ICS 143 - Principles of Operating Systems

Lectures 3 and 4 - Processes and Threads

Prof. Nalini Venkatasubramanian
nalini@ics.uci.edu

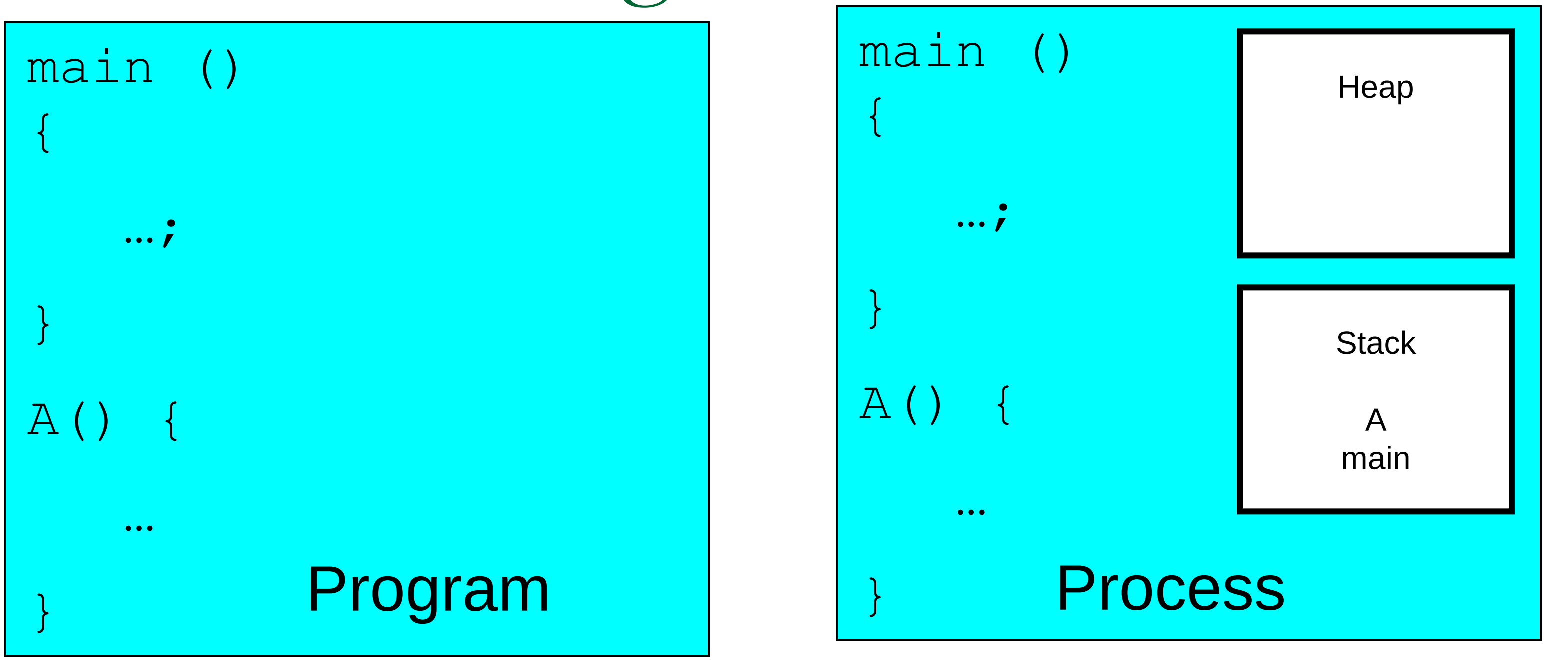
Outline

- Process Concept
- Process Scheduling
- Operations on Processes
- Cooperating Processes
- Threads
- Interprocess Communication

Process Concept

- An operating system executes a variety of programs
  - batch systems - jobs
  - time-shared systems - user programs or tasks
  - job and program used interchangeably
- Process - a program in execution
  - process execution proceeds in a sequential fashion
- A process contains
  - program counter, stack and data section

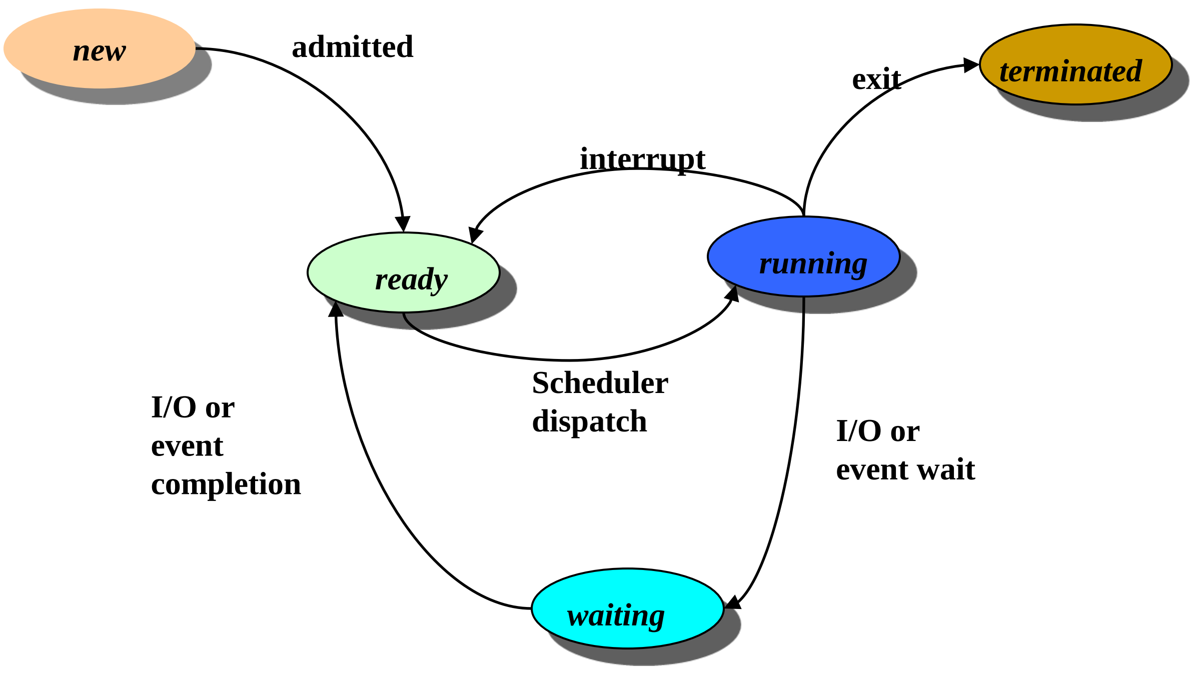
Process =? Program



- More to a process than just a program:
  - Program is just part of the process state
  - I run emacs on lectures.txt, you run it on homework.java – Same program, different processes
- Less to a process than a program:
  - A program can invoke more than one process
  - cc starts up cpp, cc1, cc2, as, and ld

Process State

- A process changes state as it executes.

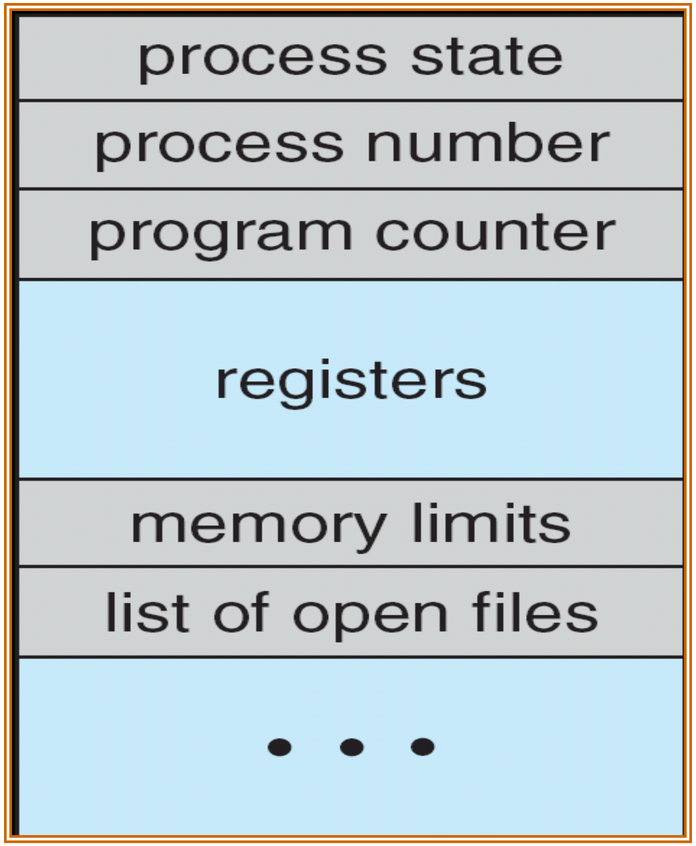


Process States

- New - The process is being created.
- Running - Instructions are being executed.
- Waiting - Waiting for some event to occur.
- Ready - Waiting to be assigned to a processor.
- Terminated - Process has finished execution.

Process Control Block

- Contains information associated with each process
  - Process State - e.g. new, ready, running etc.
  - Process Number – Process ID
  - Program Counter - address of next instruction to be executed
  - CPU registers - general purpose registers, stack pointer etc.
  - CPU scheduling information - process priority, pointer
  - Memory Management information - base/limit information
  - Accounting information - time limits, process number
    - I/O Status information - list of I/O devices allocated

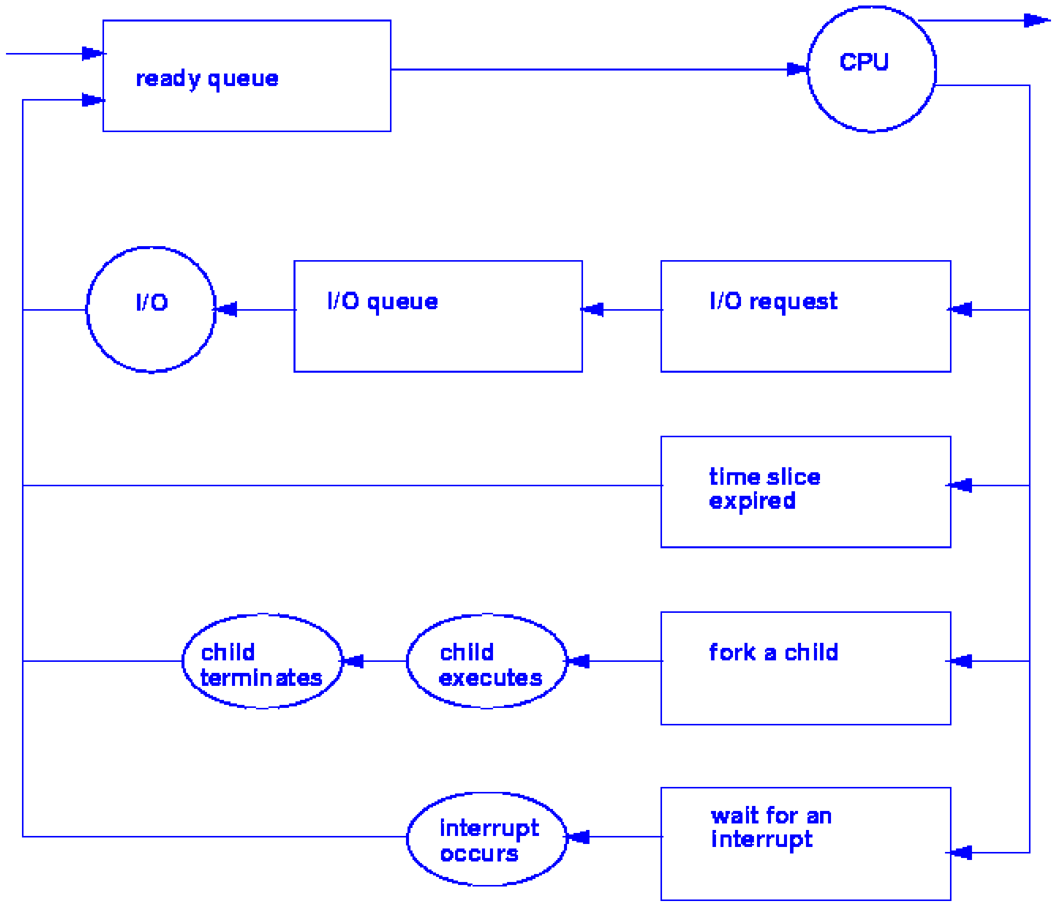


Process Control Block

Process Scheduling

Process (PCB) moves from queue to queue

When does it move? Where? A scheduling decision



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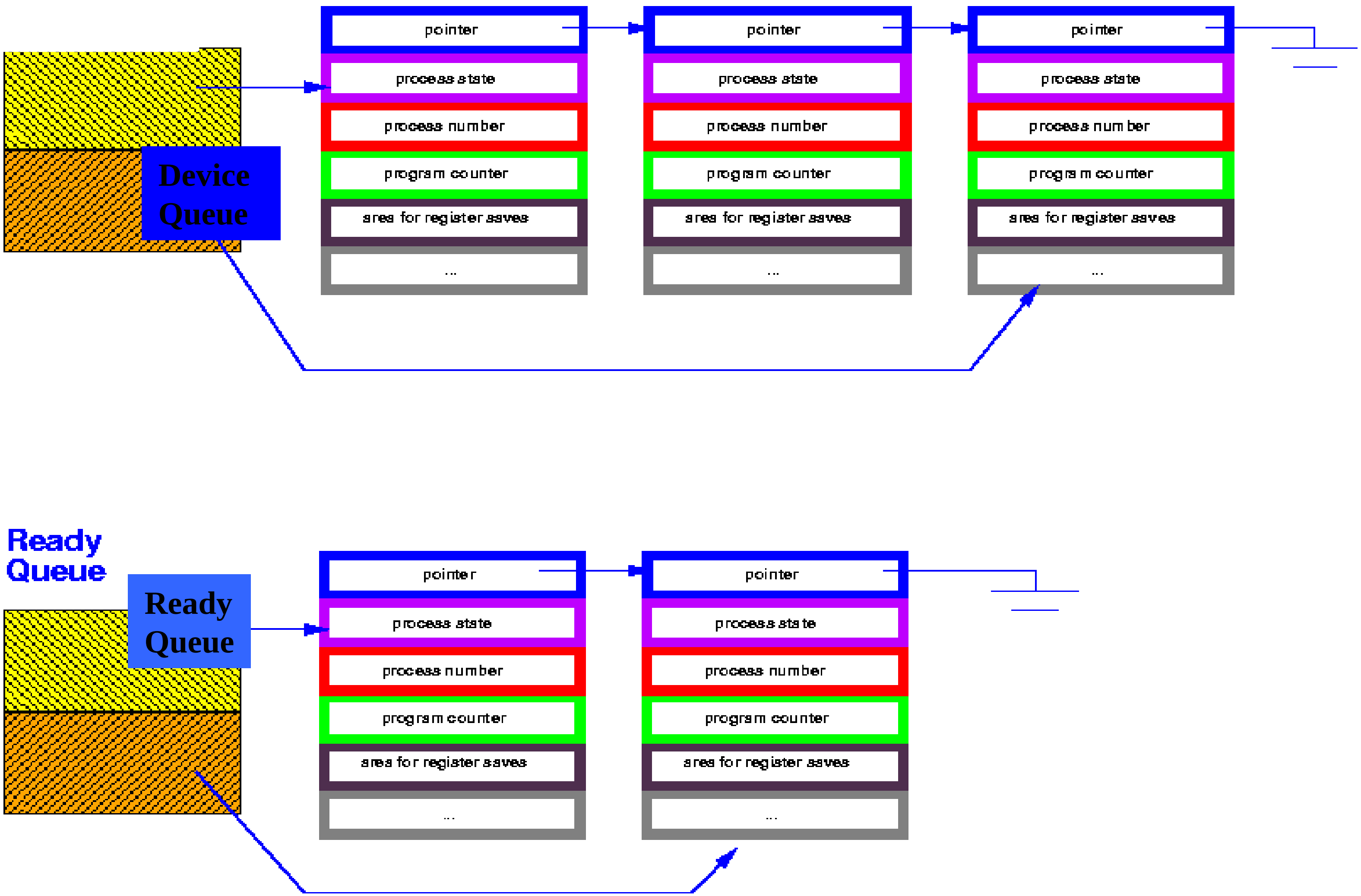
Process Scheduling Queues

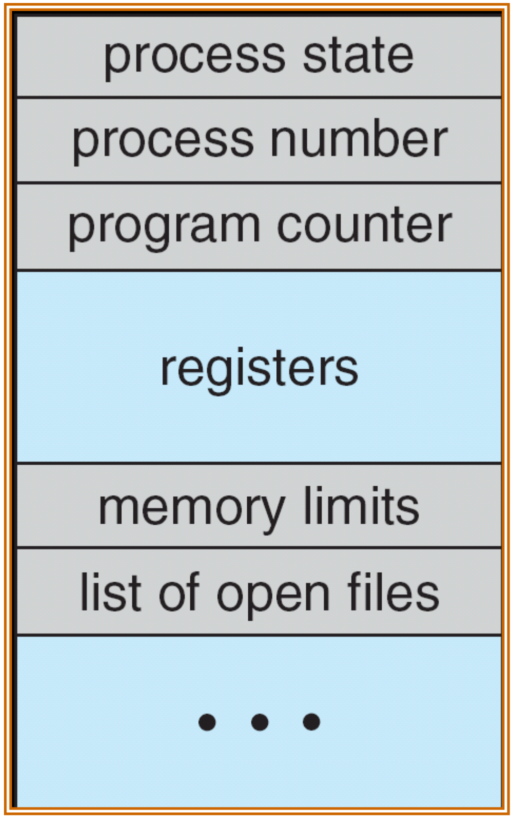
- Job Queue - set of all processes in the system
- Ready Queue - set of all processes residing in main memory, ready and waiting to execute.
- Device Queues - set of processes waiting for an I/O device.
- Process migration between the various queues.
- Queue Structures - typically linked list, circular list etc.

Process Queues



Enabling Concurrency and Protection: Multiplex processes

- Only one process (PCB) active at a time
  - Current state of process held in PCB:
    - "snapshot" of the execution and protection environment
  - Process needs CPU, resources
- Give out CPU time to different processes (Scheduling):
  - Only one process "running" at a time
  - Give more time to important processes
- Give pieces of resources to different processes (Protection):
  - Controlled access to non-CPU resources
    - E.g. Memory Mapping: Give each process their own address space

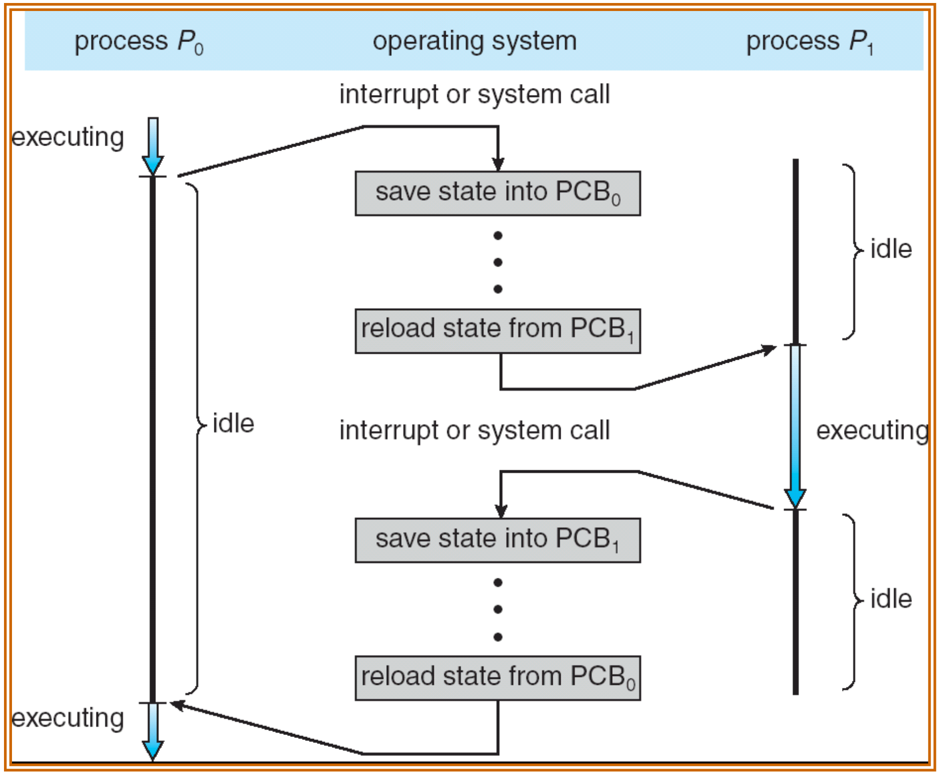


Process Control Block

Enabling Concurrency: Context Switch

- Task that switches CPU from one process to another process
  - the CPU must save the PCB state of the old process and load the saved PCB state of the new process.
- Context-switch time is overhead
  - System does no useful work while switching
  - Overhead sets minimum practical switching time; can become a bottleneck
- Time for context switch is dependent on hardware support (1- 1000 microseconds).

CPU Switch From Process to Process

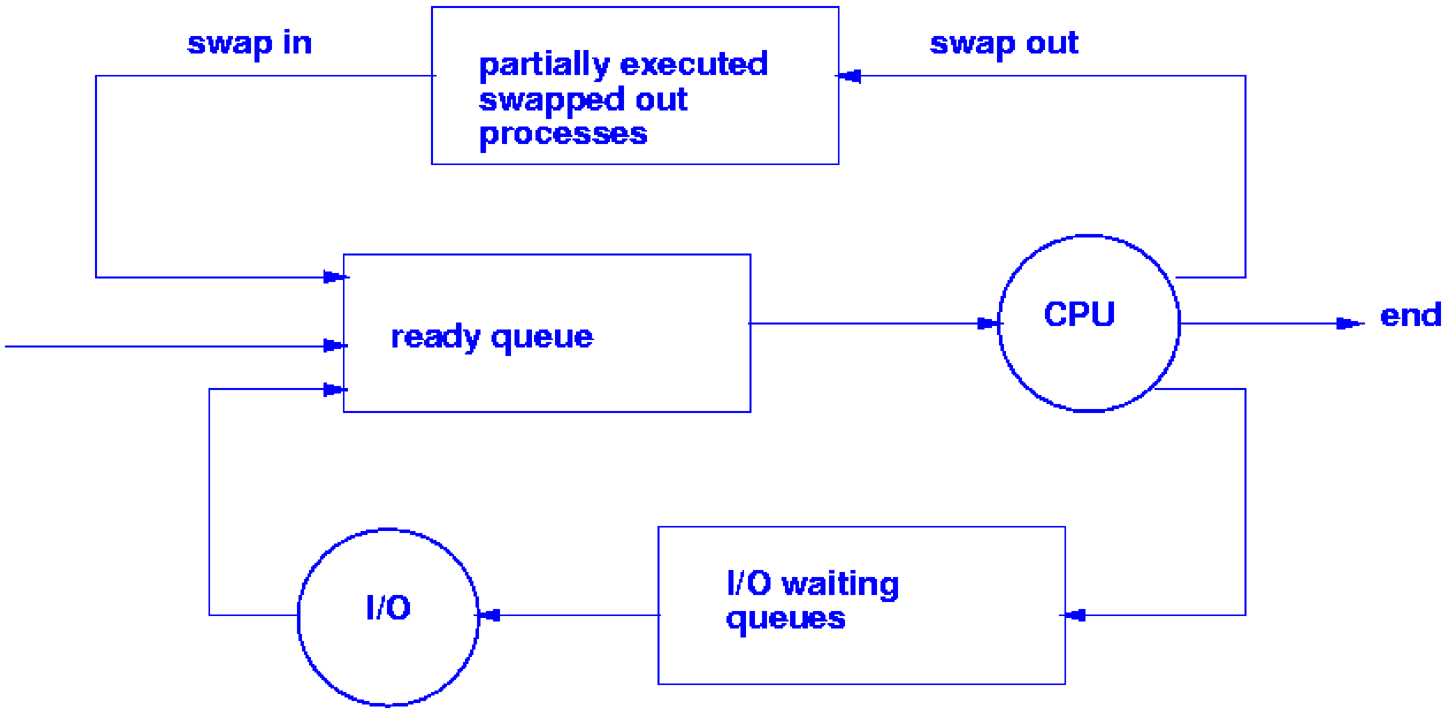


- Code executed in kernel above is overhead
  - Overhead sets minimum practical switching time

Schedulers

- Long-term scheduler (or job scheduler) -
  - selects which processes should be brought into the ready queue.
  - invoked very infrequently (seconds, minutes); may be slow.
  - controls the degree of multiprogramming
- Short term scheduler (or CPU scheduler) -
  - selects which process should execute next and allocates CPU.
  - invoked very frequently (milliseconds) - must be very fast
- Medium Term Scheduler
  - swaps out process temporarily
  - balances load for better throughput

Medium Term (Time-sharing) Scheduler



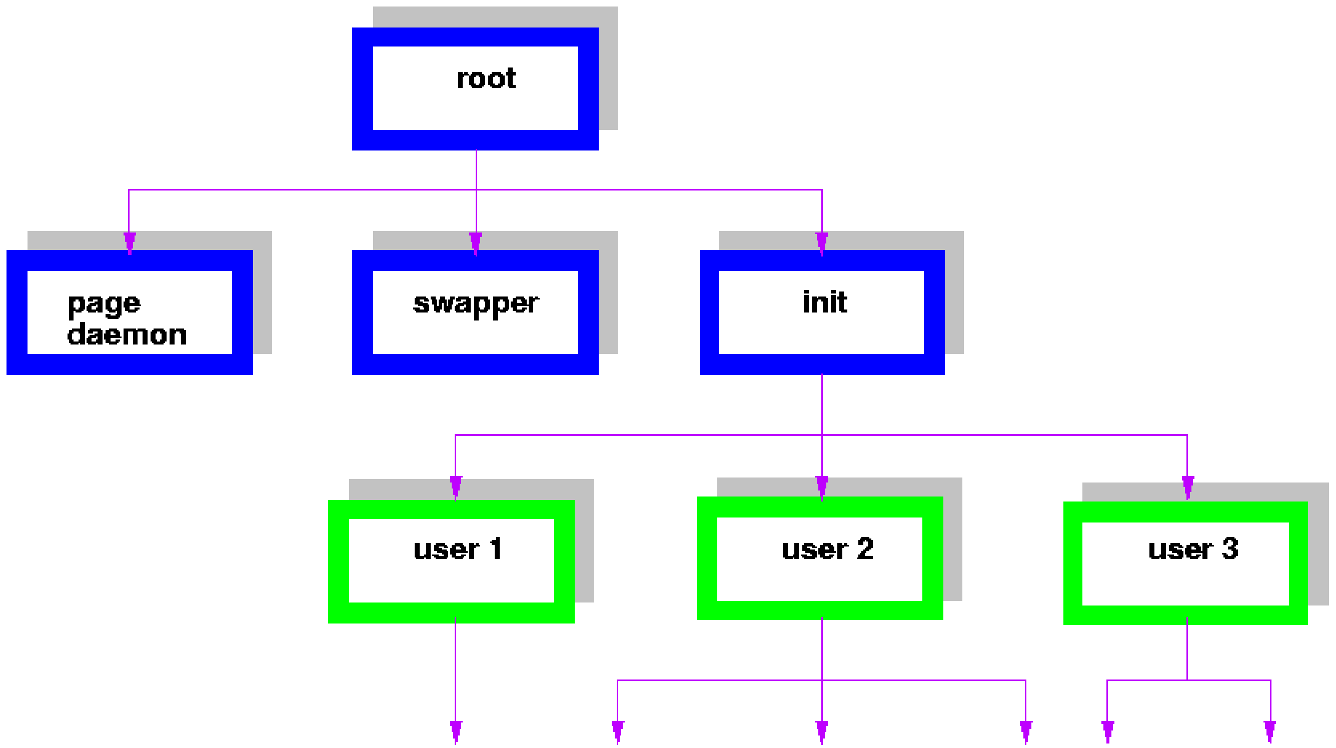
Process Profiles

- I/O bound process -
  - spends more time in I/O, short CPU bursts, CPU underutilized.
- CPU bound process -
  - spends more time doing computations; few very long CPU bursts, I/O underutilized.
- The right job mix:
  - Long term scheduler - admits jobs to keep load balanced between I/O and CPU bound processes
  - Medium term scheduler – ensures the right mix (by sometimes swapping out jobs and resuming them later)

Process Creation

- Processes are created and deleted dynamically
- Process which creates another process is called a *parent* process; the created process is called a *child* process.
- Result is a tree of processes
  - e.g. UNIX - processes have dependencies and form a hierarchy.
- Resources required when creating process
  - CPU time, files, memory, I/O devices etc.

UNIX Process Hierarchy



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What does it take to create a process?

- Must construct new PCB
  - Inexpensive
- Must set up new page tables for address space
  - More expensive
- Copy data from parent process? (Unix `fork()`)
  - Semantics of Unix `fork()` are that the child process gets a complete copy of the parent memory and I/O state
  - Originally *very* expensive
  - Much less expensive with “copy on write”
- Copy I/O state (file handles, etc)
  - Medium expense

Process Creation

- Resource sharing
  - Parent and children share all resources.
  - Children share subset of parent's resources - prevents many processes from overloading the system.
  - Parent and children share no resources.
- Execution
  - Parent and child execute concurrently.
  - Parent waits until child has terminated.
- Address Space
  - Child process is duplicate of parent process.
  - Child process has a program loaded into it.

UNIX Process Creation

- Fork system call creates new processes

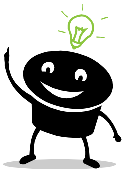
- execve system call is used after a fork to replace the processes memory space with a new program.

Process Termination

- Process executes last statement and asks the operating system to delete it (*exit*).
  - Output data from child to parent (via wait).
  - Process' resources are deallocated by operating system.
- Parent may terminate execution of child processes.
  - Child has exceeded allocated resources.
  - Task assigned to child is no longer required.
  - Parent is exiting
    - OS does not allow child to continue if parent terminates
    - Cascading termination

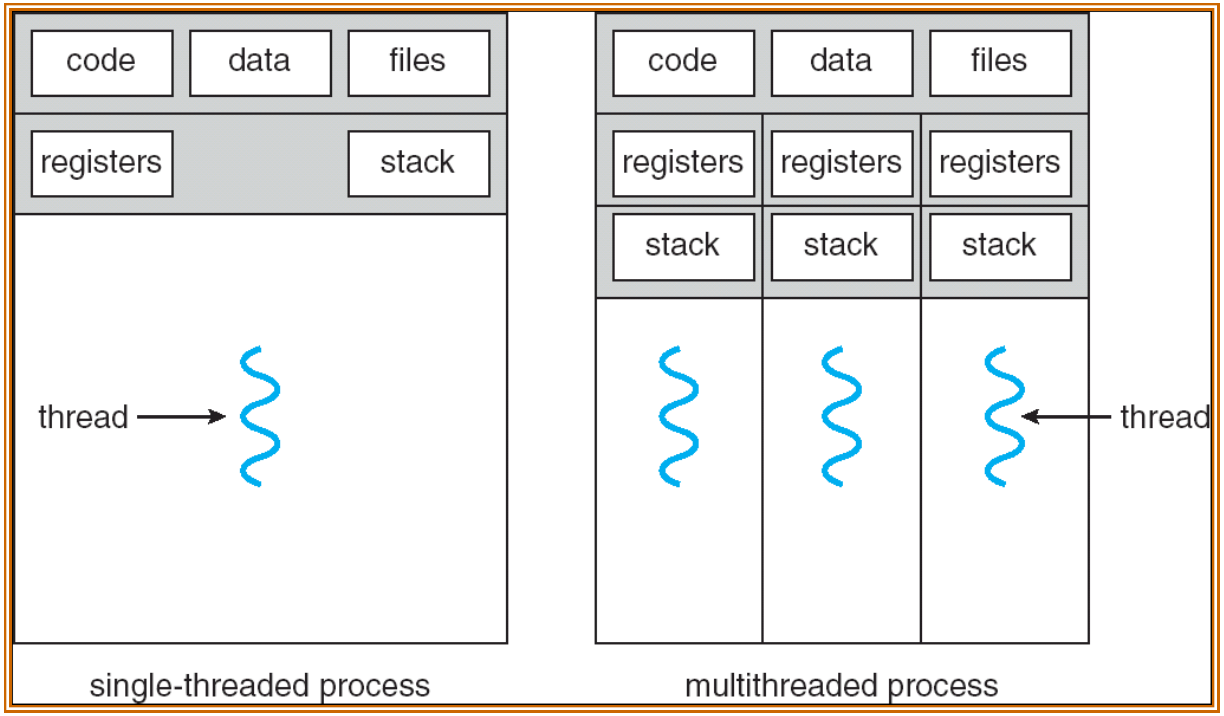
Threads

- Processes do not share resources well
    - high context switching overhead
- Idea: Separate concurrency from protection



- Multithreading: *a single program made up of a number of different concurrent activities*
- A thread (or lightweight process)
    - basic unit of CPU utilization; it consists of:
        - program counter, register set and stack space
    - A thread shares the following with peer threads:
        - code section, data section and OS resources (open files, signals)
        - No protection between threads
    - Collectively called a task.
- Heavyweight process is a task with one thread.

Single and Multithreaded Processes



- Threads encapsulate concurrency: "Active" component
- Address spaces encapsulate protection: "Passive" part
  - Keeps buggy program from trashing the system

Benefits

- Responsiveness
- Resource Sharing
- Economy
- Utilization of MP Architectures

Threads(Cont.)

- In a multiple threaded task, while one server thread is blocked and waiting, a second thread in the same task can run.
  - Cooperation of multiple threads in the same job confers higher throughput and improved performance.
  - Applications that require sharing a common buffer (i.e. producer-consumer) benefit from thread utilization.
- Threads provide a mechanism that allows sequential processes to make blocking system calls while also achieving parallelism.

Thread State

- State shared by all threads in process/addr space
  - Contents of memory (global variables, heap)
  - I/O state (file system, network connections, etc)
- State "private" to each thread
  - Kept in TCB ≡ Thread Control Block
  - CPU registers (including, program counter)
  - Execution stack
    - Parameters, Temporary variables
    - return PCs are kept while called procedures are executing

Threads (cont.)

- Thread context switch still requires a register set switch, but no memory management related work!!
- Thread states -
  - *ready, blocked, running, terminated*
- Threads share CPU and only one thread can run at a time.
- No protection among threads.

Examples: Multithreaded programs

- Embedded systems
  - Elevators, Planes, Medical systems, Wristwatches
  - Single Program, concurrent operations
- Most modern OS kernels
  - Internally concurrent because have to deal with concurrent requests by multiple users
  - But no protection needed within kernel
- Database Servers
  - Access to shared data by many concurrent users
  - Also background utility processing must be done

More Examples: Multithreaded programs

- Network Servers
  - Concurrent requests from network
  - Again, single program, multiple concurrent operations
  - File server, Web server, and airline reservation systems

- Parallel Programming (More than one physical CPU)
  - Split program into multiple threads for parallelism
  - This is called Multiprocessing

# threads Per AS: / # of addr spaces:	One	Many
One	MS/DOS, early Macintosh	Traditional UNIX
Many	Embedded systems (Geoworks, VxWorks, JavaOS,etc) JavaOS, Pilot(PC)	Mach, OS/2, Linux Windows 9x??? Win NT to XP, Solaris, HP-UX, OS X

Real operating systems have either

- One or many address spaces
- One or many threads per address space

Types of Threads

- Kernel-supported threads (Mach and OS/2)
- User-level threads
- Hybrid approach implements both user-level and kernel-supported threads (Solaris 2).

Kernel Threads

- Supported by the Kernel
  - Native threads supported directly by the kernel
  - Every thread can run or block independently
  - One process may have several threads waiting on different things
- Downside of kernel threads: a bit expensive
  - Need to make a crossing into kernel mode to schedule
- Examples
  - Windows XP/2000, Solaris, Linux,Tru64 UNIX, Mac OS X, Mach, OS/2

User Threads

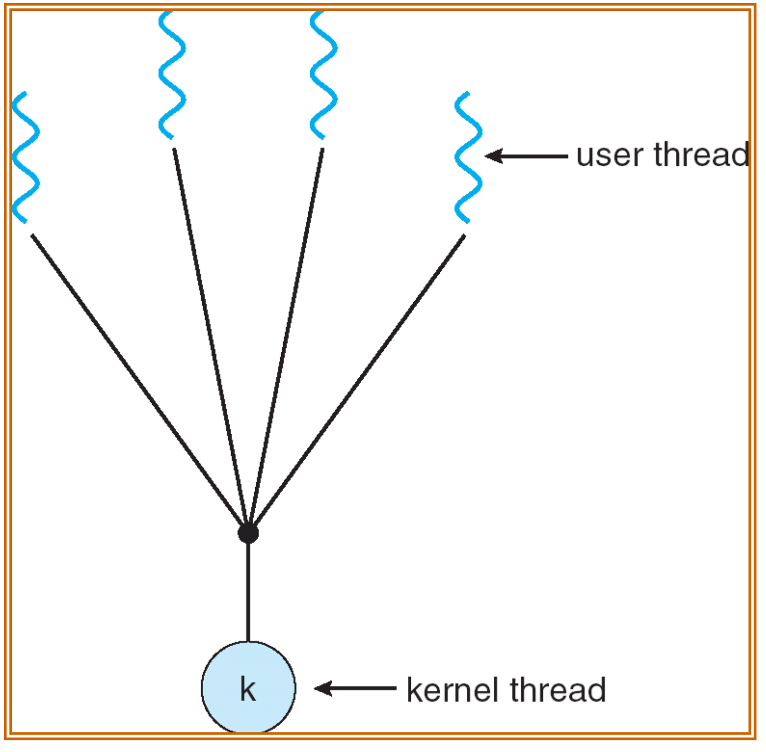
- Supported above the kernel, via a set of library calls at the user level.
  - Thread management done by user-level threads library
    - User program provides scheduler and thread package
  - May have several user threads per kernel thread
  - User threads may be scheduled non-premptively relative to each other (only switch on yield())
- Advantages
  - Cheap, Fast
    - Threads do not need to call OS and cause interrupts to kernel
- Disadv: If kernel is single threaded, system call from any thread can block the entire task.
- Example thread libraries:
  - POSIX Pthreads, Win32 threads, Java threads

Multithreading Models

- Many-to-One
- One-to-One
- Many-to-Many

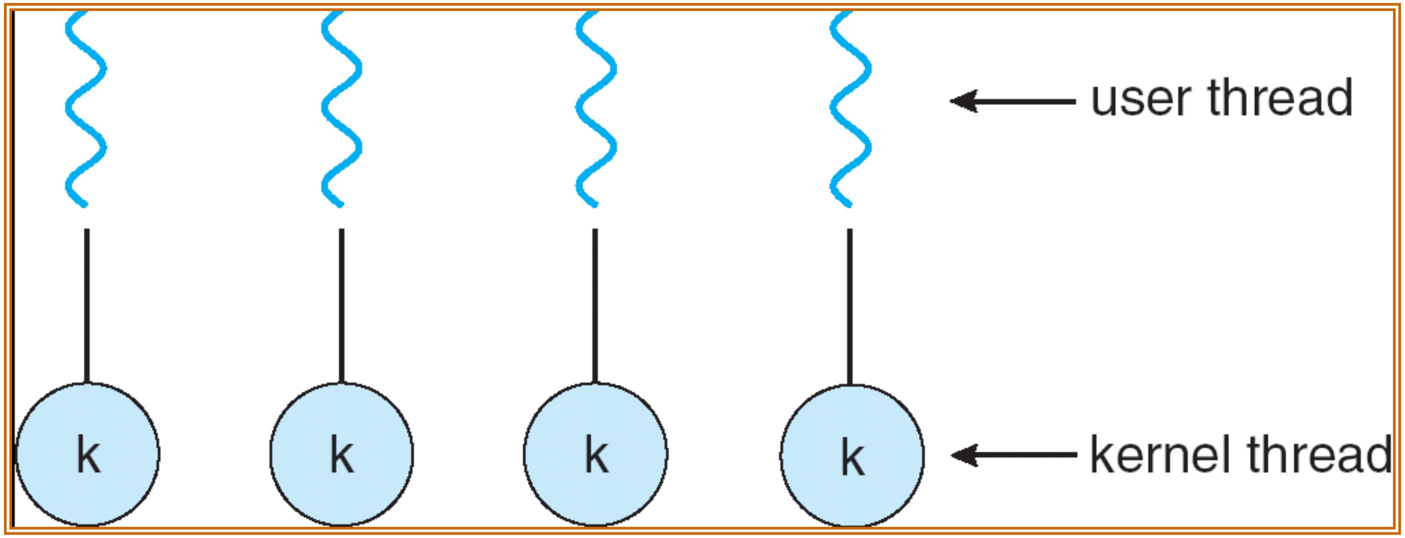
Many-to-One

- Many user-level threads mapped to single kernel thread
- Examples:
  - Solaris Green Threads
  - GNU Portable Threads



One-to-One

- Each user-level thread maps to kernel thread

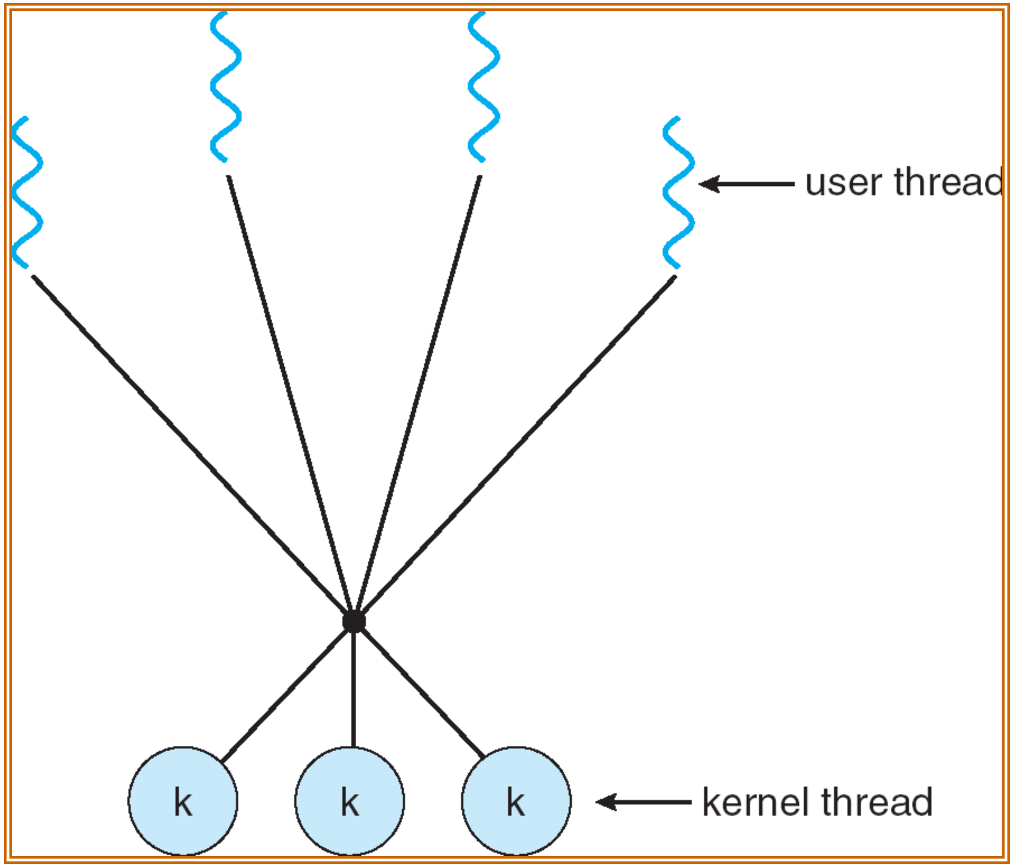


Examples

- Windows NT/XP/2000; Linux; Solaris 9 and later

Many-to-Many Model

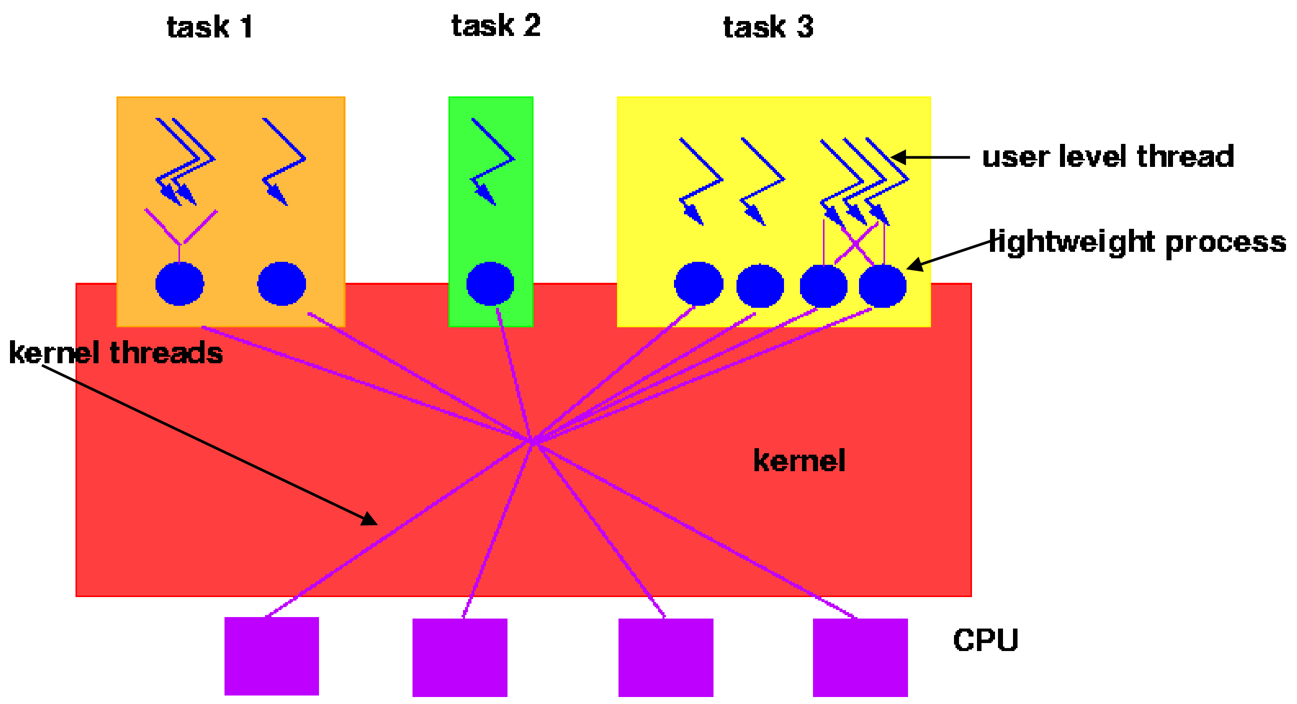
- Allows many user level threads to be mapped to many kernel threads
- Allows the operating system to create a sufficient number of kernel threads
- Solaris prior to version 9
- Windows NT/2000 with the *ThreadFiber* package



Thread Support in Solaris 2

- Solaris 2 is a version of UNIX with support for
  - kernel and user level threads, symmetric multiprocessing and real-time scheduling.
- Lightweight Processes (LWP)
  - intermediate between user and kernel level threads
  - each LWP is connected to exactly one kernel thread

Threads in Solaris 2



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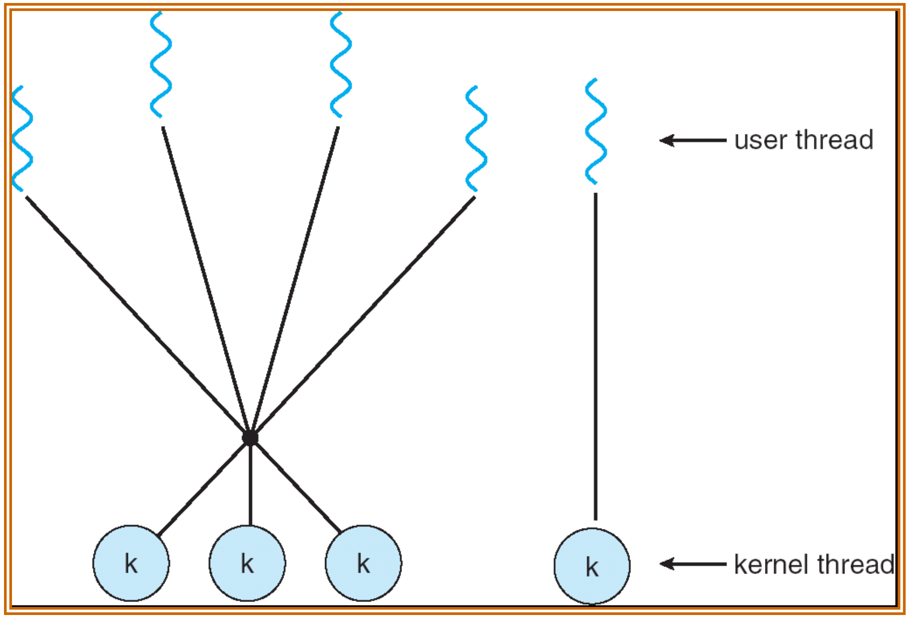
Threads in Solaris 2

- Resource requirements of thread types
  - Kernel Thread: small data structure and stack; thread switching does not require changing memory access information - relatively fast.
  - Lightweight Process: PCB with register data, accounting and memory information - switching between LWP is relatively slow.
  - User-level thread: only needs stack and program counter; no kernel involvement means fast switching. Kernel only sees the LWPs that support user-level threads.

Two-level Model

- Similar to M:M, except that it allows a user thread to be **bound** to kernel thread
- Examples
  - IRIX, HP-UX, Tru64 UNIX, Solaris 8 and earlier

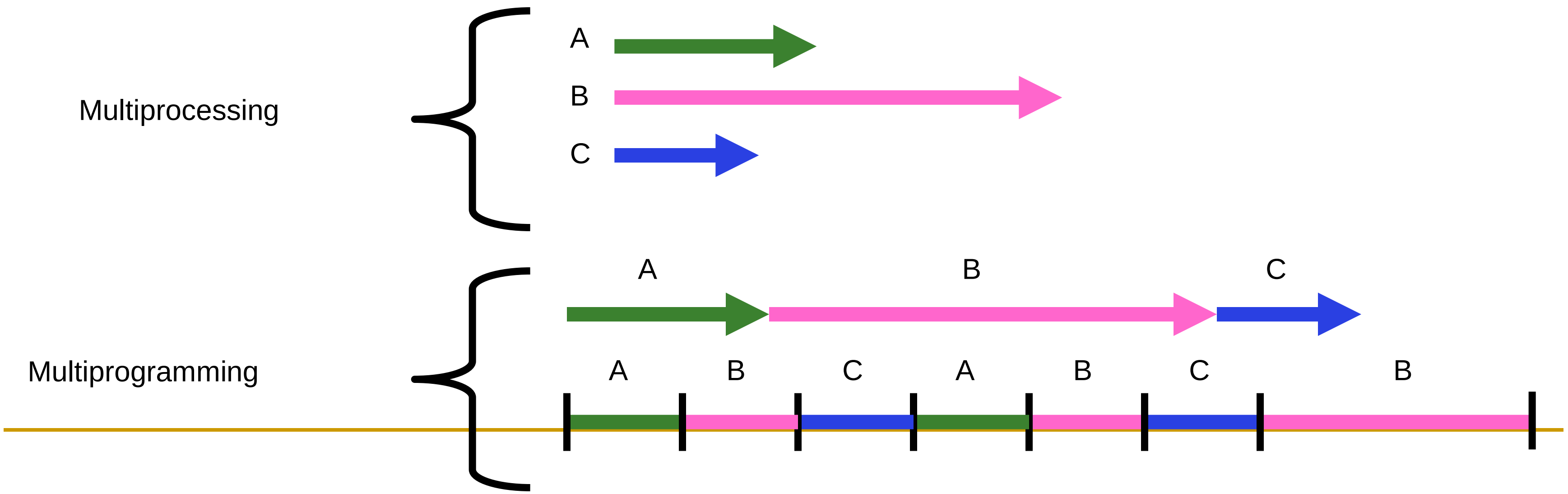


Threading Issues

- Semantics of **fork()** and **exec()** system calls
- Thread cancellation
- Signal handling
- Thread pools
- Thread specific data
- Scheduler activations

Multi(processing, programming, threading)

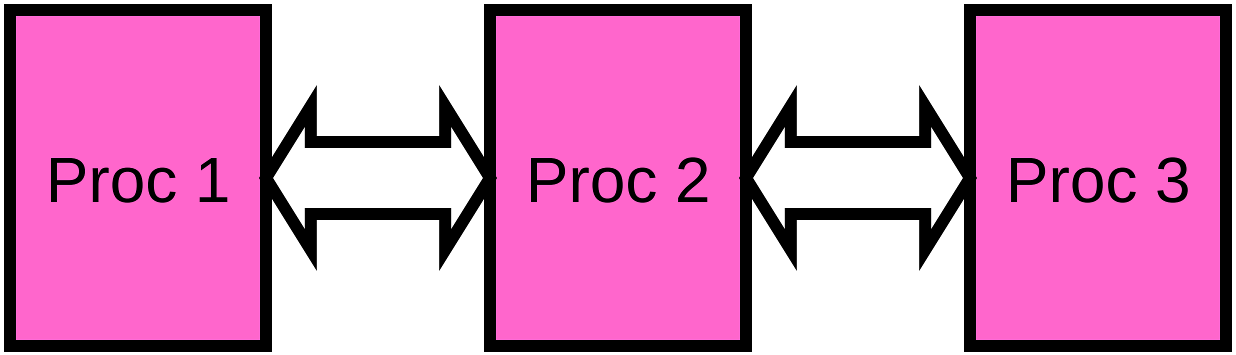
- Definitions:
  - Multiprocessing ≡ Multiple CPUs
  - Multiprogramming ≡ Multiple Jobs or Processes
  - Multithreading ≡ Multiple threads per Process
- What does it mean to run two threads "concurrently"?
  - Scheduler is free to run threads in any order and interleaving: FIFO, Random, …
  - Dispatcher can choose to run each thread to completion or time-slice in big chunks or small chunks



Cooperating Processes

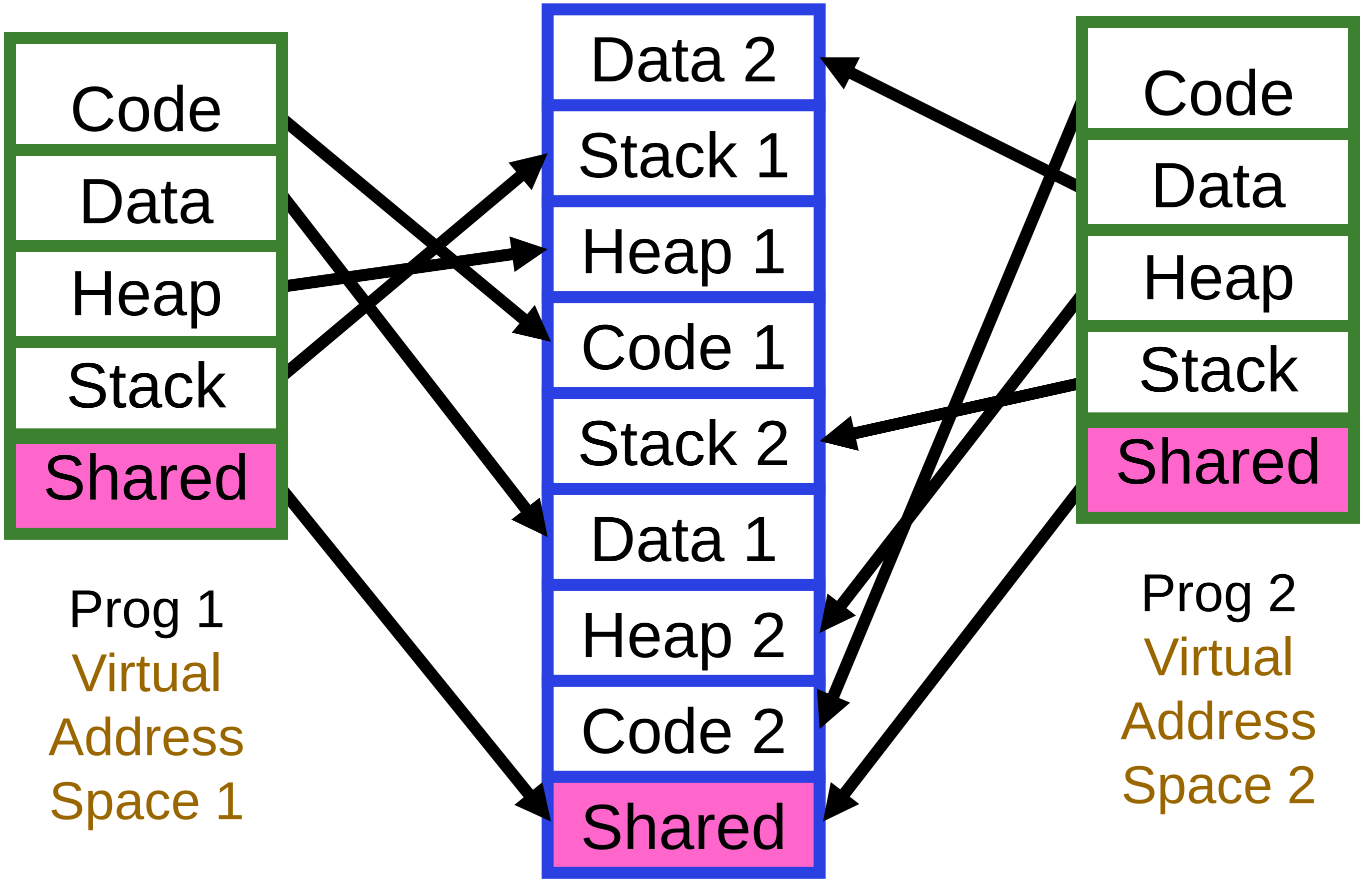
- Concurrent Processes can be
  - Independent processes
    - cannot affect or be affected by the execution of another process.
  - Cooperating processes
    - can affect or be affected by the execution of another process.
- Advantages of process cooperation:
    - Information sharing
    - Computation speedup
    - Modularity
    - Convenience(e.g. editing, printing, compiling)
- Concurrent execution requires
    - process communication and process synchronization

Interprocess Communication (IPC)



- Separate address space isolates processes
  - High Creation/Memory Overhead; (Relatively) High Context-Switch Overhead
- Mechanism for processes to communicate and synchronize actions.
  - Via shared memory - Accomplished by mapping addresses to common DRAM
    - Read and Write through memory
  - Via Messaging system - processes communicate without resorting to shared variables.
    - `send()` and `receive()` messages
    - Can be used over the network!
  - Messaging system and shared memory not mutually exclusive
    - can be used simultaneously within a single OS or a single process.

Shared Memory Communication



- Communication occurs by “simply” reading/writing to shared address page
  - Really low overhead communication
  - Introduces complex synchronization problems

Cooperating Processes via Message Passing

- IPC facility provides two operations.

  send(*message*) - message size can be fixed or variable

  receive(*message*)

- If processes P and Q wish to communicate, they need to:
  - establish a communication link between them
  - exchange messages via send/receive
- Fixed vs. Variable size message
  - Fixed message size - straightforward physical implementation, programming task is difficult due to fragmentation
  - Variable message size - simpler programming, more complex physical implementation.

Implementation Questions

- How are links established?
- Can a link be associated with more than 2 processes?
- How many links can there be between every pair of communicating processes?
- What is the capacity of a link?
- Fixed or variable size messages?
- Unidirectional or bidirectional links?

…….

Direct Communication

- Sender and Receiver 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.
  - Exactly one link between each pair.
  - Link may be unidirectional, usually bidirectional.

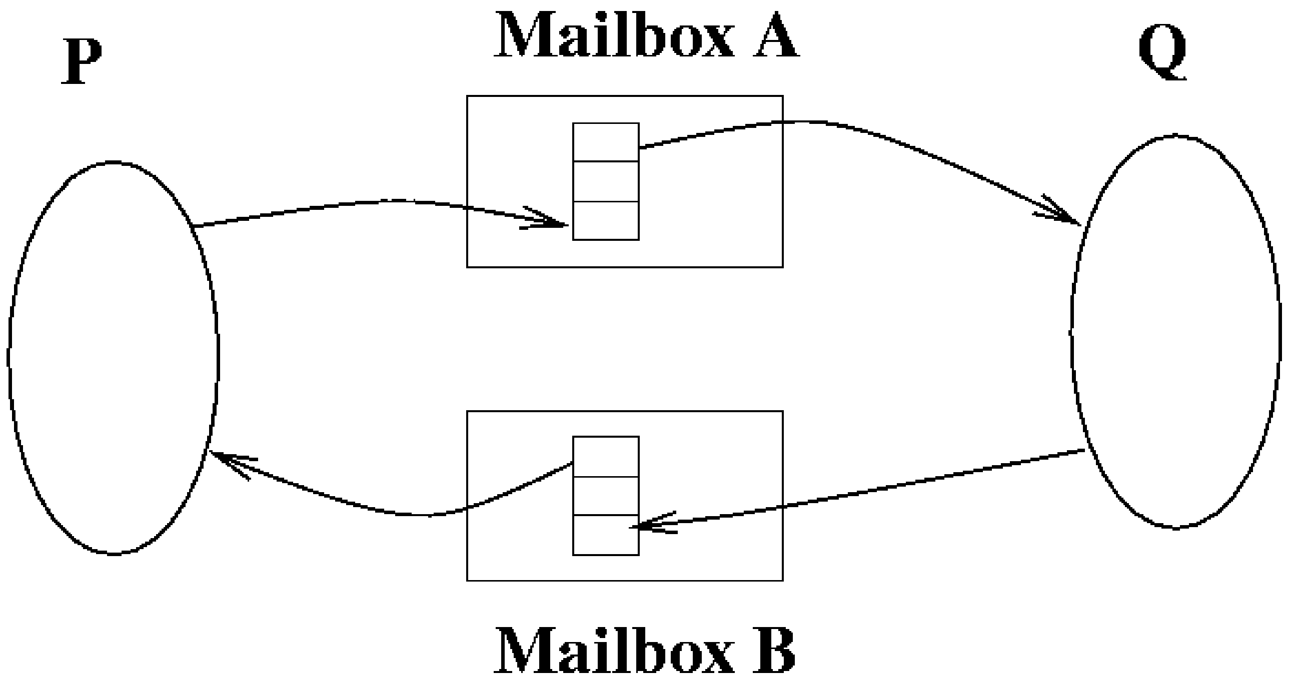
Indirect Communication

- Messages are directed to and received from mailboxes (also called ports)
  - Unique ID for every mailbox.
  - Processes can communicate only if they share a mailbox.

  Send(*A*, *message*) /* send *message* to mailbox *A* */

  Receive(*A*, *message*) /* receive *message* from mailbox *A* */
- Properties of communication link
  - Link established only if processes share a common mailbox.
  - Link can be associated with many processes.
  - Pair of processes may share several communication links
  - Links may be unidirectional or bidirectional

Indirect Communication using mailboxes



Mailboxes (cont.)

- Operations
  - create a new mailbox
  - send/receive messages through mailbox
  - destroy a mailbox
- Issue: Mailbox sharing
  - P1, P2 and P3 share mailbox A.
  - P1 sends message, P2 and P3 receive… who gets message??
- Possible Solutions
  - disallow links between more than 2 processes
  - allow only one process at a time to execute receive operation
  - allow system to arbitrarily select receiver and then notify sender.

Message Buffering

- Link has some capacity - determine the number of messages that can reside temporarily in it.
- Queue of messages attached to link
    - Zero-capacity Queues: 0 messages
        - sender waits for receiver (synchronization is called *rendezvous*)
    - Bounded capacity Queues: Finite length of *n* messages
        - sender waits if link is full
    - Unbounded capacity Queues: Infinite queue length
        - sender never waits

Message Problems - Exception Conditions

- Process Termination
  - Problem: P(sender) terminates, Q(receiver) blocks forever.
    - Solutions:
      - System terminates Q.
      - System notifies Q that P has terminated.
      - Q has an internal mechanism(timer) that determines how long   to wait for a message from P.
  - Problem: P(sender) sends message, Q(receiver) terminates. In automatic buffering, P sends message until buffer is full or forever. In no-buffering scheme, P blocks forever.
    - Solutions:
      - System notifies P
      - System terminates P
      - P and Q use acknowledgement with timeout

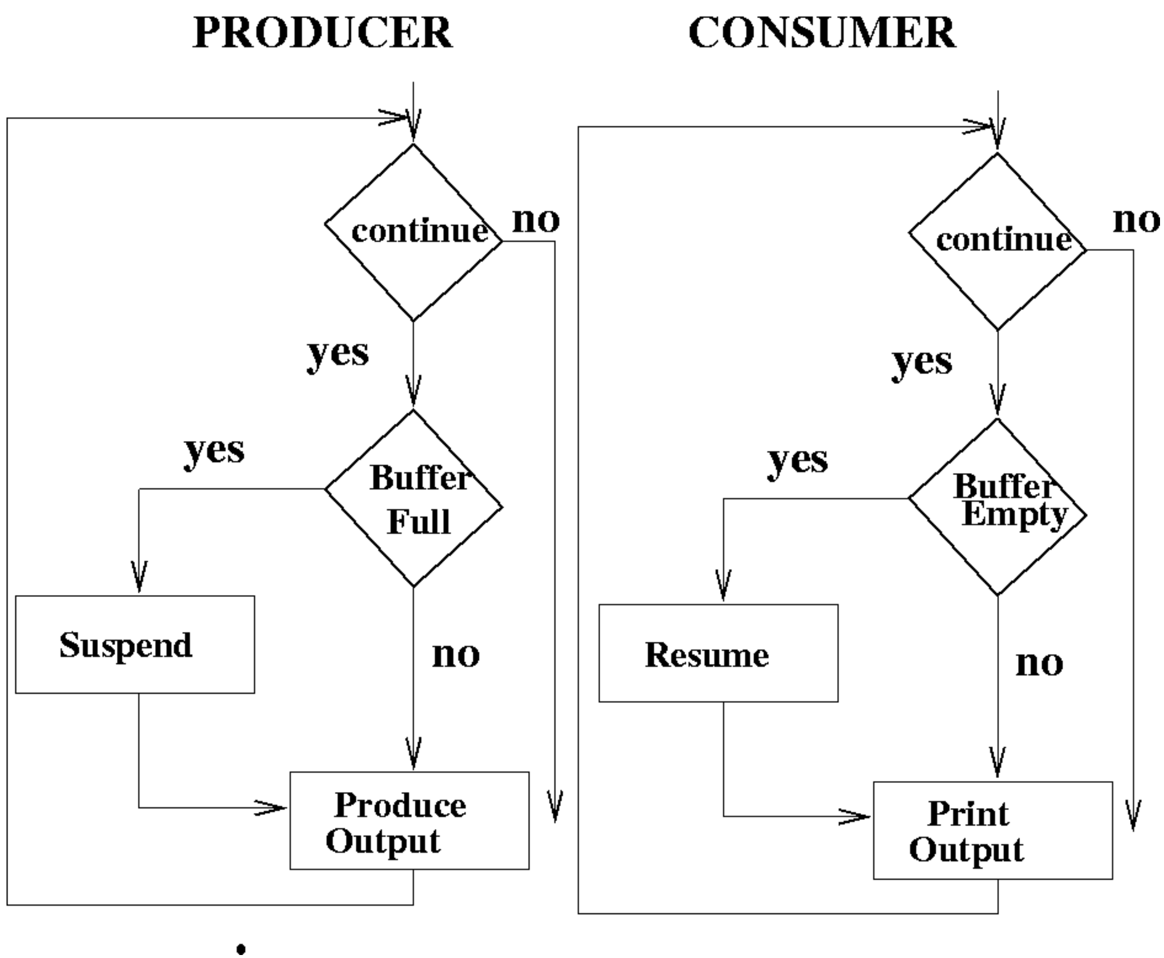
Message Problems - Exception Conditions

- Lost Messages
  - OS guarantees retransmission
  - sender is responsible for detecting it using timeouts
  - sender gets an exception
- Scrambled Messages
  - Message arrives from sender P to receiver Q, but information in message is corrupted due to noise in communication channel.
  - Solution
    - need error detection mechanism, e.g. CHECKSUM
    - need error correction mechanism, e.g. retransmission

Producer-Consumer Problem

- Paradigm for cooperating processes;
  - producer process produces information that is consumed by a consumer process.
- We need buffer of items that can be filled by producer and emptied by consumer.
    - Unbounded-buffer places no practical limit on the size of the buffer. Consumer may wait, producer never waits.
    - Bounded-buffer assumes that there is a fixed buffer size. Consumer waits for new item, producer waits if buffer is full.
  - Producer and Consumer must synchronize.

Producer-Consumer Problem



Bounded Buffer using IPC (messaging)

- Producer

  repeat

  …

  produce an item in *nextp*;

  …

  send(*consumer*, *nextp*);

  until false;

- Consumer

  repeat

  receive(*producer*, *nextc*);

  …

  consume item from *nextc*;

  …

  until false;

Bounded-buffer - Shared Memory Solution

- Shared data

var *n*;

type *item* = ….;

var *buffer*: **array**[0..n-1] **of** *item*;

in, *out*: 0..*n*-1;

in :=0; *out*:= 0; /* shared buffer = circular array */

/* Buffer empty if *in* == *out* */

/* Buffer full if (*in*+1) mod *n* == *out* */

/* *noop* means ‘do nothing’ */

Bounded Buffer - Shared Memory Solution

- Producer process - creates filled buffers

```
repeat
        …
  produce an item in nextp
    …
  while in+1 mod n = out do noop;
  buffer[in] := nextp;
  in := in+1 mod n;
until false;
```

Bounded Buffer - Shared Memory Solution

- Consumer process - Empties filled buffers

repeat

        while *in* = *out* **do** *noop*;

    nextc := *buffer[out]* ;

    out:= *out*+1 **mod** *n*;

…

consume the next item in *nextc*

…

until *false*