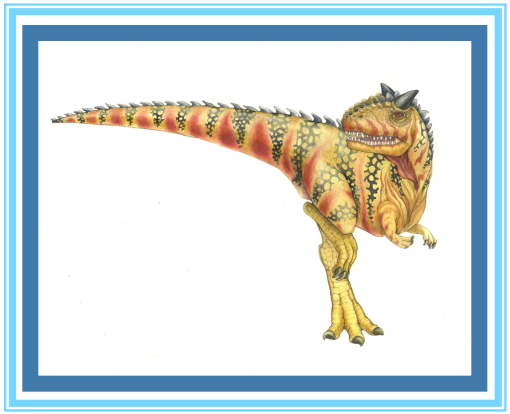
Tema 2: Procesos



- Chapter 3: Process Concept
- Chapter 4: Multithreaded Programming
- Chapter 5: Process Scheduling

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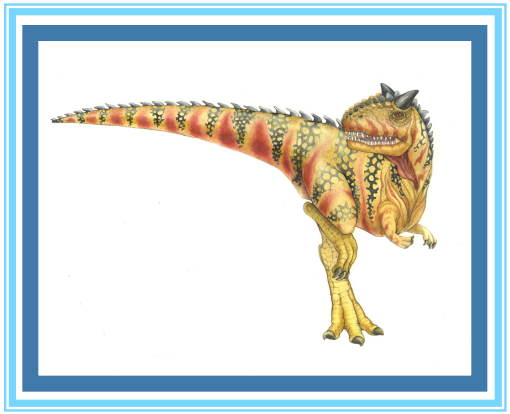
Chapter 3: Process-Concept



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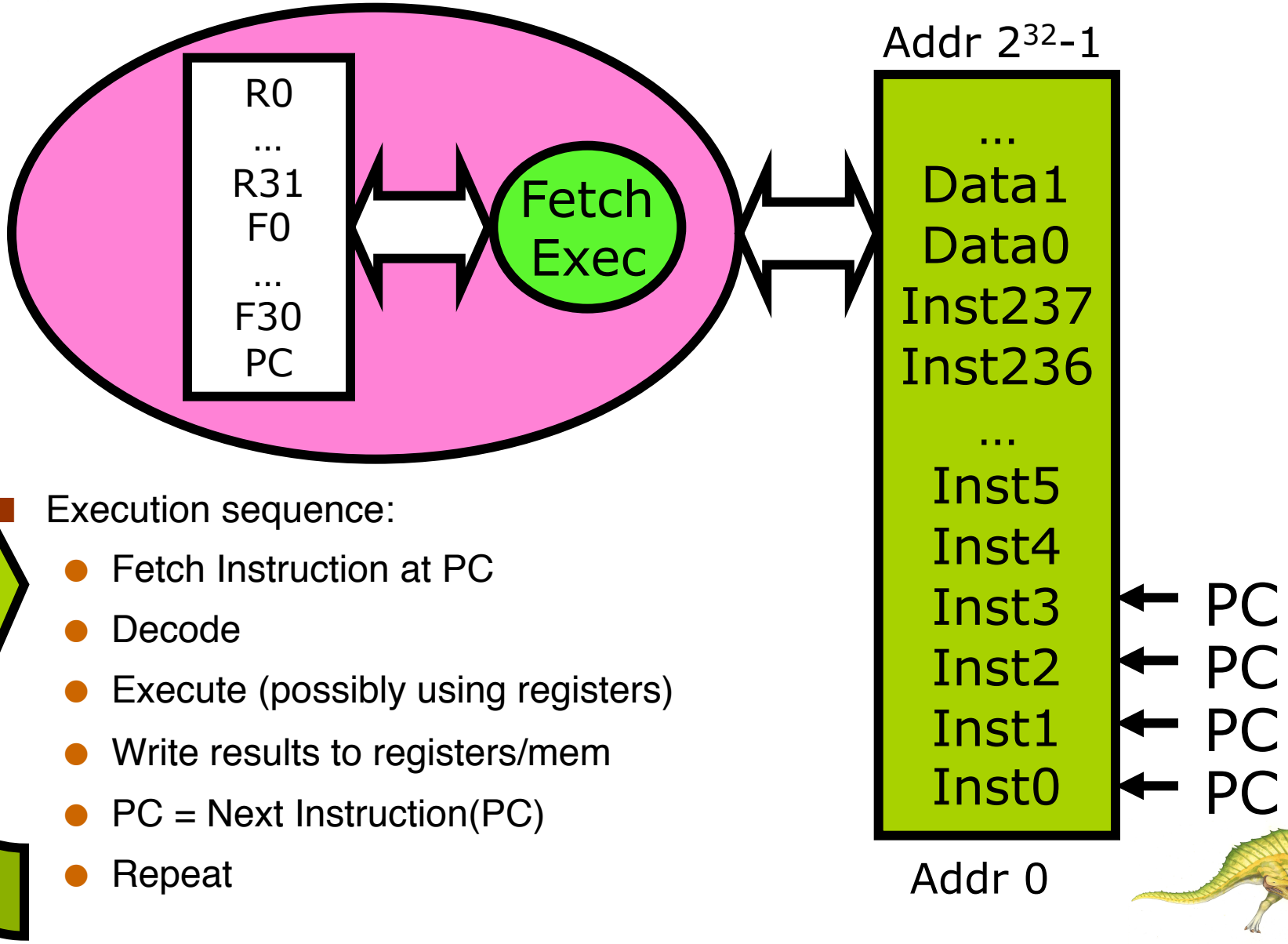
Chapter 3. Contents

- Process Concept
- Process Scheduling
- Operations on Processes
- Interproces Communication

Objectives

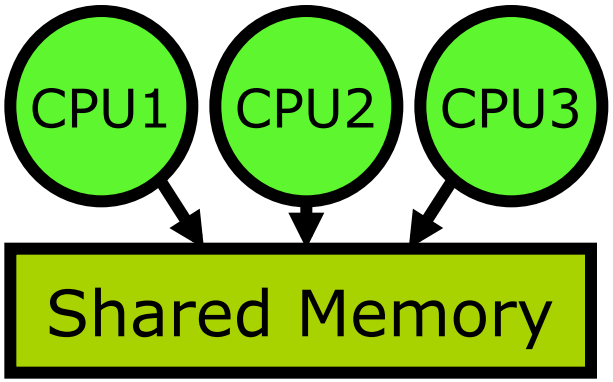
- To introduce the notion of a process -- a program in execution, which forms the basis of all computation
- To describe the various features of processes, including scheduling, creation and termination, and communication

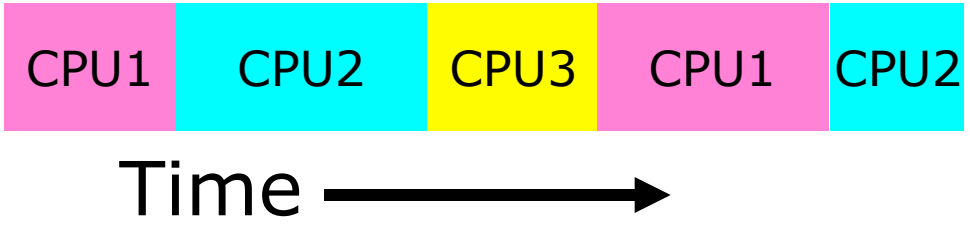
What happens during execution?



- Execution sequence:
  - Fetch Instruction at PC
  - Decode
  - Execute (possibly using registers)
  - Write results to registers/mem
  - PC = Next Instruction(PC)
  - Repeat

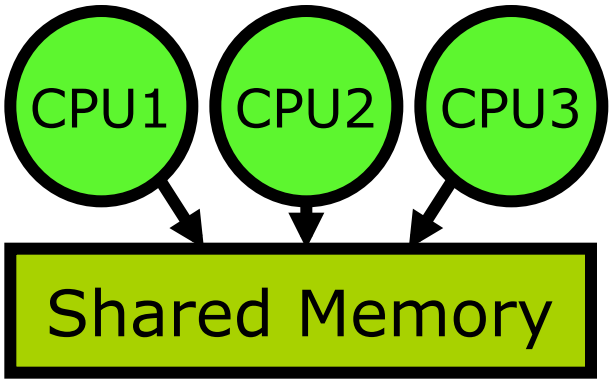
Concurrent execution (single CPU)

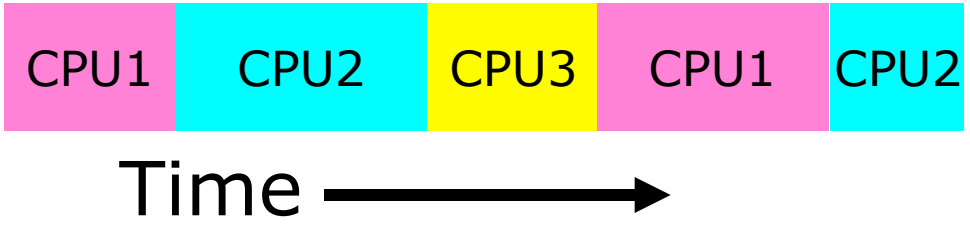




- The basic problem of concurrency involves resources:
  - Hardware: *single* CPU, single DRAM, single I/O devices
  - Multiprogramming API: users think they have exclusive access to shared resources
- How do we provide the illusion of multiple processors?: Multiplex in time!
- Basic Idea: Use Virtual Machine abstraction
  - Decompose hard problem into simpler ones
  - Abstract the notion of an executing program: process

Concurrent execution (single CPU)

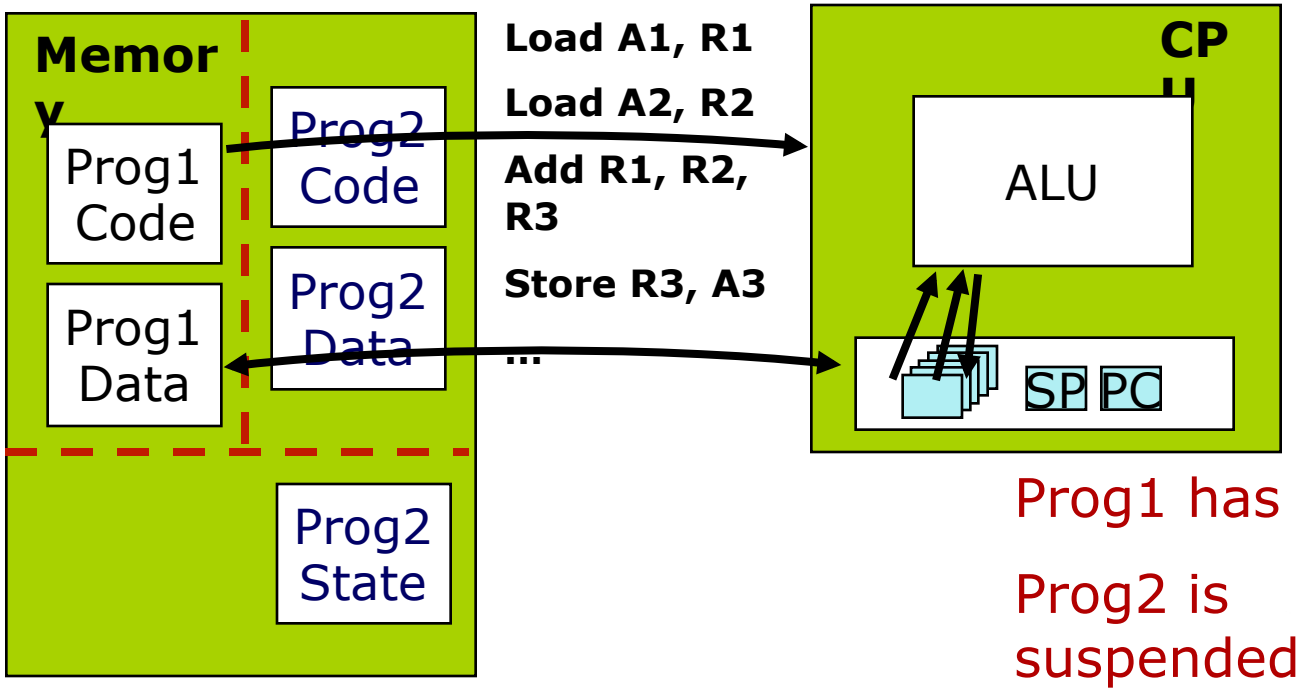




- Then, worry about multiplexing these abstract machines
  - Each virtual "CPU" (process) needs a structure to hold:
    - Program Counter (PC), Stack Pointer (SP)
    - Registers (Integer, Floating point, others…?)
  - How switch from one CPU to the next?
    - Save PC, SP, and registers in current state block
    - Load PC, SP, and registers from new state block
  - What triggers switch?
    - Timer, voluntary yield, I/O, other things

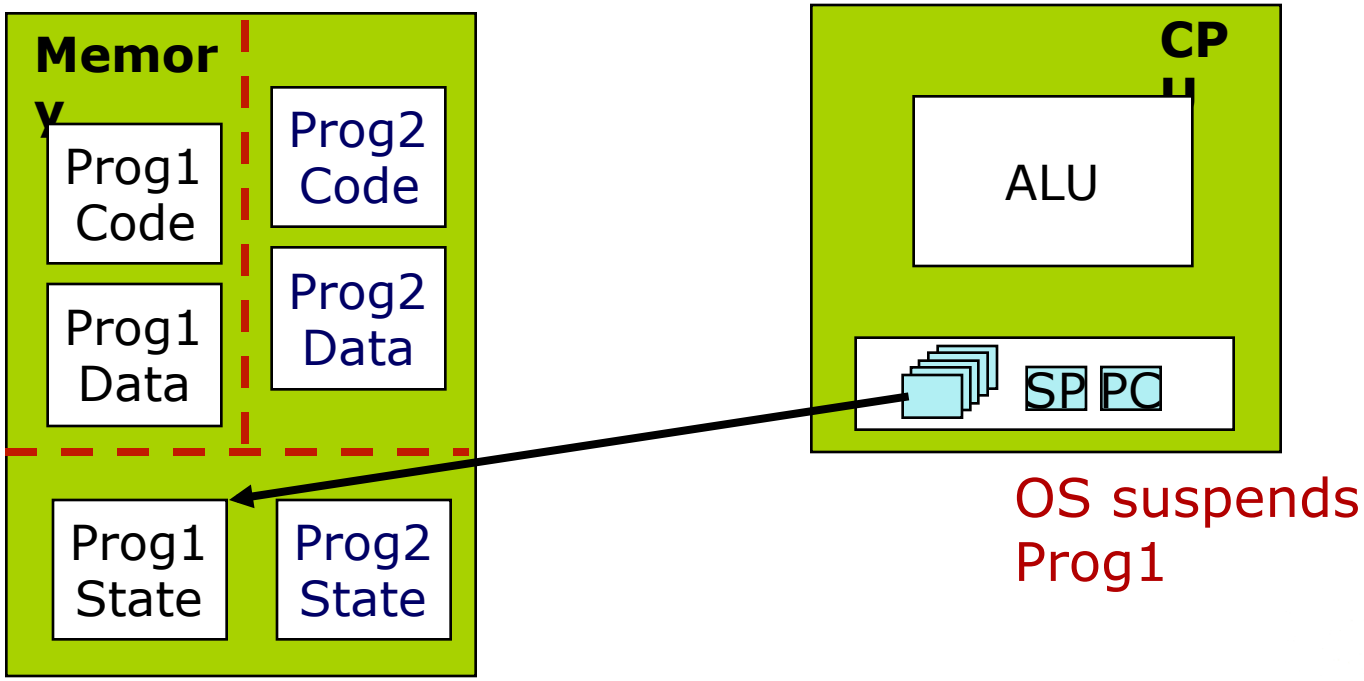
Switching among multiple processes

- Program instructions operate on operands in memory and (temporarily) in registers



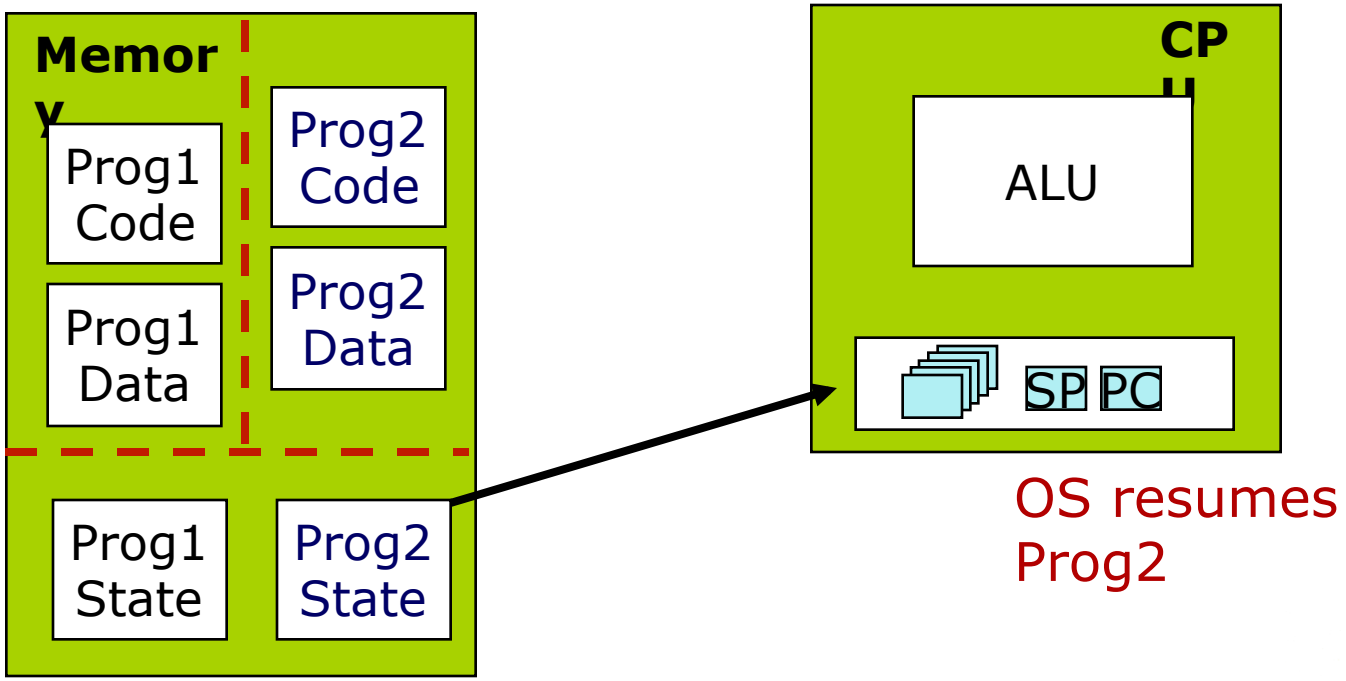
Switching among multiple processes

- Saving all the information about a process allows a process to be *temporarily suspended* and later *resumed* from the same point



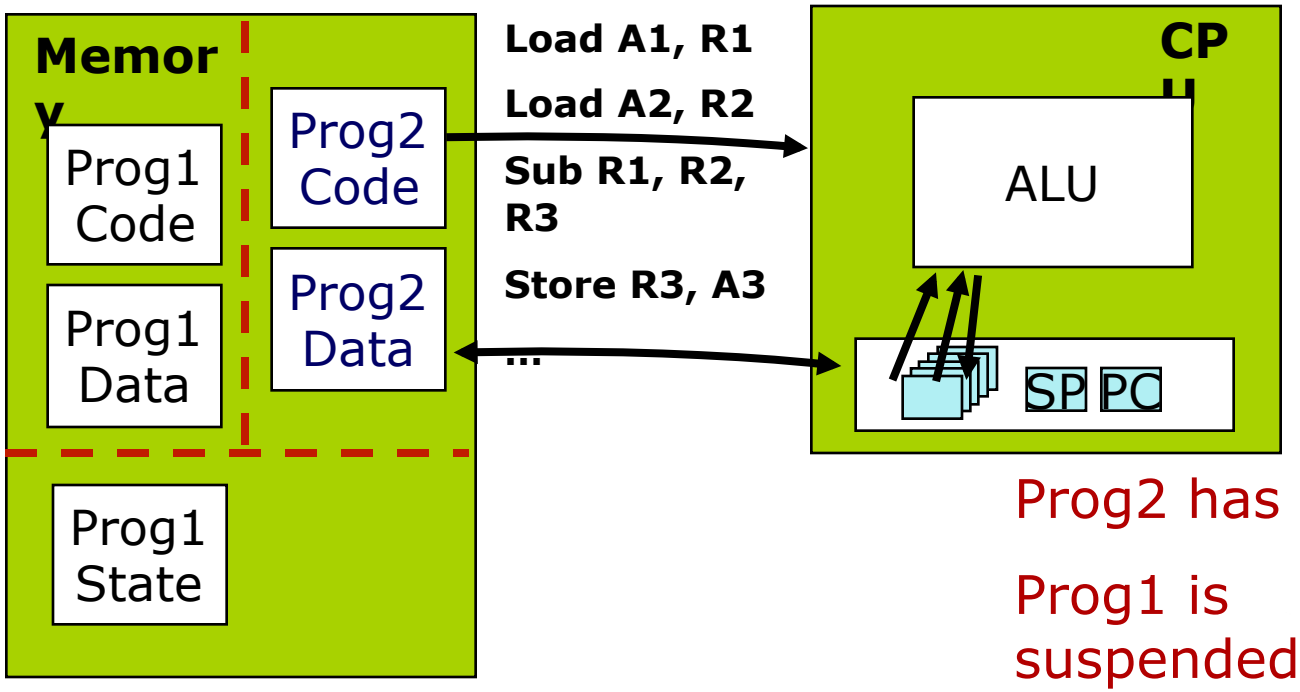
Switching among multiple processes

- Saving all the information about a process allows a process to be *temporarily suspended* and later *resumed*



Switching among multiple processes

- Program instructions operate on operands in memory and in registers

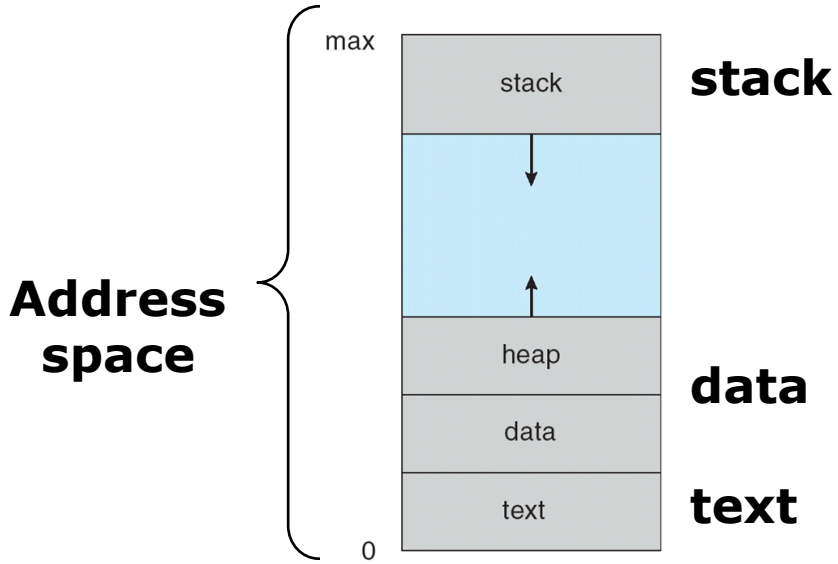


Process Concept

- An operating system executes a variety of programs:
  - Batch system – jobs
  - Time-shared systems – user programs or tasks
- Textbook uses the terms *job* and *process* almost interchangeably
- Process – a program in execution; process execution must progress in sequential fashion
  - Program
    - description of how to perform an activity
    - instructions and static data values
  - Process
    - a snapshot of a program in execution
    - memory (program instructions, static and dynamic data values)
    - CPU state (registers, PC, SP, etc)
    - operating system state (open files, accounting statistics etc)

Process address space

- Each process runs in its own virtual memory *address space* that consists of:
  - *Stack space* – used for function and system calls
  - *Data space* – variables (both static and dynamic allocation)
  - *Text* – the program code (usually read only)

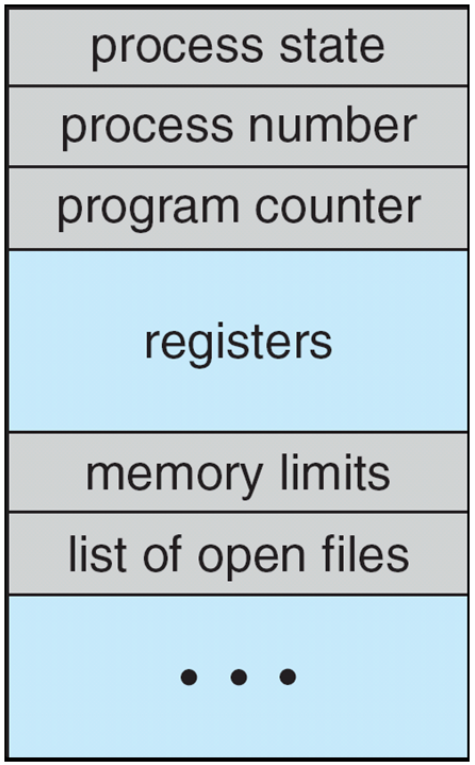


- Invoking the same program multiple times results in the creation of multiple distinct address spaces

Process Control Block (PCB)

Information associated with each process

- Process state
- Program counter
- CPU registers
- CPU scheduling information
- Memory-management information
- Accounting information
- I/O status information



The Basic Problem of Concurrency

- The basic problem of concurrency involves resources:
  - Hardware: single CPU, single DRAM, single I/O devices
  - Multiprogramming API: users think they have exclusive access to shared resources
- OS Has to coordinate all activity
  - Multiple users, I/O interrupts, …
  - How can it keep all these things straight?

How to protect process from one another?

- Need three important things:
  1. Dual mode operation
  2. Protection of memory
     - Every task does not have access to all memory
  3. Protection of I/O devices
     - Every task does not have access to every device
  4. Protection of Access to Processor:
     Preemptive switching from task to task
     - Use of timer
     - Must not be possible to disable timer from usercode

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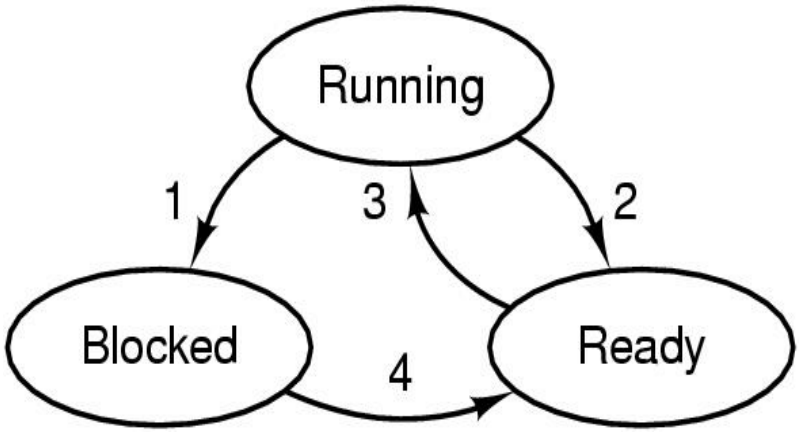
Process states



1. Process blocks for input
2. Scheduler picks another process
3. Scheduler picks this process
4. Input becomes available

- Possible process states
  - running
  - blocked
  - ready

Process Tracking

(a) Trace of Process A	(b) Trace of Process B	(c) Trace of Process C
5000	8000	12000
5001	8001	12001
5002	8002	12002
5003	8003	12003
5004		12004
5005		12005
5006		12006
5007		12007
5008		12008
5009		12009
5010		12010
5011		12011

5000 = Starting address of program of Process A
8000 = Starting address of program of Process B
12000 = Starting address of program of Process C

Process Tracking

1	5000
2	5001
3	5002
4	5003
5	5004
6	5005
----------	Time out
7	100
8	101
9	102
10	103
11	104
12	105
13	8000
14	8001
15	8002
16	8003
----------	I/O request
17	100
18	101
19	102
20	103
21	104
22	105
23	12000
24	12001
25	12002
26	12003
27	12004
28	12005
----------	Time out
29	100
30	101
31	102
32	103
33	104
34	105
35	5006
36	5007
37	5008
38	5009
39	5010
40	5011
----------	Time out
41	100
42	101
43	102
44	103
45	104
46	105
47	12006
48	12007
49	12008
50	12009
51	12010
52	12011
----------	Time out

100 = Starting address of dispatcher program

shaded areas indicate execution of dispatcher process;
first and third columns count instruction cycles;

Figure 3.3 Combined Trace of Processes of Figure 3.1

Process Tracking

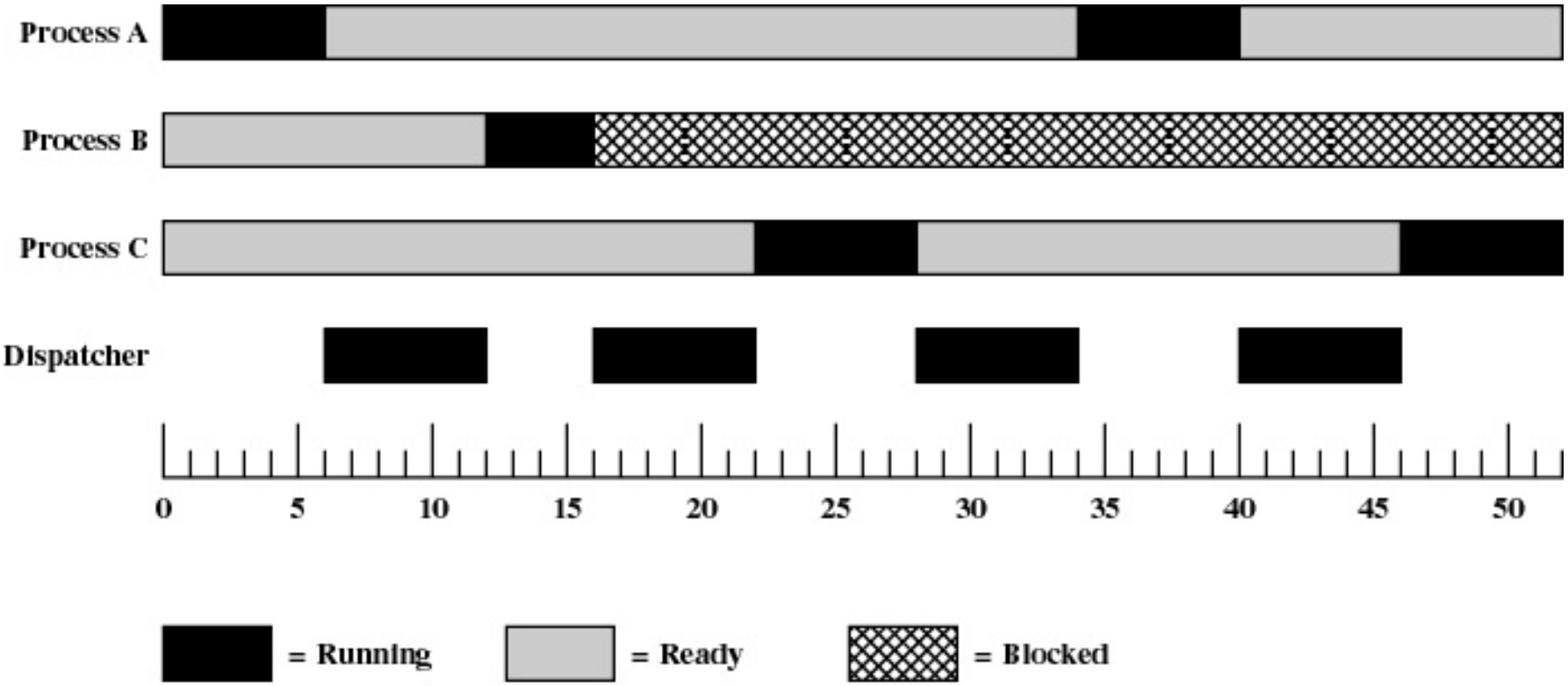
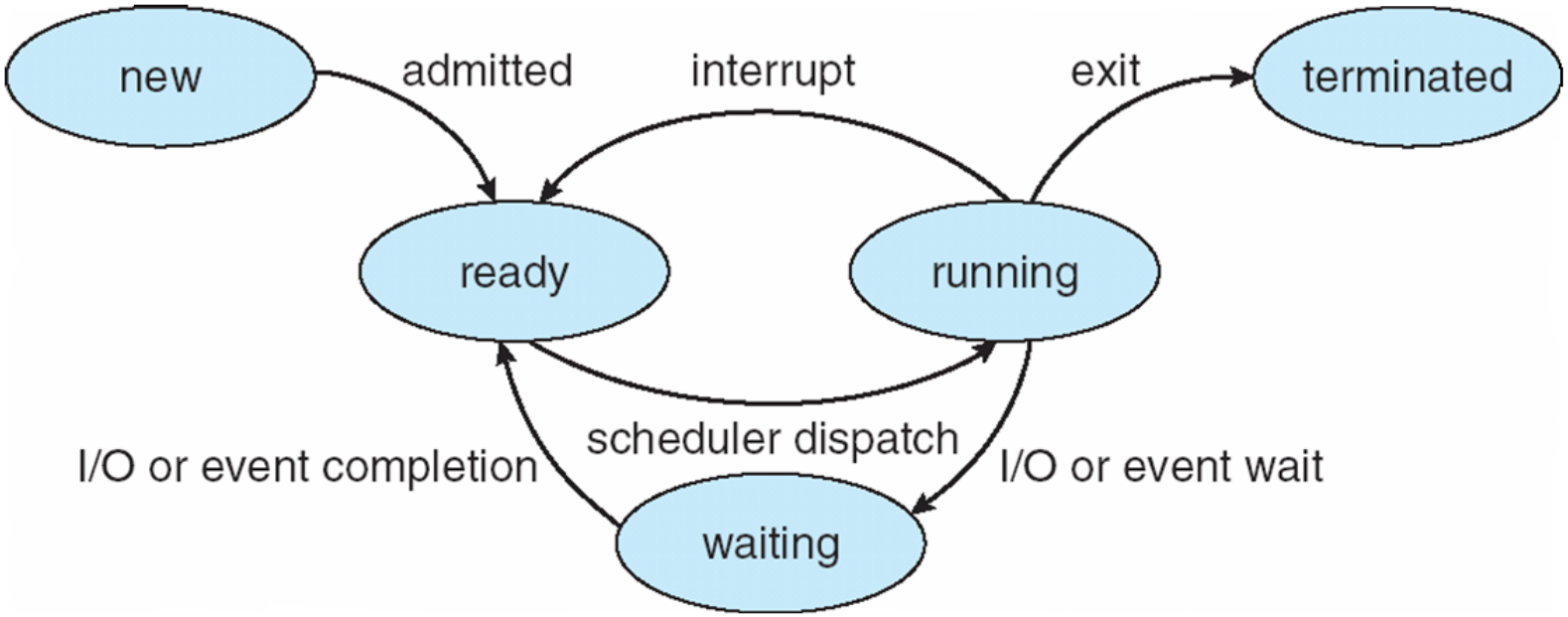


Figure 3.6 Process States for Trace of Figure 3.3

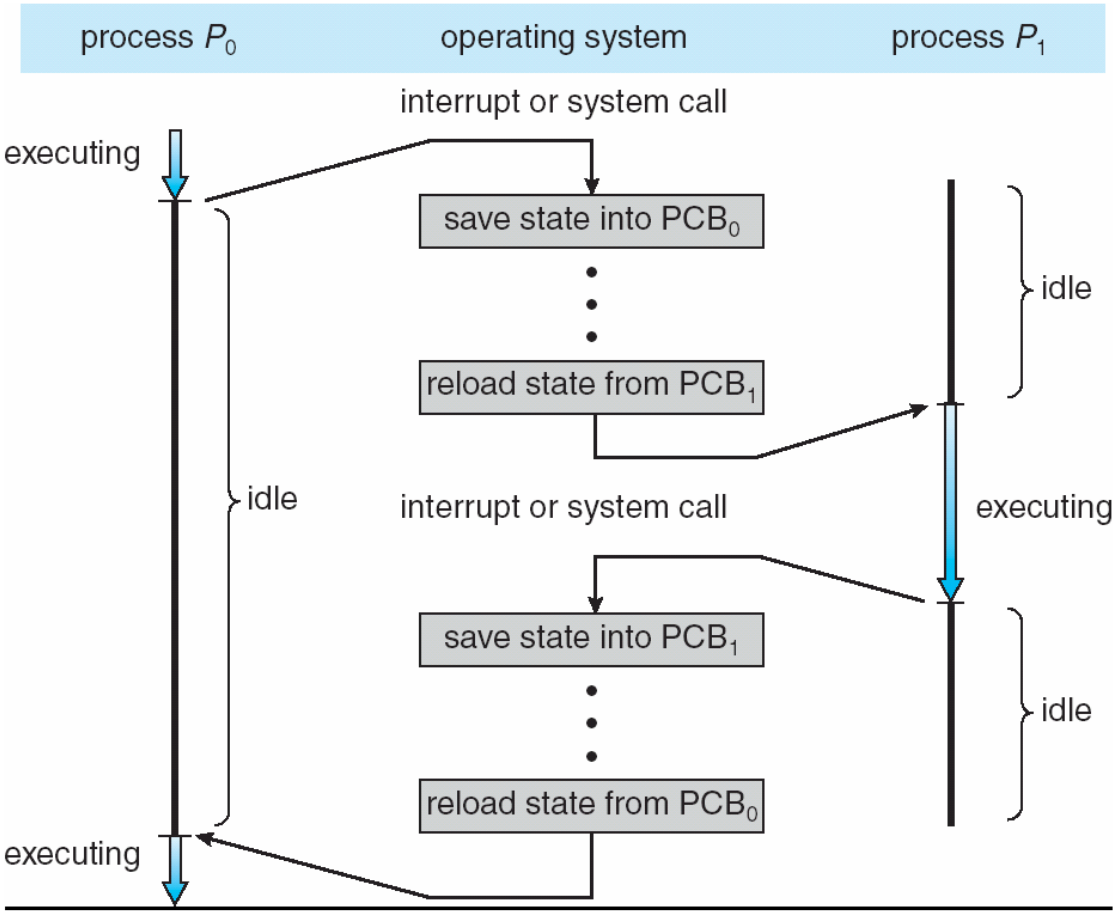
Process State

- 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



CPU Switch From Process to Process

- This PCB is saved when a process is removed from the CPU and another process takes its place (context switch).

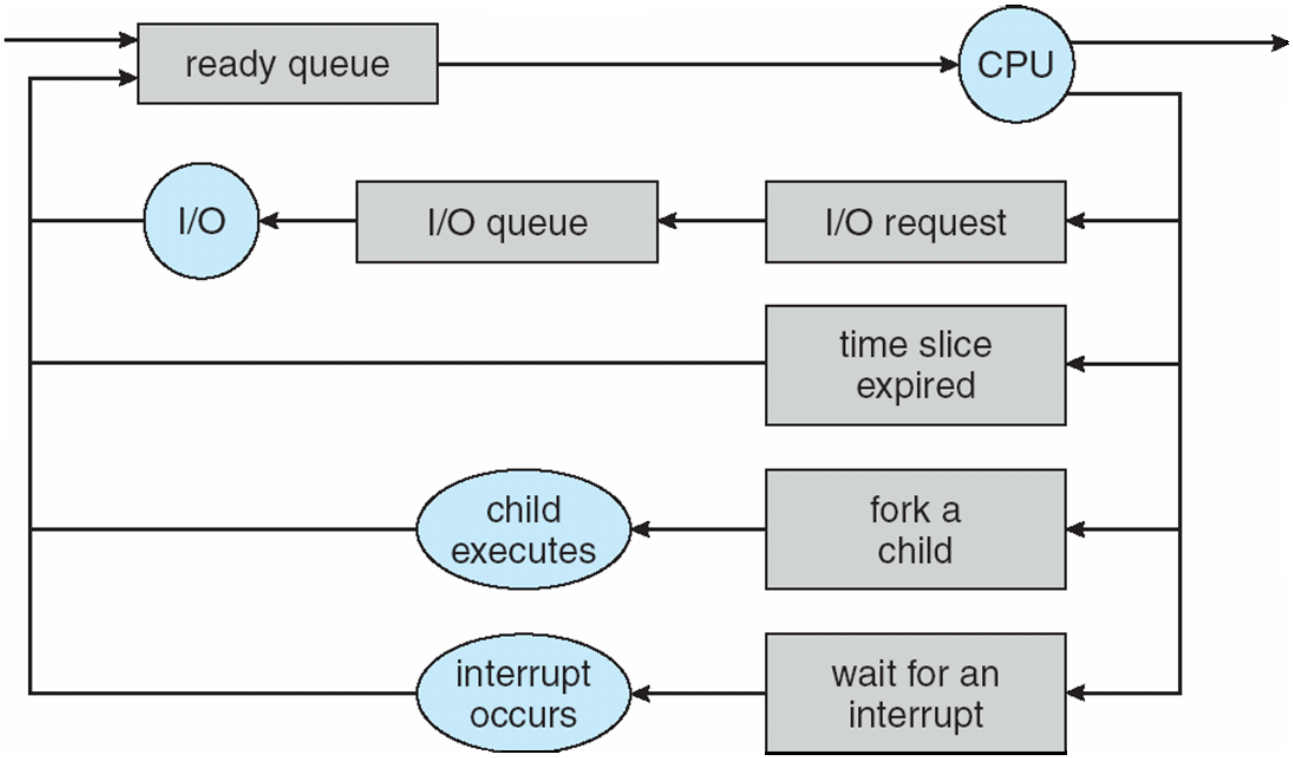


Context Switch

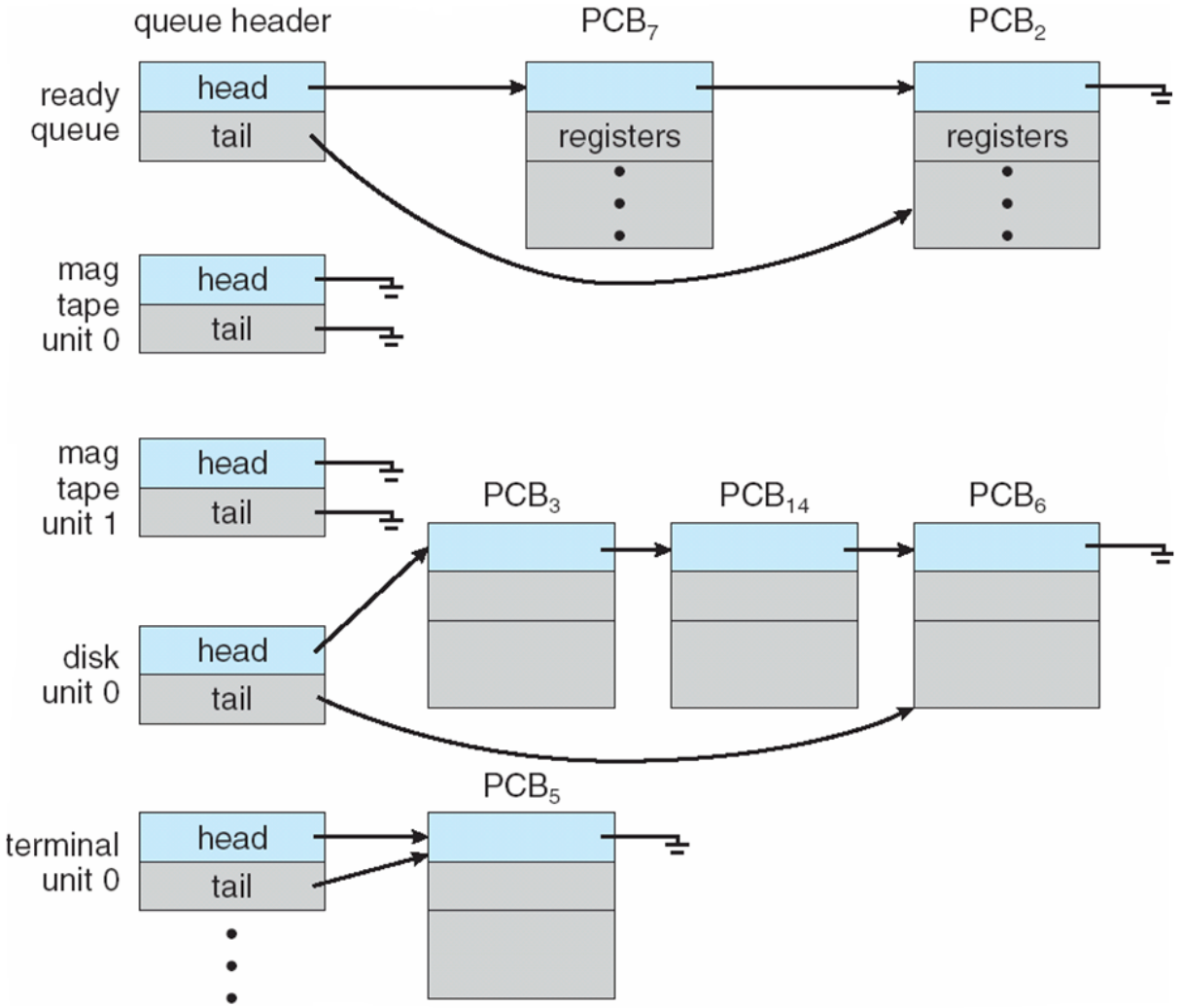
- When CPU switches to another process, the system must save the state of the old process and load the saved state for the new process via a context switch
- Context of a process represented in the PCB
- Context-switch time is overhead; the system does no useful work while switching
- Time dependent on hardware support.
  - Varies from 1 to 1000 microseconds

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
- Processes migrate among the various queues

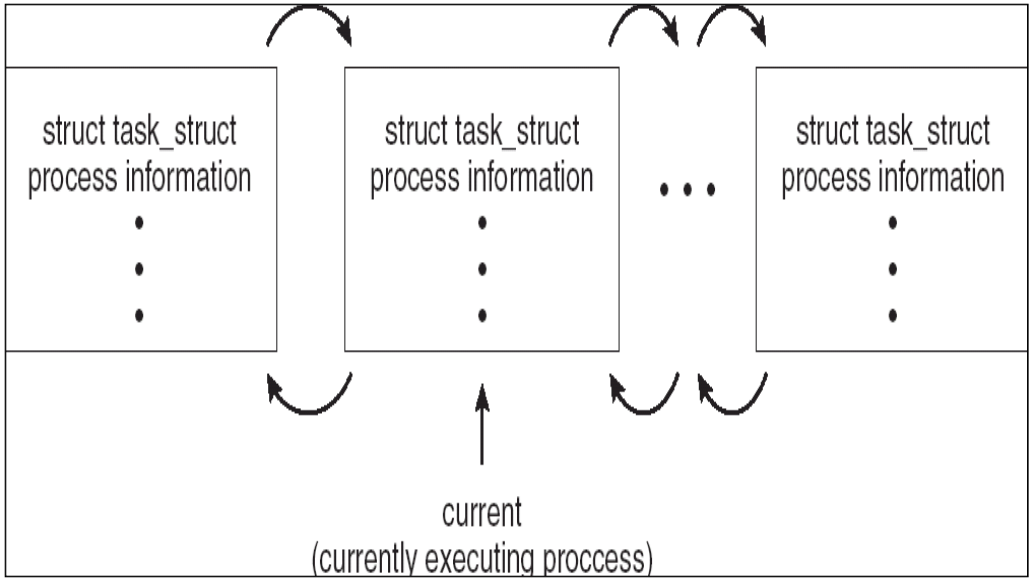


Ready Queue And Various I/O Device Queues



Active processes in Linux

- The process control block in Linux is represented by the C structure ***task_struct***
  - State of the process
  - Scheduling and memory management information
  - List of open files
  - Pointers to the process' parent and any of its children
- All active processes are represented using a doubly linked list of *task_struct* and the kernel maintains a pointer to the process currently executing



Schedulers

- **Long-term scheduler** (or job scheduler) – selects which processes should be brought into the ready queue
- **Short-term scheduler** (or CPU scheduler) – selects which process should be executed next and allocates CPU

Schedulers (Cont)

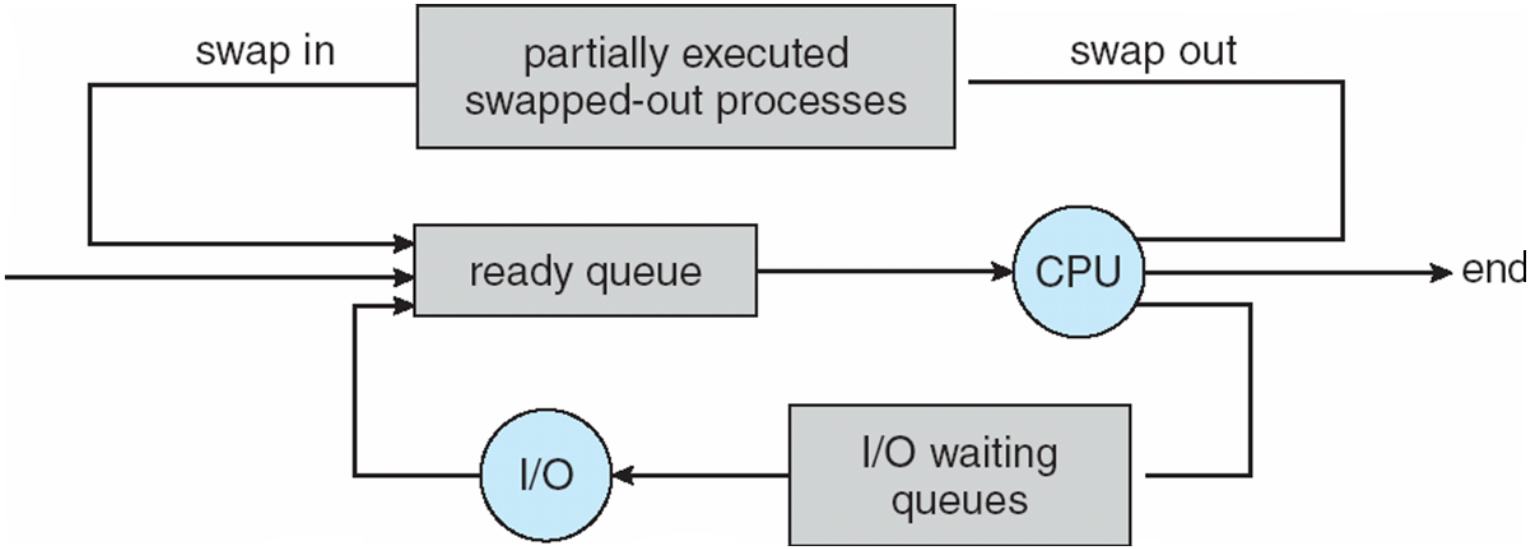
- Short-term scheduler is invoked very frequently (once every 100 milliseconds) ⇒ must be fast or else waste too much time scheduling and not executing
- Long-term scheduler is invoked very infrequently (seconds, minutes) ⇒ (may be slow).
  - The long-term scheduler controls the ***degree of multiprogramming - the number of processes in memory.***
- Long term scheduler should select a good process mix of processes to better the system performance
  - ***I/O-bound process*** – spends more time doing I/O than computations, many short CPU bursts.
  - ***CPU-bound process*** – spends more time doing computations; few very long CPU bursts.

Schedulers (Cont)

- Windows and UNIX put every new process in memory for the short term scheduler
  - With few users, little chance of running out of memory
  - If performance is bad users may just quit and solve scheduling problem

Addition of Medium Term Scheduling

- Time sharing OSs may introduce a medium term scheduler
- Removes processes from memory (and thus CPU contention) to reduce the degree of multiprogramming – ***swapping***
- Swapping may be needed to improve the process mix or to free up memory if it has become overcommitted



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How do processes get created?

Principal events that cause process creation

- System initialization
- Initiation of a batch job
- User request to create a new process
- Execution of a process creation system call from another process

Process Creation

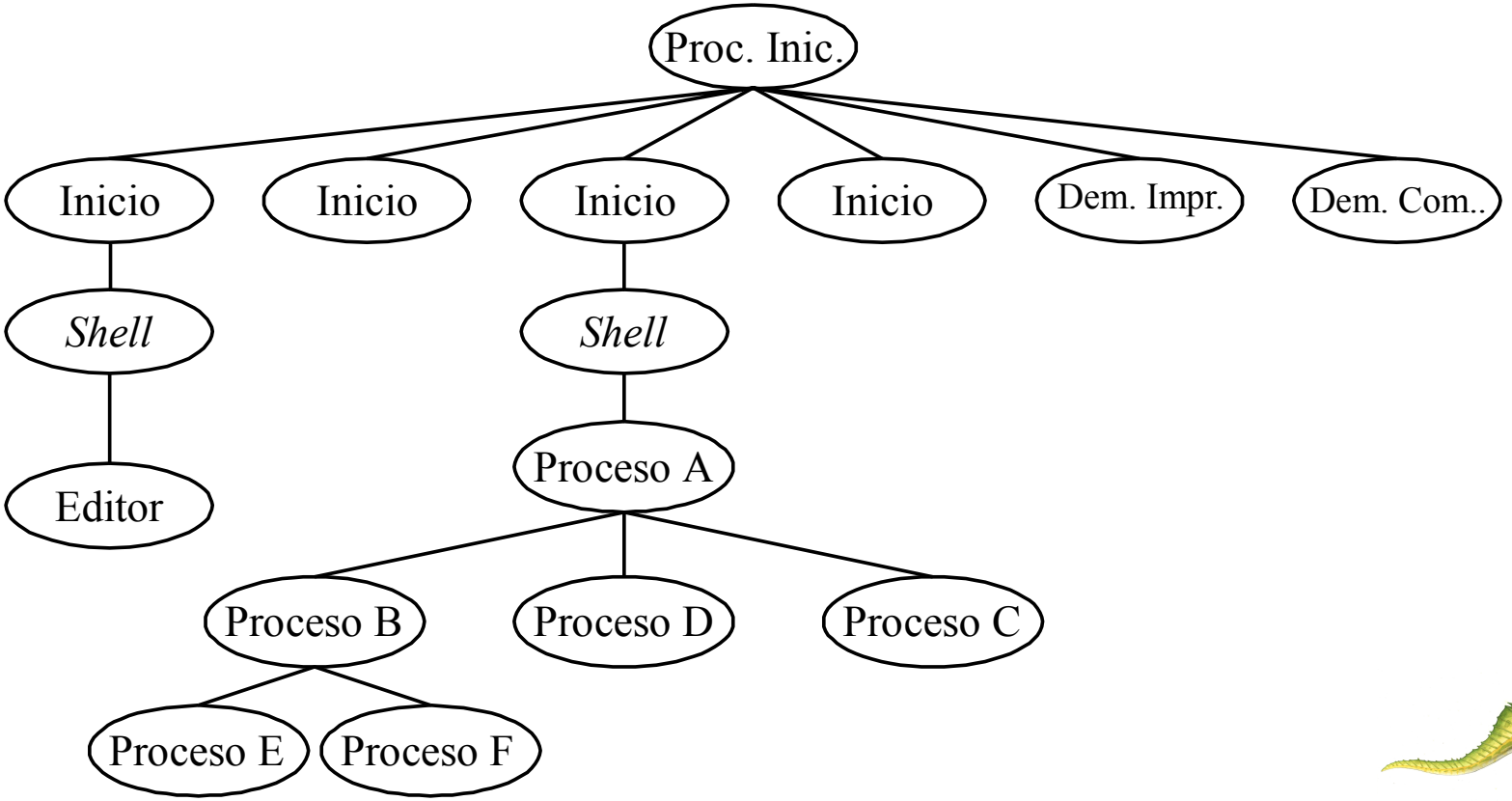
- **Parent** process create **children** processes, which, in turn create other processes, forming a tree of processes
  - special system calls for communicating with and waiting for child processes
  - each process is assigned a unique identifying number or process ID (PID)
- Child processes can create their own child processes
  - Forms a hierarchy
  - UNIX calls this a "process group"
  - Windows has no concept of process hierarchy
    - all processes are created equal
- Resource sharing
  - Parent and children share all resources
  - Children share subset of parent's resources
  - Parent and child share no resources

Process Creation (Cont)

- Execution
  - Parent and children execute concurrently
  - Parent waits until children terminate
- Address space
  - Child duplicate of parent (UNIX)
    - Child has copy of parent's address space
      - Enables easy communication between the two
      - The child process' memory space is replaced with a new program which is then executed. Parent can wait for child to complete or create more processes
  - Child has a program loaded into it directly (DEC VMS)
  - Windows NT supports both models

A tree of processes in Unix

- The first process is Init (padre del resto)
- Init creates login daemons
- Login becomes a shell
- Using the shell user spawns new processes



Process creation in UNIX

- Process creation
  - **`fork()`** system call creates new process which has a copy of the address space of the original process and returns in both processes (parent and child), but with a different return value
    - Simplifies parent-child communication
    - Both processes continue execution
  - **`execlp()`** system call used after a **`fork()`** to replace the process' address space with a new program.
    - Loads a binary file into memory and starts execution
    - Parent can then create more children processes or issue a **`wait()`** system call to move itself off the ready queue until the child completes

Process creation in UNIX

- All processes have a unique process id
  - *getpid(), getppid()* system calls allow processes to get their information
- Process termination, signaling
  - *signal(), kill()* system calls allow a process to be terminated or have specific signals sent to it

Example: process creation in UNIX

csh (pid = 22)

```
…

pid = fork()
if (pid == 0) {
   // child…
   …
   exec("ls"…);
   }
else {
   // parent
   wait();
   }
…
```

Process creation in UNIX example

csh (pid = 22)

```
…
pid = fork()
if (pid == 0) {
   // child…
   …
   exec(“ls”…);
   }
else {
   // parent
   wait();
   }
…
```

csh (pid = 24)

```
…
pid = fork()
if (pid == 0) {
   // child…
   …
   exec(“ls”…);
   }
else {
   // parent
   wait();
   }
…
```

Process creation in UNIX example

csh (pid = 22)

```
…

pid = fork()
if (pid == 0) {
   // child…
   …
   exec(“ls”…);
   }
else {
   // parent
   wait();
   }
…
```

csh (pid = 24)

```
…

pid = fork()
if (pid == 0) {
   // child…
   …
   exec(“ls”…);
   }
else {
   // parent
   wait();
   }
…
```

Process creation in UNIX example

csh (pid = 22)

```
…

pid = fork()
if (pid == 0) {
   // child…
   …
   exec(“ls”…);
   }
else {
   // parent
   wait();
   }
…
```

csh (pid = 24)

```
…

pid = fork()
if (pid == 0) {
   // child…
   …
   exec(“ls”…);
   }
else {
   // parent
   wait();
   }
…
```

Process creation in UNIX example

csh (pid = 22)

```
…

pid = fork()
if (pid == 0) {
   // child…
   …
   exec("ls"…);
   }
else {
   // parent
   wait();
   }
…
```

ls (pid = 24)

```
//ls program

main(){

   //look up dir

   …

}
```

Process creation in Unix (fork)

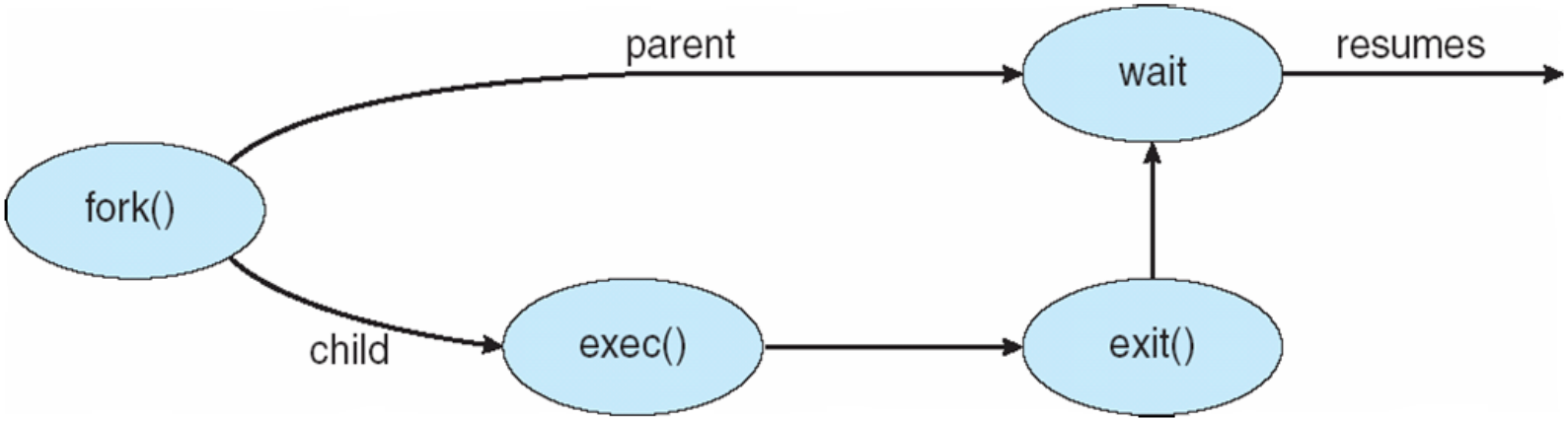
- Fork creates a new process by *copying* the calling process
- The new process has its own
  - memory address space
    - Instructions (copied from parent)
    - Data (copied from parent)
    - Stack ?? (empty)
  - register set (copied from parent)
  - Process table entry in the OS

Process Termination

- Process executes last statement and asks the operating system to delete it by using the **exit()** system call
  - Process may return a status value to parent via **wait()**
  - Process' resources are deallocated by operating system.
- Parent may terminate execution of children processes **abort()** in UNIX
  - Child has exceeded allocated resources.
  - Task assigned to child is no longer required.
  - Parent is exiting.
    - Some operating systems do not allow child to continue if its parent terminates - **cascading termination**.

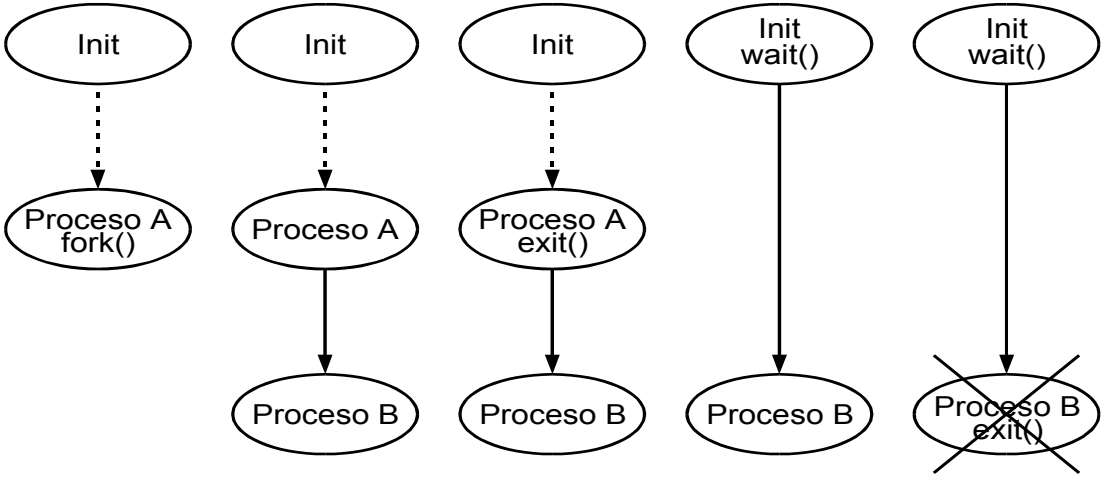
Process Termination in Unix

- In UNIX, a process can be terminated via the **exit** system call.
  - Parent can wait for termination of child by the **wait** system call
  - **wait** returns the process identifier of a terminated child so that the parent can tell which child has terminated

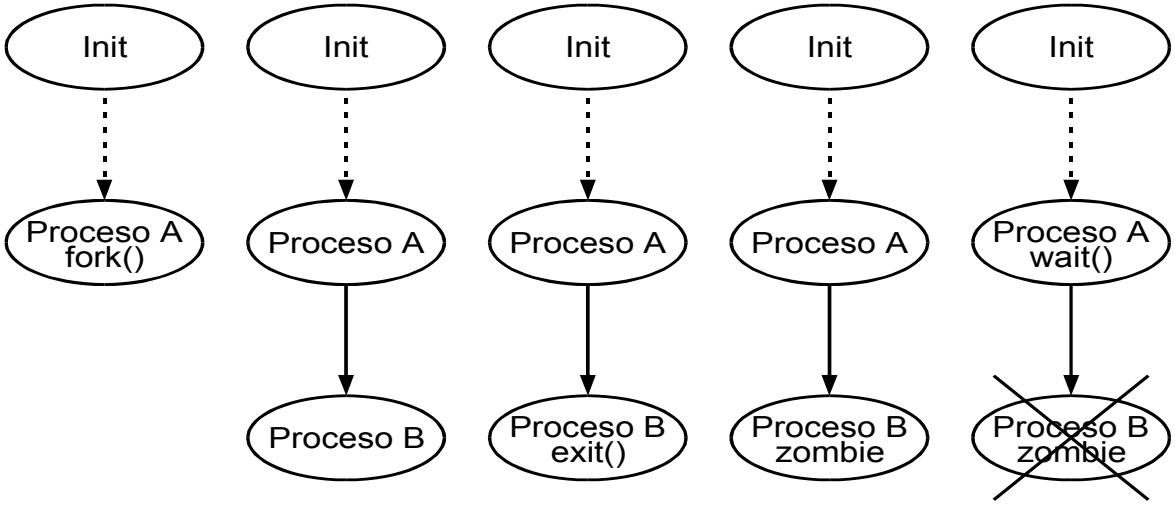


Process Termination in Unix

- If a parent terminates, all children are assigned the **init** process as their new parent



- Zombie: childrens terminate (exit) and father doesn't call to wait



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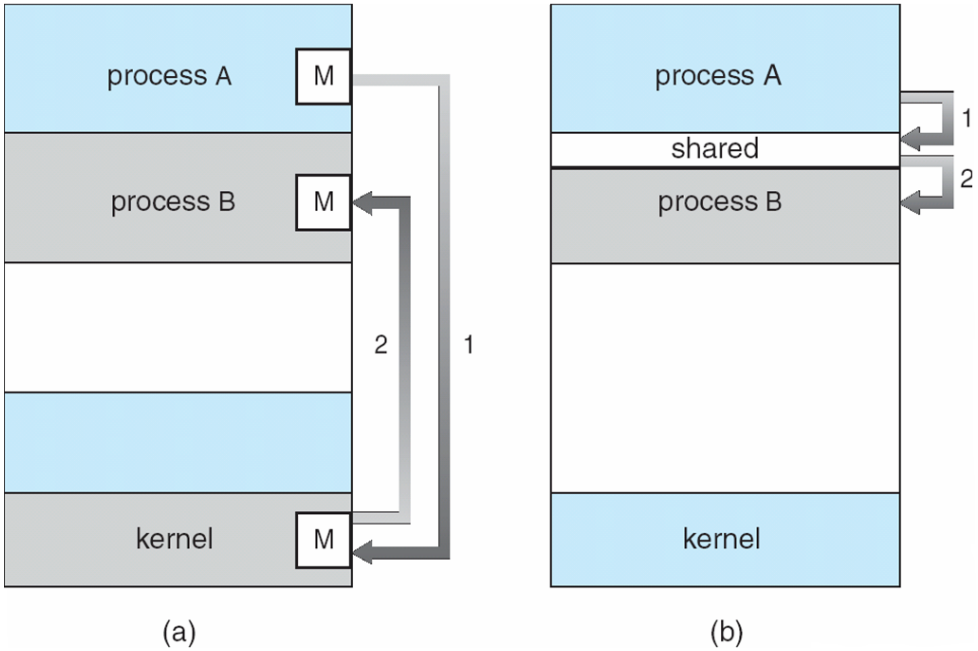
Cooperating Processes

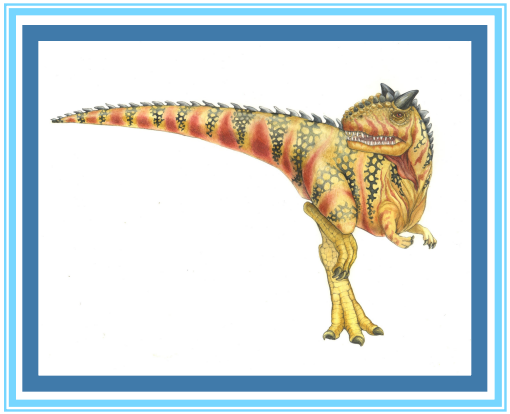
- **Independent** process cannot affect or be affected by the execution of another process
- **Cooperating** process can affect or be affected by the execution of another process
- Advantages of process cooperation
  - Information sharing
  - Computation speed-up via parallel sub-tasks
  - Modularity by dividing system functions into separate processes
  - Convenience - even an individual may want to edit, print and compile in parallel
- Cooperating processes need an **interprocess communication** (**IPC**) mechanism to exchange data
- Two models of IPC
  - Shared memory
  - Message passing

Interprocess Communication

- Message passing
  - useful for small amounts of data
  - easier to implement than shared memory
  - requires system calls and thus intervention of the kernel
- Shared memory
  - maximum speed (speed of memory) and convenience
  - system calls required only to establish the shared memory regions; further I/O does not require the kernel



Chapter 4: Multithreaded Programming



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Chapter 4. Contents

- Overview
- Multithreading Models
- Thread Libraries
- Operating System Examples
- Signals

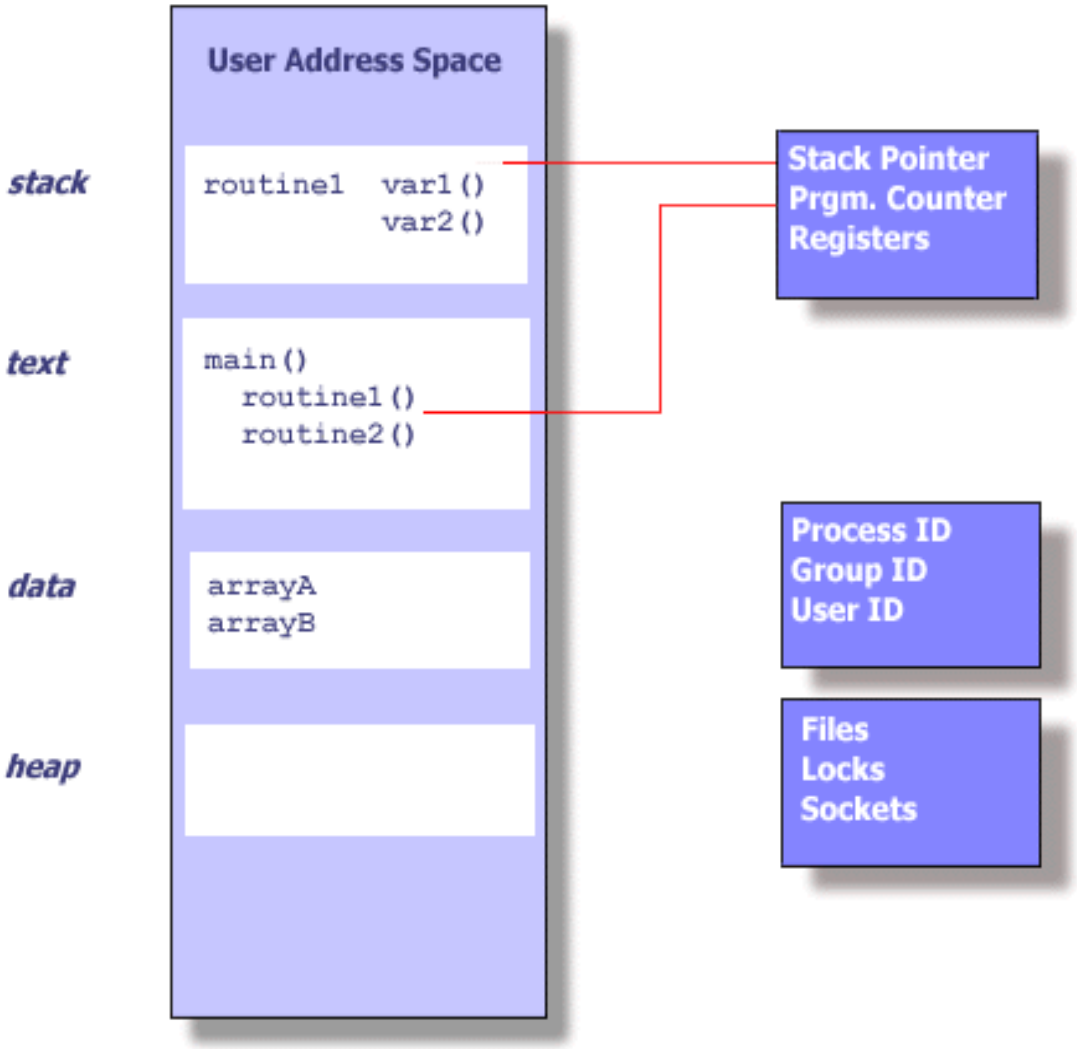
Objectives

- To introduce the notion of a thread — a fundamental unit of CPU utilization that forms the basis of multithreaded computer systems
- To discuss the APIs for the Pthreads

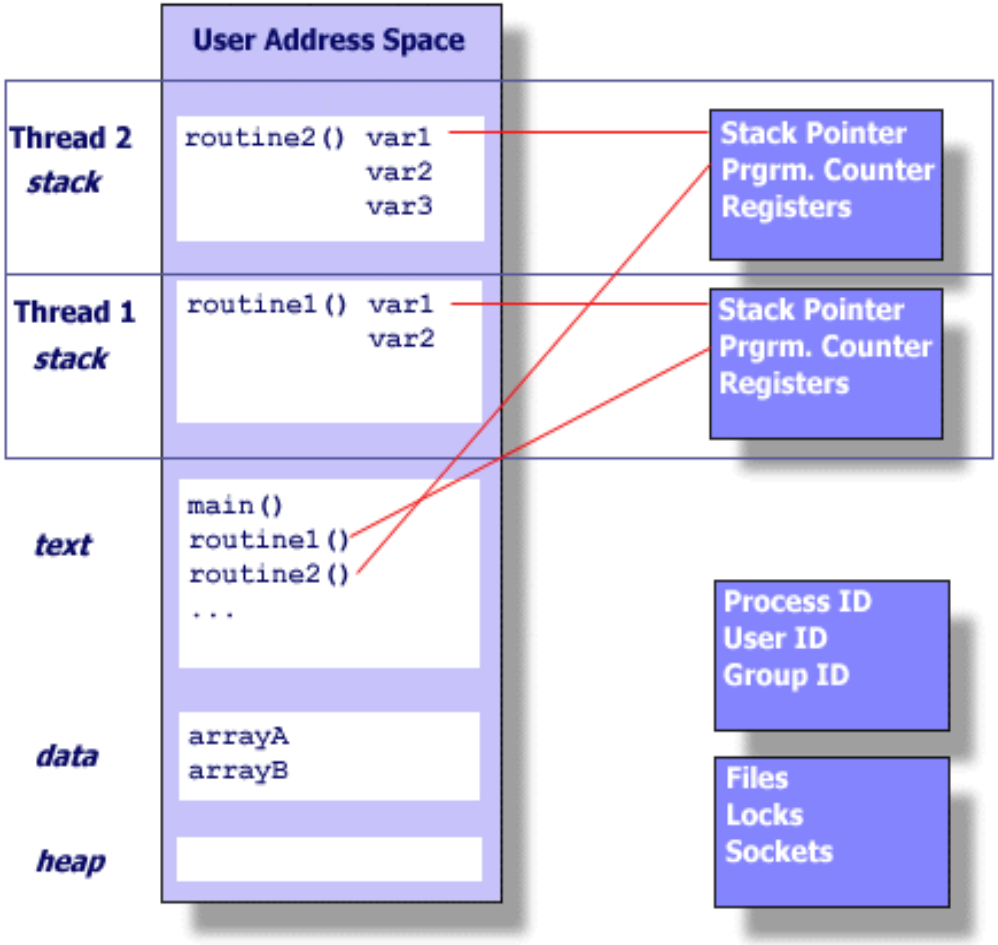
Overview

- Many software packages are **multi-threaded**
  - Web browser: one thread display images, another thread retrieves data from the network
  - Word processor: threads for displaying graphics, reading keystrokes from the user, performing spelling and grammar checking in the background
  - Web server: instead of creating a process when a request is received, which is time consuming and resource intensive, server creates a thread to service the request
- A thread is sometimes called a **lightweight process**
  - It is comprised over a thread ID, program counter, a register set and a stack
  - It shares with other threads belonging to the same process its code section, data section and other OS resources (e.g., open files)
  - A process that has multiples threads can do more than one task at a time

Single thread state within a process



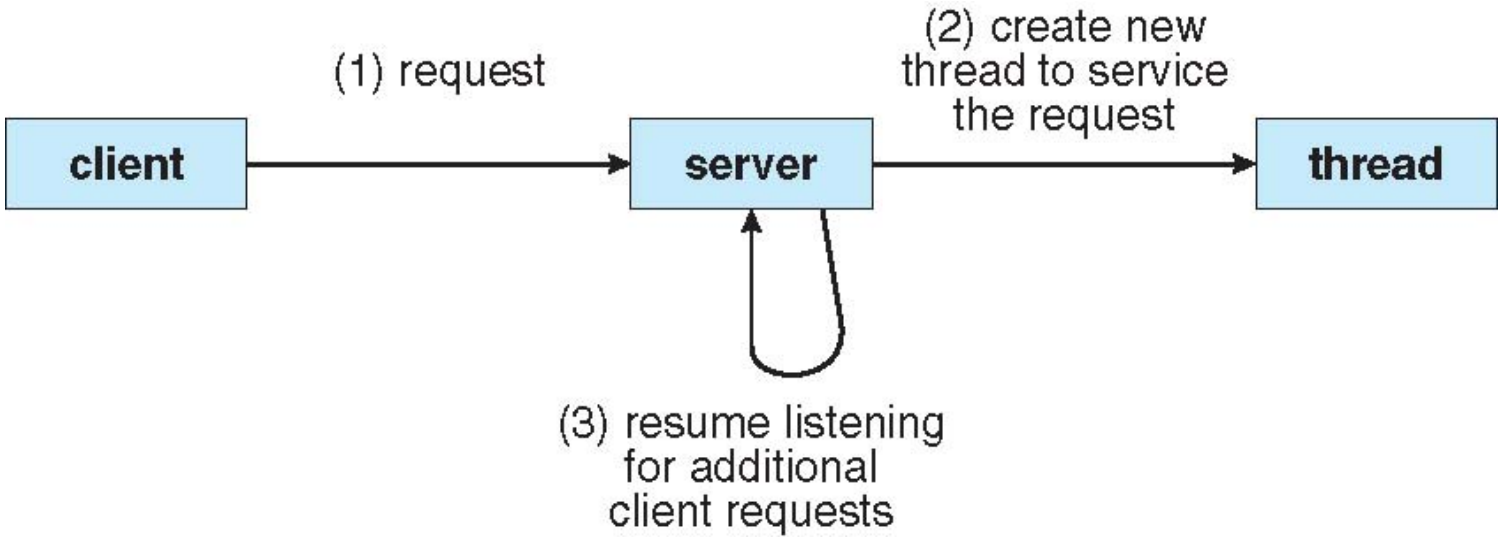
Multiple threads in an address space



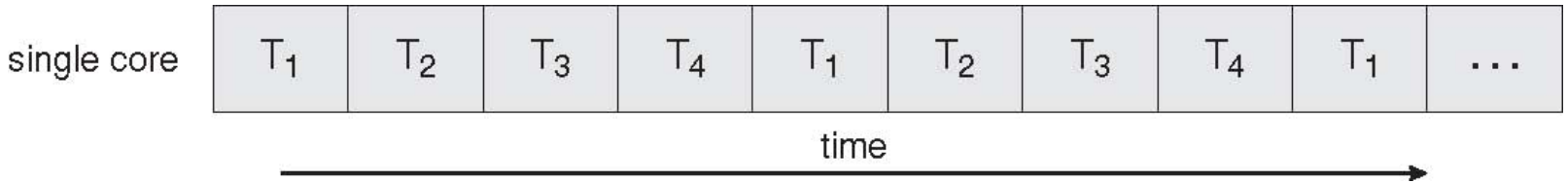
Benefits

- Responsiveness
  - One part of a program can continue running even if another part is blocked
- Resource Sharing
  - Threads of the same process share the same memory space and resources
- Economy
  - Much less time consuming to create and manage threads than processes
  - Solaris 2: creating a process is 30 times slower than creating a thread, context switching is 5 times slower
- Scalability: ***Utilization of MP Architectures***
  - Each thread can run in parallel on a different processor

Multithreaded Server Architecture



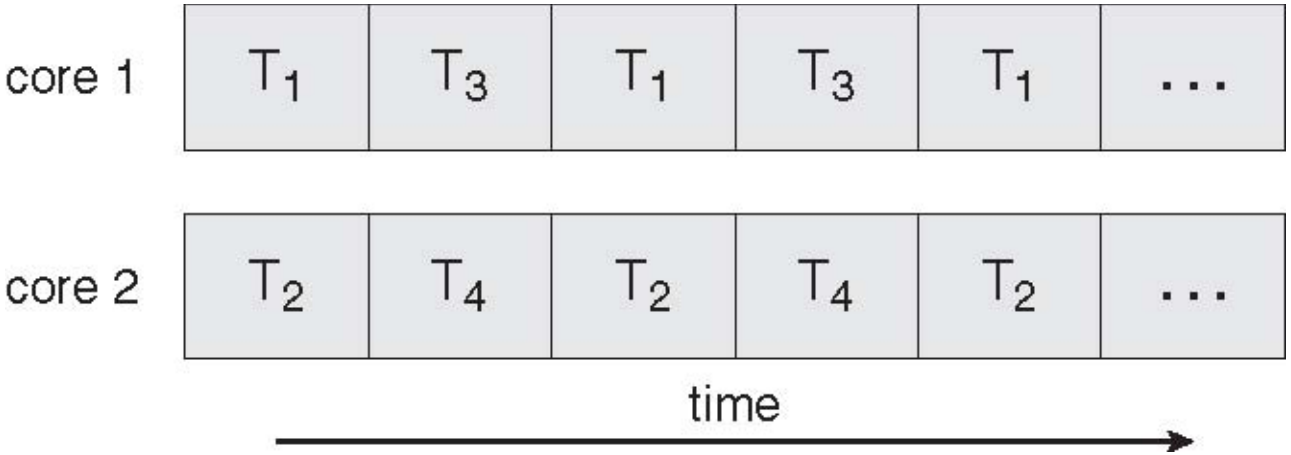
Concurrent Execution on a Single-core System



Multicore Programming

- Multicore systems putting pressure on programmers, challenges include
  - **Dividing activities**
  - **Balance**
  - **Data splitting**
  - **Data dependency**
  - **Testing and debugging**

Parallel Execution on a Multicore System



Chapter 4. Contents

- Overview
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User Threads

- Thread management done by user-level threads library library is without the intervention of the kernel
  - Fast to create and manager
  - If the kernel is single threaded, any user-level thread performing a blocking system call will cause the entire process to block
- Three primary thread libraries:
  - POSIX Pthreads
  - Win32 threads
  - Java threads

Kernel Threads

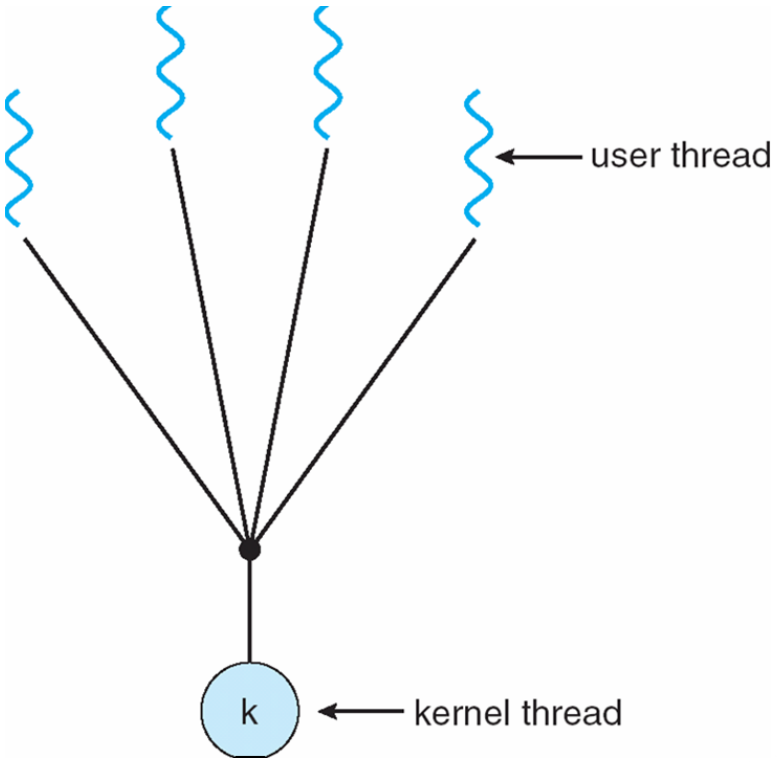
- Supported by the Kernel
  - Slower to create and manage than user threads
  - If thread performs a blocking system call, the kernel can schedule another thread in the application for execution
  - In multi-processor environments, the kernel can schedule threads on multiple processors
- Examples
  - Windows XP/2000
  - Solaris
  - Linux
  - Tru64 UNIX
  - Mac OS X

Multithreading Models

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

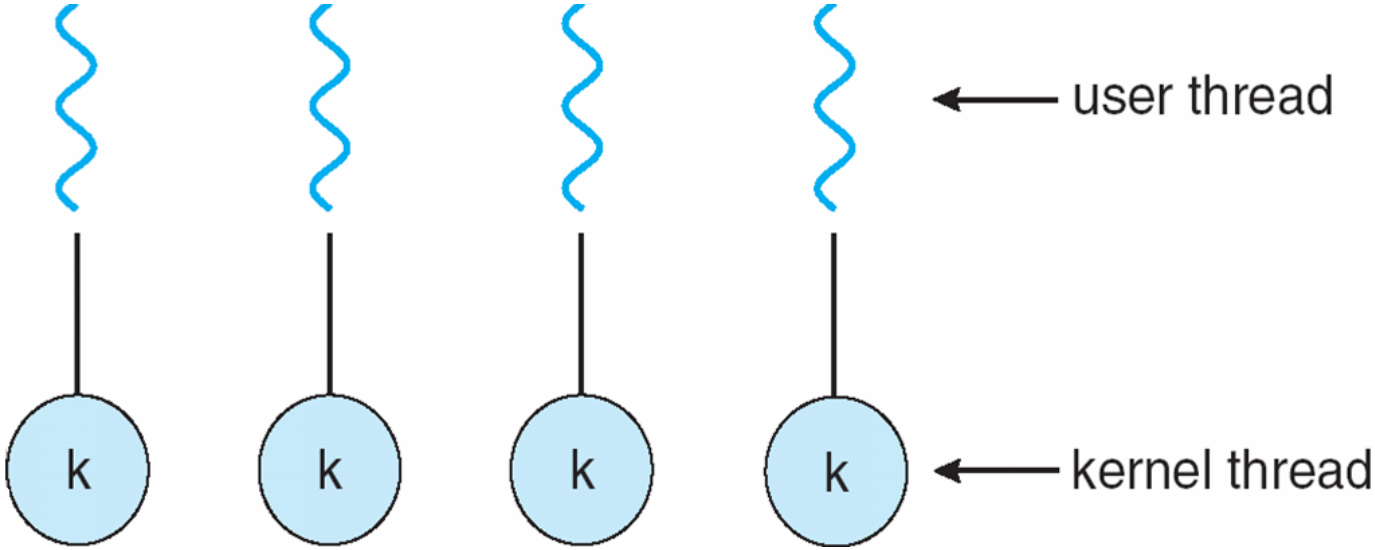
Many-to-One

- Many user-level threads mapped to single kernel thread
  - Efficient - thread management done in user space
  - Entire process will block if a thread makes a blocking system call
  - Only one thread can access the kernel, no parallel processing in MP environment
- Examples:
  - Solaris Green Threads
  - GNU Portable Threads



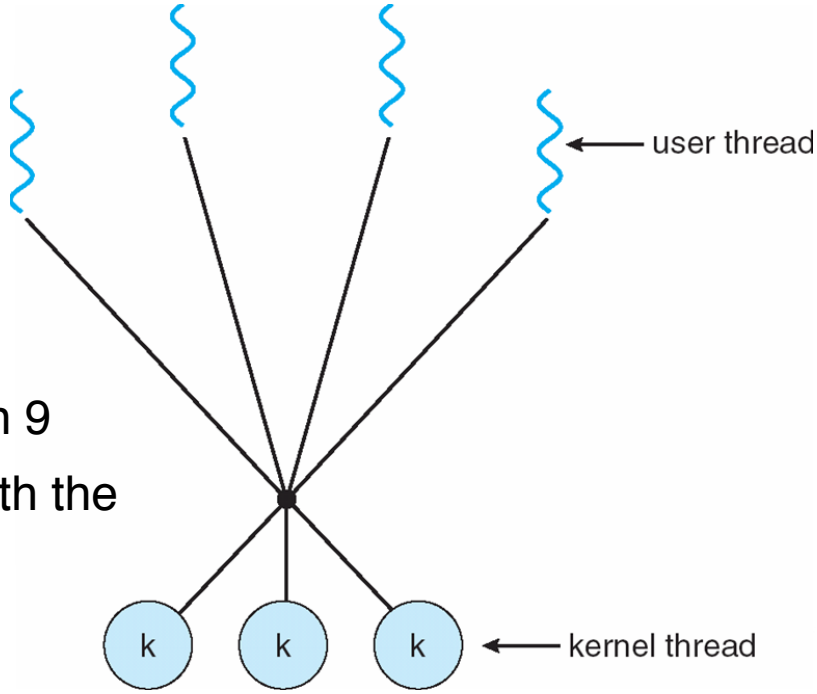
One-to-One

- Each user-level thread maps to kernel thread
  - Another thread can run when one thread makes a blocking call
  - Multiple threads an run in parallel on a MP machine
  - Overhead of creating a kernel thread for each user thread
  - Most implementations limit the number of threads supported
- Examples: Windows NT/XP/2000, Linux, Solaris 9 and later



Many-to-Many Model

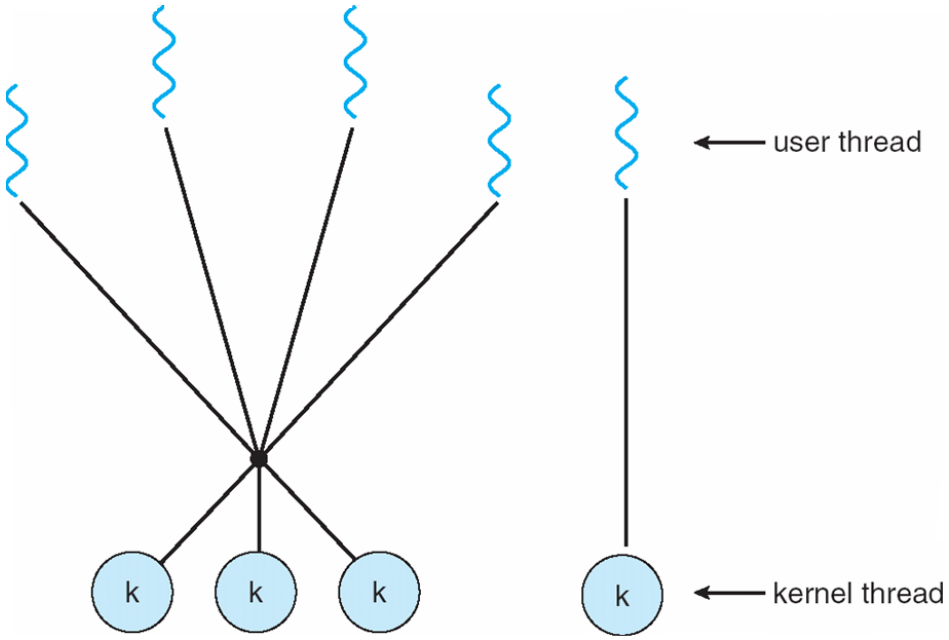
- Allows many user level threads to be mapped to smaller or equal number of kernel threads.
- As many user threads as necessary can be created
- Corresponding kernel threads can run in parallel on a multiprocessor
- When a thread performs a blocking system call, the kernel can schedule another thread for execution



- Examples:
  - Solaris prior to version 9
  - Windows NT/2000 with the *ThreadFiber* package

Two-level Model

- Has all the functionality of the many-to many model but also allows a user-level thread to be bound to a kernel thread
- Examples
  - IRIX
  - HP-UX
  - Tru64 UNIX
  - Solaris 8 and earlier



Chapter 4. Contents

- Overview
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Thread Libraries

- Thread library provides programmer with API for creating and managing threads
- Two primary ways of implementing
  - No kernel support, strictly in use space so no system calls involved
  - Kernel level directly supported by the OS. All code and data structures for the library exits in kernel spacer
    - An API call typically invokes a system call
- Three main libraries in use
    - POSIX (Portable Operating System Interface) threads
    - Win32
    - Java

Pthreads

- May be provided either as user-level or kernel-level
- A POSIX standard (IEEE 1003.1c) API for thread creation and synchronization
- Pthreads is an IEEE and Open Group certified product
- The API specifies behavior of the thread library, implementation is up to development of the library
- Common in UNIX operating systems (Solaris, Linux, Mac OS X)

Pthreads

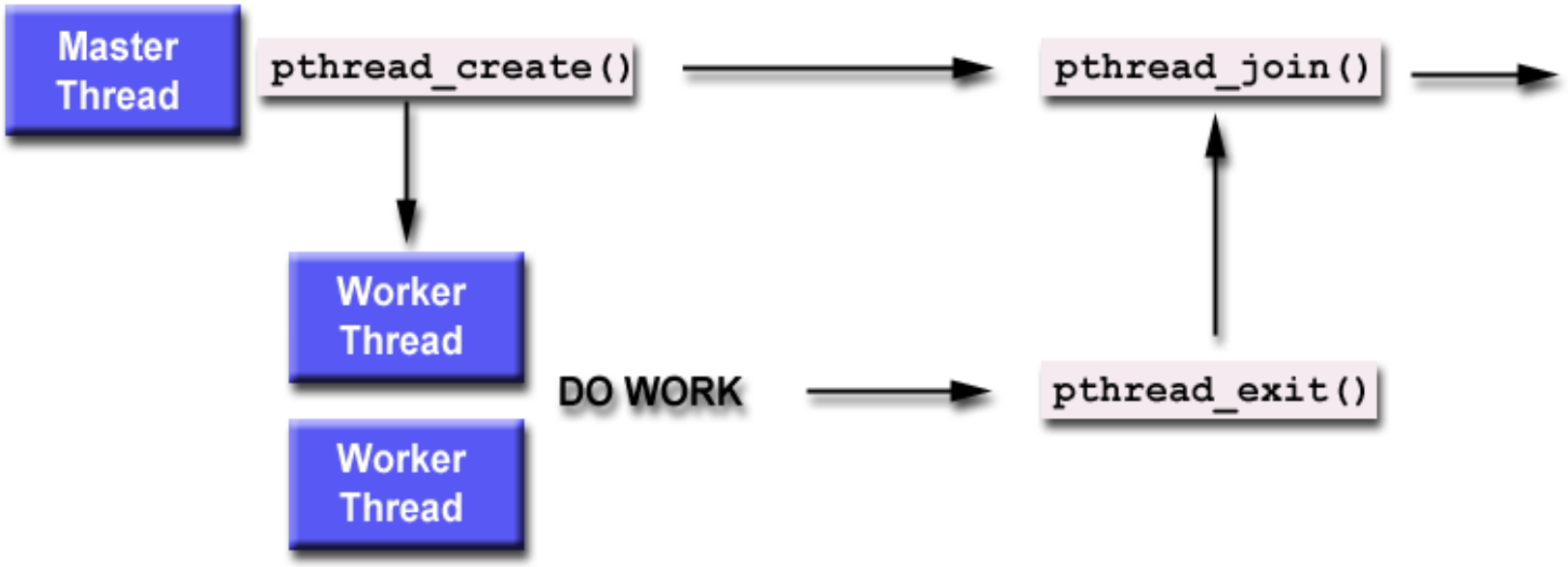
- POSIX standard threads (Pthreads)
- First thread exists in main(), typically creates the others

- pthread_create (thread,attr,start_routine,arg)
  - Returns new thread ID in “thread”
  - Executes routine specified by “start_routine” with argument specified by “arg”
  - Exits on return from routine or when told explicitly

Pthreads (continued)

- pthread_exit (status)
  - Terminates the thread and returns “status” to any joining thread
- pthread_join (threadid,status)
  - Blocks the calling thread until thread specified by “threadid” terminates
  - Return status from pthread_exit is passed in “status”
  - One way of synchronizing between threads
- pthread_yield ()
  - Thread gives up the CPU and enters the run queue

Using create, join and exit primitives



An example Pthreads program

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5

void *PrintHello(void *threadid)
{
  printf("\n%d: Hello World!\n", threadid);
  pthread_exit(NULL);
}

int main (int argc, char *argv[])
{
  pthread_t threads[NUM_THREADS];
  int rc, t;
  for(t=0; t<NUM_THREADS; t++)
  {
    printf("Creating thread %d\n", t);
    rc = pthread_create(&threads[t], NULL, PrintHello, (void *)t);
    if (rc)
    {
      printf("ERROR; return code from pthread_create() is %d\n", rc);
      exit(-1);
    }
  }
  pthread_exit(NULL);
}
```

Program Output

```
Creating thread 0
Creating thread 1
0: Hello World!
1: Hello World!
Creating thread 2
Creating thread 3
2: Hello World!
3: Hello World!
Creating thread 4
4: Hello World!
```

Chapter 4. Contents

- Overview
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Operating System Examples

- Windows XP Threads
- Linux Thread

Linux Threads

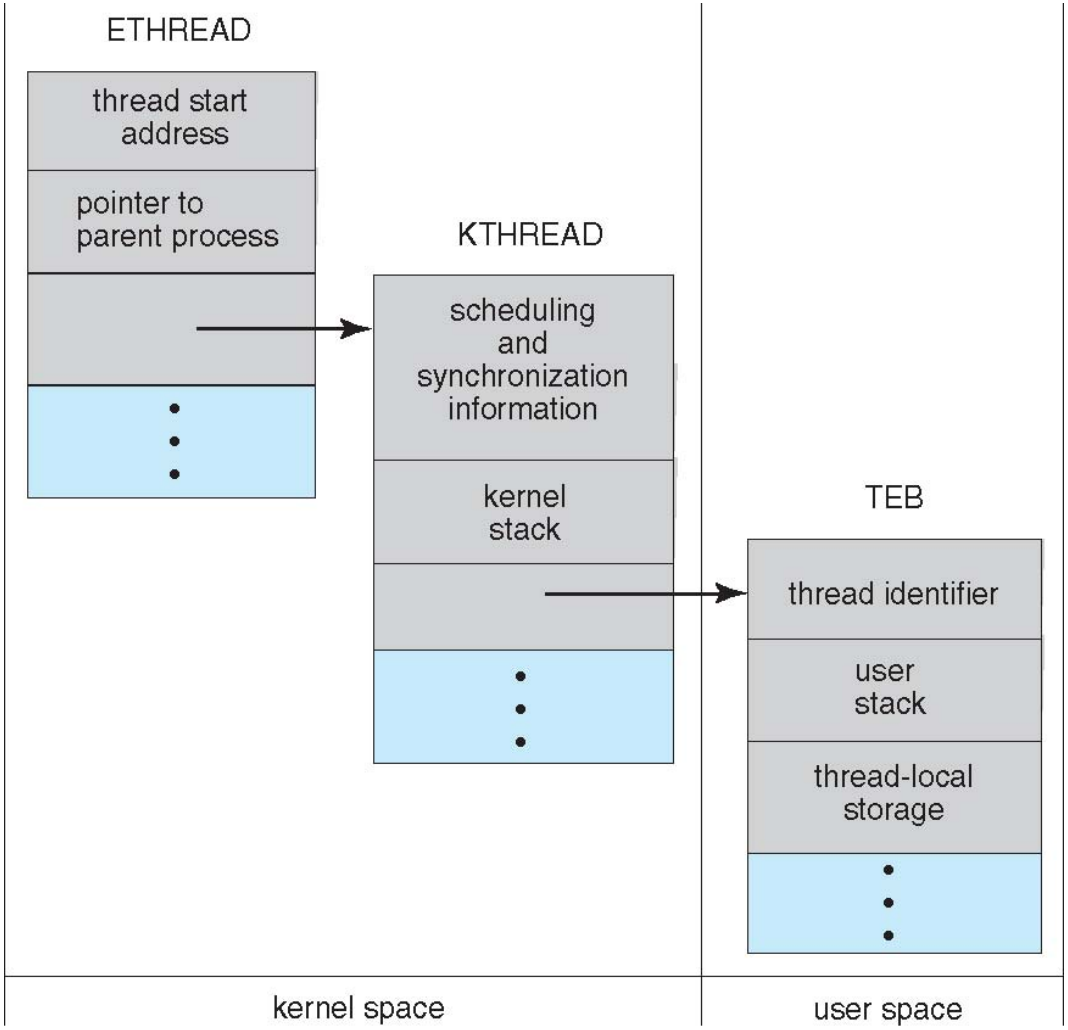
- Linux refers to them as *tasks* rather than *threads*
- Thread creation is done through **clone()** system call
- **clone()** allows a child task to share the address space of the parent task (process)

flag	meaning
CLONE_FS	File-system information is shared.
CLONE_VM	The same memory space is shared.
CLONE_SIGHAND	Signal handlers are shared.
CLONE_FILES	The set of open files is shared.

Windows XP Threads

- Implements the one-to-one mapping
- Each thread contains
  - A thread id
  - Register set
  - Separate user and kernel stacks
  - Private data storage area
- A Windows XP application runs as a separate process and each process may contain one or more threads
- The register set, stacks, and private storage area are known as the **context** of the threads
- The primary data structures of a thread include:
  - ETHREAD (executive thread block)
  - KTHREAD (kernel thread block)
  - TEB (thread environment block)
- Also provides support for a fiber library which implements the many-to-many model

Windows XP Threads



Chapter 4. Contents

- Overview
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Signal Handling

- Signals are used in UNIX systems to notify a process that a particular event has occurred
  - SIGKILL -9- (Kill : terminate immediately)
  - SIGTERM -15- (Termination : request to terminate)
  - SICHLD -17- (Child process terminated, stopped or continued)
  - SIGCONT -18- (Continue if stopped)
  - SIGSTOP -19- (Stop executing temporarily)
  - SIGTTIN -21. (Background process attempting to read from tty)
  - SIGTTOU -22- (Background process attempting to write to tty)

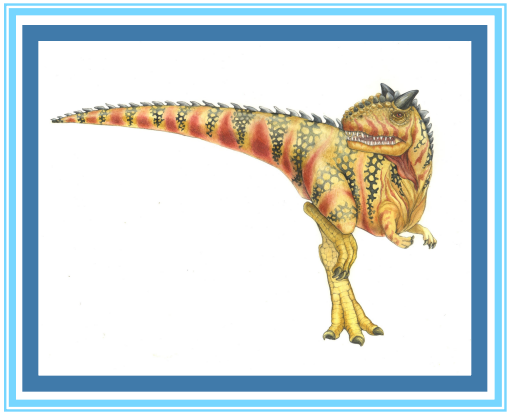
Signal Handling

- A signal handler is used to process signals
  1. Signal is generated by particular event
  2. Signal is delivered to a process
  3. Signal is handled
- Options:
  - Deliver the signal to the thread to which the signal applies
  - Deliver the signal to every thread in the process
  - Deliver the signal to certain threads in the process
  - Assign a specific threa to receive all signals for the process

Signal Handling in Unix

- Signal handlers can be installed with the `signal()` system call.
  - When the signal is intercepted , the signal handler is invoked
- If a signal handler is not installed for a particular signal, the default handler is used.
- .The process can also specify two default behaviors, without creating a handler:
  - ignore the signal (SIG_IGN)
  - use the default signal handler (SIG_DFL)
- The `sigprocmask()` call can be used to block and unblock delivery of signals.

Chapter 5: Process Scheduling



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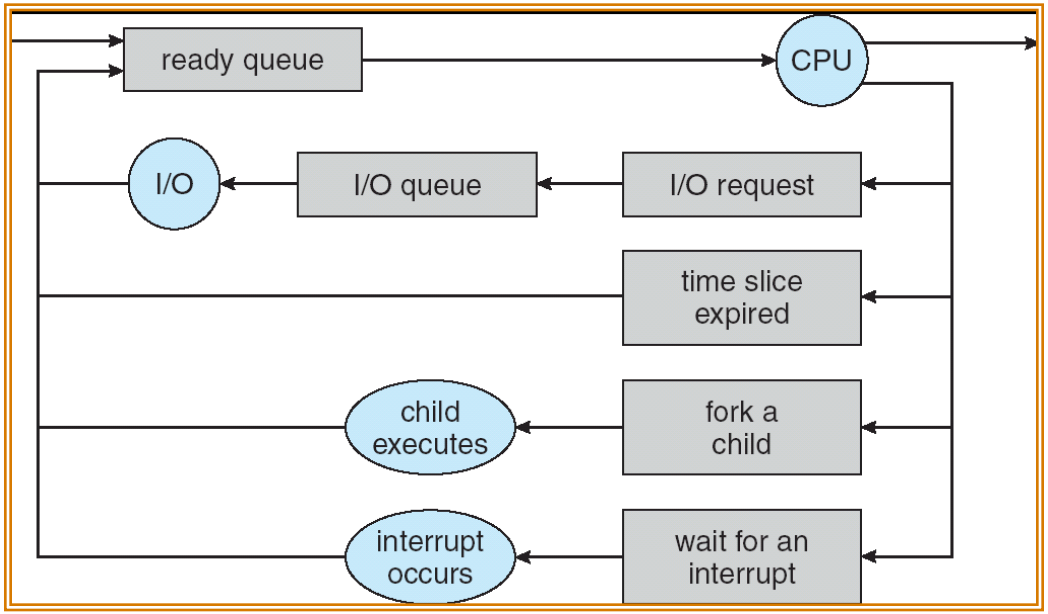
Chapter 5. Contents

- Basic Concepts. Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling. Multiple-Processor Scheduling
- Operating Systems Examples

Objectives

- To introduce process scheduling, which is the basis for multiprogrammed operating systems
- To describe various process-scheduling algorithms

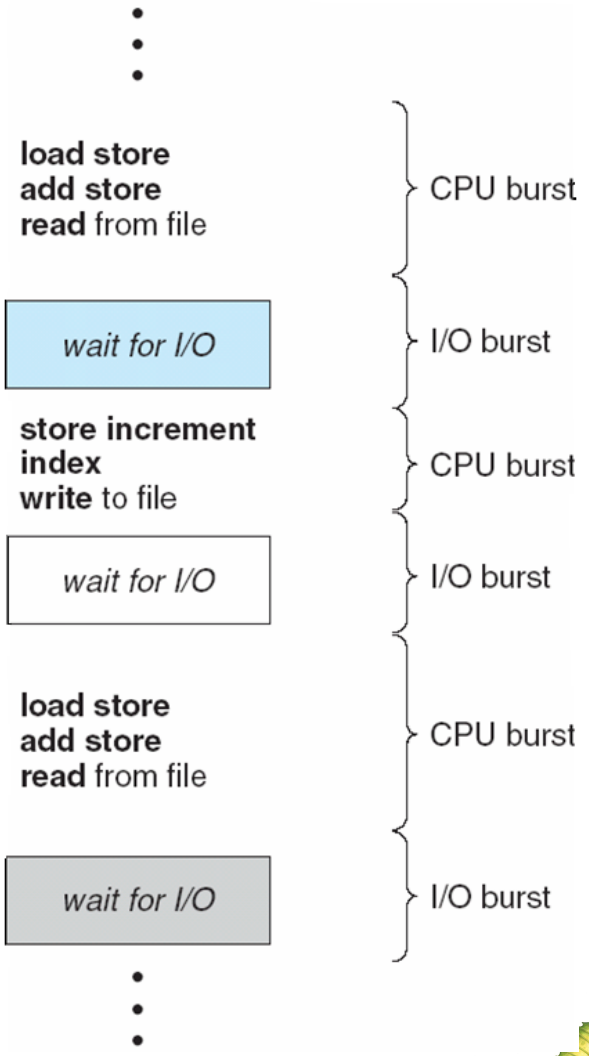
CPU Scheduling



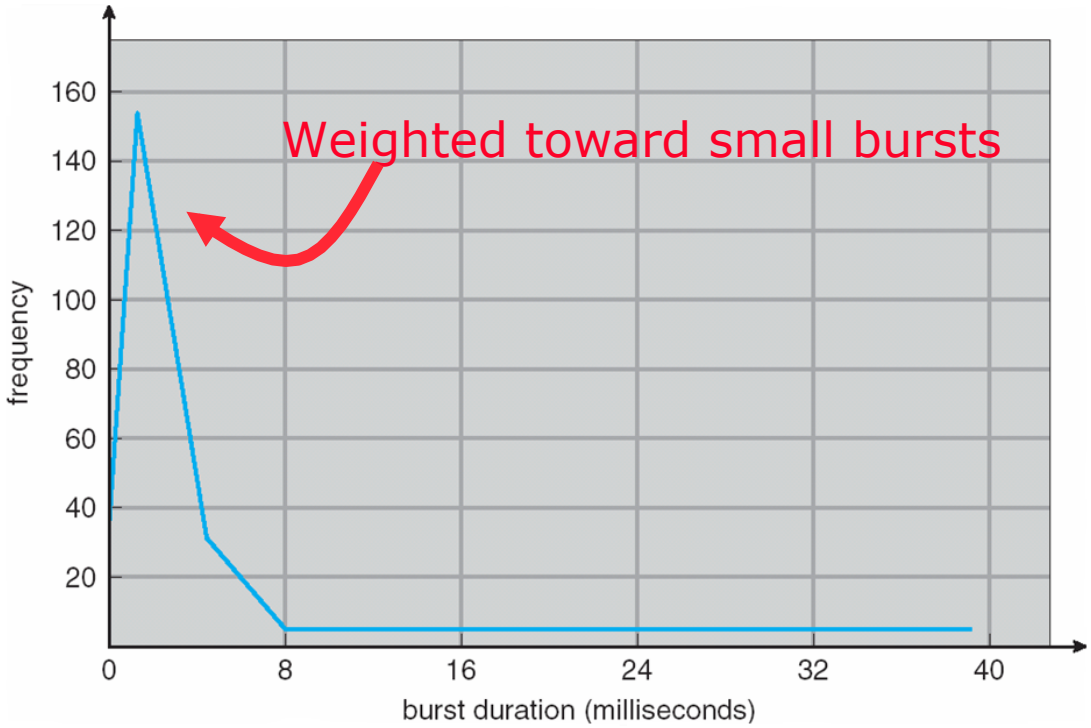
- Earlier, we talked about the life-cycle of a thread
  - Active threads work their way from Ready queue to Running to various waiting queues.
- Question: How is the OS to decide which of several tasks to take off a queue?
  - Obvious queue to worry about is ready queue
  - Others can be scheduled as well, however
- Scheduling: deciding which threads are given access to resources from moment to moment.

Assumption: CPU Bursts

- Scheduling is central to OS design: CPU and almost all computer resources are scheduled before use
- Execution model: programs alternate between bursts of CPU and I/O
  - Program typically uses the CPU for some period of time, then does I/O, then uses CPU again
  - Each scheduling decision is about which job to give to the CPU for use by its next CPU burst
  - With timeslicing, thread may be forced to give up CPU before finishing current CPU burst



Histogram of CPU-burst Times



- CPU bursts, though different by process and computer, tend to have a frequency curve as shown above
  - Characterized by many short burst and few long ones
  - The distribution can help in the selection of an appropriate scheduling algorithm

Scheduling Criteria

- **CPU utilization** – keep the CPU as busy as possible
- **Throughput** – # of processes that complete their execution per time unit
- **Turnaround time (= Completion Time)** – amount of time to execute a particular process
  - waiting to get into memory + waiting in the ready queue + executing on the CPU + I/O
- **Waiting time** – amount of time a process has been waiting in the ready queue
- **Response time** – amount of time it takes from when a request was submitted until the first response is produced, **not** output (for time-sharing environment)

Scheduling Algorithm Optimization Criteria

- Max CPU utilization
- Max throughput
- Min turnaround time
- Min waiting time
- Min response time

- In most cases we optimize the average measure
- In some circumstances we want to optimize the min or max values rather than the average – e.g., minimize the max response time so all users get good service

Chapter 5. Contents

- Basic Concepts. Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling. Multiple-Processor Scheduling
- Operating Systems Examples

CPU Scheduler

- Selects from among the processes in memory that are ready to execute, and allocates the CPU to one of them
- CPU scheduling decisions may take place when a process:
  1. Switches from running to waiting state
  2. Switches from running to ready state
  3. Switches from waiting to ready
  4. Terminates
- Scheduling under 1 and 4 is **nonpreemptive:**
  - Once the CPU has been allocated to a process, the process keeps the CPU until it releases the CPU either by terminating or switching to a waiting state
  - Used by Windows 3.1 and Apple Macintosh
- All other scheduling is **preemptive**
  - Requires mechanisms to coordinate access to shared data
  - Sections of kernel code must be guarded from simultaneous use

Dispatcher

- Dispatcher module gives control of the CPU to the process selected by the short-term scheduler; this involves:
  - switching context
  - switching to user mode
  - jumping to the proper location in the user program to restart that program
- **Dispatch latency** – time it takes for the dispatcher to stop one process and start another running

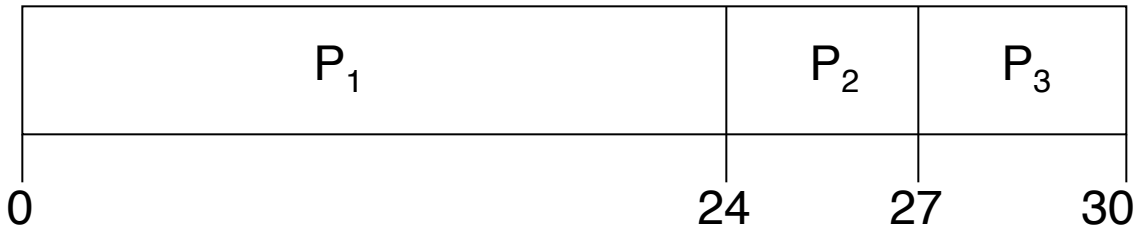
Scheduling Algorithms

Sched. \ Preem.	No Expropiat.	Expropiat.
Orden de llegada	FCFS	Round Robin
Tiempo	SJF	SRT
Prioridad	Prio. No Exp.	Prio. Exp.

First-Come, First-Served (FCFS) Scheduling

Process	Burst Time
P_1	24
P_2	3
P_3	3

- Suppose that the processes arrive in the order: P_1 , P_2 , P_3 The Gantt Chart for the schedule is:

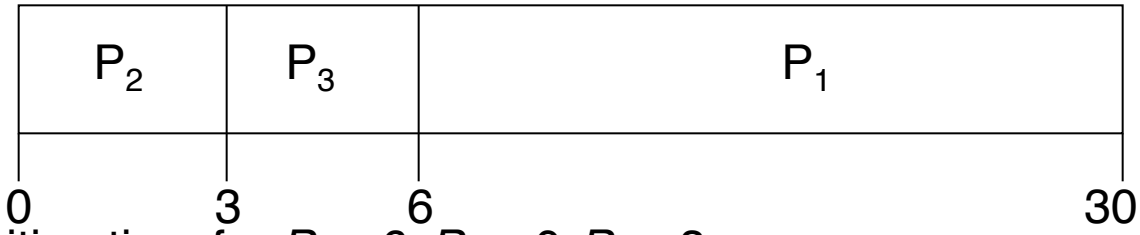


  - Waiting time for P_1 = 0; P_2 = 24; P_3 = 27
  - Average waiting time: (0 + 24 + 27)/3 = 17
  - Average completion time: (24 + 27 + 30)/3 = 27
- *Convoy effect:* short process behind long process

FCFS Scheduling (Cont)

Suppose that the processes arrive in the order: P_2 , P_3 , P_1

- The Gantt chart for the schedule is:



  - Waiting time for $P_1 = 6; P_2 = 0, P_3 = 3$
  - Average waiting time: (6 + 0 + 3)/3 = 3
  - Average completion time: (3 + 6 + 30)/3 = 13

- In second case:
  - average waiting time is much better (before it was 17)
  - Average completion time is better (before it was 27

FCFS Scheduling (Cont)

- FCFS is non-preemptive
- FCFS is simple (+)
- Not good for time sharing systems where each user needs to get a share of the CPU at regular intervals
- ***Convoy effect*** short process (I/O bound) wait for one long CPU-bound process to complete a CPU burst before they get a turn
  - lowers CPU and device utilization

Round Robin (RR)

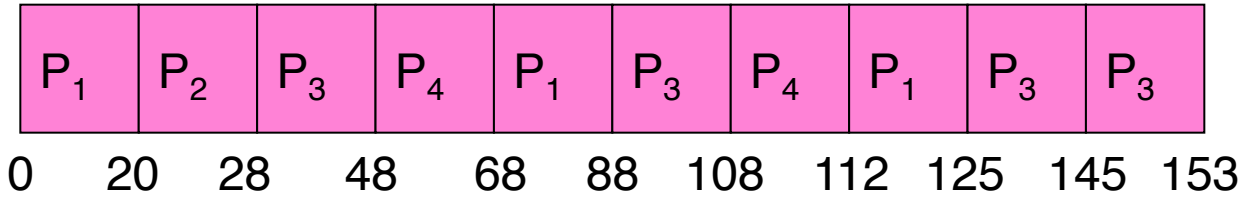
- FCFS Scheme: Potentially bad for short jobs!
  - Depends on submit order
- Round Robin Scheme
  - Each process gets a small unit of CPU time (*time quantum*), usually 10-100 milliseconds.
  - After this time has elapsed, the process is preempted and added to the end of the ready queue.
  - If there are *n* processes in the ready queue and the time quantum is *q*:
    - each process gets 1/*n* of the CPU time
    - in chunks of at most *q* time units at once.
    - No process waits more than (*n*-1)*q* time units.
- Performance
  - *q* large ⇒ FCFS
  - *q* small ⇒ Interleaved (*q* must be large with respect to context switch, otherwise overhead is too high)

Example of RR with Time Quantum = 20

- Example:

Process	Burst Time
P_1	53
P_2	8
P_3	68
P_4	24

  - The Gantt chart is:



Waiting time for P_1=(68-20)+(112-88)=72
P_2=(20-0)=20
P_3=(28-0)+(88-48)+(125-108)=85
P_4=(48-0)+(108-68)=88

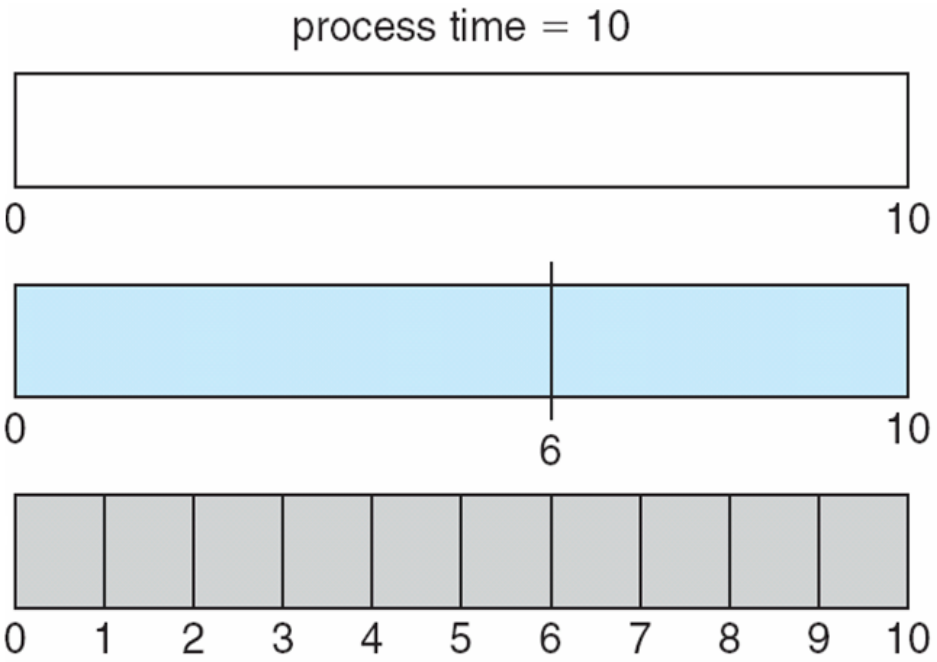
  - Average waiting time = (72+20+85+88)/4=66¼
  - Average completion time = (125+28+153+112)/4 = 104½

- Thus, Round-Robin Pros and Cons:
  - Better for short jobs, Fair (+)
  - Context-switching time adds up for long jobs (-)

Round-Robin Discussion

- How do you choose time slice?
  - What if too big?
    - Response time suffers
  - What if infinite (∞)?
    - Get back FCFS
  - What if time slice too small?
    - Throughput suffers!
    - increases context switches
- Actual choices of timeslice:
  - Initially, UNIX timeslice one second:
    - Worked ok when UNIX was used by one or two people.
    - What if three compilations going on? 3 seconds to echo each keystroke!
  - In practice, need to balance short-job performance and long-job throughput:
    - Typical time slice today is between 10ms – 100ms
    - Typical context-switching overhead is 0.1ms – 1ms
    - Roughly 1% overhead due to context-switching

Time Quantum and Context Switch Time



A smaller time quantum increases context switches

Comparisons: FCFS and Round Robin

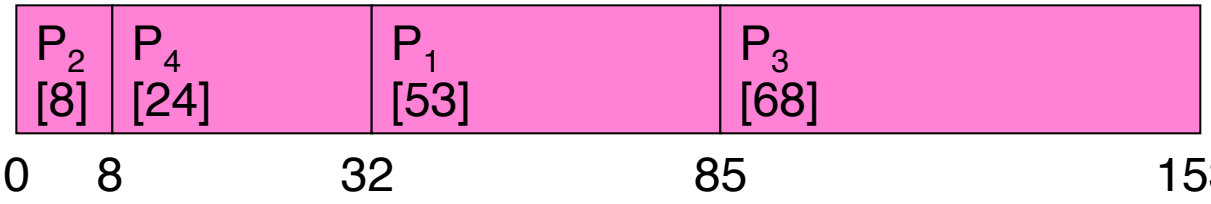
- Assuming zero-cost context-switching time, is RR always better than FCFS?
- Simple example: 10 jobs, each take 100s of CPU time
  RR scheduler quantum of 1s
  All jobs start at the same time
- Completion Times:

Job #	FIFO	RR
1	100	991
2	200	992
...	...	...
9	900	999
10	1000	1000

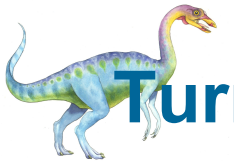
  - Both RR and FCFS finish at the same time
  - Average response time is much worse under RR!
    - Bad when all jobs same length
- Also: Cache state must be shared between all jobs with RR but can be devoted to each job with FIFO
  - Total time for RR longer even for zero-cost switch !

Earlier Example with Different Time Quantum

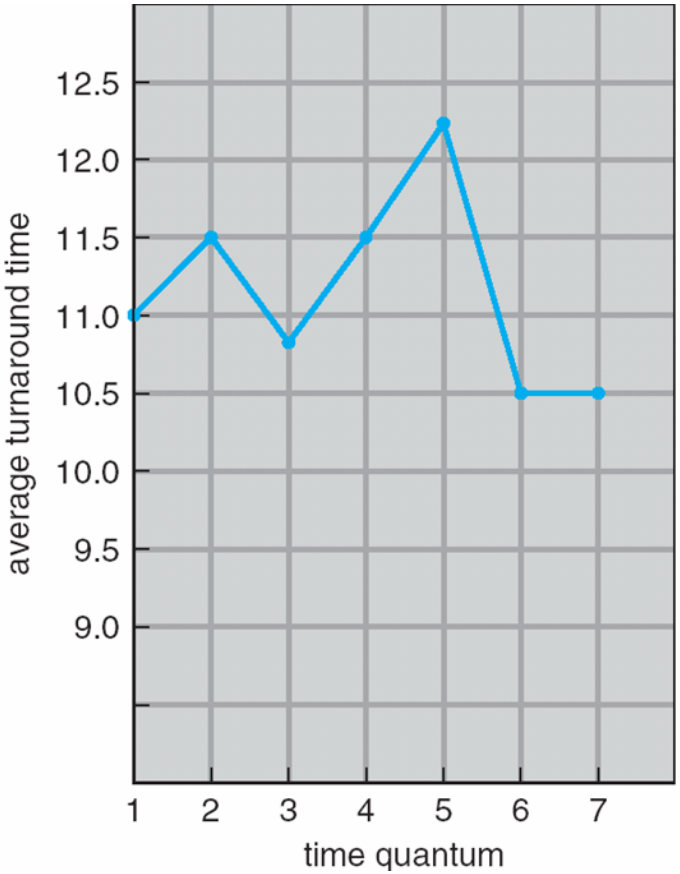
Best FCFS:



	Quantum	P_1	P_2	P_3	P_4	Average
Wait Time	Best FCFS	32	0	85	8	31¼
	Q = 1	84	22	85	57	62
	Q = 5	82	20	85	58	61¼
	Q = 8	80	8	85	56	57¼
	Q = 10	82	10	85	68	61¼
	Q = 20	72	20	85	88	66¼
	Worst FCFS	68	145	0	121	83½
Completion Time	Best FCFS	85	8	153	32	69½
	Q = 1	137	30	153	81	100½
	Q = 5	135	28	153	82	99½
	Q = 8	133	16	153	80	95½
	Q = 10	135	18	153	92	99½
	Q = 20	125	28	153	112	104½
	Worst FCFS	121	153	68	145	121¾



Turnaround Time Varies With The Time Quantum



process	time
P_1	6
P_2	3
P_3	1
P_4	7

- The average turnaround time of a set of processes does not necessarily improve as the time quantum size increases
- In general, it can be improved if most processes finish their next CPU burst in a single time quantum

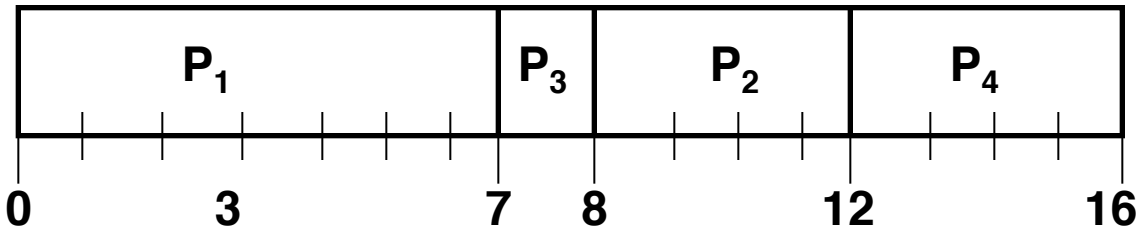
What if we Knew the Future?

- Could we always mirror best FCFS?
- Shortest Job First (SJF):
  - Associate with each process the length of its next CPU burst. Use these lengths to schedule the process with the shortest time (on a tie use FCFS)
  - ***nonpreemptive*** – once CPU given to the process it cannot be preempted until completes its CPU burst
- Shortest Remaining Time First (SRTF):
  - Preemptive version of SJF: if a new process arrives with CPU burst length less than remaining time of current executing process, preempt
- These can be applied either to a whole program or the current CPU burst of each program
  - Idea is to get short jobs out of the system
  - Big effect on short jobs, only small effect on long ones
  - Result is better average response time
  - The difficulty is knowing the length of the next CPU request

Example of SJF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

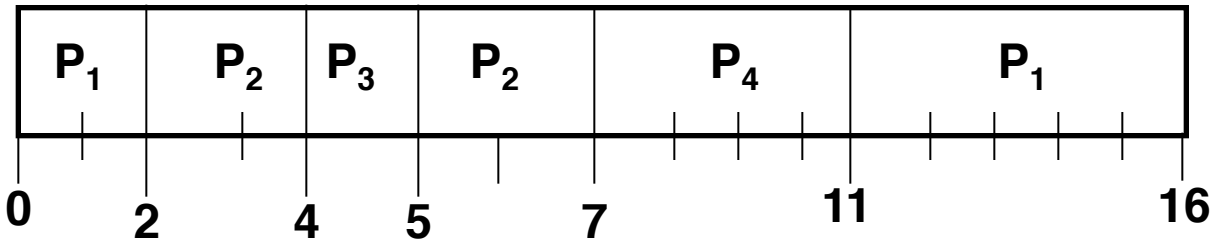
- SJF scheduling chart



- Average waiting time = (0 + 6 + 3 + 7) / 4 = 4

Example of SRTF

Process	Arrival Time	Burst Time
P_1	0.0	7
P_2	2.0	4
P_3	4.0	1
P_4	5.0	4

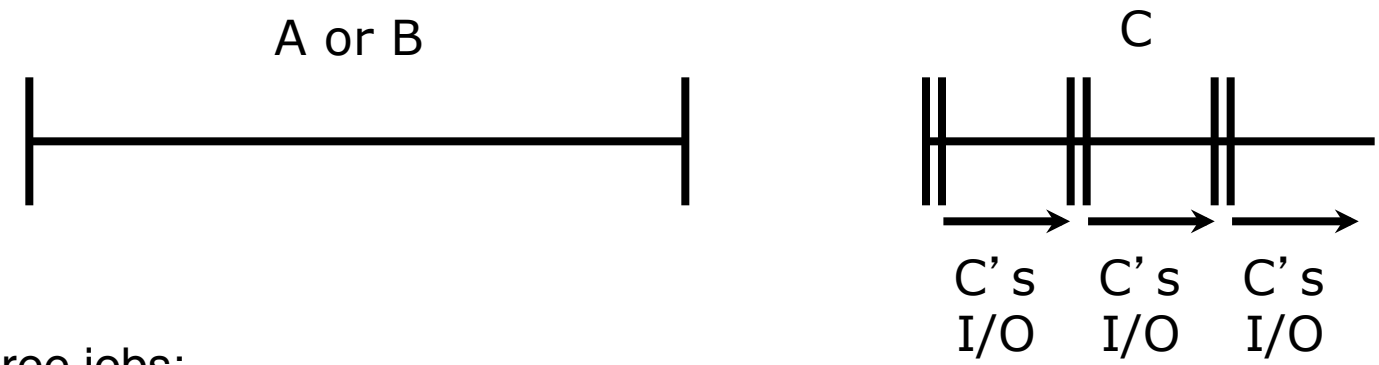


- Average waiting time = (9 + 1 + 0 +2)/4 = 3

Discussion

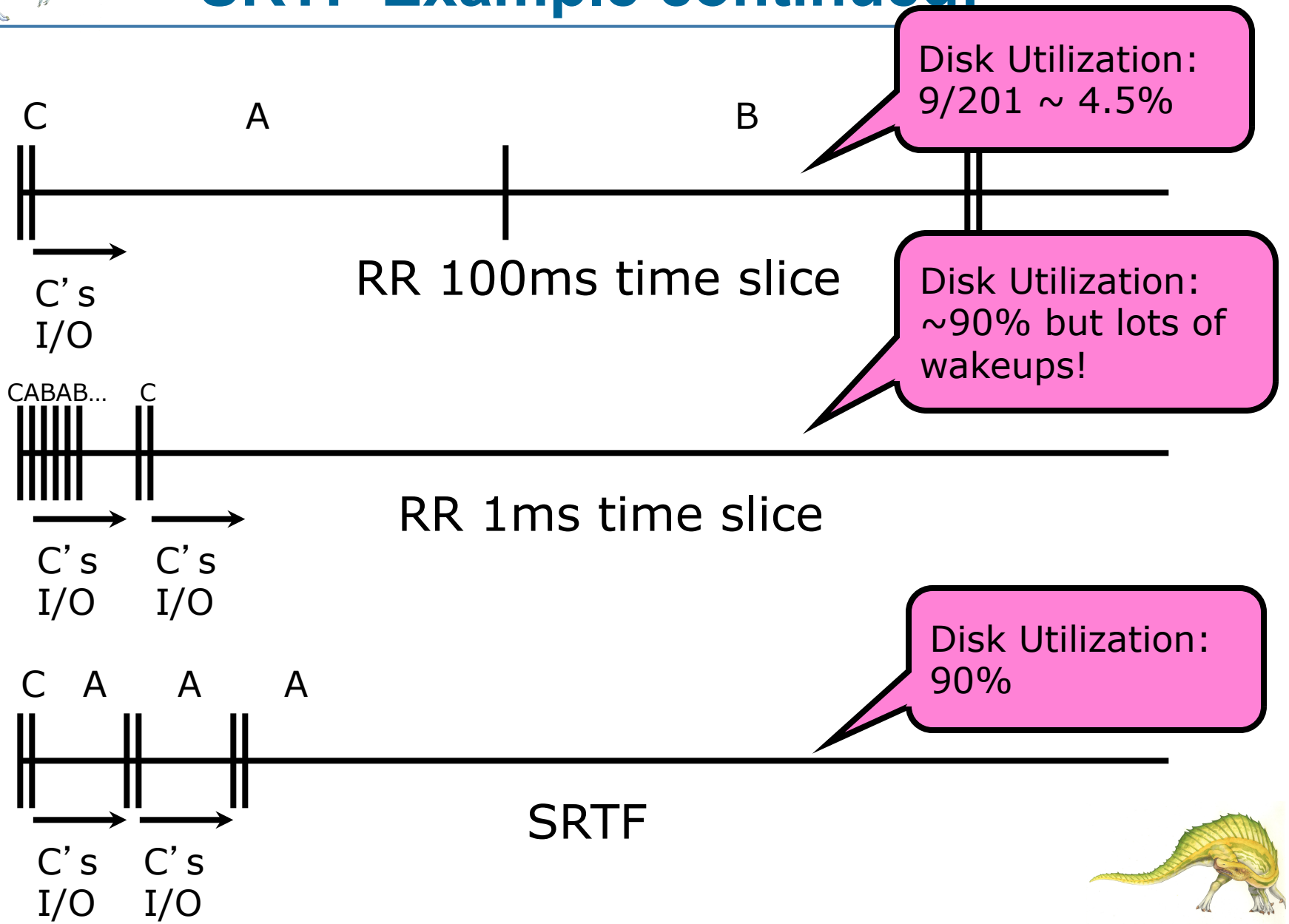
- SJF/SRTF are the best you can do at minimizing average response time
  - Provably optimal (SJF among non-preemptive, SRTF among preemptive)
  - Since SRTF is always at least as good as SJF, focus on SRTF
- Comparison of SRTF with FCFS and RR
  - What if all jobs the same length?
    - SRTF becomes the same as FCFS (i.e. FCFS is best can do if all jobs the same length)
  - What if jobs have varying length?
    - SRTF (and RR): short jobs not stuck behind long ones

Example to illustrate benefits of SRTF



- Three jobs:
  - A,B: both CPU bound, run for week
    C: I/O bound, loop 1ms CPU, 9ms disk I/O
  - If only one at a time, C uses 90% of the disk, A or B could use 100% of the CPU
- With FIFO:
  - Once A or B get in, keep CPU for two weeks
- What about RR or SRTF?
  - Easier to see with a timeline

SRTF Example continued:

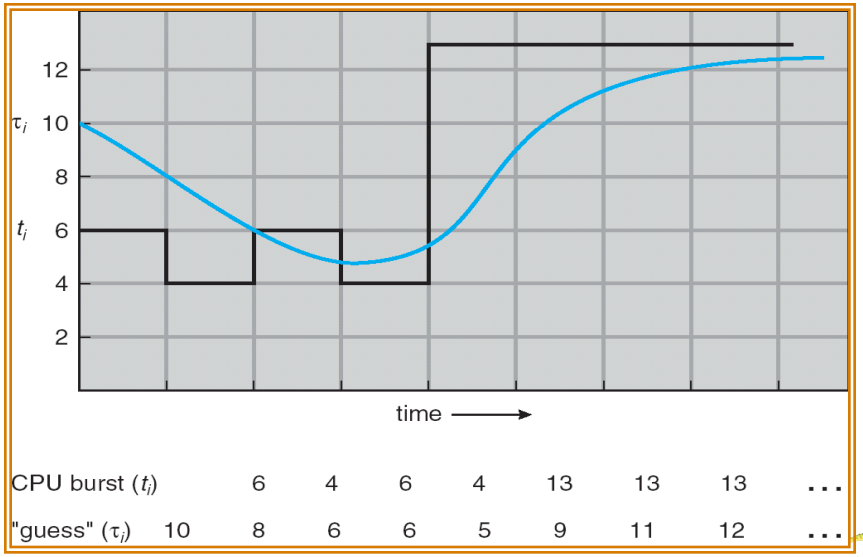


SRTF Further discussion

- Starvation
  - SRTF can lead to starvation if many small jobs!
  - Large jobs never get to run
- Somehow need to predict future
  - How can we do this?
  - Some systems ask the user
    - When you submit a job, have to say how long it will take
    - To stop cheating, system kills job if takes too long
  - But: Even non-malicious users have trouble predicting runtime of their jobs
- Bottom line, can't really know how long job will take
  - However, can use SRTF as a yardstick for measuring other policies
  - Optimal, so can't do any better
- SRTF Pros & Cons
  - Optimal (average response time) (+)
  - Hard to predict future (-)
  - Unfair (-)

Predicting the Length of the Next CPU Burst

- **Adaptive**: Changing policy based on past behavior
  - CPU scheduling, in virtual memory, in file systems, etc
  - Works because programs have predictable behavior
    - If program was I/O bound in past, likely in future
    - If computer behavior were random, wouldn't help
- Example: SRTF with estimated burst length
  - Use an estimator function on previous bursts:
    Let t_{n-1}, t_{n-2}, t_{n-3}, etc. be previous CPU burst lengths. Estimate next burst $\tau_n = f(t_{n-1}, t_{n-2}, t_{n-3}, \ldots)$
  - Function f could be one of many different time series estimation schemes (Kalman filters, etc)
  - For instance,
    exponential averaging
    $\tau_n = \alpha t_{n-1} + (1-\alpha)\tau_{n-1}$
    with $(0 < \alpha \leq 1)$



α= 1/2

Priority Scheduling

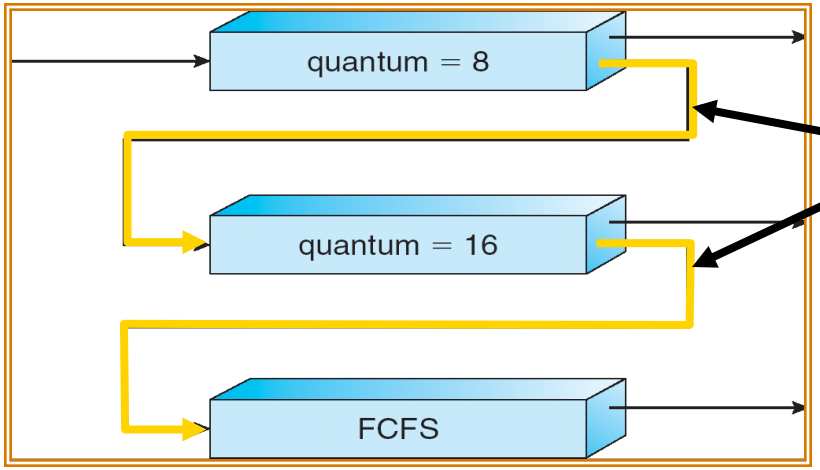
- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority (smallest integer ≡ highest priority)
  - Preemptive (compares priority of process that has arrived at the ready queue with priority of currently running process)
  - Nonpreemptive (put at the head of the ready queue)
- SJF is a priority scheduling where priority is the predicted next CPU burst time
- Problem ≡ **Starvation** – low priority processes may never execute
- Solution ≡ **Aging** – as time progresses increase the priority of the process

Priority Scheduling

Process	Burst Time	Priority
P1	10	3
P2	1	1
P3	2	4
P4	1	5
P5	5	2

Average waiting time: 8.2

Multi-Level Feedback Scheduling



- Another method for exploiting past behavior
  - First used in CTSS
  - **Multiple queues, each with different priority**
    - Higher priority queues often considered “foreground” tasks
  - **Each queue has its own scheduling algorithm**
    - e.g. foreground – RR, background – FCFS
    - Sometimes multiple RR priorities with quantum increasing exponentially (highest:1ms, next:2ms, next: 4ms, etc)
- Adjust each job’s priority as follows (details vary)
  - Job starts in highest priority queue
  - If timeout expires, drop one level
  - If timeout doesn’t expire, push up one level (or to top)

Multilevel Feedback Scheduling

- Result approximates SRTF:
  - CPU bound jobs drop like a rock
  - Short-running I/O bound jobs stay near top
- Scheduling must be done between the queues
  - **Fixed priority scheduling:**
    - serve all from highest priority, then next priority, etc.
    - Possibility of starvation: long running jobs may never get CPU
      - In Multics, shut down machine, found 10-year-old job
    - Solution: could increase priority of jobs that don't get service
  - **Time slice:**
    - each queue gets a certain amount of CPU time
    - e.g., 70% to highest, 20% next, 10% lowest
- **Countermeasure:** user action that can foil intent of the OS designer
  - For multilevel feedback, put in a bunch of meaningless I/O to keep job's priority high
    - Put in printf's, ran much faster!
  - Of course, if everyone did this, wouldn't work!

Multilevel Feedback Parameters

- Multilevel-feedback-queue scheduler defined by the following parameters:
  - number of queues
  - scheduling algorithms for each queue
  - method used to determine when to upgrade a process
  - method used to determine when to demote a process
  - method used to determine which queue a process will enter when that process needs service
- Example:
  - Job starts in highest priority queue
  - If timeout expires, drop one level
  - If timeout doesn't expire, push up one level (or to top)

Chapter 5. Contents

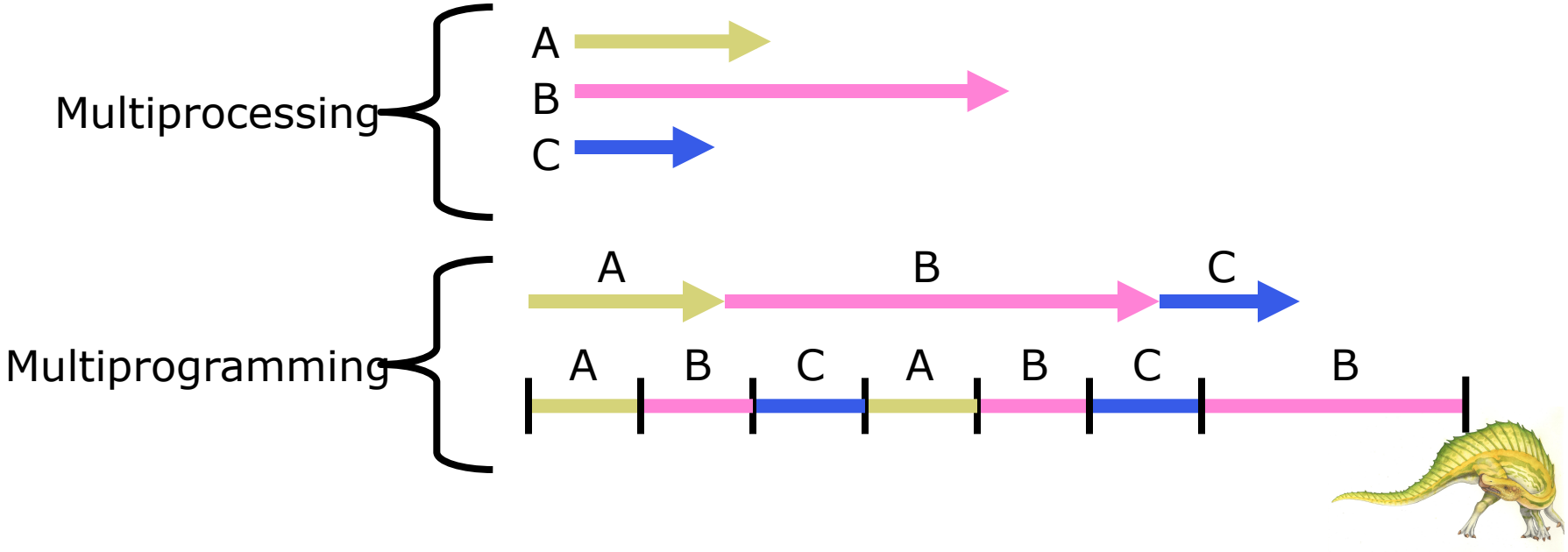
- Basic Concepts. Scheduling Criteria
- Scheduling Algorithms
- Thread Scheduling. Multiple-Processor Scheduling
- Operating Systems Examples

Thread Scheduling

- Distinction between user-level and kernel-level threads:
  - Kernel-level threads (not processes) are scheduled by the O.S.
  - User-level threads are managed by the thread library
- Many-to-one and many-to-many models, thread library schedules user-level threads to run on LWP
  - Known as **process-contention scope (PCS)** since scheduling competition takes place among threads within the process
- Systems using the one-to-one model (Windows XP, Solaris, Linux) schedule threads using the **system-contention scope (SCS)** – competition for the CPU takes place among all threads in system
- Pthread API allows specifying either PCS or SCS during thread creation:
  - PTHREAD SCOPE PROCESS schedules threads using PCS scheduling
  - PTHREAD SCOPE SYSTEM schedules threads using SCS scheduling. The only one possible for Linux and Mac OS X systems

Review: Multiprocessing vs Multiprogramming

- Remember 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



Multiple-Processor Scheduling

- When multiple CPUs are available **load sharing** becomes possible but CPU scheduling more complex
- We concentrate on **homogeneous multiprocessing:** all the processors are identical in terms of their functionality. Aproaches:
  - **Asymmetric multiprocessing** – only one processor has all scheduling decisions, I/O processing and other system activities (= only one accesses the system data structures, alleviating the need for data sharing)
  - **Symmetric multiprocessing (SMP)** – each processor is self-scheduling:
    - All processes in a common ready queue
    - Each has its own private queue of ready processes
  - All modern O.S. support SMP: Windows XP, Windows 2000, Solaris, Linux, Mac OS X

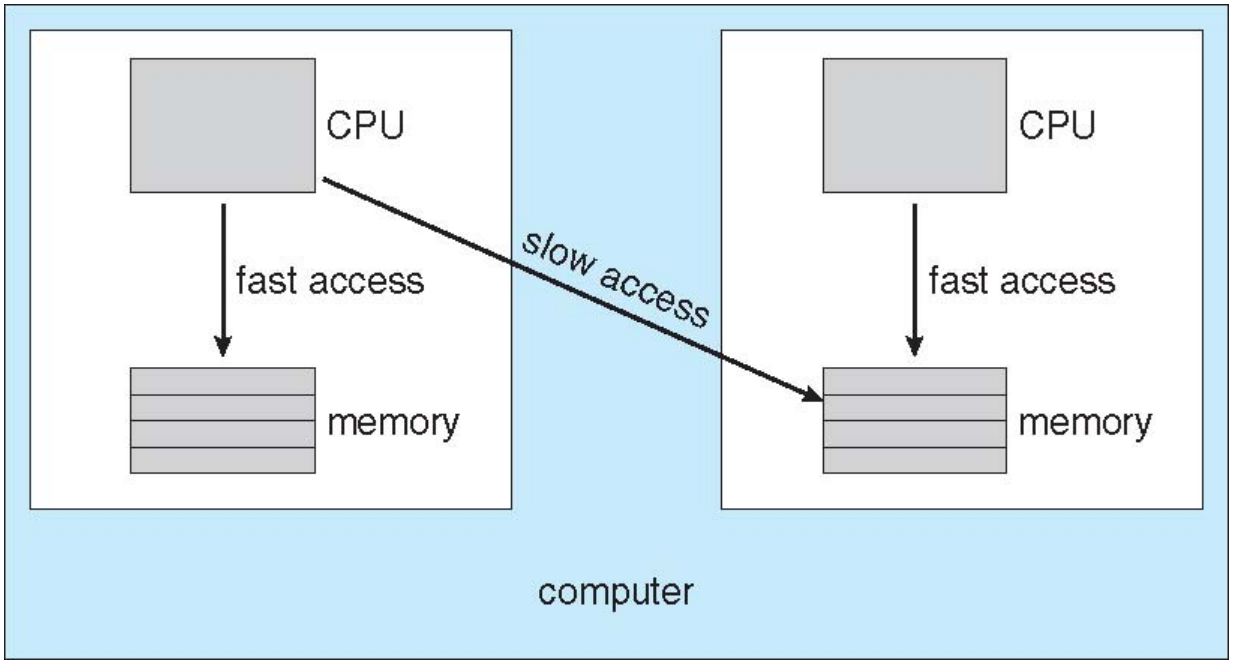
Multiple-Processor Scheduling

- **Local cache accesses.** When a process remains executing on the same processor: data most recently accessed populates the cache for that processor. If the process migrates to another processor:
  1. the contents of the cache must be invalidated for the first processor,
  2. and the cache for the second processor must be repopulated.

- **Processor affinity** – process has affinity for processor on which it is currently running
  - **soft affinity-** OS attempts to keep a process running on the same processor (but not guaranteeing that it will do so)
  - **hard affinity** (OS provides system calls allowing a process to specify that it is not to migrate to other processors)

NUMA and CPU Scheduling

- Affinity issues are affected by the main memory architecture of a system.
- NUMA = Non Uniform Memory Access. A CPU has faster access to some parts of main memory than to other parts (systems containing combined CPU and memory boards)
- System's CPU scheduler and memory placement algorithms should work together: a process that is assigned affinity to a particular CPU can be allocated memory on the board where that CPU resides.

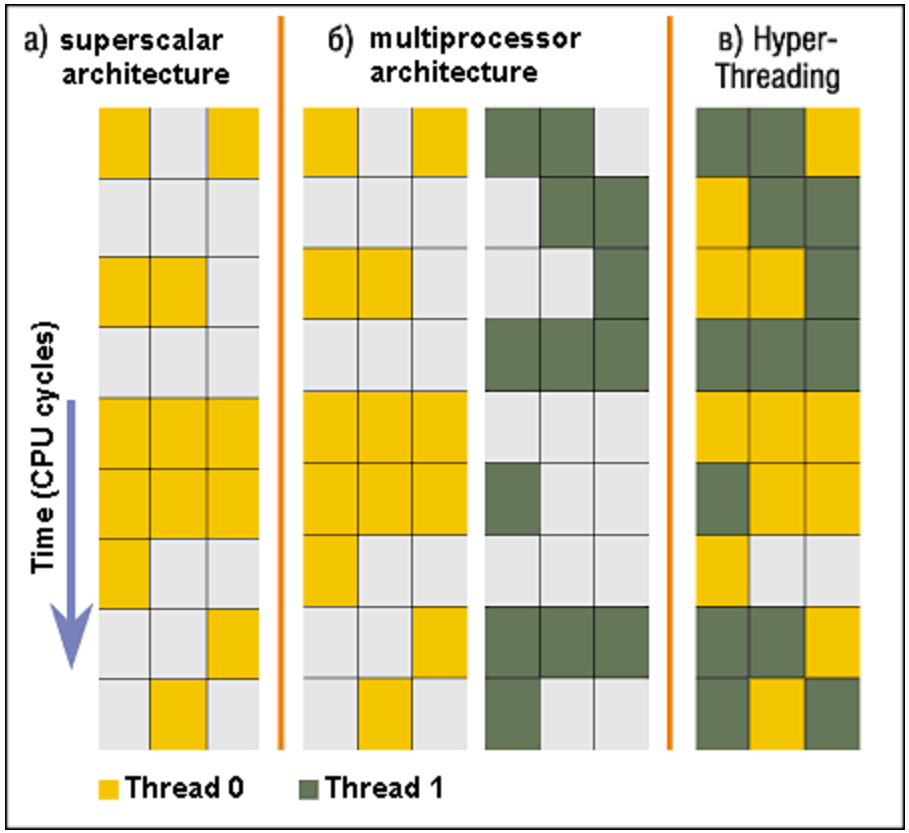


Recent trends

- Multicore Processors: Recent trend to place multiple processor cores on same physical chip
  - Faster and consume less power
- Multiple threads per core also growing: SMT/Hyperthreading
  - Takes advantage of memory stall to make progress on another thread while memory retrieve happens

SMT/Hyperthreading

- Hardware technique
  - Exploit natural properties of superscalar processors to provide illusion of multiple processors
  - Higher utilization of processor resources
- **Can schedule each thread as if were separate CPU**
  - However, not linear speedup!
  - If have multiprocessor, should schedule each processor first
- Original technique called “Simultaneous Multithreading”
  - See http://www.cs.washington.edu/research/smt/
  - Alpha, SPARC, Pentium 4 (“Hyperthreading”), Power 5



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Operating System Examples

- Windows XP scheduling
- Linux scheduling

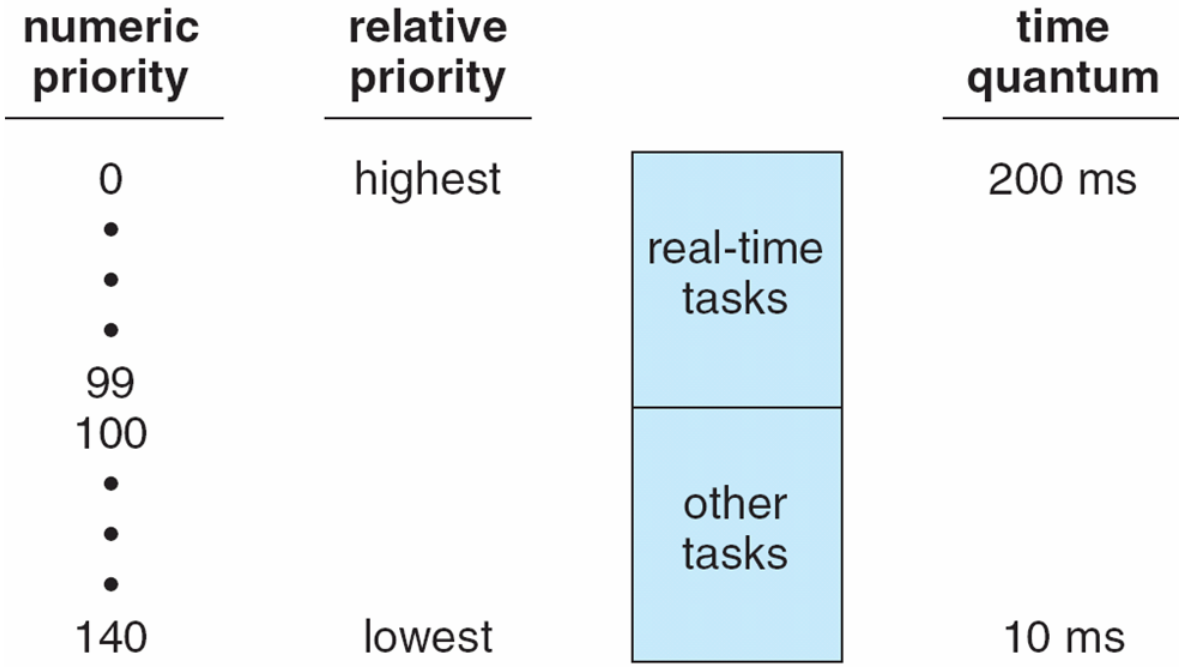
Windows XP Priorities

- Priority based, preemptive scheduling algorithm; highest priority always runs
- Priorities are divided into two classes:
  - Variable class – 1 through 15 and
  - Real time class – 16 through 31
- Priority is based on priority class it belongs to (realtime, high etc) and the relative priority within each class
  - When a threads quantum runs out the thread is interrupted. If it is in the variable priority class its priority is lowered (never below the base priority for that class)
  - Gives good response to interactive threads (mouse, windows) and enables I/O bound threads to keep the I/O devices busy while compute bound use spare CPU cycles in the background

	real-time	high	above normal	normal	below normal	idle priority
time-critical	31	15	15	15	15	15
highest	26	15	12	10	8	6
above normal	25	14	11	9	7	5
normal	24	13	10	8	6	4
below normal	23	12	9	7	5	3
lowest	22	11	8	6	4	2
idle	16	1	1	1	1	1

Linux Scheduling

- Preemptive, priority based with two separated priority ranges: time-sharing and real-time
- Higher priority tasks have longer time quanta
- **Real-time** range from 0 to 99 and **nice** value from 100 to 140



List of Tasks Indexed According to Priorities

- Constant order *O*(1) scheduling time
- Kernel maintains list of all runnable tasks (task that has time remaining on its time slice) in a runqueue data structure
  - Each **runqueue** contains two priority arrays - **active** and **expired**
  - When all active tasks have exhausted their time slices, the two priority arrays are exchanged (active ←→ expired)