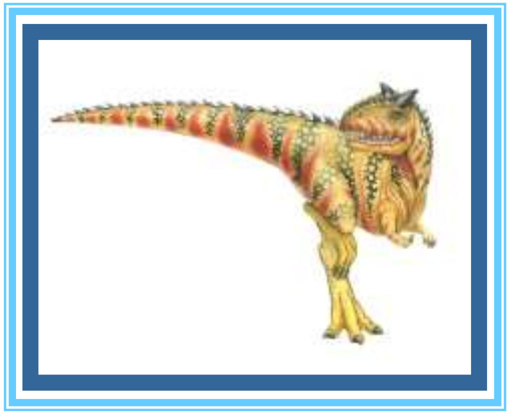
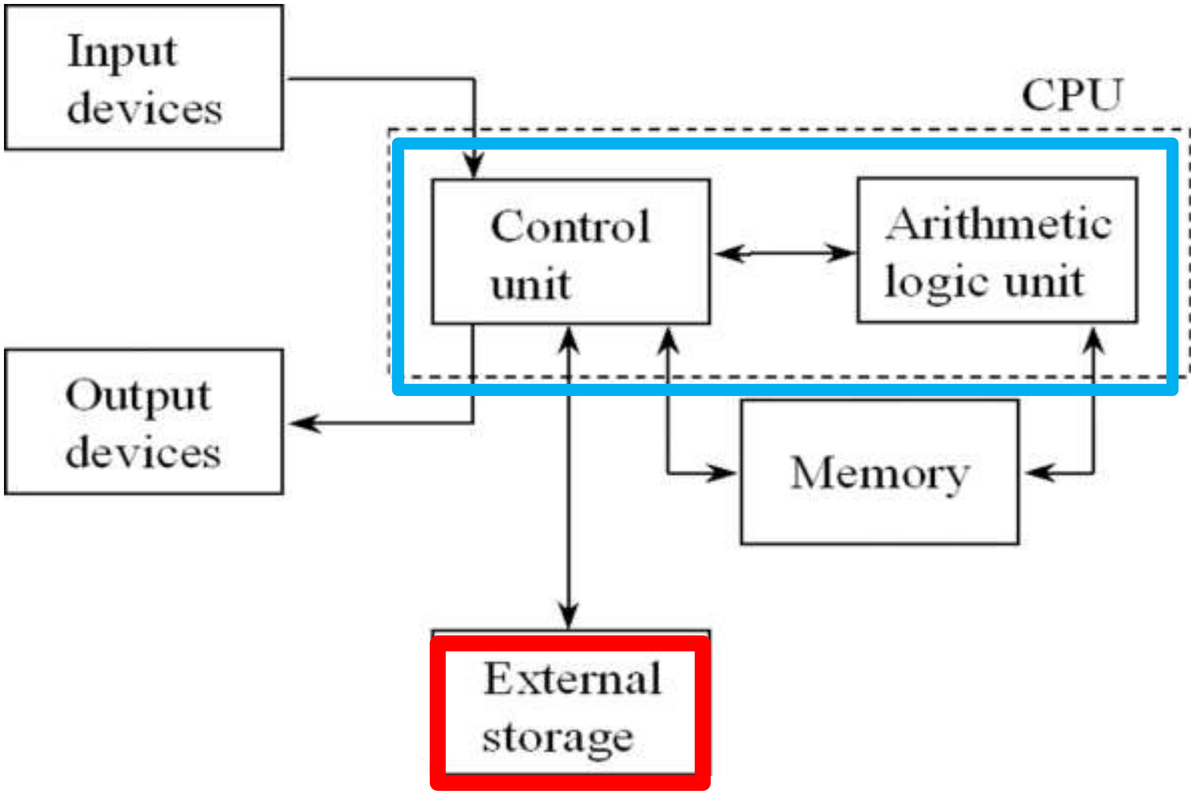
Chapter 3: Processes



Process-Objectives

- Process Concept
- 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



Process Concept (Cont.)

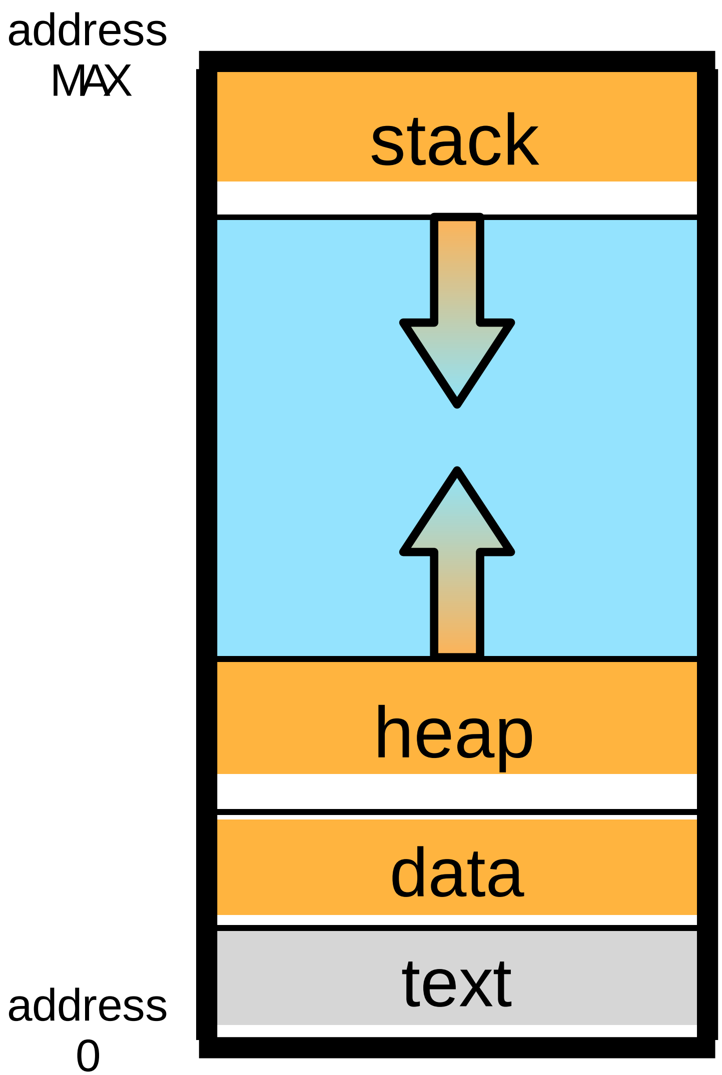
- Multiple parts
  - The program code, also called **text section**

  It also includes current activity as represented by the value of the **program counter**,and the contents of 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

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

A process in memory



Stack: Temporary data such as function parameters, local variables and return addresses.

The stack grows from high addresses towards lower address.

Heap: Dynamically allocated (malloc) by the program during runtime.

The heap grows from low addresses towards higher addresses.

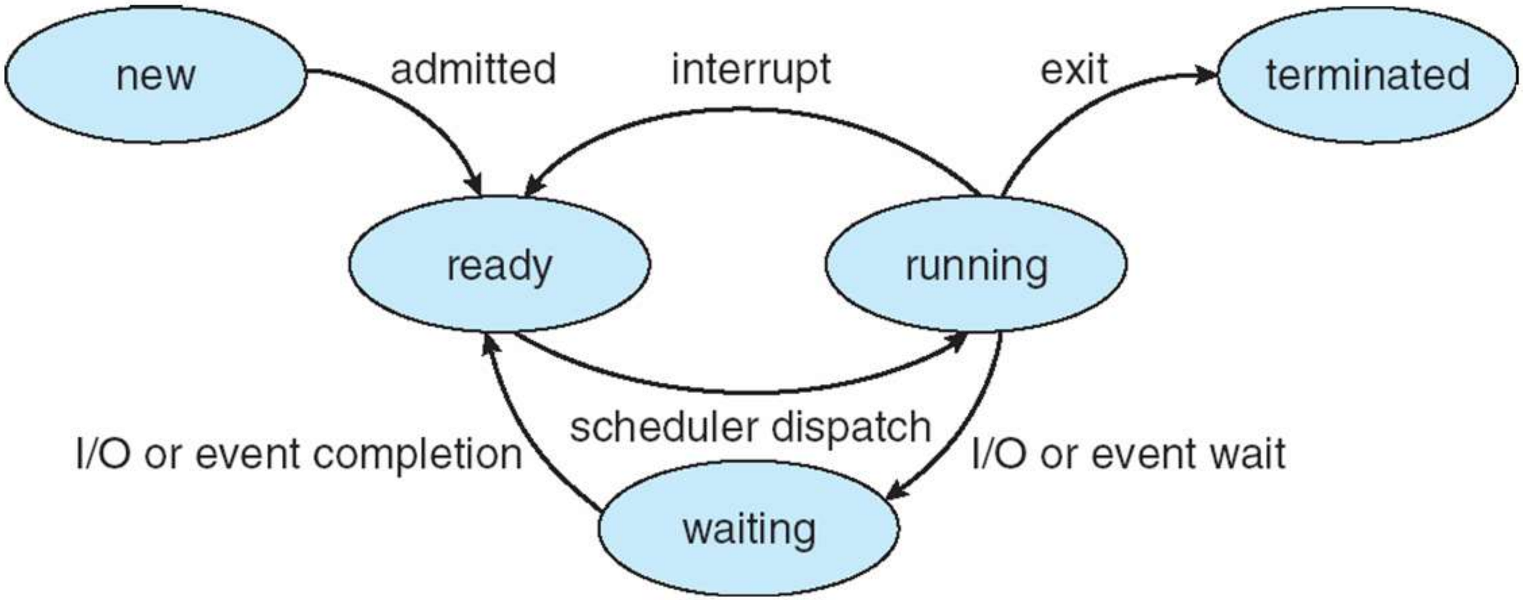
Data: Statically (known at compile time) global variables and data structures.

Text: The program executable machine instructions.

Process State

- As a process executes, it changes **state**
  - **new**: The process is being created
  - **running**: Instructions are being executed
  - **waiting**: The process is waiting for some event to occur
  - **ready**: The process is waiting to be assigned to a processor
  - **terminated**: The process has finished execution

Diagram of Process State



In general, a process can be in one of five states: new, ready, running, waiting or terminated. A process transitions between the states according to the following diagram

Exampleprogram

example.c

```c
// Example C program

#include <stdlib.h>

int x;

int main(void) {
  int y;
  char* str;
  str = malloc(50);
  exit(EXIT_SUCCESS);
}
```

Compiler

The name compiler is primarily used for programs that translate source code from a high-level programming language to a lower level language (e.g., assembly language, object code, or machine code) to create an executable program.

Executable

A compiler (for example gcc) transforms a program to an executable.

```
$ gcc example.c
```

In this example the compiler **gcc** transformed the **example.c** program into the file **a.out**.

```
$ ls
a.out  example.c
```

Process

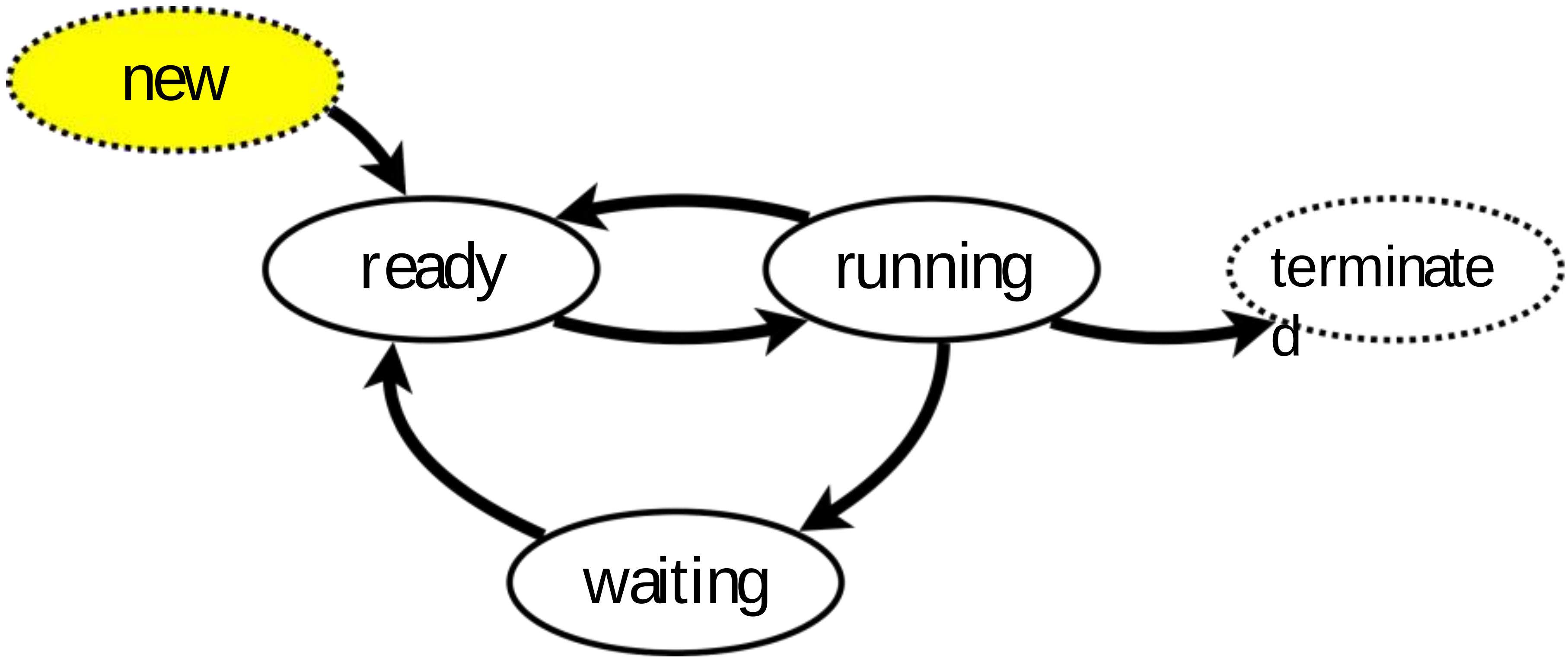
To run the program, the operating system must first create a process.

```
$ ./a.out
```

To create a process, the operating system must allocate memory for the process.

New

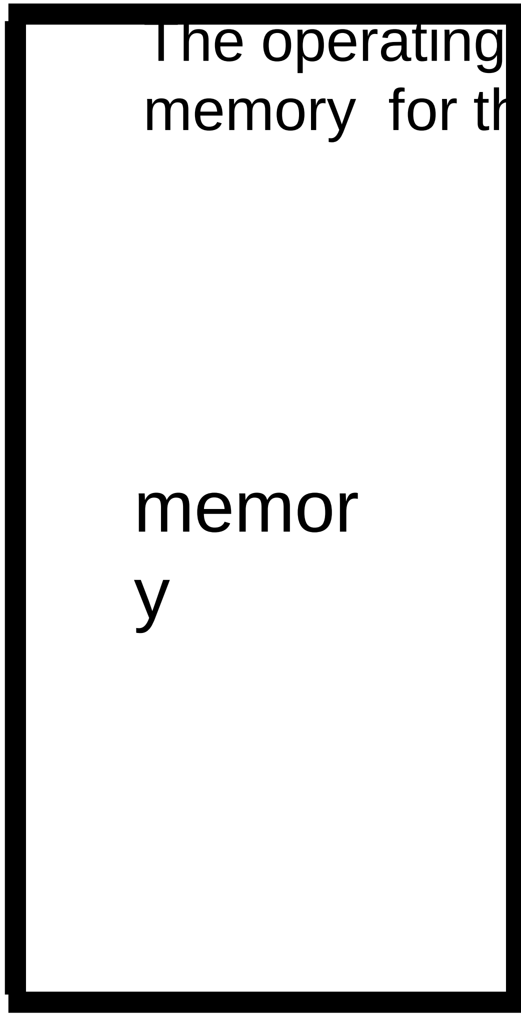
To run a program, the operating system must first allocate memory for the process.



Static memory allocation

```c
// Example C program

#include <stdlib.h>

int x;

int main(void) {
  int y;
  char* str;
  str = malloc(50);
  exit(EXIT_SUCCESS);
}
```

address MAX

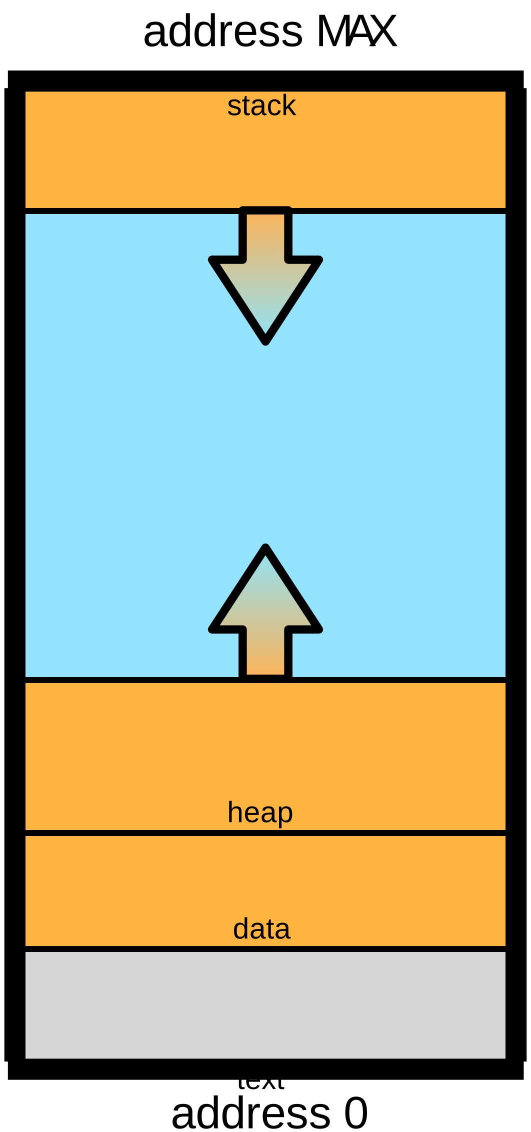


address 0

The operating system allocates a blob of memory for the new process.

Static memory allocation

```
// Example C program

#include <stdlib.h>

int x;

int main(void) {
  int y;
  char* str;
  str = malloc(50);
  exit(EXIT_SUCCESS);
}
```



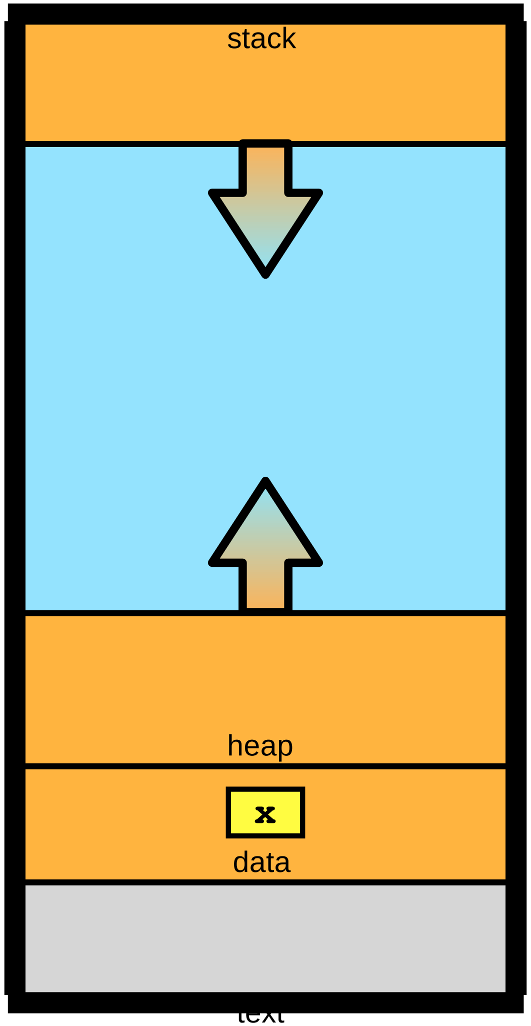
The allocated memory is divided into the following segments:

- text
- data
- heap
- stack

Static memory allocation

```c
// Example C program

#include <stdlib.h>

int x;

int main(void) {
  int y;
  char* str;
  str = malloc(50);
  exit(EXIT_SUCCESS);
}
```

address MAX

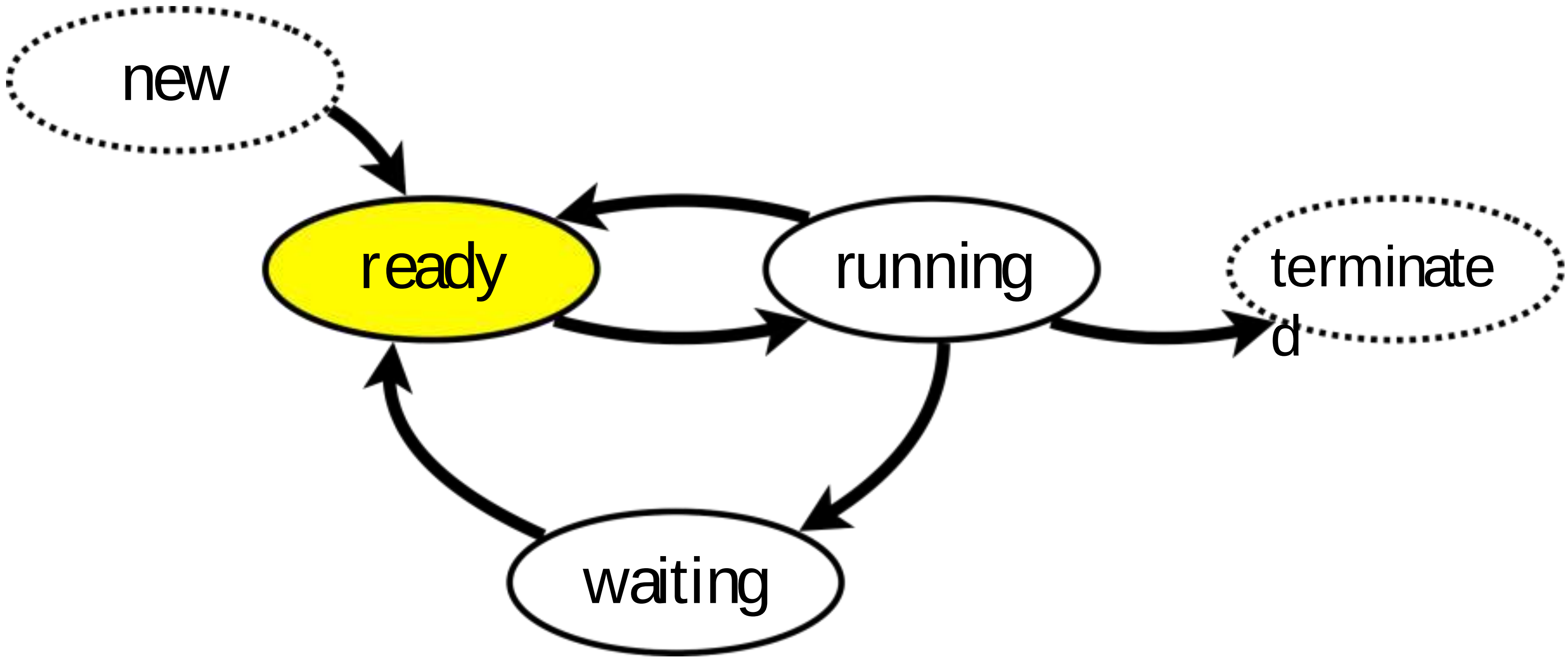


address 0

The size of the needed storage for the **global variable x** is known at compile time and storage for x is allocated in the static **data segment**.

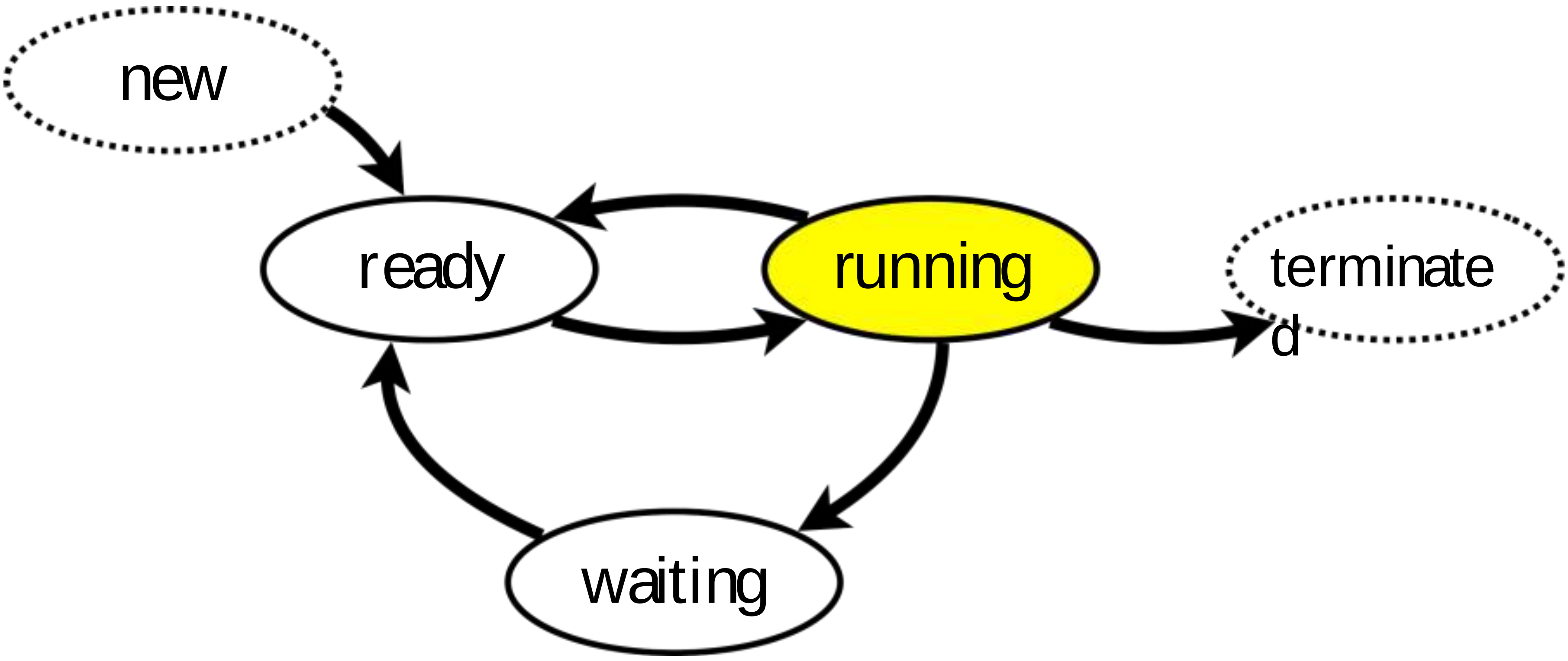
Ready

After the operating system has allocated memory for the process it is ready to execute and changes state from new to ready.



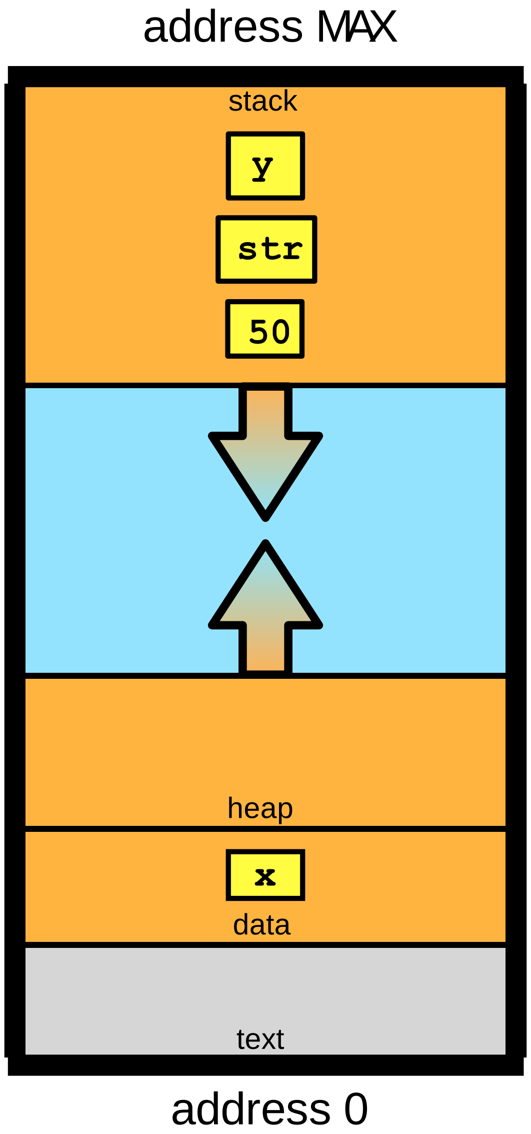
Running

When the process is selected to execute it changes state from ready to running.



Dynamic memory allocation

```c
// Example C program

#include <stdlib.h>

int x;

int main(void) {
  int y;
  char* str;
  str = malloc(50);
  exit(EXIT_SUCCESS);
}
```



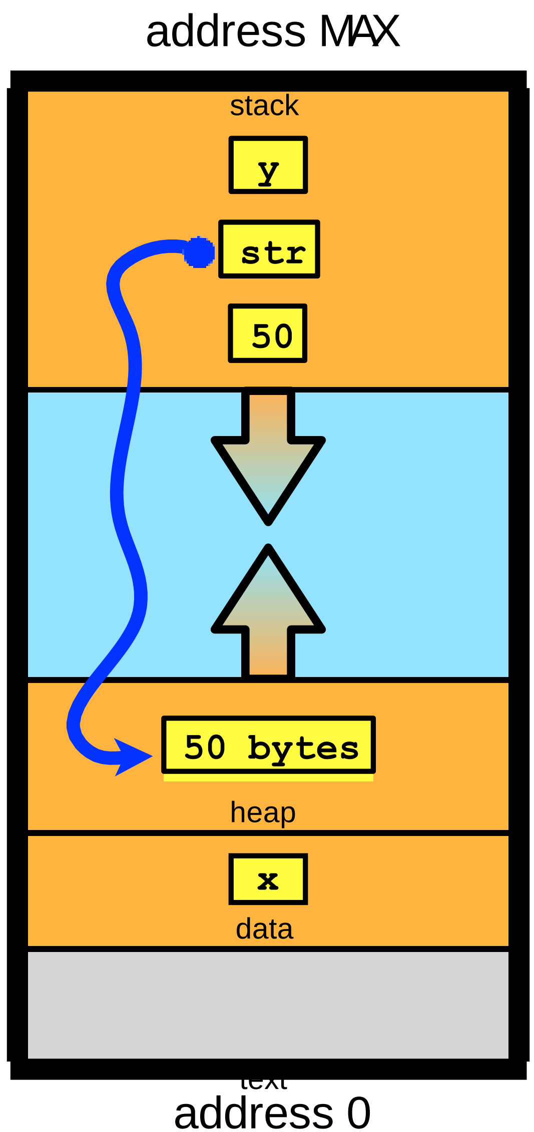
The size of the needed storage for the **local variables** **`y`** and **`str`** are also known at compile time but these are only needed within main and storage is allocated on the **stack**.

In general, the value of the **parameter** to the malloc might not be know at compile time. In this example the argument to malloc, the number 50 is pushed onto the **stack**.

Note: A compiler may also decide to put arguments in certain register.

Dynamic memory allocation

```c
// Example C program

#include <stdlib.h>

int x;

int main(void) {
  int y;
  char* str;
  str = malloc(50);
  exit(EXIT_SUCCESS);
}
```

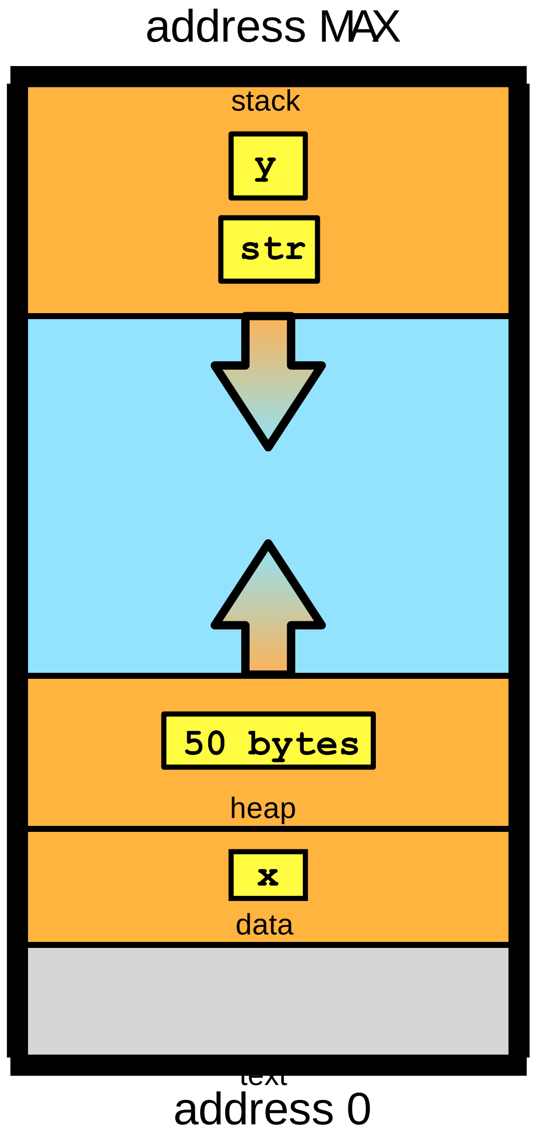


Now **`malloc`** has **dynamically** allocated memory on the heap.

The variable **`str`** stores the address to the first of the 50 bytes allocated on the heap, i.e., **`str`** is a **pointer**.

Dynamic memory deallocation

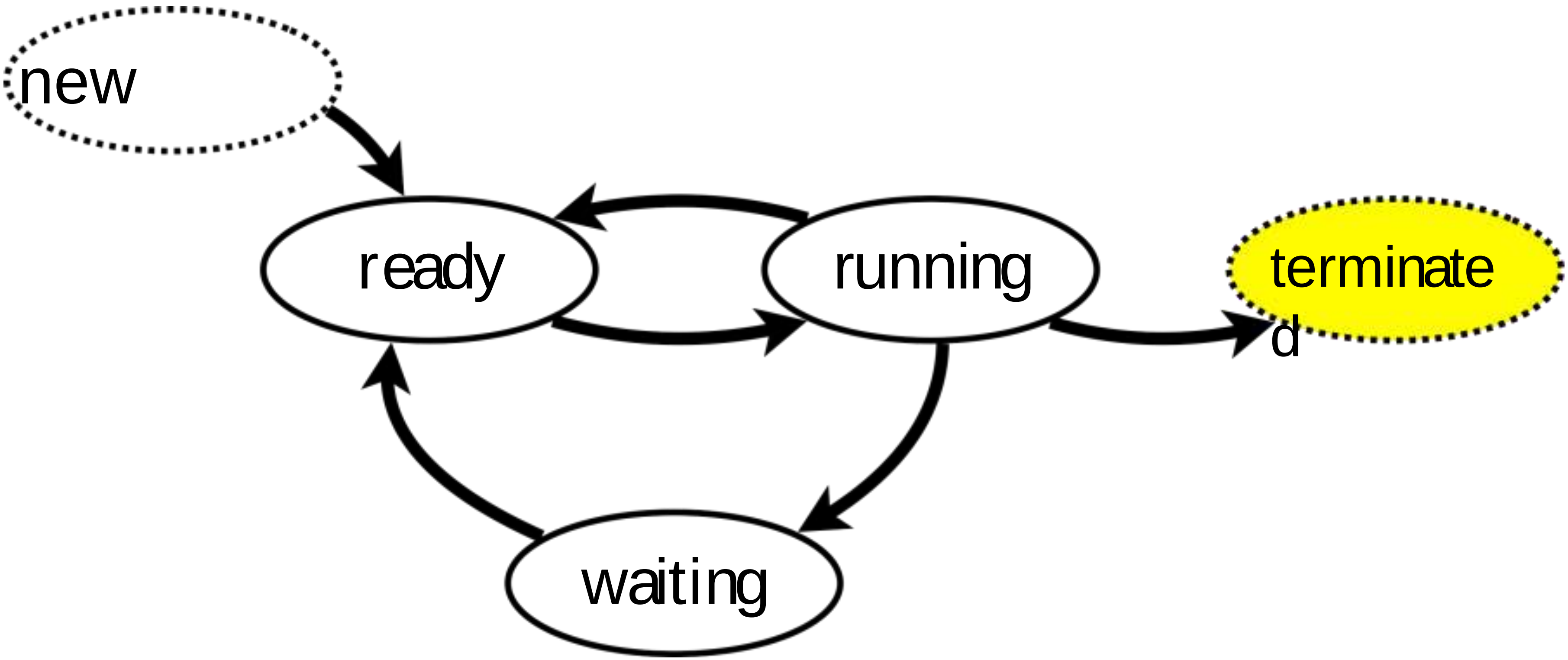
```c
// Example C program

#include <stdlib.h>

int x;

int main(void) {
  int y;
  char* str;
  str = malloc(50);
  exit(EXIT_SUCCESS);
}
```



When malloc returns, the value 50, the argument used when calling malloc is no longer needed and is popped from the stack.

Termination

When the process terminates the operating system can deallocate the memory used by the process.



Process termination

```c
// Example C program

#include <stdlib.h>

int x;

int main(void) {
  int y;
  char* str;
  str = malloc(50);
  exit(EXIT_SUCCESS);
}
```

address MAX

The program terminates with a c
and the memory allocated to the
process can be deallocated.

deallocated mem

address 0

Process Control Block (PCB)

Process Control Block (PCB)

The process control block (PCB) is a data structure in the operating system kernel containing the information needed to manage a particular process.

In brief, the PCB serves as the repository for any information that may vary from process to process.

Example of information stored in the PCB

Process Control Block (PCB)
Process id (PID)
Process state (new, ready, running, waiting or terminated)
CPU Context
I/O status information
Memory management information
CPU scheduling information

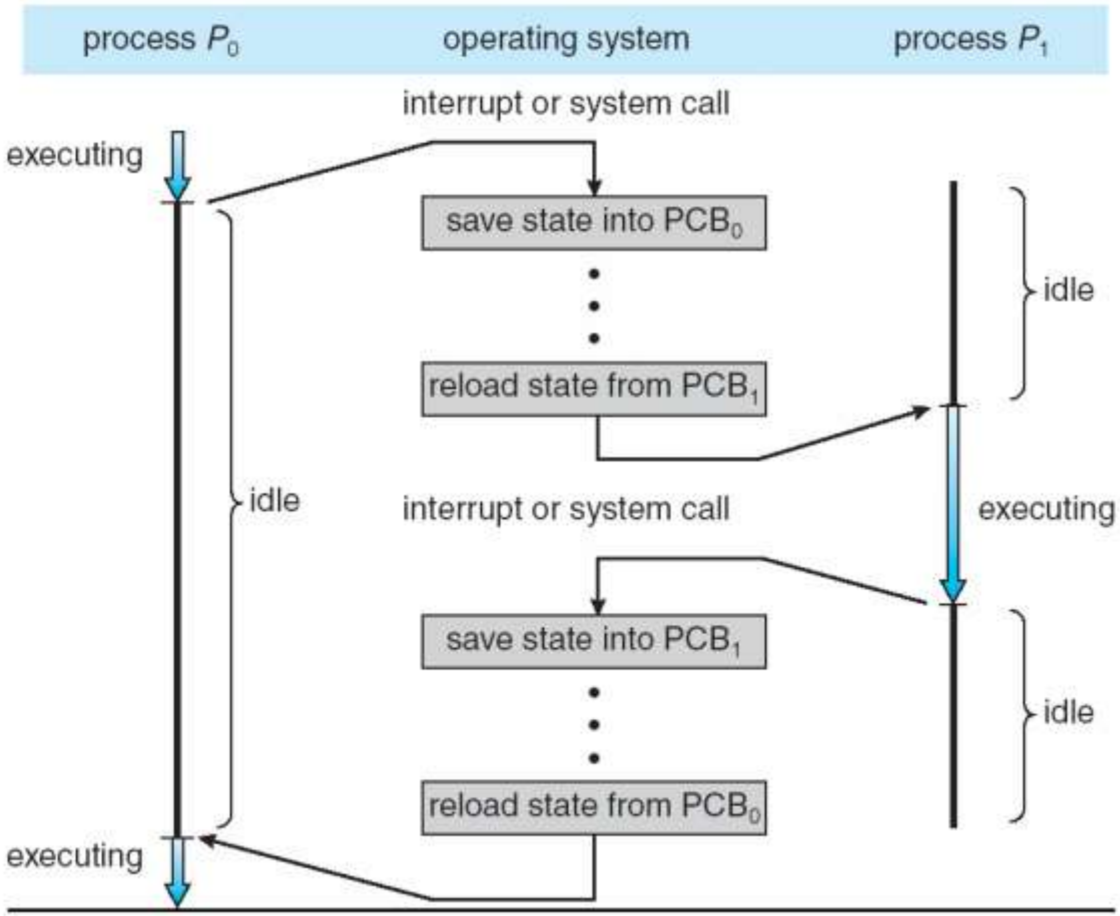
Process Control Block (PCB) also called **task control block**

Information associated with each process- It simply serves as repository for any information that vary from process to process

Process state – running, waiting, etc

- Program counter – location of instruction to next execute
- CPU registers – contents of all process-centric registers means accumulators,index registers,stack pointer etc.
- CPU scheduling information- priorities, scheduling queue pointers
- Memory-management information – It includes base and limit registers, the page tables or the segment tables, depending on the memory system used by the OS
- 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

CPU Switch From Process to Process



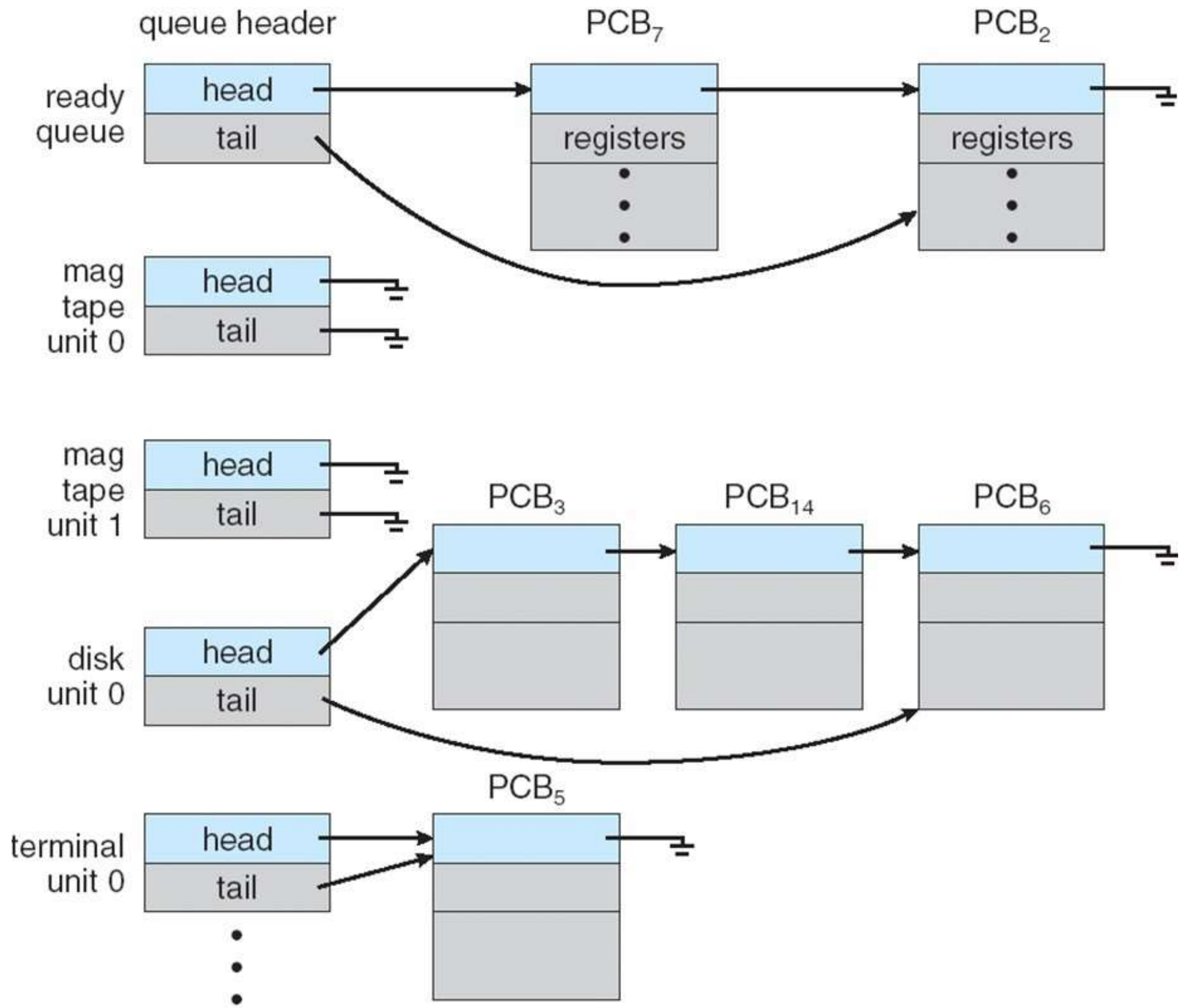
Process Scheduling

- Maximize CPU use, quickly switch processes onto CPU for time sharing
- **Process scheduler** selects among available processes for next execution on CPU
- Maintains **scheduling queues** of processes
  - **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

Process queues can be formed by linking PCBs together

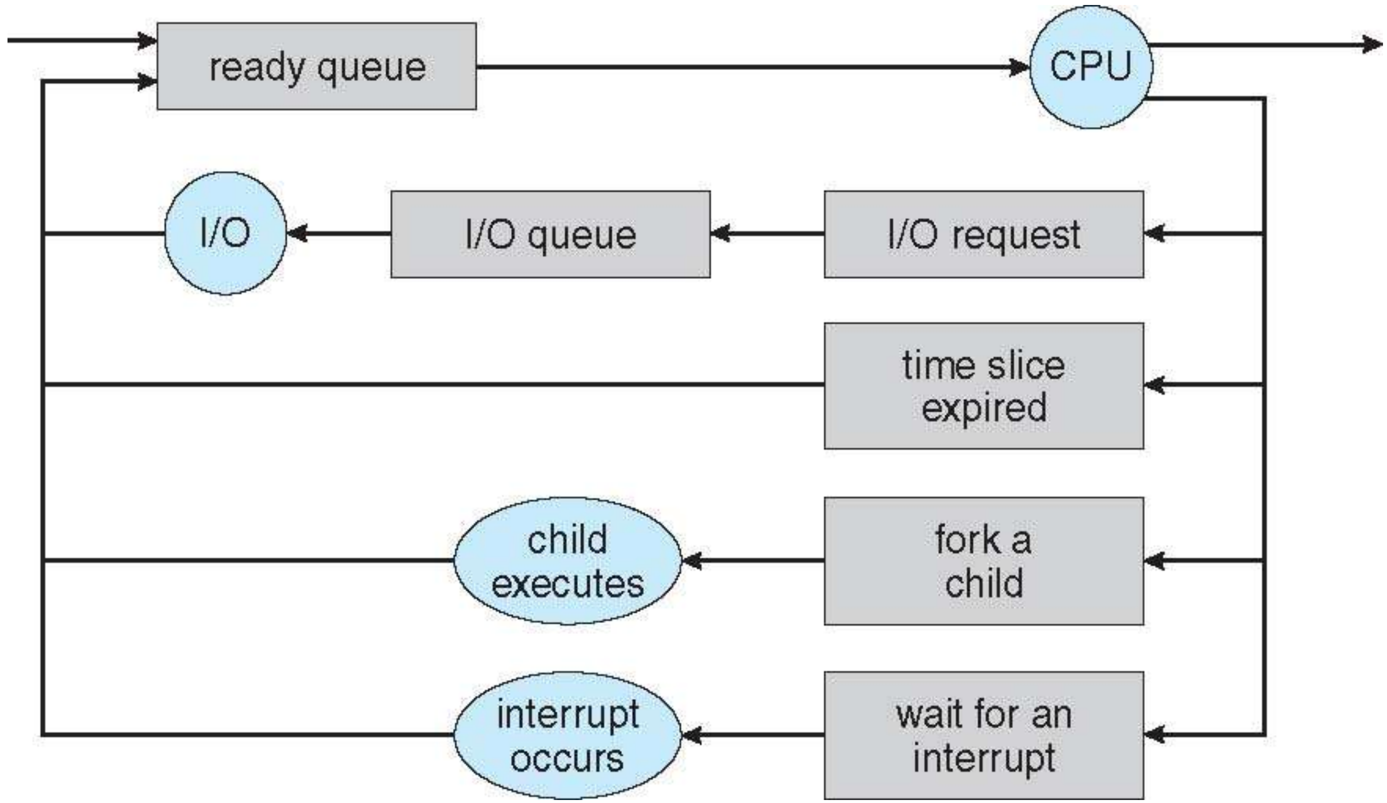
Ready Queue

Device queues



Representation of Process Scheduling

- **Queueing diagram** represents queues, resources, flows

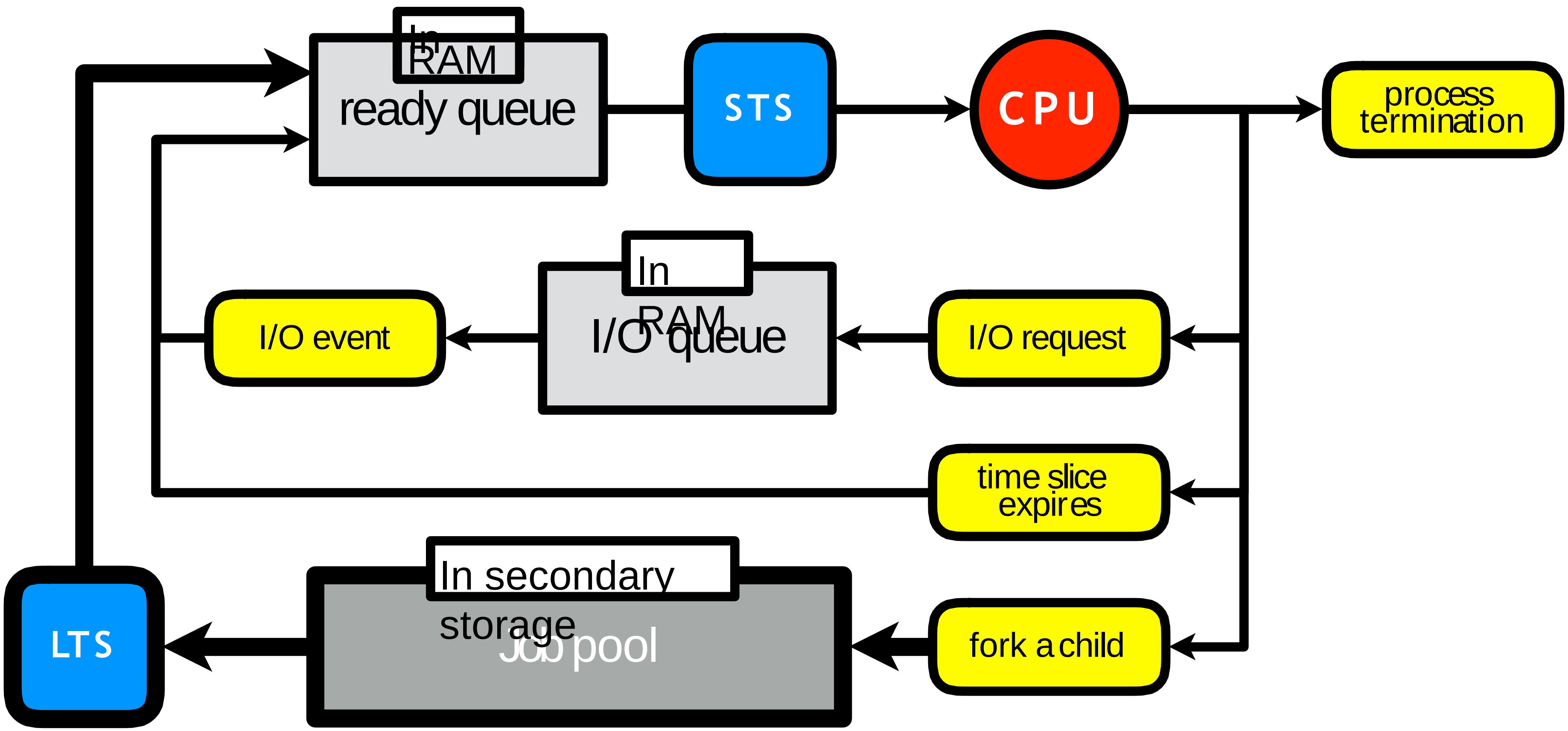


Schedulers

- **Short-term scheduler** (or **CPU scheduler**) – selects which process should be executed next and allocates CPU
  - Sometimes the only scheduler in a system
  - Short-term scheduler is invoked frequently (milliseconds) $\Rightarrow$ (must be fast)
- **Long-term scheduler** (or **job scheduler**) – selects which processes should be brought into the ready queue
  - Long-term scheduler is invoked infrequently (seconds, minutes) $\Rightarrow$ (may be slow)
  - The long-term scheduler controls the **degree of multiprogramming**
- Processes can be described as either:
  - **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
- Long-term scheduler strives for good ***process mix***

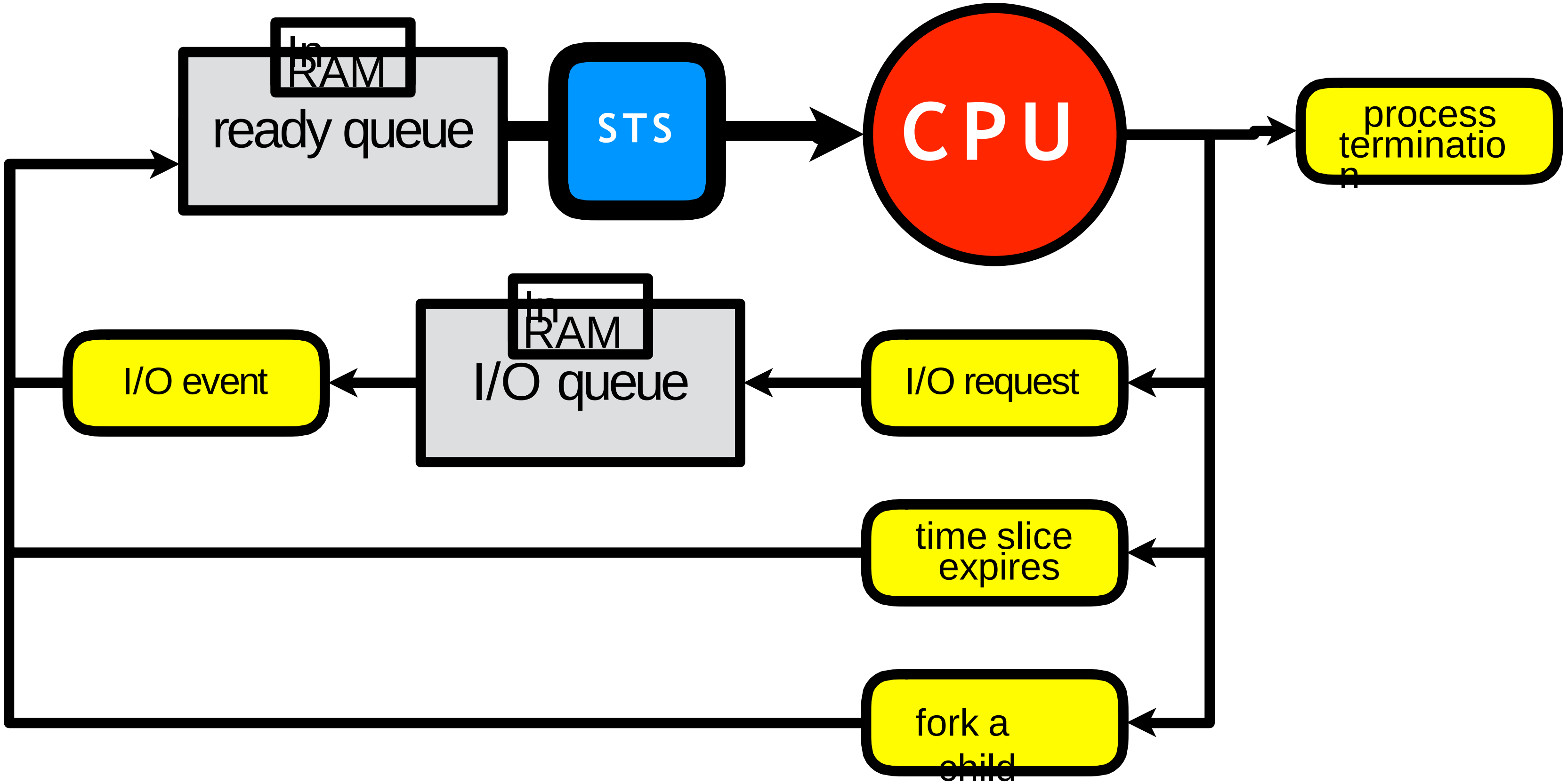
Long-term scheduler

The Long-term scheduler (LTS) () decides whether a new process should be brought into the ready queue in main memory or delayed. When a process is ready to execute, it is added to the job pool (on disk). When RAM is sufficiently free, some processes are brought from the job pool to the ready queue (in RAM).



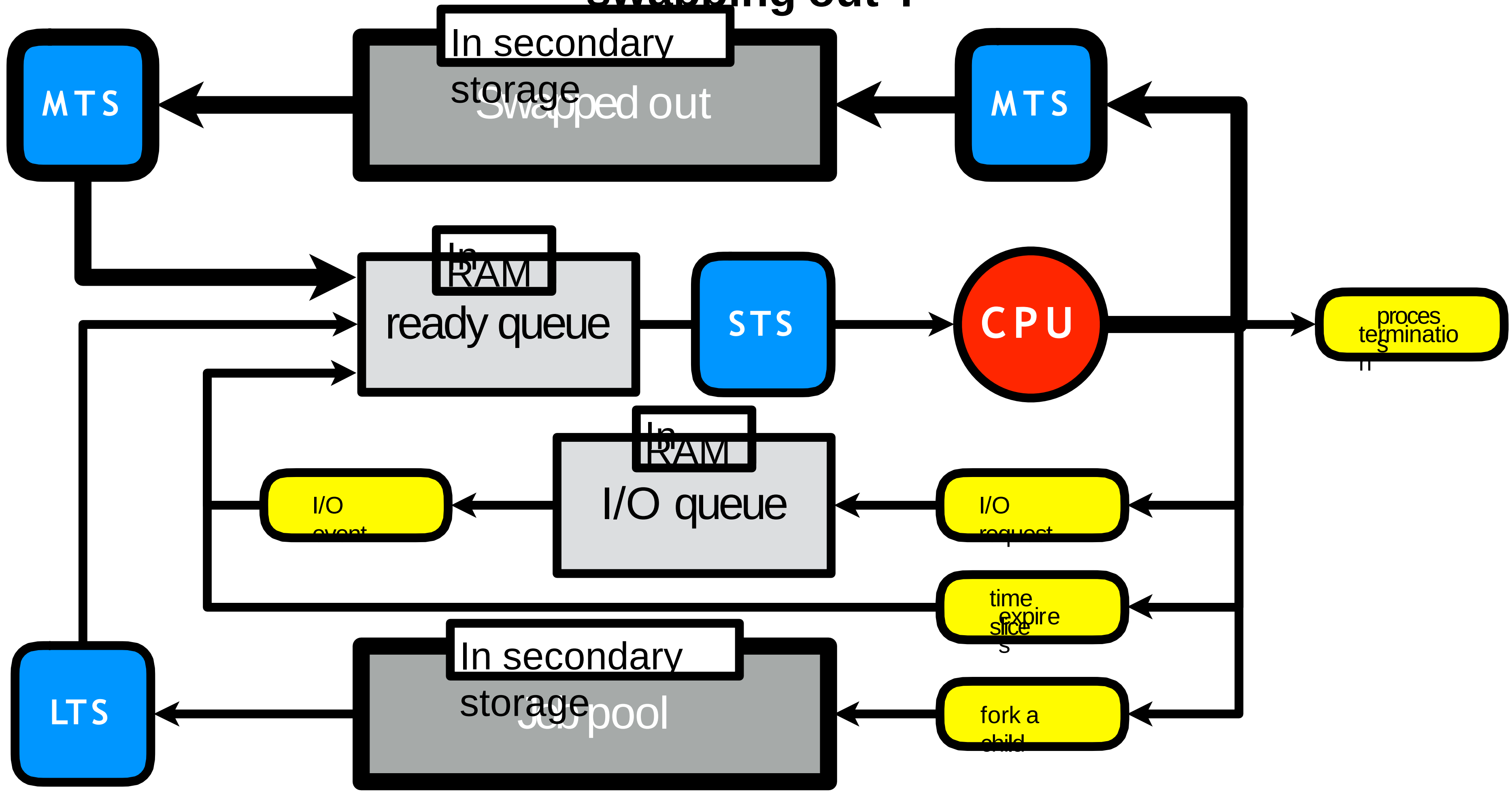
Short-term scheduler

The Short-term scheduler (STS), aka CPU scheduler, selects which process in the in memory ready queue that should be executed next and allocates CPU.



Medium-term scheduler

The medium-term scheduler (MTS) temporarily removes processes from main memory and places them in secondary storage and vice versa, which is commonly referred to as "swapping in" and "swapping out".



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
  - The more complex the OS and the PCB ➔ the longer the context switch
- Time dependent on hardware support
  - Some hardware provides multiple sets of registers per CPU ➔ multiple contexts loaded at once

Operations on Processes

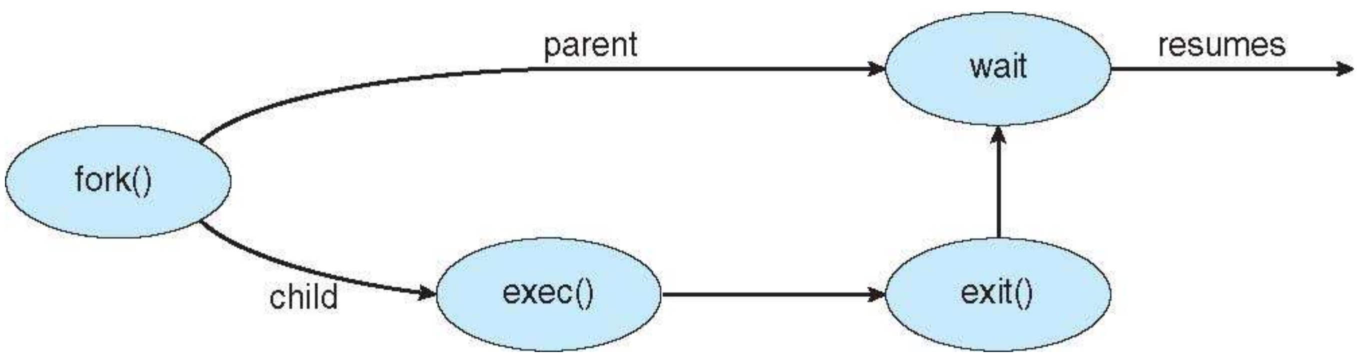
- System must provide mechanisms for:
  - process creation,
  - process termination,
  - and so on as detailed next

Process Creation

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

Process Creation (Cont.)

- Address space
  - Child duplicate of parent
  - Child has a program loaded into it
- UNIX examples
  - **`fork()`** system call creates new process
  - **`exec()`** system call used after a **`fork()`** to replace the process' memory space with a new program



C Program Forking Separate Process

```
#include <sys/types.h>
#include <stdio.h>
#include <unistd.h>

int main()
{
pid_t pid;

   /* fork a child process */
   pid = fork();

   if (pid < 0) { /* error occurred */
     fprintf(stderr, "Fork Failed");
     return 1;
   }
   else if (pid == 0) { /* child process */
     execlp("/bin/ls","ls",NULL);
   }
   else { /* parent process */
     /* parent will wait for the child to complete */
     wait(NULL);
     printf("Child Complete");
   }

   return 0;
}
```

Creating a Separate Process via Windows API

```
#include <stdio.h>
#include <windows.h>

int main(VOID)
{
STARTUPINFO si;
PROCESS_INFORMATION pi;

   /* allocate memory */
   ZeroMemory(&si, sizeof(si));
   si.cb = sizeof(si);
   ZeroMemory(&pi, sizeof(pi));

   /* create child process */
   if (!CreateProcess(NULL, /* use command line */
    "C:\\WINDOWS\\system32\\mspaint.exe", /* command */
    NULL, /* don't inherit process handle */
    NULL, /* don't inherit thread handle */
    FALSE, /* disable handle inheritance */
    0, /* no creation flags */
    NULL, /* use parent's environment block */
    NULL, /* use parent's existing directory */
    &si,
    &pi))
   {
     fprintf(stderr, "Create Process Failed");
     return -1;
   }
   /* parent will wait for the child to complete */
   WaitForSingleObject(pi.hProcess, INFINITE);
   printf("Child Complete");

   /* close handles */
   CloseHandle(pi.hProcess);
   CloseHandle(pi.hThread);
}
```

Process Termination

- Process executes last statement and then asks the operating system to delete it using the **`exit()`** system call.
  - Returns status data from child to parent (via **`wait()`**)
  - Process' resources are deallocated by operating system
- Parent may terminate the execution of children processes using the **`abort()`** system call. Some reasons for doing so:
  - Child has exceeded allocated resources
  - Task assigned to child is no longer required
  - The parent is exiting and the operating systems does not allow a child to continue if its parent terminates

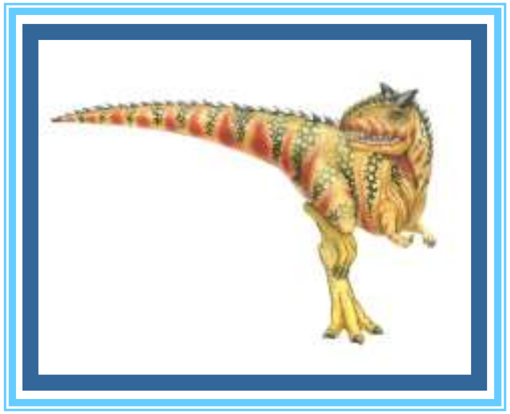
Process Termination

- Some operating systems do not allow child to exists if its parent has terminated. If a process terminates, then all its children must also be terminated.
  - **cascading termination.** All children, grandchildren, etc. are terminated.
  - The termination is initiated by the operating system.
- The parent process may wait for termination of a child process by using the **`wait()`** system call. The call returns status information and the pid of the terminated process

```
pid = wait(&status);
```

- If no parent waiting (did not invoke **`wait()`**) process is a **zombie**
- If parent terminated without invoking **`wait`**, process is an **orphan**

CPU Scheduling

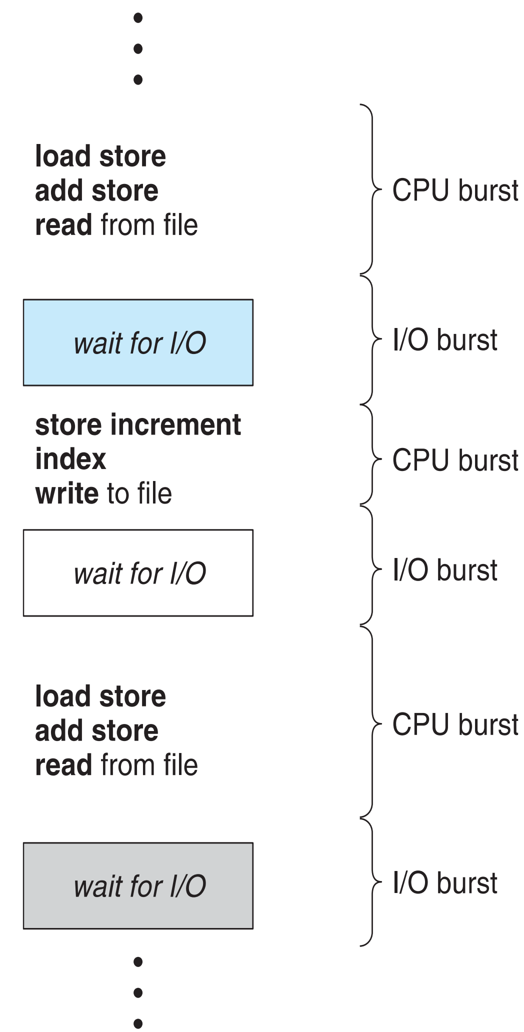


Chapter 6: CPU Scheduling

- Basic Concepts
- Scheduling Criteria
- Scheduling Algorithms
- Multiple-Processor Scheduling
- Real-Time CPU Scheduling

Basic Concepts

- Maximum CPU utilization obtained with multiprogramming
- CPU–I/O Burst Cycle – Process execution consists of a **cycle** of CPU execution and I/O wait
- **CPU burst** followed by **I/O burst**
- CPU burst distribution is of main concern



CPU Scheduler

- **Short-term scheduler** selects from among the processes in ready queue, and allocates the CPU to one of them
  - Queue may be ordered in various ways
- 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**
- All other scheduling is **preemptive**
  - Consider access to shared data
  - Consider preemption while in kernel mode
  - Consider interrupts occurring during crucial OS activities

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 Criteria

- **CPU utilization** – keep the CPU as busy as possible
- **Throughput** – # of processes that complete their execution per time unit
- **Turnaround time** – amount of time to execute a particular process
- **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)

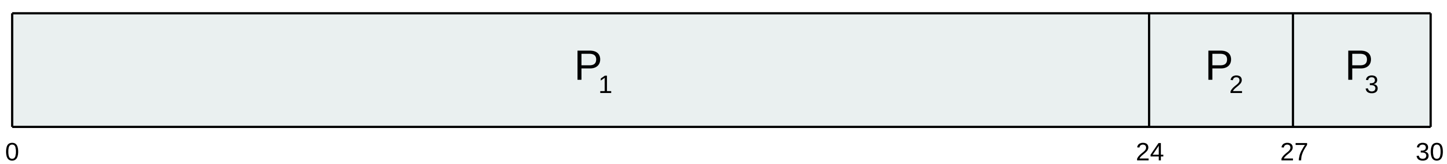
Scheduling Algorithm Optimization Criteria

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

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

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: $(6 + 0 + 3)/3 = 3$
- Much better than previous case
- **Convoy effect** - short process behind long process
  - Consider one CPU-bound and many I/O-bound processes

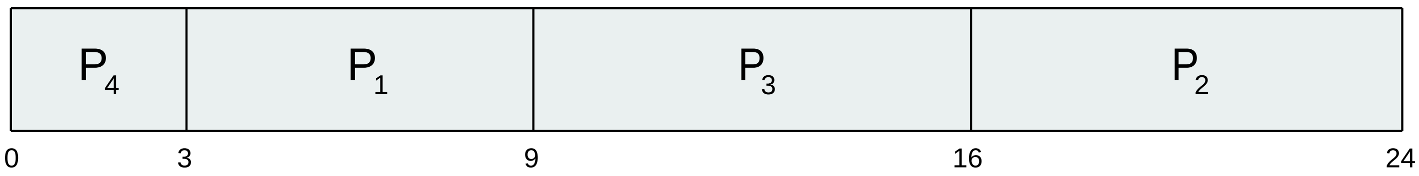
Shortest-Job-First (SJF) Scheduling

- Associate with each process the length of its next CPU burst
  - Use these lengths to schedule the process with the shortest time
- SJF is optimal – gives minimum average waiting time for a given set of processes
  - The difficulty is knowing the length of the next CPU request
  - Could ask the user

Example of SJF

Process	Burst Time
P_1	6
P_2	8
P_3	7
P_4	3

- SJF scheduling chart



- Average waiting time = (3 + 16 + 9 + 0) / 4 = 7

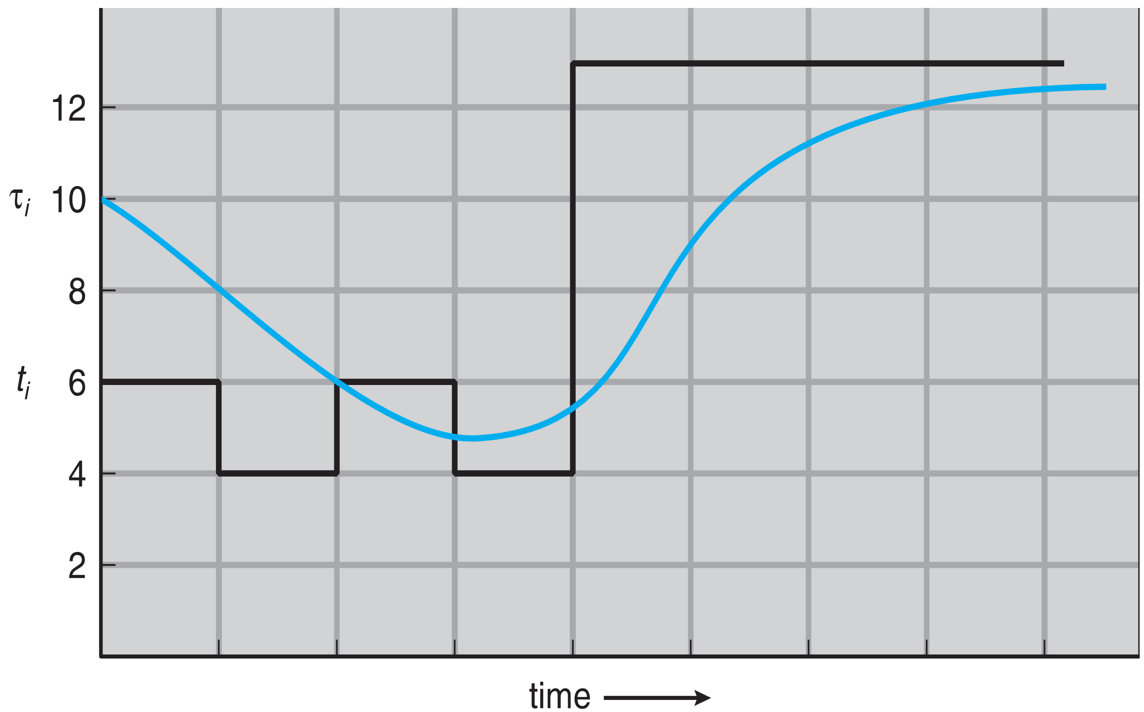
Determining Length of Next CPU Burst

- Can only estimate the length – should be similar to the previous one
  - Then pick process with shortest predicted next CPU burst
- Can be done by using the length of previous CPU bursts, using exponential averaging

  1. $t_n =$ actual length of n^{th} CPU burst
  2. $\tau_{n+1} =$ predicted value for the next CPU burst
  3. $\alpha, 0 \le \alpha \le 1$
  4. Define: $\tau_{n=1} = \alpha \, t_n + (1 - \alpha)\tau_n$.

- Commonly, α set to ½
- Preemptive version called **shortest-remaining-time-first**

Prediction of the Length of the Next CPU Burst



CPU burst (t_i)		6	4	6	4	13	13	13	…
"guess" (τ_i)	10	8	6	6	5	9	11	12	…

Examples of Exponential Averaging

- α =0
  - $\tau_{n+1} = \tau_n$
  - Recent history does not count
- α =1
  - $\tau_{n+1} = \alpha\, t_n$
  - Only the actual last CPU burst counts
- If we expand the formula, we get:

$$\begin{aligned}\tau_{n+1} = \alpha\, t_n &+ (1 - \alpha)\alpha\, t_{n-1} + \dots \\ &+ (1 - \alpha)^j \alpha\, t_{n-j} + \dots \\ &+ (1 - \alpha)^{n+1} \tau_0\end{aligned}$$

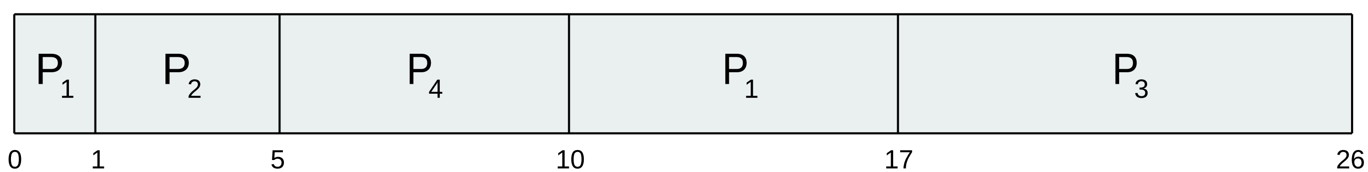
- Since both α and $(1 - \alpha)$ are less than or equal to 1, each successive term has less weight than its predecessor

Example of Shortest-remaining-time-first

- Now we add the concepts of varying arrival times and preemption to the analysis

Process	*Arrival* Time	Burst Time
P_1	0	8
P_2	1	4
P_3	2	9
P_4	3	5

- *Preemptive* SJF Gantt Chart



- Average waiting time = [(10-1)+(1-1)+(17-2)+5-3)]/4 = 26/4 = 6.5 msec

Priority Scheduling

- A priority number (integer) is associated with each process
- The CPU is allocated to the process with the highest priority (smallest integer $\equiv$ highest priority)
  - Preemptive
  - Nonpreemptive
- SJF is priority scheduling where priority is the inverse of predicted next CPU burst time
- Problem $\equiv$ **Starvation** – low priority processes may never execute
- Solution $\equiv$ **Aging** – as time progresses increase the priority of the process

Example of Priority Scheduling

Process	Burst Time	Priority
P_1	10	3
P_2	1	1
P_3	2	4
P_4	1	5
P_5	5	2

- Priority scheduling Gantt Chart

P_1	P_2	P_1	P_3	P_4

0 1 6 16 18 19

- Average waiting time = 8.2 msec

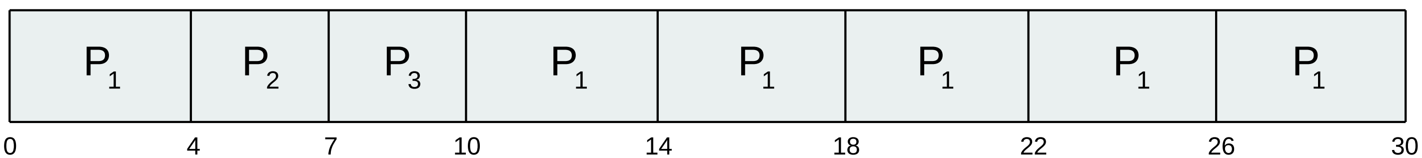
Round Robin (RR)

- Each process gets a small unit of CPU time (**time quantum** *q*), 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*, then 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.
- Timer interrupts every quantum to schedule next process
- Performance
  - q large $\Rightarrow$ FIFO
  - q small $\Rightarrow$ q must be large with respect to context switch, otherwise overhead is too high

Example of RR with Time Quantum = 4

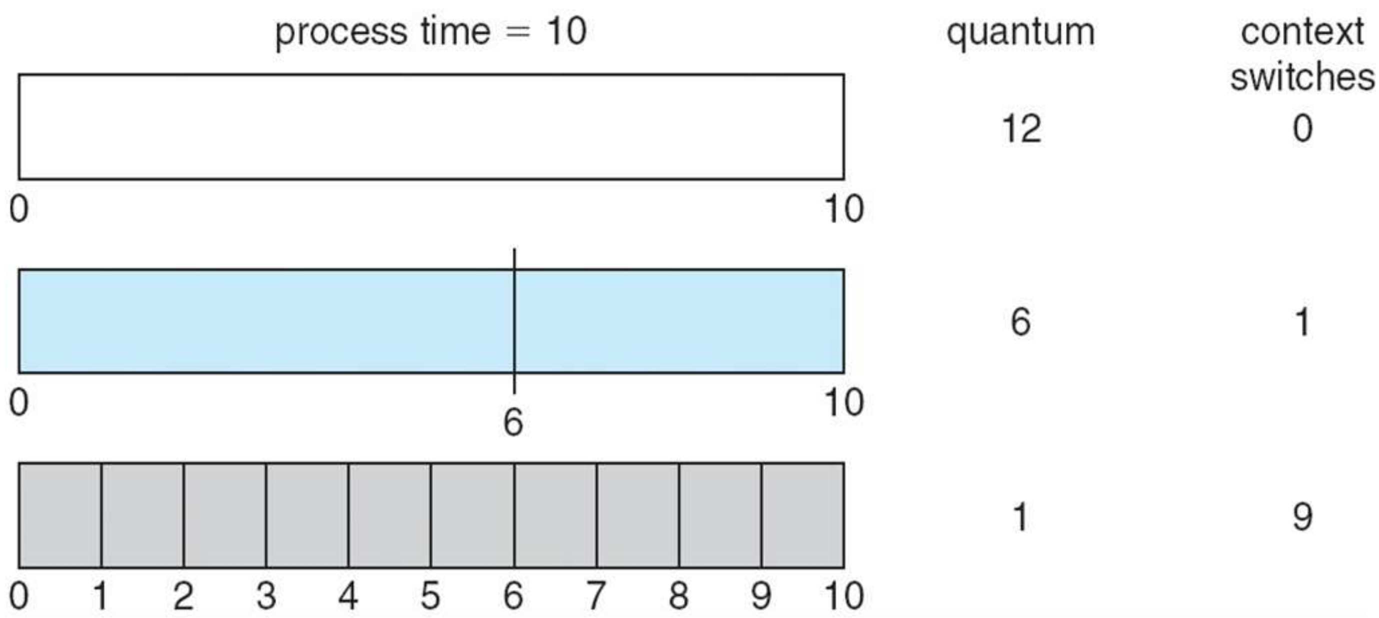
Process	Burst Time
P_1	24
P_2	3
P_3	3

- The Gantt chart is:

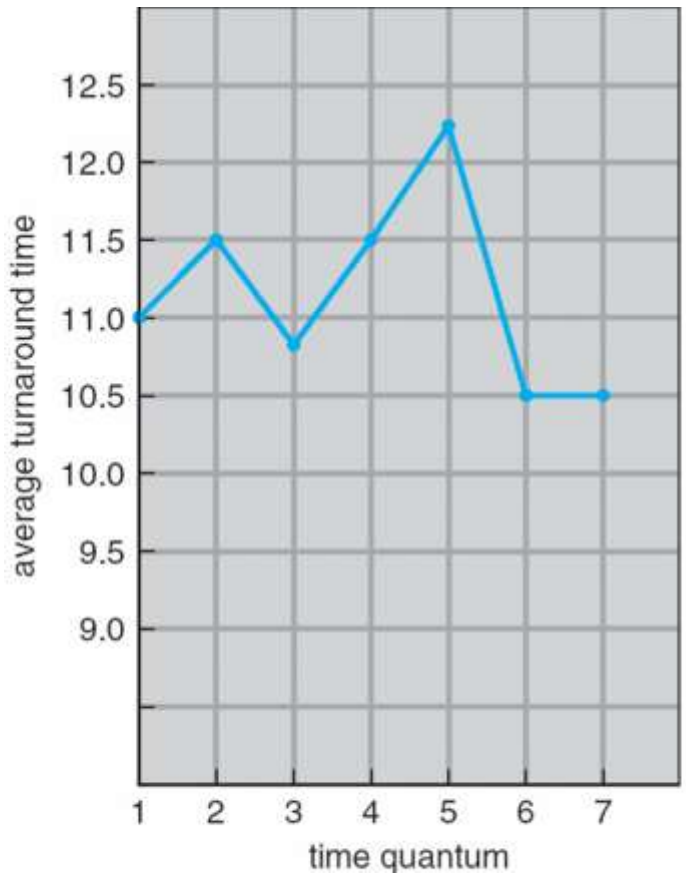


- Typically, higher average turnaround than SJF, but better ***response***
- q should be large compared to context switch time
- q usually 10ms to 100ms, context switch < 10 usec

Time Quantum and Context Switch Time



Turnaround Time Varies With The Time Quantum



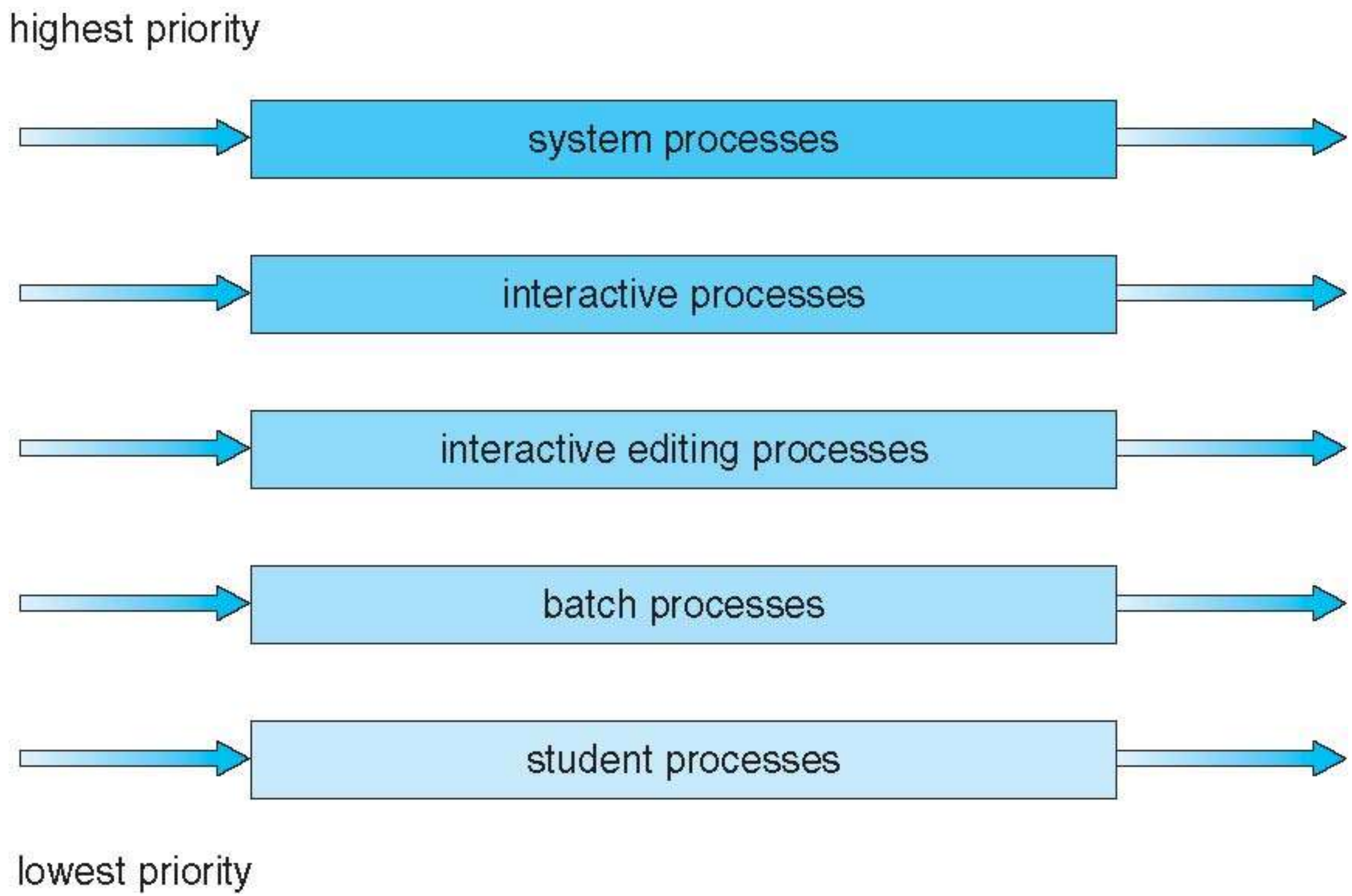
process	time
P_1	6
P_2	3
P_3	1
P_4	7

80% of CPU bursts should be shorter than q

Multilevel Queue

- Ready queue is partitioned into separate queues, eg:
  - **foreground** (interactive)
  - **background** (batch)
- Process permanently in a given queue
- Each queue has its own scheduling algorithm:
  - foreground – RR
  - background – FCFS
- Scheduling must be done between the queues:
  - Fixed priority scheduling; (i.e., serve all from foreground then from background). Possibility of starvation.
  - Time slice – each queue gets a certain amount of CPU time which it can schedule amongst its processes; i.e., 80% to foreground in RR
  - 20% to background in FCFS

Multilevel Queue Scheduling

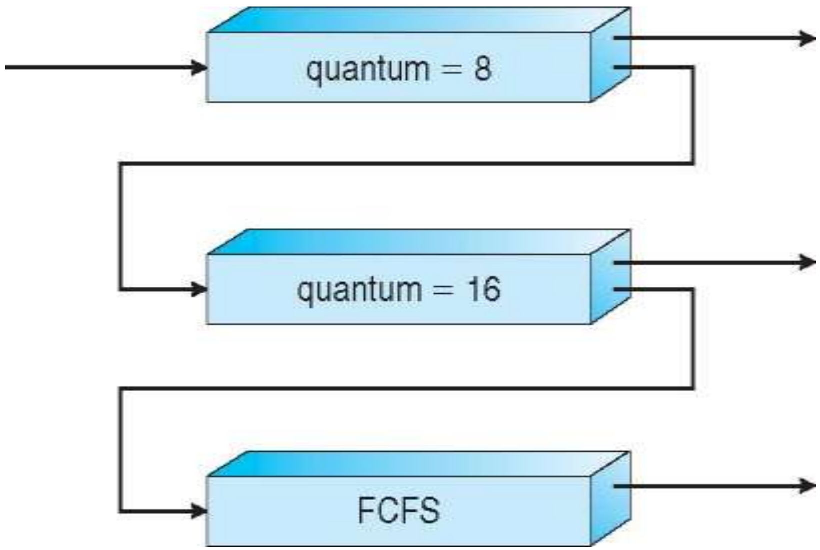


Multilevel Feedback Queue

- A process can move between the various queues; aging can be implemented this way
- 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 of Multilevel Feedback Queue

- Three queues:
  - Q_0 – RR with time quantum 8 milliseconds
  - Q_1 – RR time quantum 16 milliseconds
  - Q_2 – FCFS
- Scheduling
  - A new job enters queue Q_0 which is served FCFS
    - When it gains CPU, job receives 8 milliseconds
    - If it does not finish in 8 milliseconds, job is moved to queue Q_1
  - At Q_1 job is again served FCFS and receives 16 additional milliseconds
    - If it still does not complete, it is preempted and moved to queue Q_2



Multiple-Processor Scheduling

- CPU scheduling more complex when multiple CPUs are available
- **Homogeneous processors** within a multiprocessor
- **Asymmetric multiprocessing** – only one processor accesses the system data structures, alleviating the need for data sharing
- **Symmetric multiprocessing (SMP)** – each processor is self-scheduling, all processes in common ready queue, or each has its own private queue of ready processes
  - Currently, most common
- **Processor affinity** – process has affinity for processor on which it is currently running
  - **soft affinity**
  - **hard affinity**
  - Variations including **processor sets**

Multiple-Processor Scheduling – Load Balancing

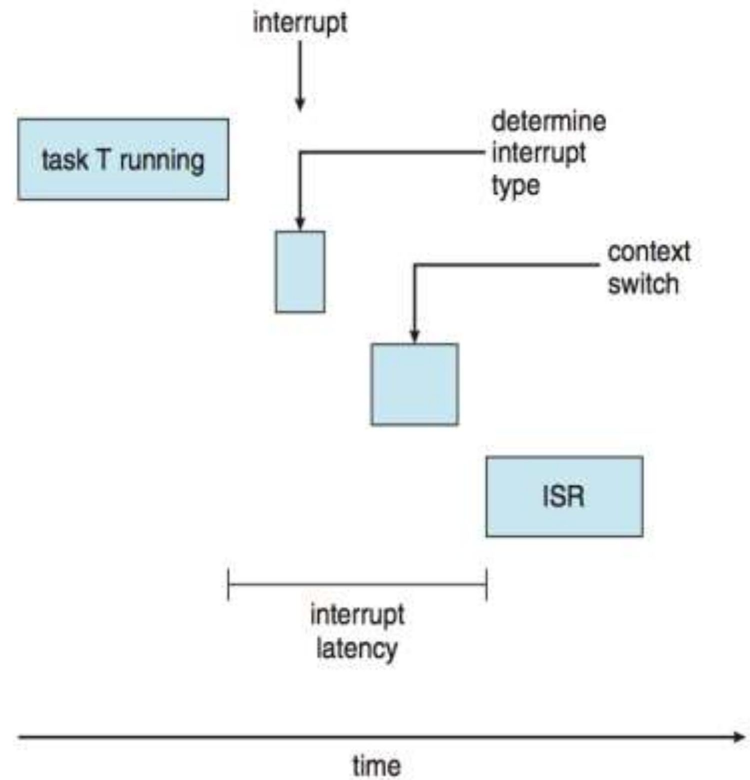
- If SMP, need to keep all CPUs loaded for efficiency
- **Load balancing** attempts to keep workload evenly distributed
- **Push migration** – periodic task checks load on each processor, and if found pushes task from overloaded CPU to other CPUs
- **Pull migration** – idle processors pulls waiting task from busy processor

Multicore Processors

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

Real-Time CPU Scheduling

- Can present obvious challenges
- **Soft real-time systems** – no guarantee as to when critical real-time process will be scheduled
- **Hard real-time systems** – task must be serviced by its deadline
- Two types of latencies affect performance
  1. Interrupt latency – time from arrival of interrupt to start of routine that services interrupt
  2. Dispatch latency – time for schedule to take current process off CPU and switch to another



Real-Time CPU Scheduling (Cont.)

- Conflict phase of dispatch latency:
  1. Preemption of any process running in kernel mode
  2. Release by low-priority process of resources needed by high-priority processes