Cooperating processes need **interprocess communication (IPC)**

Orphan : An orphan process occurs when a process's parent terminates or exits before the child process.

Interprocess Communication

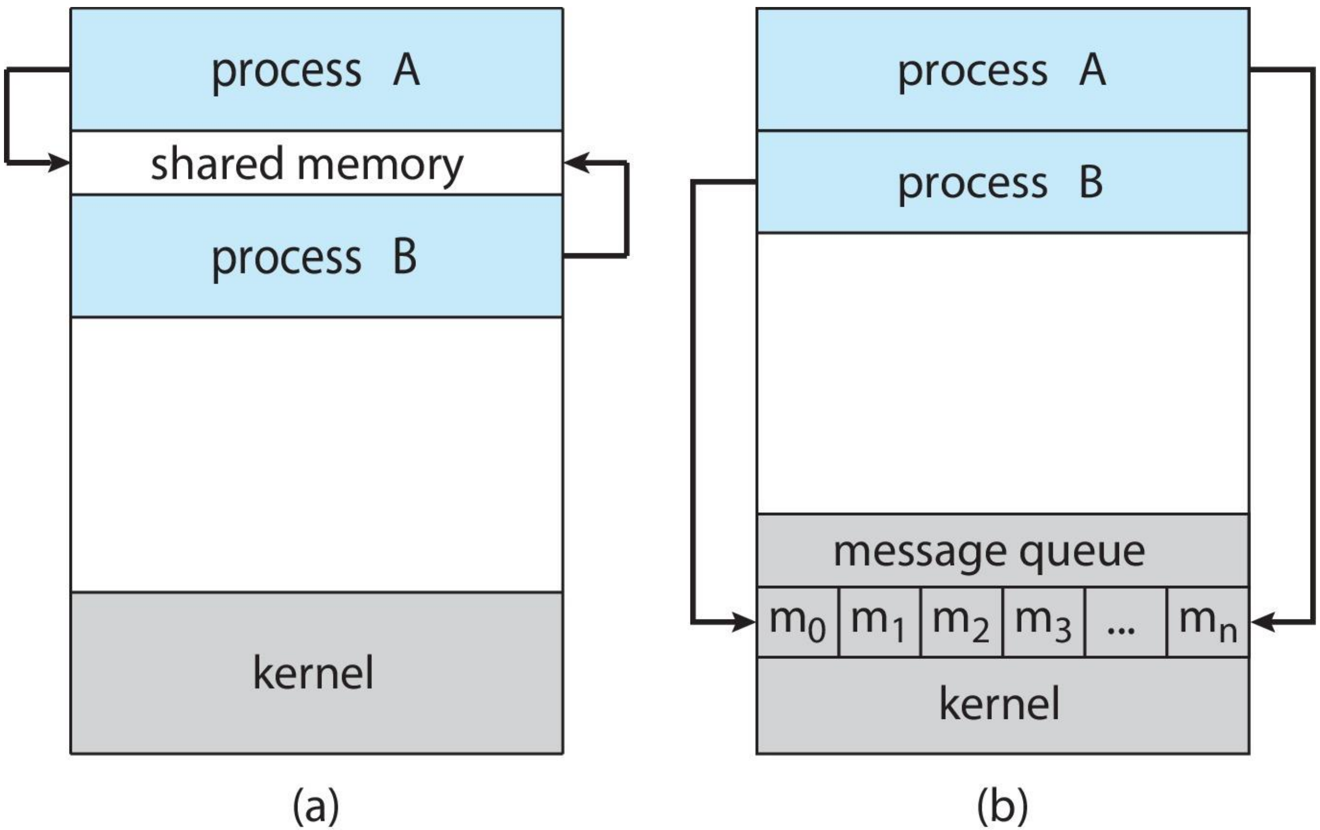
- Two models of IPC
  - **Shared memory**
    - Processes can then exchange information by reading and writing data to the shared region
    - Shared memory can be faster than message passing (Why??)
  - **Message passing**
    - communication takes place by means of messages exchanged between the cooperating processes
    - Useful for exchanging smaller amounts of data, because no conflicts need be avoided
    - easier to implement in a distributed system

Inter Process Communication (IPC) refers to the mechanisms and techniques used by operating systems to allow processes to exchange data and synchronize their actions.

Since processes in modern operating systems typically run in isolated environments (with separate memory spaces), IPC is essential for enabling processes to cooperate and share information.

Communications Models

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



IPC in Shared-Memory Systems

- Requires communicating processes to establish a region of shared memory
- Shared-memory region resides in the address space of the process creating the shared-memory segment.
  - OS tries to prevent one process from accessing another process's memory. Thus, processes agree to remove this restriction
- Exchange information by reading and writing data in the shared areas.
  - The form of the data and the location are determined by these processes and are not under the OS's control.

Producer-Consumer Problem

- Paradigm for cooperating processes:
  - *producer* process produces information that is consumed by a *consumer* process
    - e.g., a compiler may produce assembly code that is consumed by an assembler.
- 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

Bounded-Buffer – Shared-Memory Solution

- Shared data

```
#define BUFFER_SIZE 10
typedef struct {
  . . .
} item;
item buffer[BUFFER_SIZE];
int in = 0;
int out = 0;
```

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)
                ; /* empty buffer do nothing */
        next_consumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;

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

in == out means true , so if it is true the infinite loop will run doing nothing as soon as condition becomes false , the consumer starts consuming again .

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

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++;
}
```

if counter == BUFFERSIZE it means there is no free space present in the buffer so stop producing

Consumer

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

if counter == 0 it means there is nothing to be consumed.

so infinite loop runs to stop consumption

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?**

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?

Implementation of Communication Link

- Physical Implementation:
  - Shared memory
  - Hardware bus
  - Network
- Logical Implementation:
  - Direct or indirect
  - Synchronous or asynchronous
  - Automatic or explicit buffering (bounded or unbounded buffer)

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, processes need to know only each other's identity to communicate
  - 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
- Two Variants
  - Both the sender process and the receiver process must name the other to communicate (***symmetry*** in addressing)
  - Sender names the recipient; the recipient is not required to name the sender (***asymmetry*** in addressing)

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
- Mailbox can be viewed abstractly as an object into which messages can be placed by processes and from which messages can be removed.
- 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

In indirect process, the process creates a mailbox and sending and receiving is done through that mailbox. When the communication is done, then the mailbox is deleted.

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 depends on which of the following methods we choose
  - Allow a link to be associated with at most two processes
  - Allow only one process at a time to execute a receive operation (How??)
  - Allow the system to select arbitrarily the receiver (may be round robin). Sender is notified who the receiver was.

Consider a case, let there be three processes A, B, C sharing a mailbox and A sends message then who will receive the message is decided by two ways:
1. allow only one process to execute receive operation
2. select the receiver via round robin or some other algo, and receiver notifies the sender

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

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 */
}
```

- blocking send() and receive() statements

Buffering

- Whether communication is direct or indirect, messages exchanged by communicating processes reside in a temporary queue.
- 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

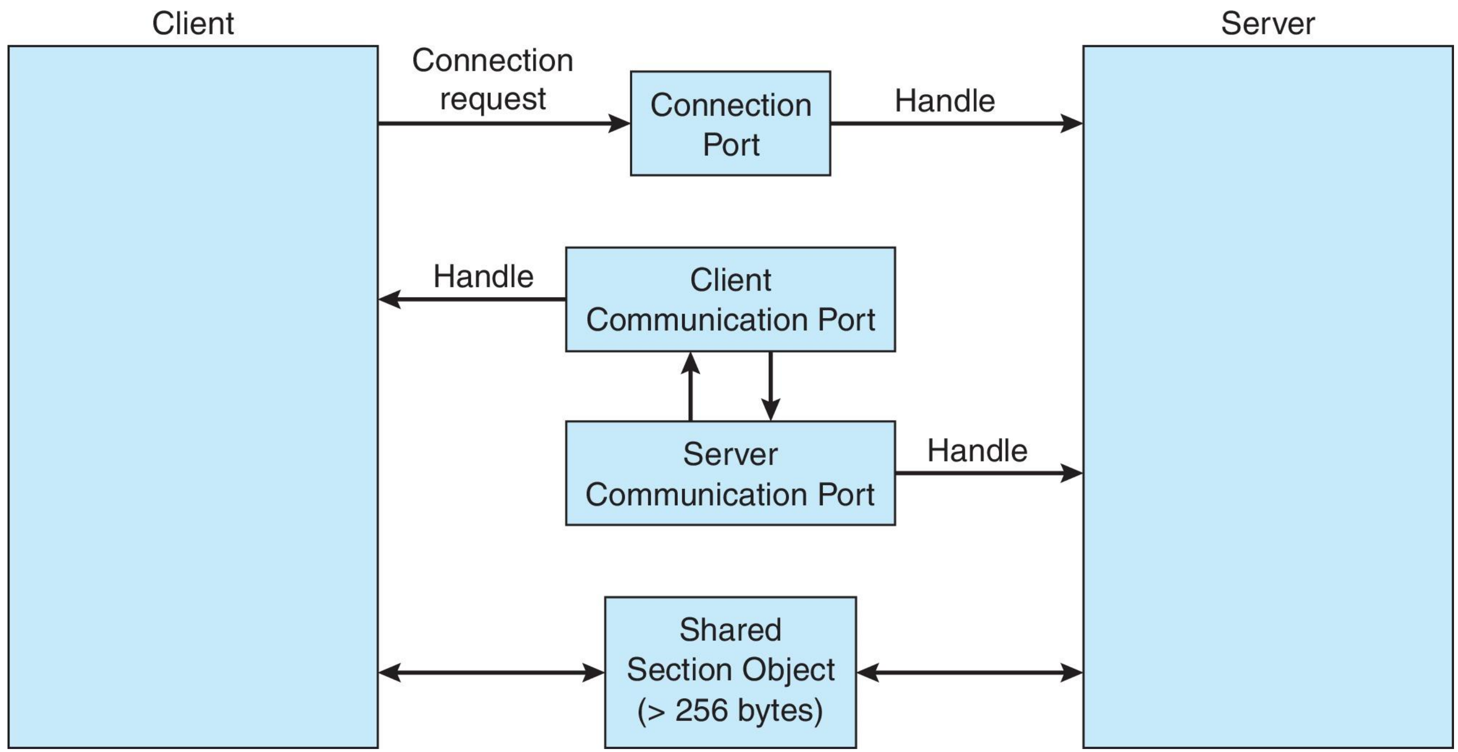
Examples of IPC Systems – Windows

- Windows provides support for multiple operating environments, or ***subsystems and* application programs** communicate with these subsystems via a message-passing mechanism.
  - application programs are clients of a subsystem server
- Message-passing centric via **advanced local procedure call (ALPC)** facility
  - Only works between processes on the same system
  - Uses ports (like mailboxes) to establish and maintain communication channels

Examples of IPC Systems – Windows

- 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.
    - one for client–server messages, the other for server–client messages
  - The client and server use the corresponding port handle to send messages or callbacks and to listen for replies.
- For small messages (up to 256 bytes), the port's message queue is used as intermediate storage
- Larger messages must be passed through a **section object**

Local Procedure Calls in Windows

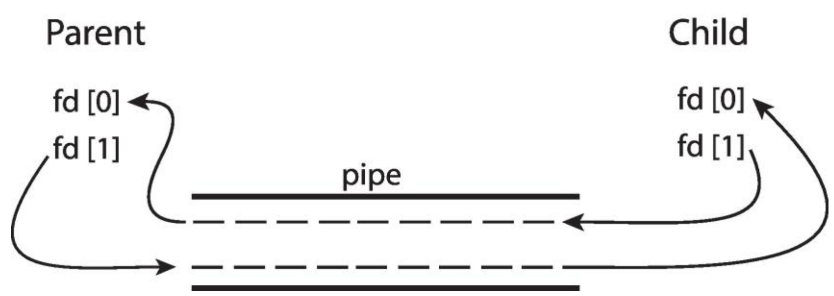


Pipes

- Acts as a channel allowing two processes to communicate
- First IPC mechanisms in early UNIX systems
- 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
  - If two-way communication is required, two pipes must be used
- Require parent-child relationship between communicating processes



- Windows calls these **anonymous pipes**
- UNIX treats a pipe as a special type of file. Thus, pipes can be accessed using ordinary read() and write() system calls

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

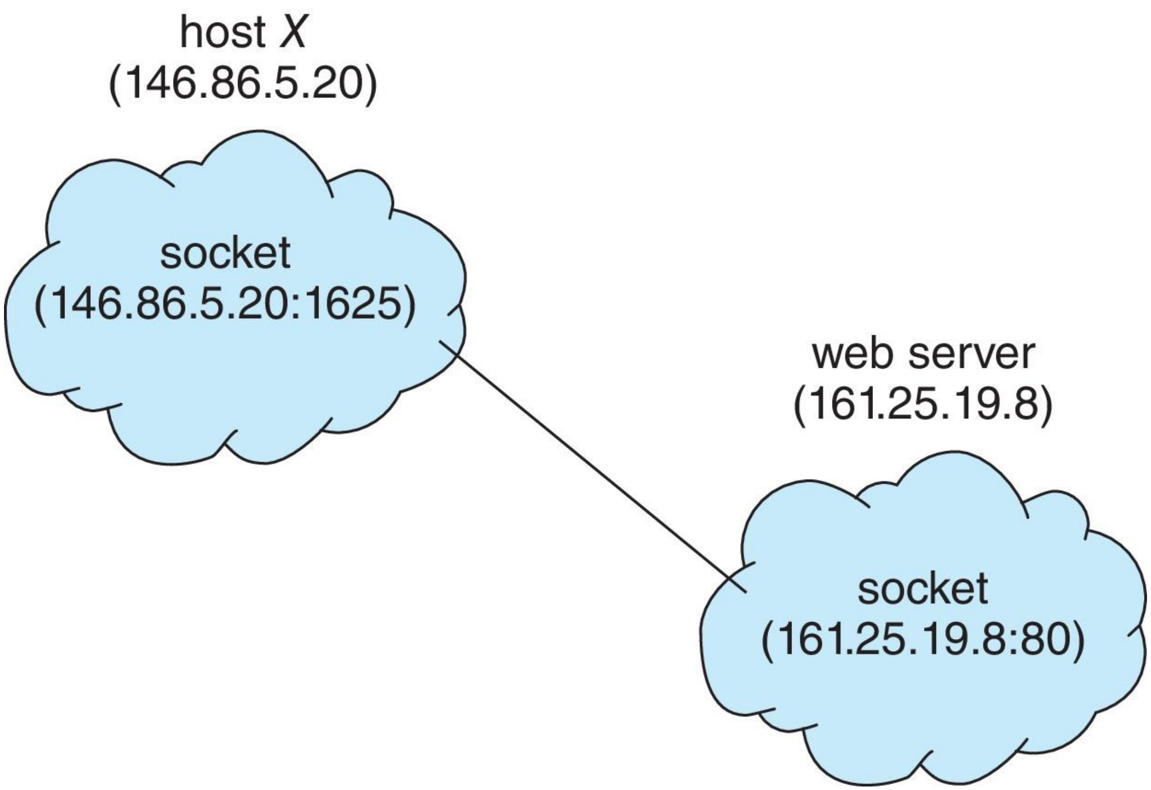
Communications in Client-Server Systems

- 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
  - FTP server listens to port 21; and a web, or HTTP, server listens to port 80
- 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

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

- Read by yourself

End of Chapter 3