

# Operating System

The **Operating System** is a “special program” that allows the isolation of the hardware from the programs that run on the computer. It provides:

- Memory management
  - Disk management
  - Peripherals management (keyboard, mouse, graphics card)
  - Management of users and programs, protecting the entire system
  - ... everything so that the programmer doesn't have to do it
- OS is a [control program](#)
- Controls execution of programs to prevent errors and improper use of the computer

OS is a [resource manager](#)

- Manages all resources

- Process management
- Memory management
- File-system management
- Mass-storage management
- I/O management

- Decides between conflicting requests for efficient and fair resource use

Usually, a general purpose OS includes:

- Kernel (the OS part that is always running in the machine)
- Middleware frameworks (ease application development)
- System programs that help to manage the system

## What Do

Sharing resources among applications

- scheduling
- allocation

Making efficient use of limited resources

- improving utilization
- minimizing overhead
- improving throughput/goodput

Protecting applications from each other

- enforcement of boundaries

## Classification

Interface

- CLI (Command-line interface)
- Batch interface (commands are entered in files)
- GUI (Graphical User Interface)

Users

- Multi-user
- Mono-user

Tasks

- Single-task - can support only a single task at any time; tasks are handled sequentially (e.g., MS-DOS)
- Multi-task - executes more than one task at a time, by sharing resources

Real-time Operating Systems (RTOS)

- Operating systems that have strict time bounds and have a predictable behavior (e.g., VxWorks,VRTX,pSOS,LynxOS,...)

Open/Closed Operating Systems:

- Proprietary
- Open systems
  - Have standardized programming interfaces and peripheral interconnects
- Open-source systems (GPL license)
- Operating systems made available in source-code format rather than just binary closed-source
- Started by Free Software Foundation (FSF), which has “copyleft” GNU Public License (GPL)
  - (GNU = GNU's Not Unix)
- Examples include GNU/Linux and BSD UNIX (included in the core of Mac OS X), and many more

How does the hw know where the kernel is and how to load it?

Starting a computer and loading the kernel is called [booting](#).

Most computers have a multistage boot

## Startup

Power up the computer (IBM - compatible PC)

- Test operation (power-up diagnostics):
  - In the power-up (and at reset) the CPU executes a jump instruction to a pre-defined address where an initial boot loader located in nonvolatile firmware (BIOS or UEFI) is run:
    - BIOS = Basic Input Output System
    - UEFI = Unified Extensible Firmware Interface
  - The initial boot loader program executes tests for verifying the correct operation of the CPU (subset of instructions) and RAM (basic tests)
    - Power-on self-test, also known as POST
  - If OK, a second boot loader is started...
- Sequence startup (boot) OS :
  - A second boot loader is started, normally from the first sector of the boot device. This second boot loader may be able to start the OS, but normally it only knows the location of the remainder of the [bootstrap loader](#) program, which in turn locates the kernel, loads it into main memory, and starts its execution.
  - Common bootstrap loader for Linux, GRUB, allows selection of kernel from multiple disks, versions, kernel options

## Initialization

OS performs its boot “routines”:

- hardware - Initialization of registers of the controllers , the system interrupts, the interrupt vector ;
- software - Initialization of data structures that represent the various system resources and algorithms that support the management of these resources .

Creation of the first cases :

- The system auxiliary processes
  - login , file system , network ...
- the interpreter commands
  - command line ( sh , bash, csh, command.com ) or windows

## Wait for interrupt

After booting, the OS is “quiet” waiting for work and ... there is a hardware interrupt

- OS performs a task that handles the interruption .
- The OS is “quiet” and ... a program requests a service - through a software interrupt or trap:
- OS triggers a task that runs the service (this interruption)

## Protection provided by the OS

Dual Mode of Operation

- “User Mode” and “Kernel Mode”
- In “User Mode” only common instructions can be performed (e.g. arithmetic and logic). In “Kernel Mode” anything can be done.
- A mode bit contains the current mode of operation
- RTI: Return from interruption
- Kernel mode assumed on traps and on interrupts

I/O Protection

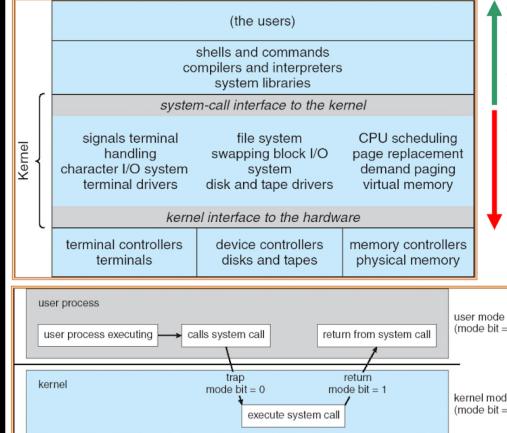
- All I/O Instructions are privileged.  
For doing I/O a trap into the operating system must be generated.

Memory Protection

- Each program can only access its memory

CPU Protection

- The CPU must remain in control of the Operating System, even if the applications does not want to let go.



## Input/Output versus CPU Usage

I/O devices and the CPU can execute concurrently

Each device controller oversees a particular device

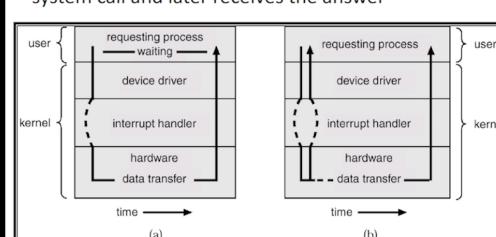
Each device controller has a local buffer

CPU moves data from/to main memory to/from local buffers

I/O is from the device to local buffer of controller  
Device controller informs CPU that it has finished its operation by causing an interrupt

Synchronous (a) versus asynchronous I/O (b)

- In (a) the application blocks on the system call
- In (b) the application resumes execution after issuing the system call and later receives the answer



## Device Status Table

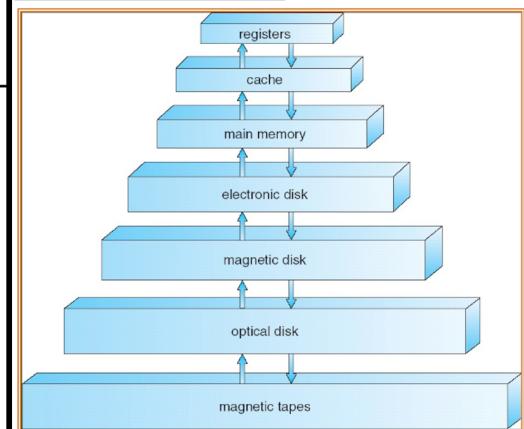
Each table entry indicates the device's type, address, and state (not functioning, idle, or busy). If the device is busy with a request, the type of request and other parameters will be stored in the table entry for that device.

If the kernel supports asynchronous I/O, it also keeps track of many I/O requests at the same time.

## Direct Memory Access [DMA]

- Used for high-speed I/O devices able to transmit information at close to memory speeds
- Device controller transfers blocks of data from buffer storage directly to main memory without CPU intervention
- Implies the capability of arbitrating the system bus
- Only one interrupt is generated per block, rather than one interrupt per byte

## Storage Hierarchy



A great part of this hierarchy is controlled by the Operating System

- Cache Management Policies
- Buffer Management Policies
- Memory Management Policies

[Principles of Locality](#):  
- Temporal Locality  
- Spatial Locality

Level	1	2	3	4
Name	registers	cache	main memory	disk storage
Typical size	< 1 KB	> 16 MB	> 16 GB	> 100 GB
Implementation technology	custom memory with multiple ports, CMOS	on-chip or off-chip, CMOS SRAM	CMOS DRAM	magnetic disk
Access time (ns)	0.25 – 0.5	0.5 – 25	80 – 250	5,000,000
Bandwidth (MB/sec)	20,000 – 100,000	5000 – 10,000	1000 – 5000	20 – 150
Managed by	compiler	hardware	operating system	operating system
Backed by	cache	main memory	disk	CD or tape

## Memory Protection

Each program must only be able to access its own memory

- Segmentation
  - Virtual Memory
- Segmentation is based on having a base pointer and a limit for each process running

- Any access made outside of its “space” generates a trap and normally leads to the process being killed

Virtual Memory is based on having a table that translates “virtual addresses” into real ones

- Normally, there is such a table for each process
- Each process sees all the address space
- An access made to an non existing page generates a trap and normally leads to the process being killed

## Multiprogramming

Multiprogramming: maintaining several jobs in memory, active at the same time, so that when the current program can no longer run (for example because it's blocked waiting for I/O), another is available to run

Optimizes resource utilization: CPU and I/O

## Multitasking

Multitasking is an extension of multiprogramming in which the execution of the active programs is time-sliced:

- Each program runs for a short period of time, then another is run.
- When a program is running and is forcibly replaced by another, typically with a higher priority, it is said to have been preempted, thus the term Preemptive Operating Systems

For implementing multitasking, a non-maskable interrupt must connected to a hardware timer

- Every few milliseconds (e.g. 100ms), the interrupt causes a task (or process) switch



## Multithreading Models

### User threads (N-to-1 model)

- Threads are implemented in a library at user space.
- The kernel is completely unaware of the existence of threads

### Kernel threads (1-to-1 model)

- Threads are implemented exclusively in kernel space
- The kernel does all the scheduling of threads

### The Many-to-Many Model

- A number of kernel threads can map to a different number of user threads

### User Level Threads

- Communication among threads is fast since it does not imply a mode switch
- Thread creation and termination are fast
- Does not require any special support by the kernel, thus being available in any OS
- If one thread blocks all threads block (e.g. on I/O)
- Only one system call can happen at a time
- Scheduling is not fair
- One thread terminates all threads terminate

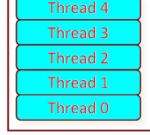
### Kernel Threads

- Communication among threads is slower since it implies going to the kernel
- Thread creation and termination is slower
- Requires that the kernel supports user visible threads
- If one thread blocks the others can continue
- Simultaneous system calls
- Fair scheduling
- Somewhat independent thread termination

## Thread Pools

Since most operating systems use a 1-to-1 model, it is important not to waste much time creating and destroying threads

### Thread Pool



- Some threads are previously created and BLOCKED waiting for work
- Whenever work appears, a managing thread wakes one thread in the pool and assigns it the work to be done
- After the thread completes the work, it returns to the pool waiting for more work

## Synchronization

- Multiprogramming**
- Multiprocessing**
  - Several processors working together
    - Includes:
      - single computers with multiple cores
      - linked computing systems that share processing
  - One form of multiprocessing
    - When >=2 processors work together

Parallelism Level	Process Assignments	Synchronization Required
Job level	Each job has its own processor and all processes and threads are run by that same processor.	No explicit synchronization required.
Process Level	Unrelated processes, regardless of job, are assigned to any available processor.	Moderate amount of synchronization required to track processes.
Thread Level	Threads are assigned to available processors.	High degree of synchronization required, often requiring explicit instructions from the programmer.

## Multiprocessing configurations

### Master/slave

#### Asymmetric

One master processor controls slave processors

- The master is responsible for managing the entire system (files, devices, processors, etc.)

Well suited for environments where processing time is divided between backend and frontend processing

#### Disadvantages

- Poor reliability - if master fails, all fails
- Poor resource use (slaves wait for master to get work)
- Many interrupts as slaves interrupt master whenever they need OS intervention (e.g. I/O)

#### Advantages

- Simplicity

### Loosely Coupled

Each processor controls its own resources: files, memory, I/O devices

Not completely independent systems because processors communicate and cooperate with others

Jobs stick to their assigned processor

- Processor assignment to ensure well balanced use of resources

Not prone to catastrophic failures as the failure of one processor does not imply the fail of the all system

### Symmetric

More reliable than loosely coupled configurations, more effective using resources, good load balancing, degrades better in the event of a failures

- Prone to races and deadlocks
- Requires synchronization!

## CONCURRENCY & SYNCHRONIZATION

### Buying milk - unsynchronized

#### Rooomate A

- 3:00 Arrive home: no milk
- 3:05 Leave for store
- 3:10 Arrive at store
- 3:15 Leave store
- 3:20 Arrive home, put milk away
- 3:25 Leave store
- 3:30 Arrive home: too much milk

#### Rooomate B

- Arrive home: no milk
- Leave for store
- Arrive at store
- Leave store
- Arrive home

**Race condition:** The situation where several processes access and manipulate shared data concurrently. The result critically depends on the timing of these processes (on the order of execution of instructions in the multiple processes), which are "racing".

### Critical Regions

Processes within a critical region cannot be interleaved without threatening integrity  
Synchronization can be achieved through lock-and-key arrangements

### Locking mechanisms

#### Test-and-Set (TS)

Single, indivisible machine instruction

Introduced in IBM System 360/370 computers

#### TS semantics

- Saves the key in a storage location – the key is 0 (resource represented by the key is free) or 1 (it is busy)
- If the key is 0 changes it to 1 and returns free to the process that issued the instruction; the process is allowed to proceed
- If the key value is 1 (resource busy), the process awaits in cycle (!)

#### Can cause starvation

- A process might never get the resource if many are testing to enter the critical region!

#### Can cause busy waiting

- The process keeps testing the value!

### WAIT and SIGNAL

TS without busy waiting

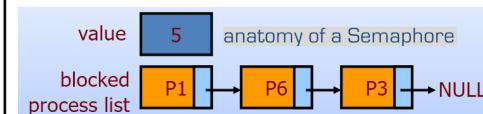
#### Semantics

- On a busy condition set the process to waiting status (WAIT)
- When a process exits the critical region, SIGNAL is activated and the OS moves the next process waiting to enter that critical region to the ready list
  - Removes busy waiting!

### Semaphores

A semaphore is a synchronization object

- Controlled access to a counter (a value)
  - Two operations: `wait()` and `post()`
  - Can also be used as a resource counter – to control access to finite resources!
- wait()**
- If the semaphore is positive, decrement it and continue
  - If not, block the calling thread (process)
- post()**
- Increment the semaphore value
  - If there was any (process) thread blocked due to the semaphore, unblock one of them.



Imagine a warehouse and an office (multiple resources), and a stock to count...

- Warehouse = resource
- Stock book in office = resource
- 1 warehouse key = semaphore controlling access to one resource
- 1 office key = semaphore controlling access to one resource
- To count stocks:

- In order to count stocks, an employee must access the office to get the stock book and to the warehouse; without both he cannot fulfill the job!
- If two employees want to count stocks and one takes the key to the office, while the other takes the key to the warehouse, they become blocked by each other!

#### Deadlock

When two or more processes are unable to make progress being blocked waiting for each other. All processes are in a waiting state.

#### Livelock

When two or more processes are alive and working but are unable to make progress.

#### Starvation

When a process is not being able to access resources that its needs to make progress

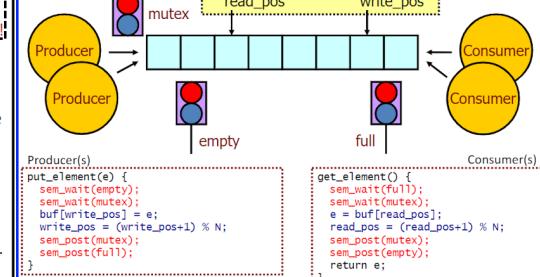
### Producer/Consumer

A producer puts elements on a finite buffer. If the buffer is full, it blocks until there's space.

The consumer retrieves elements. If the buffer is empty, it blocks until something comes along.

We will need three semaphores

- One to count the empty slots
  - One to count the full slots
  - One to provide for mutual exclusion to the shared buffer
- Note: if there was only 1 producer and 1 consumer, the mutex was not needed



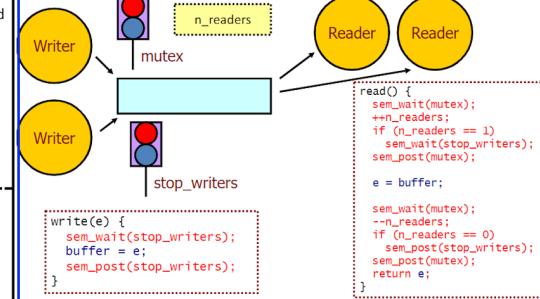
### Readers/Writers

Writer processes have to update shared data.

Reader processes have to check the values of the data. They should all be able to read at the same time.

We will need two semaphores:

- One to stop the writers and guaranteeing mutual exclusion when a writer is updating the data
- One to protect mutual exclusion of a shared variable that counts readers



The previous algorithm gives priority to readers

- Not always what you want to do

There is a different version that gives priority to writers in the original paper

Both versions can suffer from starvation problems

- |                     |                     |
|---------------------|---------------------|
| Priority to readers | Priority to writers |
| Writers can starve  | Readers can starve  |

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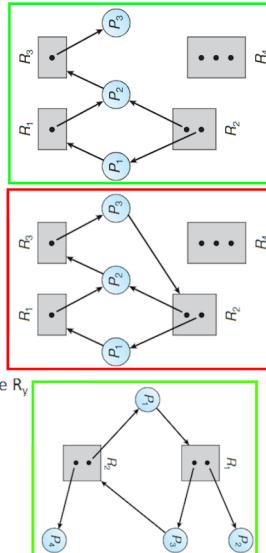
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## What is a deadlock?

- Permanent blocking of a set of processes that either compete for system resources or communicate with each other.

Deadlock arises if 4 conditions exist at the same time:

- Mutual exclusion
  - Only one process may use a resource at a time
- Hold-and-wait
  - A process holds a resource and is waiting for additional ones - a process requests all of its required resources at one time
- No-preemption
  - Resources cannot be preempted, i.e., can only be released voluntarily.
- Circular wait
  - A process is waiting for a resource held by another process that in turn is waiting for a resource held by the first



## Resource-Allocation graph

Direct graph consisting of:

- Vertices
  - Active processes (circles) - P
  - Resources (rectangles) - R
  - Each dot represents an instance of the resource

Directed edges

- $P_x \rightarrow R_y$ : Process  $P_x$  requested an instance of resource  $R_y$
- $R_y \rightarrow P_x$ : An instance of  $R_y$  has been allocated to  $P_x$

It is used to describe the resource-allocation state at a specific time

Resource-allocation graph analysis

- If a graph contains no cycles  $\Rightarrow$  **no deadlock**.
- If a graph contains a cycle ...
  - if only one instance per resource type, then **deadlock**.
  - if several instances per resource type, possibility of deadlock.

## Options for handling deadlocks in a OS:

- 1 - Prevent** deadlocks to ensure that the systems never enters a deadlock state
- 2 - Avoid** deadlocks to ensure that the systems never enters a deadlock state
- 3 - Allow** a deadlock state, **detect** it and **recover**
- 4 - Ignore** deadlocks
  - Is up to the programmers to handle deadlocks
  - Used in Linux and Windows

Prevention is accomplished by ensuring that at least one of the 4 necessary conditions for a deadlock does not happen:

- Mutual exclusion, hold-and-wait, no-preemption, circular wait

## Prevent Mutual exclusion

- Have sharable resources (e.g. read-only files)
  - However, not all resources can be sharable!

## Prevent Hold and Wait

- Guarantee that all the resources are requested and allocated before beginning execution
  - If all resources cannot be guaranteed release the ones allocated
- Or only request a resource after releasing the ones that are being held
- Both options lead to low usage of resources and may lead to starvation of a process that uses different resources

## Prevent Circular Wait

- Prevented by defining a linear ordering of resource types

## Prevent No-preemption

- If a process holding certain resources is denied a further request, that process must release its original resources.
- If a process requests a resource that is currently held by another process, the operating system may preempt the second process and require it to release its resources.

## How to avoid the occurrence of deadlocks?

- Require more information about the resources that are to be requested
- ↓
- Approaches
    - Do not start a process if its demands might lead to a deadlock.
    - Do not grant an incremental resource request to a process if this allocation might lead to a deadlock.

Deadline avoidance algorithms dynamically examine the resource-allocation state to ensure that a circular-wait condition never happens

## Safe state

In a system with a fixed number of processes and resources:

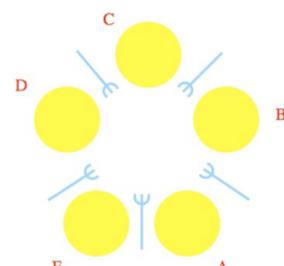
- The **state** of the system is the current allocation of resources to process.
- A **safe sequence** exists when all processes may access their needed resources without resulting in a deadlock
- A **safe state** is when there is at least one safe sequence of resource allocations that does not result in deadlock.
  - All processes can run to completion
  - The system can allocate resources to each process (up to its maximum) in some order and still avoid a deadlock.
- Unsafe state is a state that is not safe (!).
  - An unsafe state may lead to a deadlock

## Resource-allocation-graph algorithm

- Algorithm used when there is only one instance of each resource type
- The resource-allocation graph used has an additional edge – **claim edge**
  - A claim edge indicates that a process  $P_i$  may request a resource  $R_j$  in the future
  - It is depicted by a dashed line

## DINING PHILOSOPHERS

- Five philosophers sitting around a table
- Each has a plate of spaghetti
- There are forks between each pair of plates
- Philosophers need two forks to eat



## can it be prevented?

### Proposal 1:

- Instead of `take_fork((i+1) % N)`, see if it is available first
- If unavailable, **sleep** for a while and retry....

Still no good...

- what if everyone tries the left fork, waits, retries simultaneously, etc.
- Everyone can run, but no one makes progress: **STARVATION**

### Proposal 2:

- Before taking a fork, a philosopher locks a **MUTEX**
- The philosopher can then take two forks, with no interference
- When done eating, the forks are replaced and **MUTEX** is released
- Nope.... only one philosopher can eat at a time...

## Solution:

```
void philosopher(int id) {
    while(TRUE) {
        think();
        if(id % 2 == 0) { // even number: left, right
            take_fork(i);
            take_fork((i+1) % N);
        } else{ // odd number: right, left
            take_fork((i+1) % N);
            take_fork(i);
        }
        eat();
    }
}
```

## Banker's Algorithm

- An algorithm that can be used in a banking system to allocate a limited amount of money to customers. The credit is given depending on the risk of the customer, so that the bank may continue to lend.
- Can be used with systems with multiple instances of each resource type
- A strategy of resource allocation denial
- Developed by Dijkstra
- When a process enters the system, it declares the maximum number of instances of each resource type that it may need
- When resources are requested, the system must determine if their allocation leaves the system in a safe state
  - If it does -> resources are allocated
  - If it does not -> the process must wait until other process releases enough resources
- Support data structures**
  - Resource vector** – total amount of each resource in system
  - Available vector** – amount of each resource not allocated
  - Claim matrix** – total amount of resources that may be required by each process (stated before the process begins executing)
  - Allocation matrix** – current allocation of resources to processes

### Deadlock Avoidance Strategy:

(To assure that the system is always in a safe state)

- When a process makes a request for a set of resources, assume that the request is granted
- Update the system state accordingly and then determine if the result is a **SAFE STATE**.
  - If so, grant the request.
  - If not, block the process until it is safe to grant the request.

## How to detect deadlocks?

### Strategy

- Find processes whose resource requests can be satisfied
- Grant the resources and assume the process runs to completion and releases resources
  - This is an optimistic approach since the process may later request additional resources. However, what we want to detect is if a deadlock exists at this moment!
- Find another process and repeat
- The algorithm does not prevent deadlocks! It only determines if they exist at the time the algorithm runs.

### Uses 2 matrices and 1 vector

- Available**
    - Vector that indicates the number of available resources of each type
  - Allocation**
    - Matrix that has the number of resources of each type currently allocated to each process
  - Request**
    - Matrix that has the current requests of each process
- Mark each process that has a row in the Allocation Matrix (**A**) of all zeros.
    - A process with no allocated resources does not participate in a deadlock.
  - Initialize a temporary vector **W** (Work) to be equal to the Available Vector (that lists resources from **1** to **m**).
  - Find an index **i** such that process **i** is currently unmarked and the **i<sup>th</sup>** row of the Request Matrix **Q** is less than or equal to **W**.
    - That is,  $Q_{ik} \leq W_k$  ( $k=1\dots m$ ). I.e. the process i can run with the available resources.
    - If no such row is found terminate the algorithm.
  - If such a row is found mark process **i** and add the corresponding row of the allocation matrix to **W**.
    - That is: set  $W_k = W_k + A_{ik}$  ( $k=1\dots m$ ). I.e. assume that on completion the process frees all the allocated resources.
    - Return to step 3.

A **deadlock exists** if and only if there are unmarked processes at the end of the algorithm. The set of unmarked rows corresponds to the set of deadlocked processes.

- These processes do not have sufficient resources available to fulfill their requests and cannot finish their execution

## Recovery from a deadlock

- Abort all deadlocked processes.
- Successively abort deadlocked processes until deadlock no longer exists.
- Successively preempt resources until deadlock no longer exists.

## CPU scheduling

- It is the basis of multiprogrammed OSs
- It allows one process to use the processor while all others are kept on hold
- It maximizes the CPU utilization by putting on hold all processes that are waiting for some resource (e.g. I/O)
- CPU scheduling aims to make the system efficient, fast and fair
- On OSs that support kernel-level threads, it is threads that are being scheduled, not processes

## CPU scheduler

- \*mais sobre os vários tipos - pág. 2.5
- When a CPU becomes idle the OS must select one process from the **ready queue** to be executed
    - The selection is done by the **short-term scheduler**
    - It selects a process from the ones in memory that are ready to execute
  - When more processes are submitted than can be executed immediately (e.g., in a batch system) they are spooled to a mass-storage device (e.g., disk).
    - The **long-term scheduler/job scheduler** selects processes from the waiting list and loads them in memory for execution
  - Swapping enables the removal of a process from memory to reduce the level of multiprogramming. The process can be later reintroduced and continue execution
    - The swapping is done by the **medium-term scheduler**

## Dispatcher

- The dispatcher is the module that gives control of the CPU to the process selected by the short-term scheduler
  - Switches context
  - Switches to user mode
  - Restarts the program in the proper location
- The dispatcher is invoked during every process switch
  - The time it takes for the dispatcher to stop one process and start another is known as the **dispatch latency**

## Scheduling Criteria

- CPU utilization**
  - Keep the CPU as busy as possible
- Throughput**
  - Number of processes that complete their execution per time unit
- Turnaround time**
  - Amount of time to complete a particular process (from submission to completion)
- 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

- Maximum CPU utilization
- Maximum throughput
- Minimum turnaround time
- Minimum waiting time
- Minimum response time

## Scheduling Algorithms

### First-Come, First-Served [FCFS]

The process that requests the CPU first gets it first

Simple to manage with a FIFO queue

Average waiting time is often long

This is a **non-preemptive** algorithm!

- A process keeps the CPU until it terminates or requests I/O.

FCFS performs better for long processes, than for short ones

### Convoy effect

- Short processes arriving after long processes are **penalized**, since they must wait until the long process leaves the CPU

### I/O bound vs. CPU bound problem

- FCFS tends to favor processor-bound over I/O-bound processes

- Non-Preemptive Scheduling**
- Once the CPU is allocated to a process, the process keeps the CPU until it terminates or blocks. A process blocks by switching to a waiting state, such as in I/O operations or OS service requests.
- (e.g., in Windows 3.1x).

## Preemptive Scheduling

The operating system may decide and is able to take the CPU away from a running process

(e.g., in WindowsXP, Linux, Mac OS X)

## 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**.

How do you determine that? Can you guess the future?

Also known as **Shortest-Job-Next [SJN]**.

Non-preemptive: once CPU given to the process it cannot be preempted until completed; its CPU burst. This scheme is known as **Shortest-Process-Next [SPN]**.

Preemptive: if a new process arrives with CPU burst length less than remaining time of current executing process, preempt. This scheme is known as the **Shortest-Remaining-Time First [SRTF] or SRT**.

## Priority Scheduling

A priority number is associated with each process (can be anything measurable)

The CPU is allocated to the process with the highest priority:

- Preemptive
- Non-preemptive

Equal priority is scheduled in FCFS order

- If two processes have the same priority, the one closer to the head of the ready-queue is chosen.

SJF can be seen as priority scheduling where priority is the *predicted next CPU burst time*

**Problem: Starvation**

- Low priority processes may never execute

**Solution -> Aging**

- As time progresses, the priority of the process increases

## Round-Robin (RR)

Is designed especially for time-sharing systems

Similar to FCFS with added preemption

- Reduces the penalty that short jobs suffer with FCFS by using preemption based on a clock.

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.

- New processes are added to the tail of the ready queue
- If, at a given instant, a process depletes its time quantum (and still has service time) and if at that instant a new process arrives to the system, the new process is placed in the queue in front of the process that just executed (but behind other processes that are already in the 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.
- If the process CPU burst is less than  $q$ , the process will by itself release the CPU voluntarily (e.g., I/O request, process end)

### Performance

- $q$  large  $\Rightarrow$  FCFS
- $q$  small  $\Rightarrow$   $q$  must be large with respect to context switch, otherwise overhead is too high. If so, having  $N$  processes is like having a machine running at  $1/N$  of the speed.

## Highest Response Ratio Next (HRRN)

Choose next process with the highest ratio ( $R$ ):

$$R = \frac{\text{time spent waiting} + \text{expected service time}}{\text{expected service time}}$$

- This algorithm accounts for the age of the process.
- Short jobs are favored (smaller denominator)
  - ex: for a waiting of 1  $\Rightarrow \frac{1+3}{3} > \frac{1+4}{4} \Rightarrow$  short job is favored
- Aging without service (waiting time) increases  $R$ .
- If  $R$ s are equal, then uses FCFS
- **Non-preemptive!**

## Multilevel Queue Scheduling

Used when processes are easily classified into different groups (e.g., foreground vs. background)

Each process is assigned to one specific queue based on its specificities, and each queue has its own scheduling algorithm

There is an additional scheduling among queues.

Ready queue is partitioned into separate queues. E.g.

- Foreground (interactive)
- Background (batch)

Each queue has its own scheduling algorithm:

- Foreground – RR
- Background – FCFS

Scheduling must be done between the queues.

- **Fixed priority scheduling:** high priority queues must be empty for the lower to execute its processes (i.e., serve all processes 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 Feedback Queue Scheduling

Normally, when using Multilevel Queue Scheduling, processes remain in the queue they were assigned when entering the system.

- Low scheduling overhead

With **Multilevel Feedback Queue Scheduling**, **processes can move between queues!**

- **Aging** can be implemented this way

Only when the high priority queues are empty will the lower have their processes executed

Normally (not always!), a process that arrives for a higher priority queue will preempt a process from a lower priority queue

The Multilevel-feedback-queue scheduler is 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 (when it first enters)

Many configurations are possible! It can be configured to address specific needs.

Simple version of a Multilevel Feedback approach

- Sometimes there is no indication of the length of the processes and then SPN, SRT and HRRN cannot be used.
- A way to establish preferences is to penalize jobs that have been running longer
  - It focus on the time spent until now (that is known) instead of focusing in the time remaining to execute (most of the times unknown).
- A process is demoted to a lower priority queue whenever it is preempted.

Selection	Function	Decision	Mode	Throughput	Time	Response	Overhead	Effect on Processes	Starvation
FCFS	max[w]	Nonpreemptive	Not emphasized	May be high especially if there is a large variance in execution times	Minimum	May be high especially if there is a large variance in execution times	No	Penalizes short processes; penalizes I/O bound processes	No
Round Robin	constant	Preemptive (at time quantum)	Quantum is too small	Provides good response time for short processes	Minimum	Fair treatment	Penalizes long processes	Possible	No
SPN	min[j]	Nonpreemptive	High	Provides good response time	Can be high	Penalizes long processes	God balance	No	Possible
SRT	min[s - e]	Preemptive (at arrival)	High	Provides good response time	Can be high	Penalizes long processes	God balance	No	Possible
HRRN	max $\left( \frac{w+j}{s} \right)$	Nonpreemptive	High	Provides good response time	Can be high	Penalizes long processes	God balance	May favor I/O bound processes	Possible
Feedback	(see text)	Preemptive (at time quantum)	Not emphasized	Not emphasized	Can be high	May favor I/O bound processes	God balance	No	No

## Thread scheduling

Support for threads may be provided in user level - **User threads** or by the kernel – **Kernel threads**.

Only kernel threads are managed directly by the OS.

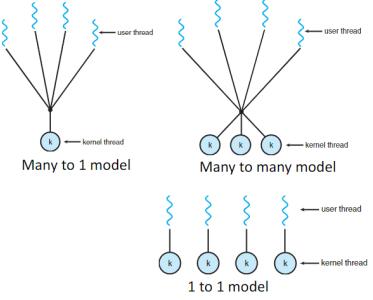
User threads are managed without kernel support.

A relationship must exist between user threads and kernel threads what leads to different models:

In OSs that support threads, it is kernel level threads that are scheduled – not processes

**User-level threads** are managed by a library and the OS is unaware of them

- To run user-level threads they must be mapped to a kernel-level thread, what can be accomplished indirectly by using a **lightweight process (LWP)**



## Lightweight Process (LWP)

Communication between kernel and the thread library may be done through an intermediate data structure - LWP.

- A LWP is seen as Virtual Processor from the thread library side
  - The library schedules its tasks into this virtual processor

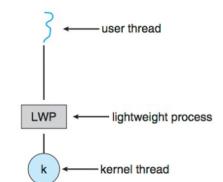
An application may require more than one LWP to

run efficiently
 

- An I/O intensive application may require more than one LWP to deal with each concurrent blocking system call. If it does not have the necessary number of LWP it will have to wait until one is freed.

- Example:

- Each LWP is attached to a kernel thread.
- It is the kernel level thread that is scheduled (to the CPU) by the OS.



## Contention Scopes

Threads can be scheduled using different contention scopes:

### Process contention scope (PCS)

- The contention scope is the process
- Scheduling is made among threads belonging to the same process

### System contention scope (SCS)

- The contention scope is the system
- Scheduling is made among all threads in the system

In systems using one-to-one model the scheduling only uses SCS, not PCS. Other models use both.

In many-to-one and many-to-many models, the **thread library** schedules **user-level threads** to an available LWP (not directly to the CPU)

- (The LWP may or may not be actually running in a CPU – depends on the kernel-thread being scheduled).

Competition for the CPU is made between threads belonging to the same process



Uses Process Contention Scope

Kernel schedules **kernel-level threads** to a physical CPU

Competition for the physical CPU is made between all system kernel-level threads



Uses System Contention Scope

## AMDAHL'S LAW

This law identifies  $speedup(f,n) = \frac{1}{(1-f)+\frac{f}{n}}$   
potential performance gains from adding additional computing cores to an application that has both serial (nonparallel) and parallel components.

S = portion of the application to perform serially

N = Number of processing cores

Example

- S = 25% and N = 2 → Speedup = 1 / (0,25 + (1-0,25)/2) = 1,6X
- S = 25% and N = 4 → Speedup = 1 / (0,25 + (1-0,25)/4) = 2,28X

Interesting Fact:

- As N tends to infinity, Speedup tends to 1/S

For an app with S=0,4 the max Speedup is 2,5X independently of the number of cores

## Multiprocessing

If a system has multiple processors, Load-Sharing becomes possible

Scheduling in a system with multiple processors is more complex and there is no one best solution

Our focus case:

- Multiprocessor scheduling for homogenous systems, i.e., systems in which the processors are all identical

## Multiple-Processor Scheduling

Asymmetric multiprocessing

- A single processor – the master server – has all scheduling decisions, I/O processing and other system activities.
- Other processors execute only user code.
- Simple approach as it reduces the needs for data sharing.

Symmetric multiprocessing (SMP)

- Each processor is self-scheduling.
  - All processes may be in a common ready queue, or each processor may have its own private queue of ready processes.
- Must avoid scheduling the same process more than once simultaneously – Critical section

## Processor Affinity

Data most recently accessed by a process populates the cache for the processor.

- successive memory accesses by the process are often satisfied in cache memory.

What happens if the process migrates to another processor?

- The contents of cache memory must be invalidated for the first processor and the cache for the second processor must be repopulated.
- HIGH COST → most SMP systems avoid migration and keep a process running on the same processor → Processor affinity

Processor affinity

- a process has an affinity for a specific processor
- Soft affinity – the OS tries to keep a process in the same processor but does not guarantee it
- Hard affinity - it is possible for a process, through system calls, to specify a subset of processors on which it may run.

## NUMA and CPU Scheduling

Non-Uniform Memory Access (NUMA)

- CPUs on a board can access the memory on that board faster than they can access memory on other boards in the system

If OS's CPU scheduler works together with memory placement algorithms, the process with affinity to a specific processor is allocated memory in that CPU board.

## Load Balancing

Keeps the workload evenly distributed across all processors in an SMP system.

- Necessary only on systems where each processor has its own private queue of eligible processes to execute. (common case in today's OSs)
- With a common run queue, load balancing is often unnecessary, because once a processor becomes idle, it immediately extracts a runnable process from the common run queue.

Two load balancing approaches:

- Push migration
  - a specific task periodically checks the load on each processor and, if it finds an imbalance, evenly distributes the load by moving (or pushing) processes from overloaded to idle or less-busy processors.
- Pull migration
  - occurs when an idle processor pulls a waiting task from a busy processor.

- EDF does not require processes to be periodic

- The only requirement is that, when a process becomes runnable, it announces its deadline to the scheduler.

Theoretically, EDF is optimal, achieving 100% of CPU use.

In practice it is impossible to achieve 100% due to the cost of context switching.

## Multicore Processors scheduling

Traditionally, SMP systems provided multiple physical processors. Today, multiple processor cores are placed on the same physical chip – **multicore processors**.

- This cores appear as a separate physical processor to the OS. Multicore processors may complicate scheduling
- May have multithreaded cores
- Common caches between different cores
  - As the number of cores per chip increases, a need to minimize access to off-chip memory takes precedence over a desire to maximize processor utilization.

Multicore scheduling levels

- Multithreaded multicore processors require two scheduling levels

First level

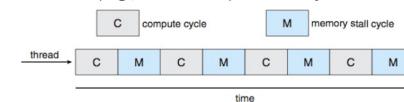
- Operating System chooses which software thread to run on each hardware thread (logical processor).
  - Any algorithm for CPU scheduling already discussed will do the job

Second level

- Each core decides which hardware thread to run
  - e.g., Round-robin, use of urgency values assigned to each hw thread

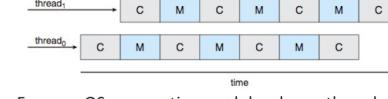
Why multithreaded processor cores?

- When a processor accesses memory, it can spend a significant amount of time waiting for the data to become available (e.g., cache miss) – **memory stalls**.



- To avoid having a processor waiting for data, 2 or more hardware threads are assigned to each core.

- If one hardware thread stalls while waiting for memory, the core can switch to another thread.



- From an OS perspective, each hardware thread appears as a logical processor that is available to run a software thread.
- On a dual-threaded, dual-core system, four logical processors are presented to the OS.

## Real-Time CPU Scheduling

Soft real-time systems provide no guarantee as to when a critical real-time process will be scheduled.

- They guarantee only that the process will be given preference over noncritical processes.

Hard real-time systems have stricter requirements.

- A task must be serviced by its deadline
  - Service after the deadline has expired is the same as no service at all

## Event Latency

Events in real-time systems

- SW (e.g., a timer expires)
- HW (e.g., a sensor generates an event)

Event latency

- Time between the occurrence of the event and its service

Types of latency that affect real-time systems:

- Interrupt latency: time between when the interrupt is received by the CPU to the start of its service routine.
  - Must have strict bounds;
  - One important factor is the amount of time interrupts are disabled in the kernel while its data structures are being updated.
- Dispatch latency – amount of time required for the scheduling dispatcher to stop one process and start another
- Conflict phase
  - Preempt processes running
  - Releases resources from low-priority processes that are needed by high priority ones
- Preemptive kernels improve dispatch latency
  - Dispatch occurs more frequently and does not depend on processes blocks

## Priority-Based Scheduling

A real-time system must respond immediately to a real-time process as soon as it requires CPU

- Applications are generally less concerned with raw speed than with the start and completion deadline of their execution.

To guarantee it, priority-based scheduling algorithms with preemption must be supported by the OS

- Processes executing must be preempted if a higher priority process is ready to run

(Priority scheduling algorithms were already studied)

However, a preemptive, priority-based scheduling only guarantees soft real-time systems!

Hard real-time systems also have deadline requirements, implying additional scheduling features.

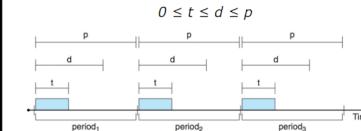
## Real-time processes

- Aperiodic task – has a strict deadline to finish and/or to start

- Periodic task – must execute once in a period T or exactly T units apart

Case of periodic processes/tasks

- Have a sequence of times that is known in advance (e.g., checking and processing data from a sensor)
- Require the CPU at constant intervals (periods) (p), a fixed processing time (t) and a deadline (d). The rate is 1/p.



- Schedulers can assign different priorities according to each process requirements

## Admission control

To address their specific requirements, real-time processes may have to announce their deadlines to the scheduler using an admission control algorithm. Based on the information received from the processes, the scheduler:

- admits the process, guaranteeing that it will complete on time;
- rejects the process as it cannot guarantee that it can be serviced by its deadline.

## Rate-Monotonic Scheduling

Schedules periodic tasks by using static priority policy with preemption:

- Upon entering the system, each periodic task is assigned a priority inversely based on its period → priorities are static!
  - The shorter the period, the higher the priority; the longer the period, the lower the priority.
  - The aim is to assign a higher priority to tasks that require the CPU more often.
- It assumes that the processing time of a periodic process is the same for each CPU burst.
- A running lower-priority process will be preempted if a higher-priority process becomes ready to run.

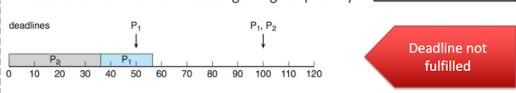
P1: period = 50; processing time = 20

P2: period = 100; processing time = 35

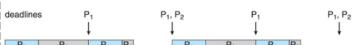
The deadline for each process requires that it completes its CPU burst by the start of its next period.

Predicted CPU utilizations = (20/50+35/100)=0,75

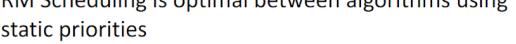
Without rate-monotonic P2 could get higher priority:



With rate monotonic, P1 gets higher priority because it has a lower period → both deadlines are fulfilled even if P2 is preempted



Deadline not fulfilled



Deadline fulfilled

RM Scheduling is optimal between algorithms using static priorities

- If it can be scheduled with static priority, RM will do it. But it can fail...

- In the case where P1 and P2 CPU utilization is:

$$(25/50)+(35/100)=0,94 \rightarrow \text{Less than } 100\% \text{ CPU}$$

- It is not always possible to fully maximize CPU resources!

## Earliest-Deadline-First (EDF)

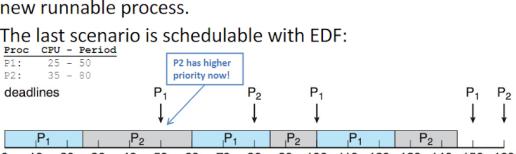
Assigns priorities according to deadlines → priorities are dynamic.

- The earlier the deadline, the higher the priority
- The later the deadline, the lower the priority.

When a process becomes runnable, it must announce its deadline requirements to the system.

Priorities may have to be adjusted to reflect the deadline of a new runnable process.

The last scenario is schedulable with EDF:



Theoretically, EDF is optimal, achieving 100% of CPU use.

## Proportional Share Scheduling

Proportional share schedulers operate by allocating T shares among all applications.

- An application can receive N shares of time, thus ensuring that the application will have  $N/T$  of the total processor time.
- Requires **Admission-control** to prevent impossible scheduling scenarios (a client requesting more shares than the ones available) and to guarantee that an application receives its allocated shares of time.

## Memory Management

In uniprogramming systems, main memory is divided between the OS memory and the memory used by the program being executed

In multiprogramming systems, multiple programs exist, each with its own memory, which must be dynamically managed

- Multiprogramming improves both the CPU utilization and the response speed to users; it implies that multiple processes must coexist in memory

Instructions executed by the CPU can only address the CPU registers or the main memory;

- Any instruction executed or data used must be in one of these direct-access memory
- If data is not in main memory, or in a register, it must be moved there to complete the execution of the instruction

Memory management determines what is in memory and when

- To optimize CPU utilization and response to users

Memory-management schemes depends heavily on the hardware available

### Requirements of a memory management system

- Relocation**
  - Programs may be moved in memory (e.g., after being swapped) and must continue working, i.e., memory references in the code must enable access to the correct physical addresses
- Protection**
  - Each process memory should be protected against interference from other processes whether accidental or intentional - Usually done by HW
- Sharing**
  - Any protection mechanism must have the flexibility to allow several processes to access the same portion of main memory (e.g., shared memory)
- Logical organization**
  - Memory used by programs may have different modules with different characteristics (e.g., some modules may be read only, other writable);
- Physical organization**
  - Memory used by a program may be in different locations (e.g., main memory, secondary memory)

For proper system operation, we must protect the operating system from access by user processes, as well as protect user processes from each other. This protection is provided by the hardware for performance reasons.

## Loading a program

The first step in the creation of an active process is to load a program into main memory

How does the loader deal with addresses in the program?

### 3 approaches to loading:

#### Absolute loading

- If final places in memory are known, all references may use **absolute addresses**
- May be done by the programmer or at compile/assembly time
- Must recompile code if starting location

changes or inserts/deletions are made in the module

- To avoid it, **symbolic addresses** can be used by the programmer, which are converted to specific addresses by the assembler or compiler

#### Relocatable loading

- Binding memory references to specific addresses, before loading, only allows the use of specific main memory addresses;
- By using **relative addresses**, the assembled/compiled program may be located anywhere in the main memory, starting at a specific point defined at initial load time

#### Dynamic run-time loading

- Relocatable loading does not enable changes in the location of a process during execution (e.g. due to a swap), if the start of the program is defined at initial load time
- Dynamic run-time loading defers the absolute address calculation until needed at run time, to enable the process to be moved during its execution. To assure that this function does not degrade performance, it must be done by hardware rather than software.

## Linking and Loading

When more than one module is needed, linking is necessary:

- Compiled or assembled modules in object-code form are linked. Library routines may be incorporated into the program or referenced as shared code that must be supplied by the operating system at run time.

## Dynamic Loading

Until now we were considering that the whole program with its data were in physical memory, for the process to execute. By using dynamic loading, a process does not have to load the entire program and all its data to physical memory

- Enables a better memory-space utilization
- A routine is not loaded until it is called
- An unused routine is never loaded

Useful when large amounts of code are needed to handle infrequently occurring cases

## Dynamic Linking

Dynamically linked libraries are system libraries that are linked to user programs when the programs are run

Dynamic linking postpones linking until execution time

- Without this facility, each program on a system must include a copy of all the routines referenced by the program (even routines from system libraries) in the executable image, wasting both disk space and main memory – **static linking**.

Uses a small piece of code (**stub**) that is included in the image for each library-routine reference. The stub contains information on how to locate the appropriate memory-resident library routine.

- Stub replaces itself with the address of the routine, and executes the routine
- Dynamic linking is particularly useful for libraries.

This system is also known as **shared libraries**.

## Address binding

Addresses may be represented differently along the different steps prior to execution. Each binding is a mapping from one address space to another.

Address binding of instructions and data to **memory physical** (absolute) **addresses** can happen at different times:

- Programming time**: if all physical addresses are specified by the programmer in the program itself; only works if memory location are known a priori; must recompile code if starting location changes.
- Compile/assembly time**: symbolic addresses in the program are converted to physical (absolute) addresses by the compiler/assembler; **absolute code** is generated; only works if memory location are known a priori; must recompile code if starting location changes.
- Load time**: the compiler must generate **relocatable code** if final memory location is not known at compile time - final binding to physical addresses is delayed until load time.
- Execution time**: binding to memory addresses must be delayed until run time if the process can be moved during its execution, from one memory place to another; the loaded program retains relative addresses that are converted to physical addresses as needed.

## Logical and physical addresses

### Logical (virtual) address

- Is a reference to memory independently of the current assignment of data to memory – a translation is needed to access physical memory
- Also referred to as virtual address
- Is generated by the CPU

### Physical address

- Addresses seen by the memory unit - they correspond to addresses in physical memory
- Is an actual location in main memory
- Is the one seen by the memory unit

Compile-time and load-time address binding methods results in identical logical and physical addresses; execution-time address bindings result in different ones

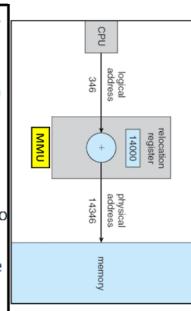
The set of all logical addresses generated by a program is named **logical/virtual address space**; the set of correspondent physical addresses is named **physical address space**.

## Memory Management Unit

The run-time mapping from virtual to physical addresses is done by hardware in a device called **Memory Management Unit (MMU)**

The programmer does not know where the program will be placed in memory when it is executed.

While the program is executing, it may be **swapped** to disk and returned to main memory at a different location (**relocated**).



Memory references must be translated in the code to actual physical memory address

- Several methods can be used in the mapping from virtual addresses to physical addresses;
- A simple method uses a generalization of the base-register scheme. In this context the register is known as **relocation register**.

## Swapping

A process must be in memory to be executed;

A process can be **swapped** temporarily out of memory to a backing store and then brought back into memory for continued execution; Swapping allows the use of a total physical address space bigger than the real physical system memory and increases multiprogramming. When the CPU scheduler decides to execute a process, it calls the dispatcher. The dispatcher checks to see if the process is in memory. If it is not, and if there is no free memory region, the dispatcher swaps out a process currently in memory and swaps in the desired process. It then reloads registers and transfers control to the selected process.

Example:

Memory to swap (in bits):	1 Mb
Disk transfer rate:	5Mb/sec
Time it takes to swap out:	1/5 sec = 200 msec
Average disk latency:	8 msec
Total time to 'swap-out' + 'swap-in':	416 msec

Major part of swap time is transfer time; total transfer time is directly proportional to the amount of memory swapped

## Contiguous Memory Allocation

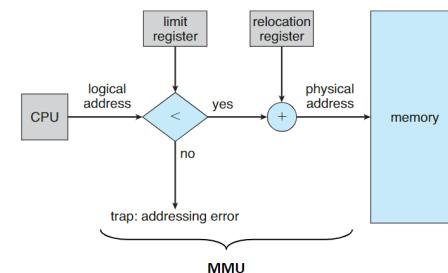
The main memory must accommodate both the OS and the user processes

Contiguous memory allocation is one method of allocating the available memory

- Each process is contained in a single section of memory that is contiguous to the section containing the next process

Two partitions are usually allocated:

- OS partition
- User processes partition (where all user processes are located)



Memory must be allocated to processes that are created

- Hole** – block of available memory; holes of various size are scattered throughout memory.
- When a process arrives, it is allocated memory from a hole large enough to accommodate it.
- Operating system maintains information about:
  - allocated partitions
  - free partitions (holes)

**External Fragmentation:** **Internal Fragmentation:**

When there is no block large enough to accommodate a process, although overall there may be enough memory

When memory is allocated in fixed-sized chunks, leading to some internal memory not being used

## Memory Management techniques

### Fixed Partitioning

#### Equal-size partitions

- Any process whose size is less than or equal to the partition size can be loaded into an available partition.
- If all partitions are full, the operating system can swap a process out of a partition
- If the program is too big to fit a partition, the programmer must design it to allow that only parts are in main memory at any one time (using overlays).
- Main memory use is inefficient. Any program, no matter how small, occupies an entire partition: **internal fragmentation**.

#### Unequal-size partitions

- Can assign each process to the smallest partition within which it will fit
- Processes are assigned in such a way as to minimize wasted memory within a partition (minimizes **internal fragmentation**)

#### Placement algorithm:

- Assign each process the smallest partition within which it fits
  - Needs one queue for each partition to manage swap-outs
  - Minimizes internal fragmentation
  - Has a common queue for all processes or one queue per partition
- When a new program is loaded a swap-out of other may occur

#### Advantages:

- Relatively simple to implement and require minimal OS software and processing overhead.
- Any process with  $\text{size} \leq \text{partition size}$  can be loaded into an available partition
- Disadvantages:
  - The number of partitions specified at system generation time limits the number of active (not suspended) processes in the system.
  - Because partition sizes are preset at system generation time, the use of main memory is inefficient. All programs, despite their size, occupy an entire partition  $\rightarrow$  **internal fragmentation**.
  - A program may be too big to fit into a partition

## Dynamic Partitioning

Partitions are of variable length and number.

Process is allocated exactly as much memory as required.

Eventually get holes in the memory. This is called **external fragmentation**.

Must use **compaction** to shift processes so they are contiguous, and all free memory is in one block.

- Time consuming task!

### Placement algorithms

- Operating system must decide which free block to allocate to a process, to avoid the need of compaction.
- First-fit:** Allocate the *first* hole that is big enough
  - Fast: can stop searching after finding the first adequate block
  - External fragmentation
- Best-fit:** Allocate the *smallest* hole that is big enough
  - Must search entire list, unless ordered by size
  - Produces the smallest leftover hole: External fragmentation
- Worst-fit:** Allocate the *largest* hole
  - Must also search entire list
  - Produces the largest leftover hole
- Next-fit:** Scans memory from the location of the last placement and chooses the next available block that is large enough

## Buddy System

Normally used to allocate memory in the kernel

In a buddy system blocks are available in  $2^k$  sizes with a minimum of  $2^1$  and a maximum of  $2^k$

- Generally,  $2^k$  is the size of the entire memory available for allocation
- $k$  changes with the specific system

If a request of size  $s$  is made and

$$2^{k-1} < s \leq 2^k$$

Then, entire block is allocated.

- Otherwise, block is split into two equal buddies.
- Process continues until smallest block greater than or equal to  $s$  is generated

The buddy system maintains a list of holes (unallocated blocks) of each size  $2^k$

When a  $2^k$  block becomes free, it may be coalesced with a corresponding buddy to produce a block of size  $2^{k+1}$

It's a very fast system!

Compromise between internal and external fragmentation.

## Segmentation

Memory-management scheme that supports user view of memory segments. A segment is a logical unit of data.

- Programmers do not usually think of memory as a linear array of bytes
- A programmer sees memory as methods, procedures, functions and data structures with no care of their addresses in memory

A program has several segments, each with a name (a number in real implementations) and a length;

Different segments may have different lengths;

There is a maximum segment length;

Logical addresses consist of two parts:  $<s,d>$

- A segment number ( $s$ )**
- A segment displacement/offset ( $d$ )**

Since segments are not equal, segmentation is similar to dynamic partitioning.

- Segmentation does not avoid external fragmentation and may need compaction.

### Segmentation Hardware

Implements the translation from user addresses to physical addresses

Uses a **segment table** where each entry has a **segment base** (starting physical address) and a **segment limit** (length of the segment)

## Paging

As happens with segmentation, paging permits the physical space of a process to be non-contiguous.

To achieve this, physical main memory is divided in small fixed-size blocks (**frames**) and processes are divided in blocks of the same size (**pages**).

Paging is used in most OSs.

External fragmentation is avoided.

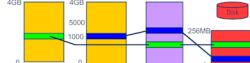
Internal fragmentation only affects the last page of a process. It also solves the problem of fitting the memory blocks onto a backing store whenever swapping-out is necessary.

### Basic Method

- Divide physical memory into fixed-sized blocks called **frames** (typically 4KB)
- Divide logical memory into blocks of same size called **pages** (typically 4KB)
- Keep track of all free frames
- To run  $n$  pages from a program,  $n$  free frames have to be found;
  - (With no virtual memory, the  $n$  frames are the total size of the process – more on this later)
- The program is then loaded to the free frames from the file system or from a backing store
  - The backing store uses blocks of the same size as frames and pages
- Set up a **Page Table** to translate logical to physical addresses

Using paging, the logical and physical address spaces are separated, which enables that a process in a 64 bit machine can have a logical 64 bit address, while the physical memory does not necessarily have that space ( $2^{64}$ )

**processes**    **page table**  
**physical memory**



## Address Translation

Each address ( $m$  bits) generated by CPU is divided in two:

- Page number ( $p$ )** – used as an index into a **page table** which contains the **base address** of each page in physical memory
- Page offset ( $d$ )** – displacement within the page; combined with the **base address** defines the physical memory address that is sent to the memory unit

### Example

32 bit system with 20 bits for page number and 12 bits for page offset

Page Number: 20 bits	Page Offset: 12 bits
----------------------	----------------------

Logical address space =  $2^{32} = 4294967296 = 4\text{GB}$

Page size =  $2^{12} = 4096 = 4\text{KB}$

Number of pages =  $2^{20}$

## Logical to physical mapping

3 decimal digit system with 1 digit for page number and 2 digits for page offset

Page table: 0 1 2 3 4 5 6 7 8 9  
Page Number: 1 decimal digit  
Page Offset: 2 decimal digits

Maximum of 10 pages: 0..9  
Page size of 100 bytes: 0..99

To which physical address does the logical address  $205_{10}$  correspond?

$$\begin{aligned} \text{page} &= 2_{10}; \text{offset} = 5_{10} \\ \text{Page } 2 &\Rightarrow \text{Frame } 5 \\ \text{Physical address} &= 505_{10} \end{aligned}$$

Frame number 11  
Frame number 12

## Hardware support to access a page table

Page table is kept in main memory

- Page-table base register (PTBR)** points to the page table
  - Changing page tables in context-switch only requires the change of this register (stored in the process control block)
- Page-table length register (PTLR)** indicates the size of the page table
  - In this scheme every data/instruction access requires two memory accesses. One for accessing the page table entry and one for the needed data/instruction!
    - Intolerable overhead!

The two memory access problem can be solved by the use of a special fast-lookup **hardware cache** called **Translation Look-Aside Buffer (TLB)**

- Small number of **entries**... 32-1024
- Separate data and instructions TLB may be used
- All entries of the table are evaluated in parallel.
  - If the page number is found the frame number is returned and used to access memory.
  - If the page number is not in the TLB a **TLB miss** is generated and a memory reference to the page table in memory must be made.

### Protection

Memory protection is implemented by associating protection bits with each frame, normally kept in the page table.

- E.g.: one bit can define a page to be read-write or read-only.
- Attempts to violate the settings generate a HW trap to the OS
- Finer levels of protection are possible.

### Valid-invalid bit attached to each entry in the page table:

- "valid" indicates that the associated page is in the process' logical address space, and is thus a legal page
- "invalid" indicates that the page is not in the process' logical address space

### Example

- System using 14-bit addresses ( $2^{14}-16384$ )
- Program using only 0-10468 logical addresses
- Only addresses beyond page 5 are invalid

Normally a program does not use all its available address range. So, there is no need to have a page-table with entries for all pages in the logical address range, as the space would be unused, and the memory wasted



A **Page-table length register** can be used to indicate the size of the table

- All logical addresses that exceed the PLTB are returned as **invalid**

### Shared pages

#### Shared code

- Paging allows sharing common non-modifying code (saves memory space!)
- Only one copy of read-only (reentrant) code shared among processes
  - Heavily used programs benefit the most (e.g., editors, run-time libraries, etc.)
- Each user table maps the shared pages on the same physical copy of the program (i.e., in the same frames).

#### Private code and data

- Each process keeps a separate individual copy of the code and data
- The pages for the private code and data can appear anywhere in the physical address space

Shared pages may also be used by OS to implement shared memory IPC

### Example

- Text editor used by 3 users
  - Data for each process is different
  - Only one copy of the editor is kept in physical memory saving memory
- Each user process shares a 3 page editor program

## Structure of Page Tables

### Hierarchical Paging

Divide the page table in smaller pieces.

- The entire page table can itself be pagged.

- The entire page table is divided in pages
- A root table (page directory) indicates if the page is valid or invalid (if it does not contain valid pages)
- Saves memory by not allocating invalid regions of memory, not used by a program
- Many pages of the logical address space of a program are not really used (as the program uses less than the maximum addressable space)
  - E.g., not all available heap space is used!
- If a single level is used many PTE (Page Table Entries) are marked as invalid

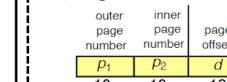
A logical address (on 32-bit machine with  $4\text{KB}=2^{12}$  bytes page size) is divided into:

- a **page number** consisting of 20 bits.
- a **page offset** consisting of 12 bits.

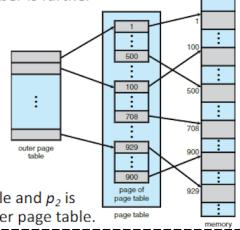
Since the page table is paged, the page number is further divided into:

- a 10-bit **outer page number ( $p_1$ )**.
- a 10-bit **inner page number ( $p_2$ )**.

Thus, a logical address is as follows:



Where  $p_1$  is an index into the outer page table and  $p_2$  is the displacement within the page of the outer page table.



## Hashed Page Tables

Common in address spaces > 32 bits

The virtual page number is hashed into a page table. This page table contains a linked list of elements hashing to the same location.

Virtual page numbers are compared in this chain searching for a match. If a match is found, the corresponding physical frame is extracted.

A single page table entry can store the mapping for multiple physical page frames.

Another way to optimize the page table, reducing its size.

### Inverted Page Tables

One hash table for all processes

One **page table in the system** with one entry for each real page of memory (sorted by physical address)

Entry consists of the virtual address of the page stored in that real memory location, with information about the process that owns that page.

**Decreases memory** needed to store each page table (it has only one page table and one entry for each page of physical memory), but **increases time** needed to search the table when a page reference occurs

- Use hash table to limit the search to one (or at most a few) page-table entries

## Paging + Segmentation

### Paging:

- Transparent to the programmer
- Eliminates external fragmentation

### Segmentation

- Modularity
- Simplifies handling of growing data structures if dynamic segment sizes are allowed
- By using multiple segments, it allows programs to be altered and recompiled independently, without requiring the entire set of programs to be relinked and reloaded

A combined paging and segmentation system:

- Breaks address space into segments, at the discretion of the programmer
- Breaks each segment into a number of fixed-size pages
- For the programmer, a logical address still consists of a segment number and a segment offset
- For the system, the segment offset is viewed as a page number and page offset for a page within the specified segment

### Address Translation

Associated with each process there is a segment table and a number of page tables, one per process segment.

For each running process, a register holds the starting address of the segment table.

## Address Translation Comparison

	Advantages	Disadvantages
<b>Segmentation</b>	Fast context switching: segment mapping maintained by CPU	External fragmentation
<b>Paging (single-level page)</b>	No external fragmentation, fast easy allocation	Large table (virtual memory size) Internal fragmentation
<b>Paged segmentation</b>	Table size ~ # of pages in virtual memory, fast easy allocation	Multiple memory references per page access
<b>Two-level pages</b>	Table size ~ # of pages in physical memory	Hash function more complex
<b>Inverted Table</b>	Table size ~ # of pages in physical memory	Hash function more complex

### NOT RELATED - BUT MIGHT BE IMPORTANT - EXEC FAMILY

- exec**: This is a family of functions that replace the current process image with a new one.
- exec1**: Executes a program located at a specific path, with a list of arguments where the list is terminated by a null pointer. **exec1** allows you to specify an array of pointers to environment variables.
- execvp**: Executes a program found in the system's **PATH**
- execve**: Executes a program located at a specific path, with an array of arguments. **execve** also allows you to specify an array of pointers to environment variables.

## Virtual Memory

All instructions being executed must be in main memory

- If all instructions must be in physical memory, then the physical memory is the limit of the size of the program
- However:
  - Many programs have code rarely used (e.g., error handlers, specific features)
  - Not all allocated memory in data structures such as arrays or lists is actually used
  - Not all code is needed at the same time

Virtual Memory is a technique to allow the execution of processes not completely in memory.

- Allows programs to be larger than the available physical memory

With Virtual Memory:

- A program can be larger than the physical memory available
- More programs can be used at the same time, as each program uses less physical space
- Less I/O is needed to load or swap programs
- The programmer task is easier as it does not have to worry about the physical memory limits
- Allows the separation between logical memory and physical memory
- Files and memory can be shared by two or more processes through page sharing

As seen before, the separation between the physical memory and the logical address space, allows for

- More "logical memory" than what physically exists
- Easy sharing of memory between processes
- Efficient/Fast process creation (copy-on-write)

## Fetch Policy

How do we bring pages from disk to main memory?

- Demand paging only brings pages into main memory when a reference is made to a location on the page. When a process is restarted after a swap-out, every page is only brought in after each page fault generated.

- Less I/O needed ☺
- Less memory needed ☺
- Faster response ☺
- More users ☺
- Many page faults when process first started ☹

- Pre-paging brings in more pages than needed. Some OSs keep a working set containing all the pages in use before the process was suspended and they bring them to memory before restarting the process.

- Efficient if pages reside contiguously on disk ☺
- Uses up memory ☹

## Demand paging

Demand paging allows that a program only loads the needed pages into physical memory

- Is similar to a paging system with swapping, but in this case not all process is swapped in/out
- It uses a pager (in contrast to a swapper that manipulates the entire process) to "swap" individual pages as they are needed

Pages in memory and in disk must be distinguished

- With each page table entry a valid/invalid bit is associated  
valid  $\Rightarrow$  legal AND in-memory  
invalid  $\Rightarrow$  not legal OR not-in-memory  
(not legal = page is not mapped in the address space of the process)
- Initially, valid=invalid bit is set to 0 on all entries

During address translation, if valid/invalid bit in page table entry is 0  $\Rightarrow$  page fault

## Steps on Handling a Page Fault

- Memory reference (instruction with memory access or instruction fetch)
- An invalid page causes a trap to the OS. The OS checks internal tables to determine whether the reference was a valid or invalid (not legal) memory access
  - Invalid access terminates the process
  - If the reference is valid but the page was not loaded to memory, it is now loaded
- Find a free frame and read page from disk to memory
- Alter page table
- Restart instruction that was interrupted by the trap.

## I/O Interlock

Sometimes, pages must be locked in memory

- E.g., When I/O is done to/from the memory by a device using DMA (Direct-Memory Access)
- If the page is replaced during the I/O, the device would write/read to/from a wrong page

A locked page cannot be replaced

- Uses a "lock bit" associated to each frame

\* 1 page 15

## Copy-on-Write

Virtual memory permits fast process creation (forking) by using Copy-on-Write.

- Copy-on-Write allows both parent and child processes to initially share the same pages in memory, bypassing the initial need for demand paging and minimizing the pages to be allocated for the new process.
- Only pages that can be modified need be marked as copy-on-write. Pages that cannot be modified (e.g., executable code) can be shared by the parent and child.
- Only when a process modifies a shared page (write), the page is copied
- Sometimes the pages are never modified (e.g. call of exec() after a fork())
- Copy-on-Write allows more efficient process creation as only modified pages are copied
- Free pages are allocated from a pool of zeroed-out pages

## Memory Mapped Files

Using Paging and Virtual Memory also allows for Memory-Mapped Files

- Memory-mapped files allows file I/O to be treated as routine memory access by mapping a disk block to a page in memory.
- A file is initially read using demand paging. A page-sized portion of the file is read from the file system into a physical page. Subsequent reads/writes to/from the file are treated as ordinary memory accesses.
- Simplifies file access by treating file I/O through memory rather than read()/write() system calls.
- Also allows several processes to map the same file allowing the pages in memory to be shared.

When a page fault occurs and there are no free frames on the physical memory (all memory is in use) the OS must decide what to do:

- Swap out entirely another process, reducing the level of multi-programming (i.e., less different programs in memory)
- May be useful in certain situations (e.g. when thrashing occurs)
- Replace a page in memory for the new one read from the disk – Page Replacement

Some considerations:

- Use a dirty (modify) bit in the page or frame to reduce overhead of page transfers – it indicates that the page or frame have been modified - only modified pages are written back to disk (swap-out).
- Page removed should be the page least likely to be referenced in the near future.
- Try to predict the future behavior based on the past behavior.

If a page fault occurs in an executing process:

- Find the location of the desired page on disk
- Find a free frame to load the desired page:
  - If there is a free frame, use it.
  - If there is no free frame, use a page replacement algorithm to select a victim frame
  - If victim is dirty write it back to disk
- Read the desired page into the (newly) free frame; update the page and frame tables
- Restart the process

If there are no free frames and the victim frame is dirty, two page transfers are needed, doubling the page-fault servicing time.

**Goal: get the lowest page-fault rate**

## Page Replacement Algorithms

### 1- FIFO Page Replacement

Each page is time-stamped according to when it was brought into memory.

Page that has been in memory the longest is replaced.

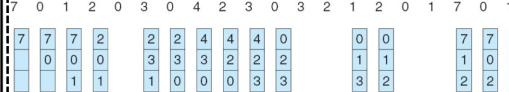
Implemented with a simple queue

- New pages in memory go to the tail
- When needed, replace the page in the head of queue

**Pros:** Simplest algorithm to implement

**Cons:**

- The page replace victim may be one heavily used or one that was rarely used



### 2- Optimal Replacement

Replaces the page that will not be used for the longest period of time – needs to know the future reference string!

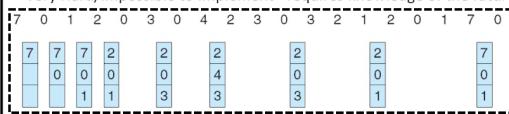
**Is a Conceptual Model**

- Mainly used for comparison studies
  - To measure how good real algorithms are

**Pros:** Best algorithm

**Cons:**

- Very Hard/Impossible to Implement - requires knowledge of the future!



### 3- LRU – Least Recently Used Algorithm

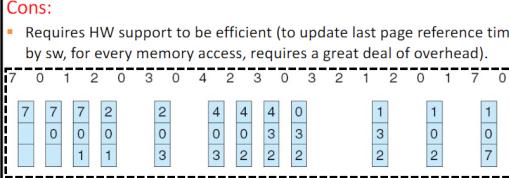
Replaces the page that has not been referenced for the longest time.

**Pros:**

- Accounts for the past use of the pages, providing better performance than FIFO

**Cons:**

- Requires HW support to be efficient (to update last page reference time by sw. for every memory access, requires a great deal of overhead).



## 4 Additional Reference Bits Algorithm (LRU approximation)

While not providing full HW support to LRU, many systems provide a reference bit (use bit).

- The reference bit is set by HW per page whenever a page is accessed (r or w)

Allows to implement aging of pages (i.e. approximate the LRU). Additional use info may be used if at regular intervals the OS saves the reference bits.

**E.g.**

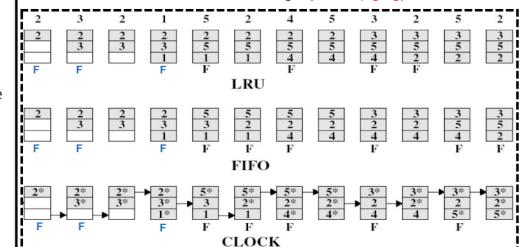
- To keep history of last 8 periods, the reference bit for each page may be periodically recorded by the OS in a byte (for example each 100ms). The last reference value from each period, for each page entry, is inserted in the high order bit and the others are shifted right. The page with a lowest value is the LRU (more than one can have the same value)

## 5- Clock Replacement Algorithm (LRU approximation)

If only 1 bit is used the algorithm is called second-chance or clock algorithm

**Algorithm**

- When a page is first loaded into a frame in memory, set use bit = 1
- Whenever a page is referenced (after the reference that generated the page fault), set use bit = 1
- A pointer moves through pages, in a circular way, to indicate the next potential replacement victim.
- When it is time to replace a page, the first frame encountered with the use bit set to 0 is replaced
  - When a page is replaced, the pointer is set to the next frame after the one just updated
- During the search for replacement, each use bit found at 1 is set to 0 and has a second chance of not being replaced (aging)



## Frame allocation

How to allocate the fixed number of frames available to existing processes?

Lower number of frames allocated per process => higher number of page faults => slower execution

The minimum number of frames per process depends on the specific computer architecture

- E.g., If the instruction set has an instruction that can reference memory in 2 different pages, each process should have at least 2 frames allocated

The maximum number of frames depends on the available physical memory.

## Allocation algorithms

### Equal allocation

- Each process gets the same number of frames

$$\# \text{frames allocated} = \# \text{available frames} / \# \text{existing processes}$$

- Leftovers can be used as a free-frame buffer pool

However, a process may not need all the frames ... Different processes have different needs

### Proportional allocation

- Allocate available memory to each process according to its size

### Global replacement

- A process can select a replacement frame from the set of all frames (even from frames allocated to other processes)

### Local replacement

- A process can only select a replacement frame from its own allocated frames

## Trashing

A high paging activity, with a high number of successive faults and replaces, where the time spent paging is longer than the time spent executing is called trashing.

- If a process does not have "enough" pages, the page-fault rate is very high, leading to a low CPU utilization!

- Operating system detects the low CPU use and thinks that it needs to increase the degree of multiprogramming to compensate

- Another process is added to the system

- More processes will have faults => High I/O => Low CPU use

### To avoid trashing

- A local replacement algorithm may limit the effects

- A process that starts trashing cannot "steal" pages from other processes, therefore limiting the trashing effects to other processes

- However, the average time for servicing any page increases as one process keeps trying to swap pages

To prevent trashing a process must have as many pages as it needs

- One approach: working-set strategy



# Trashing Locality

## Locality

- Set of pages that are actively used together
- A process migrates from working with “one locality” to another
  - E.g., when a function is called a new locality is defined
- Localities actually overlap
- If enough pages are allocated to accommodate the current process locality, it only faults until all those pages are in memory. After, no more faults occur until the locality is changed!

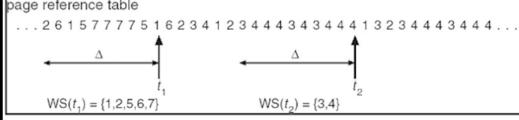
## Why does trashing occurs?

- $\Sigma$  size of locality > total memory size

## Working-set

The working-set model is based on locality

Working-set of a process  $p_i$ : set of pages in the most recent  $\Delta$  page references (e.g. 10,000 accesses)



- It is the set of pages a process is currently working on. (Captures the current locality!)
- Working-set size of a process  $p_i$  ( $WSS_i$ ) is the number of pages in its set
- The accuracy of the working set depends on choosing the right  $\Delta$ 
  - if  $\Delta$  too small  $\Rightarrow$  will not encompass entire locality
  - if  $\Delta$  too large  $\Rightarrow$  will encompass several localities
  - if  $\Delta = \infty \Rightarrow$  will encompass entire program

## Working-set model use

$m$  = total number of frames available

Process  $i$  needs  $WSS_i$  pages

$D = \Sigma WSS_i \Rightarrow$  total demand for frames in the system  
if  $D > m \Rightarrow$  Thrashing

### Policy:

- if  $D > m$ , then suspend one of the processes
  - Reduce multiprogramming
  - If there are enough extra frames, then initiate another process

=> Keeps multiprocessing high and trashing low

## Storage Management

Main memory is usually too small to accommodate all programs and data permanently



Secondary storage options are needed

The file system provides mechanisms to enable storage and access to both programs and data

OS I/O subsystem must provide a simple interface to access all the different devices and optimize the I/O for maximum concurrency

## Mass-Storage Structure

### Disk scheduling

#### Disk's structure

- Disks are addressed as large 1-dimension arrays of *logical blocks*, where the logical block is the smallest unit of transfer.
- Each array of logical blocks is mapped into the sectors of the disk sequentially.
  - Sector 0 is the first sector of the first track on the outermost cylinder
  - Mapping proceeds in order through that track, then the rest of the tracks in that cylinder, and then through the rest of the cylinders from outermost to innermost.

### Disk scheduling - Performance parameters

- To read or write, the disk head must be positioned at the desired track and at the beginning of the desired sector
- Seek time
  - Time it takes to position the head at the desired track.
  - Typical seek time = 5-10ms
- Rotational delay or rotational latency
  - Time it takes for the beginning of the sector to reach the head.
  - Average rotational delay: 5ms (5400 rpm disk) - 3ms (10000 rpm)
- Access time
  - $T_a = (\text{seek time}) + (\text{rotational delay})$
  - The time it takes to get in position to read or write.

### Transfer time (T)

- Time to transfer the data once the head is in position
  - Data transfer occurs as the sector moves under the head
- $$T = \frac{\text{size}}{r \times \text{tracksize}}$$
- size = number of bytes to transfer  
r = rotational speed (rotations per second)  
tracksize = track size in bytes

### Average Total Access Time ( $T_a$ )

- $T_a = (\text{Seek time}) + (\text{rotational delay}) + (\text{transfer time})$

$$T_a = T_{\text{seek}} + \frac{1}{2 \cdot r} + \frac{\text{size}}{r \cdot \text{tracksize}}$$

$T_{\text{seek}}$  = Average seek time (s)

r = Rotational Speed (RPS - rotations per second)

tracksize = Track size (bytes)

size = Size to transfer (bytes)

Consider a disk with average seek time of 10 ms, rotation speed of 10,000 rpm, 512-byte sectors with 320 sectors per track. Suppose we want to read a file with 2560 sectors for a total of 1310720 bytes.

### What is the Total Transfer Time?

- Assuming continuous allocation of the file

First, we assume that the file is stored contiguously on disk and occupies all the sectors in 8 adjacent tracks (8 tracks x 320 sectors/track = 2560 sectors).

This corresponds to a sequential storage of the file.

$T_1 = \text{Time to read first track:}$

- $T_1 = 10 \text{ (seek time in ms)} + 3 \text{ (rotational delay)} + 6 \text{ (read 320 sectors)} = 19 \text{ ms}$
- Next reads the seek time will be 0.
- Each of the 7 successive tracks are read in (3 + 6) ms
- If it must deal with rotational delay in each track; otherwise, it would be just 6ms

Total time =  $19 + 7 \times 9 = 82 \text{ ms} = 0.082 \text{ seconds}$

- Assuming scattered allocation of the file

Now, assume the file is spread over the disk and the accesses to the sectors are distributed randomly.

For each sector we have:

- $T_{\text{sector}} = 10 \text{ (seek)} + 3 \text{ (rotational delay)} + 0.01875 \text{ (read 1 sector)} = 13.01875 \text{ ms}$
- Total time =  $2560 \times 13.01875 = 33328 \text{ ms} = 33.328 \text{ seconds}$
- In this case it is 406 times slower!!!

### Disk performance – some observations

- Seek time is the main reason for differences in performance

Seek time  $\approx$  seek distance

The order in which the sectors are read from the disk has a tremendous effect on I/O performance.

For a single disk request there will be a number of I/O requests.

If requests are selected randomly, we will get the worst possible performance!

### Disk I/O operations also include several queuing delays

When a process needs I/O from a disk it issues a system call to the OS:

If the device (disk drive) and I/O channel are available, the request is served

- If the disk drive is available, it is assigned to the process
- If the I/O channel used by the disk is shared between devices, additional wait time may be required

If it is busy, the request is put in a queue

When the current request is completed, the OS must choose the next request to service

## Disk scheduling ALGORITHMS!

### Example to compare disk scheduling algorithms:

- At the same time, different processes are reading from a disk. The requested blocks by reception time, are located in the following cylinders:
  - 98, 183, 37, 122, 14, 124, 65, 67
  - The requests are put in a requests queue
  - The disk head is initially at cylinder 53

### First-Come-First-Served (FCFS)

- Is the simplest algorithm (FIFO)

Is fair (every request is served and by the order received)

1<sup>st</sup>: move from 53 to 98      2<sup>nd</sup>: move from 98 to 183      (...)

1<sup>st</sup>: move from 98 to 183      2<sup>nd</sup>: move from 183 to 37      (...)

1<sup>st</sup>: move from 183 to 37      2<sup>nd</sup>: move from 37 to 122      (...)

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1<sup>st</sup>: move from 67 to 53      2<sup>nd</sup>: move from 53 to 98      (...)

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1<sup>st</sup>: move from 67 to 53      2<sup>nd</sup>: move from 53 to 98      (...)

1<sup>st</sup>: move from 98 to 183      2<sup>nd</sup>: move from 183 to 37      (...)

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1<sup>st</sup>: move from 67 to 53      2<sup>nd</sup>: move from 53 to 98      (...)

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# RAID Levels

USES: RO -> non-critical data where performance is v important (video editing, gaming) / R1 -> critical data requiring high availability (OS drives, DBs) / R2 -> rare (inefficient) / R3 -> large sequential data access (media streaming, scientific computing) / R4 -> ready-heavy apps where redundancy is important (data warehousing) / R5 -> balance R/W performance w/ fault tolerance (file servers & web svrs)

Category	Level	Description	I/O Request Rate (Read/Write)	Data Transfer Rate (Read/Write)	Typical Application	R6 -> high-availability systems where data integrity & fault tolerance are critical (mission-critical apps, high-availability systems)
Striping	0	Nonredundant	Large strips: Excellent	Small strips: Excellent	Applications requiring high performance for noncritical data	
Mirroring	1	Mirrored	Good/Fair	Fair/Fair	System drives, critical files	
Parallel access	2	Redundant via Hamming code	Poor	Excellent		
	3	Bit-interleaved parity	Poor	Excellent	Large I/O request size applications, such as imaging, CAD	
	4	Block-interleaved parity	Excellent/Fair	Fair/Poor		
Independent access	5	Block-interleaved distributed parity	Excellent/Fair	Fair/Poor	High request rate, read-intensive, data lookup	
	6	Block-interleaved dual distributed parity	Excellent/Poor	Fair/Poor	Applications requiring extremely high availability	

## RAID 4 – Block-interleaved parity

- The striping unit is a disk block
- Improves performance for reads, since for reading a block is only necessary to access one disk. Reading of different blocks is made in parallel.
- Writing implies a *read-modify-write* cycle with only one data disk and the parity disk being affected
  - Contention in the parity disk – only one write is possible at a time as the parity disk (only 1) must be updated
- Multiple reads at the same time are possible
- Requires a minimum of 3 drives

## RAID Levels – conclusions

- RAID 0, RAID 1 and RAID 5 are extremely common.
- If redundancy is not needed RAID 0 is the one with best performance at a lower price
- RAID level 1 is popular for applications that require high reliability with fast recovery.
- RAID 2 and RAID 4 are worst than RAID 3 and RAID 5 respectively
- RAID 3 is a good option to the transfer of big contiguous blocks of data
- RAID 5 is the more balanced choice
- RAID 6 is adequate to high availability scenarios
- Beware: many modern motherboards claim to support RAID-0, RAID-1 and/or RAID-5. In most cases, this is done in software, not hardware!
  - Performance wise, it's completely different!

## RAID 0 - Non-redundant striping

- Does not include redundancy or provide data protection
- Simply strips blocks across different disks
- Best write performance of all RAID levels
- Lower cost - each disk is 100% used as there is no redundancy
- Can be implemented with any number of disks
- Availability is bad!
  - Adding more disks makes it worse.
- Requires a minimum of 2 drives

## RAID 2 – Redundancy through Hamming Code

- Uses error correction codes
- Typically Hamming Code to enable the correction of 1-bit errors and the detection of 2-bit errors
- Simple parity code cannot correct errors and can detect only an odd number of bits in error
- Hamming codes can detect up to two-bit errors or correct one-bit errors without detection of uncorrected errors.
- Uses bit-level striping
- The reading implies using all disks, the ones that have the data and the auxiliary parity disks
- The writing of one block implies changing all disks

## RAID 5 – Distributed block-interleaved parity

- Improves RAID 4 by distributing the parity blocks by all disks instead of a dedicated one.
- Enables simultaneous writes and reads
- Only some writes are less efficient than RAID 1 due to the read-modify-write cycle
- The additional cost corresponds to 1 additional disk (a parity disk that is distributed by all others)
- Permits recovery from the failure of 1 disk
- Best cost/performance for transaction-oriented networks; Very high performance, very high data protection; Can also be optimized for large, sequential requests.
- Very commonly used
- Requires a minimum of 3 drives
- Sometimes RAID 0, RAID 1 and RAID 5 are combined:
  - RAID 0+1: Striping + Mirroring
  - RAID 1+0: Mirroring + Stripping
  - RAID 5+0: Block-Interleaved Distributed Parity + Striping
  - RAID 0+1+5: Striping + Mirroring + Block-Interleaved Distributed Parity

## RAID 1 – Disk mirroring

- Disk information is duplicated
- Does not use striping
- Allows parallel reading from different blocks but implies duplicated writes (the duplicated writes do not penalize time as are done in parallel)
  - Excellent read performance (twice the I/O)
- 50% of disk space is redundant -> High cost
- Very commonly used!
- Requires a minimum of 2 drives

## RAID 3 – Bit-interleaved parity

- Like RAID 2, uses bit-level striping
- Disk controller can tell us which disk has failed. Thus, it is possible to use the other drives to reconstruct the data – a detection code like the one used in RAID 2 is not needed.
- Stripe parity is generated on writes and recorded on the parity disk; parity is checked on reads.
- RAID Level 3 requires a minimum of 3 drives to implement.
- Requires only 1 redundant disk (to save parity data), independently of the number of data disks -> low cost
- Redundancy
  - The failure of one disk still permits the availability of data
  - Lost info can be rebuilt using the other working disks
  - If more than one disk fails information cannot be recovered
- Performance
  - As data is divided in strips very high data transfer rates are possible
  - Any read involves parallel transfer of data from all data disks
  - Good for sequential reads (e.g., multimedia) but not for transaction processing as only one I/O operation can be executed at a time.

## RAID 6 – Dual redundancy

- An extension of RAID-5 : similar read and worst write performance
- Permits recovery from the simultaneous failure of 2 disks
- Requires 2 parity disks, each using a different parity generator algorithm
- Writing of a block implies a read-modify-write cycle with 6 disk accesses (3 reads and 3 writes, corresponding to the data disk and the 2 parity disks) - substantial write penalty when compared to RAID 5.
- Used in high-availability scenarios
- Requires a minimum of 4 drives

- E.g.: RAID 0+1 versus RAID 1+0
  - RAID 0 provides performance
  - RAID 1 provides reliability

# File System Structure

File systems provide efficient and convenient access to the disk (or other secondary storage) allowing data to be stored, located and retrieved easily.

The more common secondary storage is the disk.

The file system:

- Resides permanently on secondary storage.
- Provides a user interface to storage and mapping logical to physical.
- Provides an efficient and easy way to access the storage.

The file system structure provides a logical storage unit

To improve I/O efficiency, I/O transfers are performed in blocks, each block containing one or more disk sectors (if using a disk).

File systems are generally composed of different layers, each serving/using the adjacent ones.

The different layers reduce complexity but add overhead and decrease performance.



## Layered File System

- Application programs
  - Request I/O
- Logical File System
  - Manages metadata information (file system structures excluding data itself)
  - Manages the directory structure
  - Maintains file structure via file control blocks
    - File control blocks contain info about the file
  - Translates filename into a file number, file handle, location
- File-organization module
  - Translates logical block addresses to physical
  - Tracks unallocated blocks
- Basic File System
  - Issues generic commands to the device driver to read and write blocks of data
  - Manages memory buffers and caches that hold file system, directory and data blocks
- I/O control
  - Device drivers and interrupt handlers that permit the data transfer between main memory and the secondary storage system
  - Receives high level commands and translates them to specific device instructions (low level hardware commands)
    - Devices
    - Secondary storage

# Sectors and Blocks

## Disk sector

- Smallest individual reference to disk
- 512 bytes to 4096 bytes (4KB)

## File System Block

- Minimum unit of storage that the file system uses
  - 512 bytes, 1024 bytes (1KB), 2048 bytes (2KB), ..., 32678 bytes (32KB)
- Files smaller than a block size will have internal fragmentation
- Bigger blocks mean that OSs can address bigger disks with the same address size, but more space is wasted when files are not multiple of a block size

## File System Implementation

Several **on-disk** and **in-memory** structures are used to implement a file system. While they may be different in different OSs, the principles are similar.

### On disk:

- Boot Control block (per volume)
  - Contains information on how an OS can boot from that volume. May be empty if no OS exists in the volume. Also known as "boot block" or "partition boot sector".
  - Usually the first block of volume.
- Volume Control block
  - Has volume or partition details such as the number, size of and free blocks. Also known as "super block" or "master file table"
- Directory structure (per file system)
  - Organizes the files
- FCB (File Control Block) (per file)
  - Contains details of the file
- In memory:
  - Mount table
    - Has information about each mounted volume
  - Directory structure cache
    - Holds directory information of recently accessed directories
  - System-wide open-file table
    - Has a copy of the FCB of each open file, among other information
  - Per process open-file table
    - Has a pointer to the appropriate entry in the system-wide open-file table, among other information
  - Buffers
    - Holds blocks that are being read or written to disk (or other secondary storage)

### Creation of new files:

- Files are created by allocating a new FCB or selecting one free.
- In Unix, both files and directories are treated as files. In Windows they have different calls and are treated differently.
- To create directories, the file-organization module maps the directory I/O into disk-blocks

## Open a file:

- The system call open() passes the filename to the logical file system
- A search is made in the open-wide open-file table to see if any other process is using the file.
- If it is, a per-process open-file table entry is created pointing to the system-wide one.
- If it is not, the file name is searched in the directory structure and, when found, the FCB is copied to the system-wide table. A pointer to that table is created in the per-process open file table.
- The per-process open-file table points to the respective entry in the system-wide open-file table, keeps a pointer to the current location of the file (for read and write operations of the file by the process) – File pointer, and saves the access mode in which the file was open.

## Read a file:

- open() returns a pointer to the file entry in the per-process open-file table.
- All file operations are then performed via this pointer.
- This pointer is called file descriptor in Unix and file handle in Windows.

## Close a file:

- Removes the per-process table entry
- Decrements the system-wide table entry that has a counter indicating how many processes have the file open
- If the counter reaches 0 any updated metadata is copied to disk and the entry is removed

## Partitions and Mounting

- Partitions contain a file system ("cooked" partition) or none ("raw" partitions).
- Raw disks are used when no file system is needed (e.g., for databases, Unix swap files).
- Boot information can be stored in a separate partition with its own format (at boot time the OS is not loaded and cannot interpret the format).
- The boot loader loaded is executed and has information on the file systems used and where to find the kernel and start its execution.
- Dual-booted systems rely on the boot-loader to select and start one of the existing OSs.
- The root partition contains the OS kernel and is mounted at boot time. Other volumes can be mounted at boot time or later.
- A disk can have multiple partitions, each containing a different type of file system and a different operating system.

## Directory Implementation

Directories contain information (attributes, location, ownership, etc.) about files.

- Directories provide a mapping between file names and the files themselves.
- Many times, they are Hierarchical and Tree-Structured (but not necessarily)

## Implementation of directories

- As a linear list
  - Linear list of filenames with pointers to the data blocks
  - Finding a file requires linear search
- Using a hash table
  - Complements the linear list with a hash table decreasing the access time

## Virtual File Systems

- Modern OSs concurrently support multiple types of file systems.
- How can it be achieved?
  - Different directory and file routines for each file system – too complex.
  - Use object-oriented techniques to simplify, organize and modularize the implementation – most used approach!
    - Allows different file systems to be implemented within the same structure
    - Even supports the use of network file systems
    - Uses a Virtual File System layer
- Three layers:
  - File system interface – open(), read(), write(), close()
  - Virtual file system (VFS)**
    - Separate operations from implementation
    - Unique identification of each file across the network
  - Specific implementations of each file system type
- Virtual File Systems (VFS) provide an object-oriented way of implementing file systems.
- VFS allows the same system call interface (the API) to be used for different types of file systems.
- The API is defined by the VFS interface, rather than by any specific type of file system.

## File allocation Methods

Let's assume that we want to create a new file...

How are blocks allocated to the file?

- Space must be used effectively
- Files must be accessed quickly

### Contiguous allocation

- Requires that each file occupies a set of contiguous blocks on the disk
- Is defined by a disk address and a length – in block units (block address and length in number of blocks)

#### Pros:

- Simple to implement
- Random access to any part of the file (only necessary to know where it begins)

#### Cons:

- Waste of space due to **external fragmentation** – compaction is an option but the performance penalty is high
- Dynamic storage-allocation problem – where to allocate given N free spaces?
- Files cannot grow – estimate the size of a new file is not always simple

### Linked allocation

- Each file is a linked list of disk blocks placed anywhere in the secondary storage
- Directory contains a pointer to the first and last file blocks
- Each block contains a pointer to the next block

#### Pros:

- Simple – needs only the start address
- Free-space management system – no waste of space
- No external fragmentation

#### Cons:

- No random access (to read a specific block of the file, the blocks must be followed till the block is found, starting at the first)
- No accommodation of the principle of locality (data blocks are spread all over the disk)
- Space waste by the pointers (e.g. 4bytes in a 512-byte block)
- Reliability (a pointer can be lost)

#### An important variation => FAT / FAT32

### FAT/FAT32 (variation of Linked allocation)

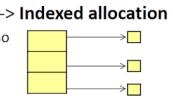
- Has a File Allocation Table (FAT) in the beginning of the disk
- The table has **one entry for each disk block**, indexed by block number
- Each FAT entry points to the next block that a file is occupying
- Last block contains a special EOF (end-of-file) value
- An unused block contains value 0
- Each directory entry contains the name and attributes of a certain file, as well as the number of its first block
- Directories are implemented as "special files"
- If FAT is not cached it implies many disk head seeks (read FAT, read block, read FAT, read block,...)

### Indexed allocation

- In **linked allocation** pointers are scattered all over the disk what results in:
  - Without a FAT it does not support efficient random access
  - Poor support for locality!

#### Solution: Bring together all pointers! -> **Indexed allocation**

- One special block called **Index Block** does so
  - inode (indexed node)** in Unix!
- Each file has its own Index block, which is an array of disk-block addresses



## Indexed allocation (2)

- The directory contains the address of the index block
- To find block  $i$  the  $i^{th}$  pointer entry in the index block is used
- Pros:
  - Supports direct access (random access)
  - No external fragmentation
- Cons:
  - Space wasted by the index block (e.g., A file occupying 2 blocks must have an additional just for the index block!)
  - No accommodation of the principle of locality (data blocks are spread all over the disk)
- To minimize the space overhead, the size of the index block should be as small as possible
- Some files may not have sufficient space to hold all pointers needed!

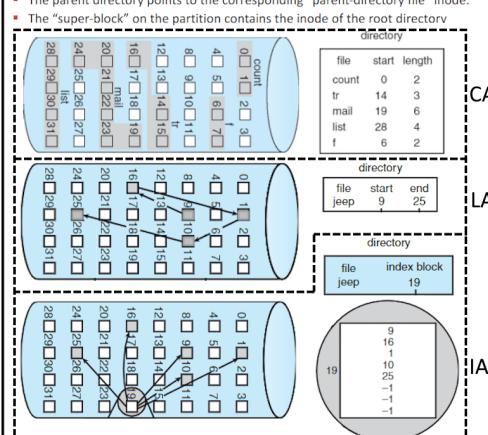
Example:

- Consider an index block of 4KB
- Consider that each entry of index is a 32 bit address representing a disk block
- Each disk block is also of 4KB

- The number of pointers in the index block is:
  - 4KB (index block) / 4bytes (address) = 1024
  - Thus, the maximum file size is:
    - $1024 \times 4KB = 4MB <= \text{Largely insufficient!}$

## Unix solution: inodes (indexed nodes)

- There is one inode per file.
- The inode object holds all the information about a named file except its name and the actual data contents of the file
- Items contained in an inode object include owner, group, permissions, timestamp, etc.
- Uses **combined multi-level indexing**
  - 10 direct pointers (for the first 40KB of the file – uses 4KB disk blocks)
  - 1 single indirect pointer (for the next 4MB of the file)
  - 1 double indirect pointer (for the next 4GB of the file)
  - 1 triple indirect pointer (for the next 4TB of the file)
- Directories implementation
  - Directories are just normal files marked with a "directory" attribute.
  - The content of a "directory file" consists in a mapping of the file names it contains to its corresponding inodes.
  - Sub-directories point to the corresponding "sub-directory file" inode.
  - The parent directory points to the corresponding "parent-directory file" inode.
  - The "super-block" on the partition contains the inode of the root directory



## Free-Space Management

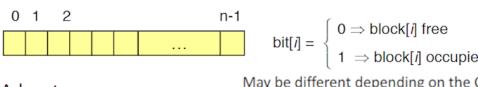
Let's assume that we want to create a new file...

How do I know which blocks are available? How do I reuse space from deleted files?

To keep track of free space the OS maintains free-space "list" (may not be a list) that records of all free blocks

### Bit Vector

- The free-space "list" is implemented as a bit vector where each block is represented by a bit.



#### Advantages:

- Simple to implement
- Fast to search the first available block

#### Disadvantages:

- Becomes inefficient unless it can be kept in memory at all times
- (1TB disk with 4KB blocks  $\Rightarrow$  256 MB bitmap!)

## Linked List of Free Blocks

- Linked list of free blocks, keeping a pointer to the first one

#### In general, it's not efficient:

- To traverse the list it's necessary to read several blocks

#### Optimizations

- Grouping:** store the addresses of N free blocks in the first entry of the list
- Counting:** allocation and releasing of blocks is normally done in groups; thus, store the addresses of contiguous blocks in the list – each entry consists of address + number of contiguous free block

## Efficiency and Performance

### Efficiency

- The efficiency of disk usage depends on:

- Disk allocation and directory algorithms
- Types of data kept in the file directory entry
  - (e.g., Maintaining a last access/write data implies added overhead as the directory entry must be rewritten)
- Size of pointers used to access data
  - (e.g., 64 bits requires more space than using 32 bits – more disk space used)

### Performance

- Independently of the algorithms used, performance can be further improved by using other techniques

- disk cache** – use main memory to keep frequently used blocks
- free-behind / read-ahead** – techniques to optimize sequential access
- improve PC performance by dedicating section of memory as virtual disk, or RAM disk

- Once blocks are read from the disk cache (or other secondary storage) to the main memory, the OS may cache them:

- Buffer cache** – blocks are kept under the assumption that will be used again soon

- Page cache** – uses virtual memory techniques to cache file data rather than file blocks
- File accesses use virtual memory addresses rather than the file system, enhancing the performance

- Unified virtual memory** – some systems use page caching to cache both process pages and file data
  - E.g., Solaris, Linux, Windows

### Page cache and buffer cache

- Page cache** caches pages rather than disk blocks using virtual memory techniques.

- Memory-mapped I/O uses a page cache

- Routine I/O through the file system uses the **buffer (disk) cache**

### Double caching

- Requires caching file system data twice
- Wastes memory and I/O cycles due to the extra data movement within system memory

### Unified Buffer cache

- A **unified buffer cache** uses the same page cache to cache both memory-mapped pages and ordinary file system I/O.
- Used in some versions of Unix.

## Recovery

Data loss or data inconsistency, due to system failure, must be avoided

Different methods are used to deal with file system corruption

### Consistency Checking

- Whatever the cause of corruption in data/OS structures, the file system must be able to detect the problems and then correct them.

- Consistency checker - compares data in directory structure with data blocks on disk and tries to fix inconsistencies (E.g.: **fsck** in Unix; **chkdsk** in MS\_DOS)

### Log-Structured (or journaling) File Systems

- The file system records each update as a transaction

- All transactions are written sequentially to a log file

- A transaction is committed once it is written to the log; at this time, the system call can return to the user process

- However, some of the file system structures may not yet be updated
  - The transactions in the log are asynchronously written to the file system
  - When all required changes are done, the transaction is removed from the log

- If the file system crashes, all remaining transactions in the log must still be performed

- Used in most operating systems today:
  - NTFS, Veritas, EXT3, XFS, ReiserFS

### Backup and restore

- Backups of a file system can be done using specific system programs

- E.g., Backup of a magnetic disk to another secondary storage (such as floppy disk, magnetic tape, other magnetic disk, optical, cloud)

- Different backups may be done

- Full-backups

- Incremental backups

- In case of a failure the recovery consists in restoring the data saved in the backup

# SECURITY

Ensures the authentication of system users

Protects the integrity of data and code

Protects the physical resources available (e.g., CPU, memory, disks, networking)

Prevents unauthorized access, destruction or alteration of data

Considers the external environment where the system operates

A system is **secure** if resources are used and accessed as intended under all circumstances

- Unachievable

- Security breaches must be minimized

**Security breaches can be intentional (malicious) or accidental**

Some terms used:

- **Intruders** – those who attempt to breach security

- **Threat** – a potential security violation (e.g., existing vulnerability)

- **Attack** - attempt to break security

## Security violation categories

### Breach of confidentiality

- Unauthorized reading of data

### Breach of integrity

- Unauthorized modification of data

### Breach of availability

- Unauthorized destruction of data

### Theft of service

- Unauthorized use of resources

### Denial of service (DOS)

- Prevention of legitimate use of the system

## Security violation methods used by attackers

### Masquerading (breach authentication)

- The breach of authentication results in an incorrect identification of the user by the system; the user can gain access or escalate privileges that should not have.

### Replay attack

- Repeats a valid transmission of data; can also involve message modification

### Man-in-the-middle attack

- Intruder sits in data flow, masquerading as sender to receiver and vice-versa

### Session hijacking

- Intercept an already-established session to bypass authentication

## Security must occur at four levels to be effective:

### Physical

- Data centers, servers, connected terminals must be physically secured against entry by intruders

### Human

- Give user authorizations to system access carefully

- Avoid social engineering - phishing, dumpster diving

### Operating System

- Protection mechanisms, debugging

### Network

- Intercepted communications, interruption, DOS

## Program Threats

### Threats caused by the use of programs

#### Trojan Horse

- Code segment that misuses its environment

- When executed by an user, grants the rights from that user to the user that created the program

#### Login spoofing (variation of a Trojan horse)

- Emulates a login program – steals user/password from a user that thinks is logging into the system

#### Spyware (variation of a Trojan horse)

- Comes with other software (either freeware, shareware or even commercial software)

- Normally download ads, open pop-up windows or capture information of user system and return it to a central server

- Some create **covert channels** in which unknown communication occurs without user knowledge

- Up to 90% of spam is delivered by spyware-infected systems (theft of service)

#### Trap Door

- Hole left by a program or system designer to allow him to access the program system

- Specific user identifier or password that circumvents normal security procedures

- A trap door can be included in a compiler that generates code with a specific trap door (the source code of the program, if inspected, would not contain any problem!)

- To detect a trap door an inspection of all the source code of all the components of a system must be made!!

#### Logic Bomb

- Program that initiates a security incident under certain circumstances.

#### Stack and Buffer Overflow

- Most common way for an attacker out of the system gain unauthorized access to the target system

- An authorized user may also use it to escalate privileges

- Exploits a bug in a program (overflow of either the stack or memory buffers)

- Failure of programmer to check bounds on inputs, arguments

## Viruses

- Code fragment embedded in legitimate program
- Self-replicating, designed to infect other programs/computers
- Very specific to CPU architecture, operating system, applications
- Usually via email or as a macro
- File / parasitic
  - Appends itself to a file and its execution does not prevent the execution of the host program.
- Boot
  - Infects the boot sector of the system and executes before the OS. Also known as memory viruses as they do not appear in the file system.
- Macro
  - Written in high level language. Executed by a program that runs that type of macros (e.g. spreadsheet)
- Source code
  - Looks for source code and includes the virus in that code.
- Polymorphic
  - Changes every time it is installed to avoid having a **virus signature**
- Encrypted
  - Is encrypted to avoid detection. The virus first decrypts and then executes.
- Stealth
  - Avoids detection by changing parts of the system that could detect them.
- Tunneling
  - Install itself in the interrupt-handler chain to avoid detection.
- Multipartite
  - Infects multiple parts of the system.
- Armored
  - Coded to be hard to understand and therefore be harder to detect and avoid.

## Rootkits

- Program(s) that enable(s) administrator-level access to a computer or computer network. Their main aim is to be hidden and remain undetected.
- Five kinds of rootkits by place where they hide:
  - Firmware rootkit
    - Hidden in the BIOS
  - Hypervisor rootkit
    - Runs the OS in a virtual machine under its control.
  - Kernel rootkit
    - Hides as a loadable kernel module
  - Library rootkit
  - Application rootkit

## Some defenses possible

- Anti-virus
- Code-signing
  - Only run unmodified code from reliable software vendors
- Sandboxing
  - Limits execution to a limited range of virtual addresses enforced at run time.
- Interpretation
  - Run untrusted applets interpretively and not let them control the hw (e.g. interpret Java applets in a browser). Each instruction can be analyzed before being executed.

## User Authentication

The OS protection system depends on the ability to identify the programs and processes currently executing, which in turn depends on the ability to identify each user of the system.

- User authentication is crucial to identify an user correctly, as protection systems depend on user ID

User identity is often established through one or more of:

- user knowledge of something (e.g., user identifier and **password**)
- user possession of something (e.g., a card or key)
- user specific attribute (e.g., fingerprint, retina pattern)

## Passwords

Most common approach used

Different passwords may be required for different access rights (for convenience this does not happen often)

### Password vulnerabilities

- If simple, can be guessed (or brute forced)
- Accidental exposure (e.g. password written in a paper, shoulder surfing – intruder sees the user typing the password)
- Sniffing (can be done by another user with access to the network)
- Trojan horse keystroke logger
- Transference from one user to other (password borrows!!)

Passwords must be kept secret – how can the system try to accomplish it?

- Demand frequent change of passwords
- Keep history of old passwords to avoid repeats
- Check for ease of guessing
- Log all invalid access attempts (but not the passwords themselves)
- Use one-time passwords
  - Use a function based on a seed to compute a password – the system presents one part of the password and the user responds based in a function
  - Hardware device / calculator to generate the password
- Use biometrics
  - Use some physical attribute (fingerprint, hand scan)
- Use multi-factor authentication

### How to keep the password secret within the computer?

- Only store encrypted password, never decrypted
- Use algorithm easy to compute but difficult to invert
- Traditional Unix systems keep user account information, including one-way encrypted passwords, in a text file called '/etc/passwd'. As the file is readable it can pose security risks.

### Procedure:

- Overflow an input field, command-line argument or input buffer until it writes into the stack
- Overwrite the current return address on the stack with the return address of the exploit code. When routine returns from call, returns to hacked address.
- The following overflow data is the exploit code to be called from the stack

## Implementing Security Defenses

**Defense in depth** is most common security theory – uses multiple layers of security

Implement a **Security policy** - describes what is being secured and how to implement the security

Vulnerability assessment compares real state of system / network compared to security policy

Intrusion detection endeavors to detect attempted or successful intrusions

- **Signature-based** detection spots intrusions based on known bad patterns

- **Anomaly detection** spots differences from normal behavior

- Can detect **zero-day** attacks (i.e. detect previously unknown methods of intrusion)
- **False-positives** and **false-negatives** are a problem

## Virus protection

- Searching all programs or programs at execution for known virus patterns

- Or run in **sandbox** so can't damage system

- Avoid opening any e-mail attachments from unknown users

- Practice **safe computing** – avoid sources of infection, download from only "good" sites, etc.

Auditing, accounting, and logging of all or specific system or network activities

- May decrease system performance

## Firewall

**firewall** is placed between trusted and untrusted hosts

- The firewall limits network access between these two **security domains**

- However, it can be tunneled or spoofed

- Tunneling allows disallowed protocol to travel within allowed protocol (i.e., telnet inside of HTTP)
- Firewall rules typically based on host name or IP address which can be spoofed

## Personal firewall

is software layer on given host

- Can monitor / limit traffic to and from the host

## Application proxy firewall

understands protocols used by applications and can control them (i.e., SMTP)

**System-call firewall** monitors all important system calls and apply rules to them (i.e., decides if a program can execute a specific system call)

## PROTECTION

Security is easier to achieve if there is a clear model of what is to be protected and who is allowed to do what.

Protection refers to mechanisms for controlling the access of programs, processes or users to available system resources

In one protection model, computer consists of a collection of objects, hardware or software

Each object has a unique name and can be accessed through a well-defined set of operations

### Protection problem

- ensure that each object is accessed correctly and only by those processes that are allowed to do so

## Principles of Protection

Guiding principle in designing protection of an OS – **principle of least privilege**

- Programs, users and systems should be given just enough **privileges** to perform their tasks

- Limits damage if entity has a bug or gets abused

- The privileges can be static (during the life of a system or process)

- Or dynamic (changed by process as needed) – **domain switching**, **privilege escalation**

- A similar concept is applied to data access - "Need to know"

- If the process does not have to know it is not given permission to access data

### "Grain" aspects to consider

- Rough-grained privilege management is easier and simpler - least privilege is now done in large chunks

- For example, traditional Unix processes either have the privileges of the associated user or of the root

- Fine-grained management is more complex and implies more overhead

- File ACL (Access Control Lists), RBAC (Role-Based Access Control)

## Domain Structure

To facilitate protection, a process operates within a **protection domain** which specifies the resources it may access. The ability to execute an operation on an object is an **access right**.

Access-right = <object-name, rights-set>

Domain = set of access-rights

A domain can be realized in different ways such as user, process or procedure

object domain	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	printer
D <sub>1</sub>	read			
D <sub>2</sub>				print
D <sub>3</sub>			read	execute
D <sub>4</sub>	read write			read write

# Virtualization

Inside a virtual machine, guest operating systems run in an environment that seems to them as native hardware, creating the illusion that each environment has its own private computer.

- The environment behaves as if it was native hardware but also protects, manages and limits the virtual machines.

Virtualization enables a single machine to simultaneously run multiple OSs or different instances of the same OS.

Virtualization creates a virtual system on which operating systems and applications can run.

A virtual machine abstracts the hardware of a single computer into several different execution environments

Several components

- Host** – underlying hardware system
- Virtual machine manager (VMM) or hypervisor** – creates and runs virtual machines by providing an interface that is **identical** to the host
  - (Except in the case of paravirtualization)
- Guest** – process provided with virtual copy of the host
  - Usually, an operating system

A single physical machine can run multiple operating systems concurrently, each in its own virtual machine

## Implementations

### Type 0 hypervisors

- Hardware-based solutions that provide support for virtual machine creation and management via firmware
  - IBM LPARs and Oracle LDOMs are examples

### Type 1 hypervisors

- Operating-system-like software built to provide virtualization
  - Including VMware ESX, Joyent SmartOS, and Citrix XenServer
- Also includes general-purpose operating systems that provide standard functions as well as VMM functions
  - Including Microsoft Windows Server with HyperV and RedHat Linux with KVM

### Type 2 hypervisors

- Applications that run on standard operating systems but provide VMM features to guest operating systems
  - Including VMware Workstation and Fusion, Parallels Desktop, and Oracle VirtualBox

## Other variations

### Paravirtualization

- The guest OS is modified to work in cooperation with the VMM to optimize performance

### Programming-environment virtualization

- VMS do not virtualize real hw but create an optimized virtual system
  - Used by Oracle Java and Microsoft.NET

### Emulators

- Allow applications written for one hardware environment to run on a very different hardware environment, such as

## Some virtualization techniques

### Trap-and-Emulate

- Virtual machine guests execute in user mode
- Only host Kernel runs in kernel mode
  - Not safe to let guest kernel run in kernel mode too!
- A VM needs two modes – virtual user mode and virtual kernel mode
  - Both of which run in real user mode
- How can actions such as system calls, interrupts or execution of privileged instructions, be executed by the virtual kernel?
- Actions in guest that usually cause switch to kernel mode must cause switch to virtual kernel mode
  - When the kernel in the guest attempts to execute a privileged instruction, that causes an error (because the system is in user mode) and causes a trap to the VMM in the real machine.
  - The VMM gains control and executes ("emulates") the action that was attempted by the guest kernel on behalf of the guest. It then returns control to the virtual machine -> trap-and-emulate
- User mode code in guest runs natively on the hw with the same performance as the native system
- Kernel mode code runs slower due to trap-and-emulate
  - Especially a problem when multiple guests running, each needing trap-and-emulate
- Hardware support in CPUs and extra modes provided by the CPU minimize the problem

### Binary translation

- If guest vCPU is in user mode, guest can run instructions natively
- If guest vCPU is in kernel mode (guest believes it is in kernel mode)
  - VMM examines every instruction the guest is about to execute by reading a few instructions ahead of program counter
  - Non-special-instructions run natively
  - Special instructions translated into new set of instructions that perform equivalent task
- Basics are simple, but implementation very complex!**
- Implemented by translation of code within VMM
- Code reads native instructions dynamically from guest, on demand, generates native binary code that executes in place of original code
- Performance of this method would be poor without optimizations
  - Products like VMware use caching
  - Translate once, and when guest executes code containing special instruction cached translation used instead of translating again
- Testing showed booting Windows XP as guest caused 950,000 translations, at 3 microseconds each, or 3 second (5%) slowdown over native

### Hardware assistance

- All virtualization needs some HW support
- More support -> more feature rich, stable, performance of guests
- Intel added new VT-x instructions in 2005 and AMD the AMD-V instructions in 2006
  - CPUs with these instructions remove need for binary translation
  - Generally, define two more CPU modes – "guest" and "host"
- VMM can enable host mode, define characteristics of each guest VM, and then switch to guest mode, passing control to guest OSs

OS thinks it is running natively, and only sees devices the VMM for that guest device causes a trap to the VMM (that takes control

of the interaction)

- VCPUs (Virtual CPUs) are provided to save CPU context switches of guests

## Virtualization and OS components

### How do VMMs provide core OS functions?

#### CPU Scheduling

- Virtualization sw presents one or more virtual CPUs to each VM running;
- The VMM has its own threads and guest threads (from the VMs) to run
- If there are enough physical CPUs, the VMM can allocate one to each virtual CPU requested by each guest
  - In this case, each guest acts like a native OS on a native CPU
- When not enough physical CPUs are available, the VMM schedules its own threads (for guest management, I/O management, etc.) and the guest threads, on available physical CPUs
- Even if the scheduler algorithm used by the VMM provides fairness between guest VMs (e.g., allocating physical CPUs in the same proportion of the allocated guest CPUs) it may result in poor user response
- Examples:
  - An OS that tries to give a limited time slice to each process, when virtualized, cannot guarantee that time slice as the VMM scheduling may deeply affect this time
  - Real time OSs cannot guarantee their timings
- As each guest OS believes that it own the CPU, receiving all the CPU cycles available, the fact that it does not may affect some of its functions, such as the time-of-day clock
- To correct this, VMMs supply applications to install in each type of guest OS permitted. This application correct clock drift and supply other functions such as virtual device management

#### Memory Management

- Memory is one of the major keys to performance
- More users of memory add more pressure on memory use
- VMMs usually overcommit memory – the total memory configured in guests usually exceeds the available physical memory
- Before memory optimization can occur, VMMs establish how much real memory each guest will get based on their initial needs, system load, etc.
- To reclaim memory from the guests, the VMM uses different mechanisms:
  - It uses a nested page table that re-translates the guest page table to the real page table; this additional indirection level can be used to optimize the guest's use of memory, without its knowledge
  - Another method to reduce memory pressure is to determine if a given page has been loaded more than once

## I/O

- VMs do not always represent hardware exactly, when I/O is concerned
- Virtualization provides specific virtualized devices to guest OSs
- I/O devices may be dedicated to guests, allowing each guest direct access to those devices, greatly improving performance
- Shared access to devices implies that the VMM must provide protection in its use. VMMs become part of every I/O operation, checking it for correctness and routing data to and from devices and guests
- In networking VMMs act as virtual switch to route network packets between the guest addresses; VMMs may also provide bridging (direct access) or NAT to guests

## Storage Management

- Both boot disk and general data access need be provided by VMM
- Need to support potentially dozens of guests per VMM (so standard disk partitioning not sufficient)
- Type 1 hypervisors – storage guest root disks and config information within file system provided by VMM as a disk image
- Type 2 hypervisors – store as files in file system provided by host OS
  - To create a new guest, it is enough to duplicate the file
  - By moving the file to another system, the guest is moved
- Physical-to-virtual (P-to-V) convert native disk blocks into VMM format
- Virtual-to-physical (V-to-P) convert from virtual format to native or disk format
- VMM also needs to provide access to network attached storage (just networking) and other disk images, disk partitions, disks, etc.

### Page Fault Rate ( $p$ )

- $0 \leq p \leq 1.0$
- if  $p = 0$ , no page faults
- if  $p = 1$ , every reference is a fault

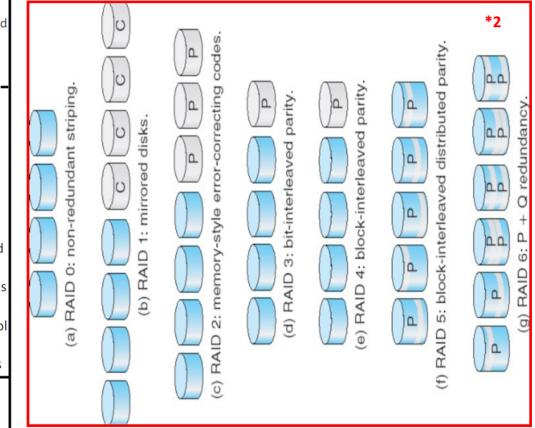
### Memory access time ( $ma$ )

- Normally ranges from 10-200 ns

### Effective Access Time (EAT)

$$EAT = (1-p) \times ma + p \times \text{page fault overhead}$$

[swap out + swap in + OS overhead]



## Operating System Architecture and Structures

### Microkernel:

- Moves as much as possible from the kernel into "user" space
- The main function of the microkernel is to provide communication between the client program and the various services that are also running in user space. Communication is provided through message passing
  - e.g., Mach, XNU (used in OpenStep and Darwin, part of MAC OS X)
- Benefits:**
  - Easier to extend a microkernel
  - Easier to port the operating system to new architectures
  - More reliable (less code is running in kernel mode)
  - More secure
- Detriment:**
  - SLOW: Performance overhead of user space to kernel space communication

### Monolithic:

- Everything is put below the system-call interface and above the physical hardware
- Provides the file system, CPU scheduling, memory management, and other operating-system functions; a large number of functions for one level
- Benefits:**
  - Less reliable (more code is running in kernel mode)
  - Less secure
  - Not so easy to port to new architectures (... it depends)

## Virtual Machines

### Process Virtual Machines:

- "Abstract Machine" that runs bytecode (e.g. Java, MS.NET)
- Good for portability, allowing running the same unmodified application in different physical architectures
- Designed to execute computer programs in a platform-independent environment

### System Virtual Machines:

- Software that allows different operating systems to be run in parallel giving them the illusion of "having a whole machine"
  - e.g., VMWARE, XEN, VirtualBox, ...
- Some Virtual Machines run on top of the hardware: IBM z/VM
- Others run on top of the host OS: XEN, VMWARE, VirtualBox, etc
- Allows for server consolidation, software testing, software fault tolerance, etc.

## Disadvantages

### Sharing of physical machines impacts...

- Performance Isolation (CPU, IO)
- Failure isolation between virtual machines
- A crash of the host machine can affect many different VMs
- Higher entrance cost
- Security

## Building blocks

It is generally difficult to provide an **exact** duplicate of an underlying machine

- Especially if only dual-mode operation is available on CPU
  - user and kernel modes
- Is getting easier over time as CPU features support VMM
- Most VMMs implement a **virtual CPU (vCPU)** to represent state of CPU per guest, as guest believes it to be
  - When guest context is switched onto CPU by VMM, the information from vCPU is loaded and stored

## Deadlocks

claim / max M = alloc M + requests M !!!

Consider the following scenario where 5 processes (P1..P5) are using 4 different types of system resources (A..D). Next tables present the resources allocated, the maximum number of resources needed and the resources available.

Allocation: Max: Available:

	A	B	C	D		A	B	C	D		A	B	C	D
P1	0	0	1	2	P1	0	0	1	2	P1	1	5	2	0
P2	1	0	0	0	P2	1	7	5	0	P2	2	3	5	6
P3	1	3	5	4	P3	2	3	5	6	P3	0	6	5	2
P4	0	6	3	2	P4	0	6	5	2	P4	0	6	5	6
P5	0	0	1	4	P5	0	6	5	6	P5	0	6	5	6

a) Is the system in a safe state? Use the Banker's algorithm to prove.

P1 já está em condições de ser completado. Com os 2 recursos D ganhos e 1 recurso A, P3 pode ser completado. (...) P2, P4, P5. Dado que todos os processos conseguiram terminar, o sistema está num safe state.

b) If P2 requests the resources [0,4,2,0] should it be allowed?

Completando P1, P3, P4 e P5 anteriormente o available vector tem os valores (3, 14, 12, 12). Neste cenário, P2 ainda precisa de (1, 7, 5, 0) - (1, 0, 0, 0) + (0, 4, 2, 0) = (0, 11, 7, 0). Dado que nenhum dos valores ultrapassa o AV, o pedido deve ser permitido.

Consider the following scenario where 4 processes are using 4 different types of system resources.

Allocation Matrix A: Requests Matrix Q: Vector Available

	R1	R2	R3	R4		R1	R2	R3	R4		R1	R2	R3	R4
P1	0	0	1	0	P1	1	0	2	0	P1	2	1	0	0
P2	0	0	1	1	P2	2	0	0	1	P2	1	0	1	1
P3	2	0	0	1	P3	1	0	1	1	P3	0	1	1	1
P4	0	1	2	0	P4	2	1	0	0	P4	0	1	0	0

Are any of the processes in a deadlock? Apply the deadlock detection algorithm to answer.

Sim, P4 e P1 podem ser completados, mas P2 e P3 necessitam ambas de R4, sendo que cada um tem 1 R4 alocado.

## Scheduling

Notes to exercises

- If two processes arrive at the same time, the one that first enters the ready-queue is the one that is in the higher line in the table where the processes characteristics are defined;
- When a new process arrives and, at the same time, the process that is running leaves the processor, it is the process that was running that will go to the end of the ready-queue (i.e., the process that just arrived gets first into the ready-queue);
- If two processes have the same characteristics, the one closer to the head of the ready-queue is chosen.

Consider 5 processes (P1..P5) with the following behaviour:

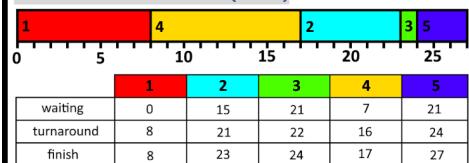
Process	Arrival time	Processing time (ms) (CPU burst)	Priority
P1	0	8	4
P2	2	6	1
P3	2	1	2
P4	1	9	2
P5	3	3	3

- B.1 – Assume that the highest priority is 1 and use a Gantt to depict the scheduling of the processes using the following algorithms:

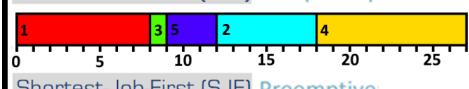
B.2 – For each algorithm create a table with the following values:

(a) Turnaround Time; (b) Waiting Time; (c) Finish Time

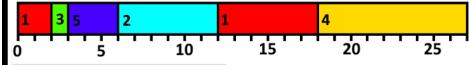
### First-Come, First-Served (FCFS)



### Shortest-Job-First (SJF) Non-preemptive



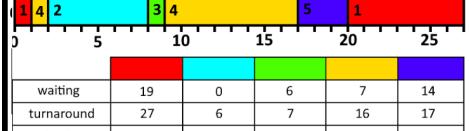
### Shortest-Job-First (SJF) Preemptive



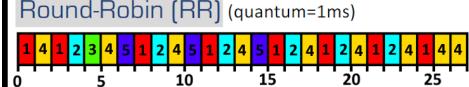
### Priority Scheduling Non-preemptive



### Priority Scheduling Preemptive



### Round-Robin (RR) (quantum=1ms)



The table below describes three periodic tasks.

	C <sup>1</sup>	D <sup>2</sup>	T <sup>3</sup>
Task A	4	6	8
Task B	4	12	16
Task C	6	24	32

- Construct a timing diagram for the execution of the tasks that spans from time t=0 to time LCM (Task A, Task B, Task C)<sup>4</sup>. Create the diagram by simulating the execution of the tasks using EDF scheduling. The first instance of each task arrives at time 0.

<sup>1</sup> C = Worst case execution/computing time

<sup>2</sup> D = Deadline (within the period)

<sup>3</sup> T = Period

<sup>4</sup> Shortest repeating cycle = least common multiple (LCM) of periods

LCM(8, 16, 32) = 32

Execution of all tasks using EDF:			
Task A	Task B	Task C	
Finish time of last run	30	26	22
Number of runs	4	2	1

## Memory

Consider the following free memory partitions (by order):

- 100KB, 500KB, 200KB, 300KB and 600KB

The following requests to place programs in memory are made (by order of the request) :

- 212KB, 417KB, 112KB, 426KB

What is the result of executing Best-Fit, First-Fit and Worst-Fit algorithm? And which makes the most efficient use of memory?

	100KB	500KB	200KB	300KB	600KB
Best-Fit	417KB		112KB	212KB	426KB
First-Fit	212KB		112KB		417KB
Worst-Fit	417KB			112KB	

Best-fit é mais eficiente.

Consider a logical address space of 64 pages of 1024 bytes each, mapped onto a physical memory of 32 frames.

- How many bits are there in the logical address?

Logical address: 16 bits  $2^6 = 64 ; 2^{10} = 1024$

Page number =  $2^6$  Page offset =  $2^{10}$

- How many bits does the physical address have?

Physical address: 15 bits 32 frames =  $2^5$  frames  $2^5 = 32 ; 2^{10} = 1024$

Frame number =  $2^5$  Frame offset =  $2^{10}$

Consider a computer with 256 MBytes of physical memory having a virtual memory of 2 GBytes through paging. The number of pages occupies the first 20 more significant bits of the logical address.

- What is the maximum number of pages?

$2^{20}$

- What is the size of each page?

$2^{12} \text{ 256GB} / 2^{20} = (2^{31} / 2^{20}) \text{ Bytes} = 2^{11} \text{ Bytes}$

- If a PTE (Page Table Entry) occupies 8 bytes, which will be the maximum size of the Table of Pages?

Maximum size = 8MB  $2^{20} \text{ bits} * 8 \text{ Bytes} = 2^{23} \text{ Bytes}$

- What if it was an inverted page table?

If limited by the size of physical memory = 128kB x 8 bytes

- How many pages will the Table of Pages occupy?

$4096 \cdot 2^{23} / 2^{11}$

Consider a computer system with a 32-bit logical address and 4-KB page size. The system supports up to 512 MB of physical memory. How many entries are there in each of the following?

- A conventional single-level page table?

$2^{20} \text{ entries} (1\,048\,576) \quad 4\text{KB} \rightarrow 2^{12}\text{MB} \rightarrow 32\text{-12} = 20$

- An inverted page table?

$2^{17} \text{ entries} (131\,072) \quad 512\text{MB} / 4\text{KB} = 2^{17}$

Consider a paging system with the page table stored in memory. Each memory reference takes 200 nanoseconds.

- How long does a paged memory reference take? (do not consider a TLB)

400 nanoseconds mem. ref. to see the table (200) + mem. ref. for the needed instruction (200)

- If we add TLB, and 75 percent of all page-table references are found in the TLB, what is the effective memory reference time?

(Assume that finding a page-table entry in the TLB takes zero time, if the entry is there.)

Effective access time = 250 nanoseconds.

$$\text{EAT} = 0,75 * (0 + 200) + 0,25 * 400 = 250 \text{ ns}$$

- A machine has a simple pagination system, 32 bits logic addresses, a page table size with 1024 entries, 128 frames of memory, and uses a LRU page replacement algorithm.

- Consider that initially all frames are empty with the exception of the frame that contains the code.

- How many page-faults does the following code generate?

```
char A[2*1024*1024]; // table in address 0x02800000 (start of a page)
for (int i=0; i<2*1024*1024; i++)
    A[i]=0;
```

Page-faults generated = 1 page size is  $2^{10} (32 - 10 = 22)$ , and the size of A is  $2^{21}$ . therefore, only 1 page needed.

A computer has a virtual address with 32 bits and uses segmentation+paging. There are 16 equal segments, and each page has 4KB. Each PTE (Page Table Entry) has 4 bytes.

- What is the maximum virtual address space of a process?

- How many bits are there in the logical address? How many for each Segment, Page and Offset?

- What is the size of each Page Table?

- How many pages does each Page Table occupy?

segs: 16  $\rightarrow$   $2^4$   
off: 4KB  $\rightarrow 2^{12}$   
pages: 32  $\rightarrow 4 - 12$

4KBytes =  $2^{12}$  bytes

- $2^{32} = 4\text{GB}$

- Segments: 4 bits; Pages: 16 bits; Offset: 12 bits

- $2^{18} \text{ bytes } 2^{16} * 2^{12} = 2^{18}$

- $2^6 \cdot 2^{18} / 2^{12} = 2^6$

Considering the segment table below what are the physical addresses for the following logical addresses?

Segment	Base	Length

## Storage

Suppose that a disk drive has 5,000 cylinders, numbered 0 to 4999. The drive is currently serving a request at cylinder 2150, and the previous request was at cylinder 1805. The queue of pending requests, in FIFO order, is:

2069, 1212, 2296, 2800, 544, 1618, 356, 1523, 4965, 3681

Starting from the current head position, what is the total distance (in cylinders) that the disk arm moves to satisfy all the pending requests for each of the following disk-scheduling algorithms?

- a) FCFS - total seek distance is 13,011.
- b) SSTF - total seek distance is 7586. [see how they work!](#)
- c) SCAN - total seek distance is 7492. [pag. 11](#)
- d) LOOK - total seek distance is 7424.
- e) C-SCAN - total seek distance is 9917.
- f) C-LOOK - total seek distance is 9137.

A disk has rotational speed of 15,000 rpm, 512 bytes per sector, 400 sectors per track, 1000 tracks on the disk and an average seek time of 4ms. We want to transmit a file of size 1 MByte, which is stored contiguously on the disk.

(Assume no seek time between adjacent tracks; do not consider rotational delay between adjacent tracks)

- a) What is the transfer time for this file?
- b) What is the rotational delay in this case?
- c) What is the average (total) access time for this file?
- d) What is the total time to read 1 sector?
- e) What is the total time to read 1 track?

- a) T=transfer time = 20.48ms [formulas on pag. 11](#)
- b) Rotational delay = (average 180 degree wait) =  $1/2r=2\text{ms}$
- c) Average total access time = 26.48ms
- d) Total time to read 1 sector (512 Bytes) = 6.01ms.
- e) If the disk uses sequential organization, then the total time to read 1 track (400 sectors per track) = 10ms

Consider a RAID Level 5 organization comprising five disks, with the parity for sets of four blocks on four disks stored on the fifth disk. How many blocks are accessed in order to perform the following?

- a) A write of one block of data
- b) A write of seven continuous blocks of data
- a) A write of one block of data requires: read of 1 data block, read of 1 parity block, write of 1 data block, write of 1 parity block. The computation of the new parity based on the differences between the new and old contents of the target block must be done
- b) If the seven contiguous blocks begin at a four-block boundary, the write can be done as: 7 writes of data blocks, 2 writes on parity blocks, 1 read of a data block. It includes the computation of the parity of the first 4 blocks (that will all be modified) and the computation of the parity of the last 3 modified blocks and the one that is not changed.

Consider a representation of an inode in Unix that has 12 pointers: 10 direct pointers, 1 indirect pointer and 1 double indirect pointer.

Suppose that each block occupies 4KBytes and that the pointer to a block occupies 64 bits.

- a) Which is the maximum size of a file on this system?
- b) Supposing that the inode is in memory cache, how many blocks must be read from the disk to read the first 2MB of the file? (consider that initially only the inode is in the cache)

a) Total size = 1,050,664KB

block size: 4KB ( $2^{12}$  B)

pointer size: 64b ( $2^{16}$ )

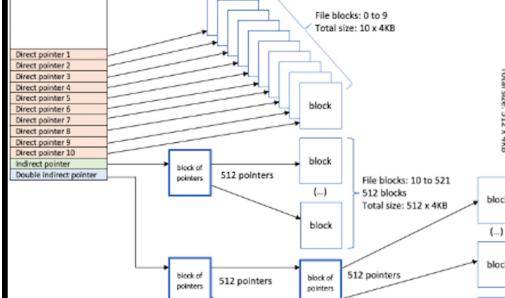
pointer per block:  $2^{12} / 2^{12} = 2^{10}$  = 2<sup>9</sup>B

indirect pointer:  $2^{12} * 2^{10} = 2^{21}$  B = 2MB

2x indirect pointer:  $2^{21} * 2^{10} = 2^{30}$  B = 1GB

b)  $513 = 10$  direct accessed blocks +1 (block with indirect pointers) +502

Inode



Considere um sistema com 512Mbytes de memória física e uma memória virtual de 1GByte que usa paginação. O número de páginas ocupa os 20 bits mais significativos do endereço lógico.

Qual o número máximo de páginas por processo?

$2^{20}$

Qual o tamanho de cada página?

$2^{10}$

Qual o tamanho máximo da tabela de páginas sabendo que cada PTE ocupa 8 bytes?

$2^{20} * 2^3 = 2^{23}$

Qual o número de bits necessário para o endereço físico?

$\log(512MB) = 29$

Qual o número de bits necessário para o endereço lógico?

$\log(1GB) = 30$

Consider the following representation of an Unix file inode:

- 14 pointers: 10 direct pointers, 2 single indirect pointers, 1 double indirect pointer and 1 triple indirect pointer.
- Each block has 4KBytes and each pointer to a block has 32 bits.
- a) What is the maximum possible size of a file in this system?

pointer per block:  $2^{12} / 2^2 = 2^{10}$

indirect pointer =  $2^{12} * 2^{10} = 2^{22}$

2x indirect pointer =  $2^{22} * 2^{10} = 2^{32}$

3x indirect pointer =  $2^{32} * 2^{10} = 2^{42}$

TOTAL:  $10 * 4KB + 2 * 4MB + 4GB + 4TB$

- b) Consider that the main inode table (which contains the file information) occupies 100 bytes. How much space will the inode structure occupy (main table + any other pointer tables) to store a file with the maximum supported size?

diretos: N/A main table: 100B

indiretos:  $2 * 2^{12} = 2^{13}$

2x indiretos:  $2^{13} + 2^{10} * 2^{12} = \dots + 2^{22}$

3x indiretos:  $2^{13} + 2^{22} + 2^{10} * 2^{10} * 2^{12} = 2^{32}$

soma de tudo?

- c) Suppose that caching exists and that each cache block occupies 4KBytes. How many disk accesses will be necessary to put 1 in every bit of a file with maximum possible size? (to simplify suppose that initially the cache is empty and that it has an infinite size)

diretos: 1 por cada

indiretos: 1 pelo bloco do ponteiro +  $2^{10}$  (1 por cada pointer)

2x indiretos:  $1 + 2^{10} + 2^{10} * 2^{10}$

3x indiretos:  $1 + 2^{10} + 2^{10} * 2^{10} + 2^{10} * 2^{10} * 2^{10}$

TOTAL:  $10 * \text{Dir} + 2 * \text{Ind} + 2^{10} * \text{Ind} + 3 * 2^{10}$

## EN 2020/21

Diga o que entende por esperaativa quando usada numa solução para o problema da secção crítica. Esta solução pode resolver o problema? Se sim, deve ser usada? Esperaativa, quando usada para o problema da secção crítica, consistem num processo verificar continuamente uma condição que, quando true, permitirá a entrada na região crítica. Apesar de resolver o problema, não deve ser usada pois consome recursos desnecessariamente. Em alternativa, usar outros métodos de sinc. (semáforos, mutexes, cond vars).

Explique em que consiste o copy-on-write e de que forma pode otimizar a criação de processos. No Linux, a vantagem do copy-on-write mantém-se mesmo que após o fork() o utilizador faz logo um exec()

CoW é o mecanismo que faz com que, após um fork(), as páginas de memória do pai não sejam imediatamente copiadas. Inicialmente, o processo pai e o filho partilham as mesmas páginas, mas quando é detetada a escrita numa página partilhada, esta é copiada. Deste modo, a criação de processos é optimizada pois não são copiadas partes de memória desnecessárias. Este processo verifica-se na chamada de exec() após fork(), uma vez que sem CoW, as páginas seriam copiadas na íntegra, já que elas são substituídas após a chamada de exec().

Que vantagens e desvantagens existem no uso de uma tabela de páginas invertida? Como há apenas 1 entrada na page table por cada endereço físico, é poupar espaço em sistemas com grandes espaços de memória virtual e pequenos espaços de memória física, sendo que a velocidade de procura pelo endereço correto na PT pode ser diminuída. Mesmo usando uma hash table, o proc. torna-se complexo e podem sempre haver colisões.

Acha que é possível existir Thrashing num sistema operativo que tenha poucos processos a executar? Justifique. Sim, para haver Thrashing, é necessário gastar + tempo a resolver conflitos de programação do que a executar os programas, ou seja, não está diretamente relacionado com a quantidade de processos em execução. Pode acontecer com poucos processos se, por exemplo, o tamanho dos working sets for superior ao tamanho da memória disponível.

Considera que tem um sistema de memória paginada hierárquico, com 2 níveis, com um espaço de endereçamento virtual de 4GByte (2<sup>32</sup> bytes). Sabendo que cada página de memória ocupa 8KBbytes e que cada PTE ocupa 64 bits:

Se cada tabela de páginas de 2.º nível tiver de caber numa única página de memória, qual a divisão de bits no endereço lógico?

$8KB = 2^{13}B \Rightarrow \text{offset} = \log(2)(2^{13}) = 13$  PTE =  $64B = 2^{16}B$

$\text{Nentradas} = 2^{13}/2^3 = 2^{10} \Rightarrow p2 = \log(2)(2^{10}) = 10$

$<\!p1, 9, p2, 10, \text{offset } 13\!>$

Qual o tamanho ocupado pela tabela de páginas de 1.º nível?

$p1 * PTE = 2^9 * 2^3 = 2^{12}B$

No total, quantas páginas de 8KB são ocupadas por todas as tabelas de páginas?

$2^9 \text{ tabelas de } 2^9 \text{ nível a ocupar uma página } \Rightarrow 2^9 * 1 = 512 \text{ páginas}$

1 tabela de 1º nível a ocupar  $2^{12}/8KB = 4KB/8KB = 1/2 \text{ página}$

Ao todo, são necessárias 513 páginas.

Considere um sistema onde existem 8 páginas de processos (1 a 8) e 4 page frames em RAM. Vão ser feitos acessos à memória usando a string  $W(1); W(3); R(2); R(3); W(5); R(3); R(8); R(1); W(6)$ :

Supondo que inicialmente todas as frames estão vazias, que  $R(\dots)$  é uma operação de leitura, que  $W(\dots)$  é uma operação de escrita e que o sistema faz uso do modify-bit, preencha a tabela abaixo considerando os algoritmos pedidos:

	W1	W3	R2	R3	R5	R3	R8	R1	W6
F0	1M	1M	1M	1M	5M	5M	5M	5M	5M
F1		3M	3M	3M	3M	3M	3M	1	1
F2			2	2	2	2	2	2	6M
F3				8	8	8	8	8	8
PF count	1	2	3	4	5			6	7
SO count						1		2	
LRU	W1	W3	R2	R3	R5	R3	R8	R1	W6
F0	1M	1M	1M	1M	5M	5M	5M	5M	6M
F1		3M							
F2			2	2	2	2	2	1	1
F3				8	8	8	8	8	8
PF count	1	2	3	4	5			6	7
SO count						1		2	
LRU	W1	W3	R2	R3	R8	R5	R3	R1	W6
F0	1M	1M	1M	1M	1M	5M	5M	5M	5M
F1	c	3M	6M						
F2	c	2	2	2	2	2	2	1	1
F3	c	8	8	8	8	8	8	8	8
PF count	1	2	3	4	5			6	7
SO count								1	

c: clock position / u: usebit = 0

Suponha que temos um sistema Linux com blocos de disco de 4KB e ponteiros com 32 bits. Nesse sistema os inodes têm 8 ponteiros diretos, 1 ponteiro indireto e 1 ponteiro duplamente indireto para blocos. O sistema acabou de fazer um reboot pelo que todas as caches se encontram limpas e não existe nenhum inode em mem.

Qual o tamanho máximo de um ficheiro neste sistema?

pointers por bloco:  $4KB / 32b = 2^{12} / 2^2 = 2^{10}$

indirect pointer:  $2^{12} * 2^{10} = 2^{22}$

TOTAL:  $8 * 4KB + 4MB + 4GB$

2x indirect pointer:  $2^{22} * 2^{10} = 2^{32}$

Qual o número mínimo de blocos que é preciso ler do disco para ler o inode do ficheiro [/usr/teste.pdf](#)?

4 blocos (superbloco, b. da diretoria root, b. da diretoria usr, b. do test.pdf)

Depois de ler o inode do ficheiro, quantos mais blocos é necessário ler para aceder ao byte 32770 desse mesmo ficheiro?

O byte 32770 está no bloco  $\lceil 32770 / 2^{12} \rceil = 9$

Para aceder ao bloco 9, precisamos de aceder ao bloco apontado pelo ponteiro indireto e de seguida o bloco específico que contém o byte em questão, ou seja, precisamos de ler 2 bloco após o inode.

**ER 2017/2018**

Num sistema de tipo este um processo não deve conseguir usar memória que não lhe pertença. Explique como isso é garantido pelo sistema operativo.

Isto é garantido pelo SO ao associar "valid-bits" a cada PTE. Desse modo, o processo só pode aceder a uma dada pág. se o v-b da PTE estiver ativo.

Pode também haver um "Page-table length register", com o tamanho da tabela de cada proc. Acessos a endereços maiores que a tabela negados.

No entanto, em alguns casos, é necessário permitir que um processo possa aceder à memória usada por outro processo. Explique em que casos é necessário e de que forma o sistema operativo pode permitir o acesso de um processo à memória de outro processo.

Através de "Shared-Pages", vários processos mapeam as páginas parti-lhadas para a mesma page frame física. Isto pode ser necessário na implementação de IPCs.

A interrupção preemptiva de processos implica a existência de uma interrupção de relógio que permite interromper um processo em execução para dar lugar a outro. Tendo em conta os algoritmos de escalonamento que conhece, será que sempre que existe pelo menos um processo à espera para executar a interrupção de relógio leva à comutação de processos? Justifique.

Não necessariamente, nos algoritmos não-preemptivos o processo ativo tem de acabar a sua tarefa atual antes de comutar. Mesmo que haja uma interrupção de relógio, ele não vai ser trocado se ainda não tiver acabado a sua tarefa.

Qual a utilidade do Translation Look-aside Buffer num sistema de paging?

O TLB serve como uma cache que guarda um número relativamente pequeno de PTEs, tornando a pesquisa de págs bastante mais rápida.

Indique 2 formas de fazer o sistema mudar de user level para kernel level mode.

- Interrupts: Sinal para o CPU que interrompe o código atual e transfere o fluxo de execução para outro pedaço de código

- Systemcalls: Pedido de um programa para uma ação ser executada em kernel-mode (I/O, fork(), file write, etc.)

Considere um sistema de gestão de memória com um tempo de acesso à cache de 10ns e um tempo de acesso à memória principal de 200ns. Para o EAT (Effective Access Time) ser de 11 ns, qual terá de ser a hit ratio da cache?

p: pag. fault rate / m: mem. access

EAT =  $(1 - p) * m + p * [\text{swap-out} + \text{swap-in} + \text{OS overhead}] \ll$

pag. fault overhead  
11 =  $(1 - p) * (10 + 200) + p * (200 + 200) \ll$   
data check  
11 =  $210 - 210 * p + 400 * p \gg p < 0$

não funciona se assumirmos que o tempo de acesso após cache hit é

(cache + instruction fetch)

Suponha que tem um sistema de gestão de memória que usa páginas de 1KB e onde cada PTE (Page Table Entry) tem 4 bytes. Se os endereços lógicos ocuparem 34 bits, quantos níveis de páginas precisa para que cada tabela de páginas caiba numa única página? Como será feita a divisão dos bits no endereço lógico?

Cada pág. tem  $2^{10}/2^2 = 2^8$  PTEs.

offset (log(2)(1KB))

Com 1 nível, para endereçar cada pág., usamos  $8 + 10 = 18 < 34$

Com 2 níveis, temos  $p1 = 8, p2 = 8, offset = 10 \gg 26 < 34$

Com 3 níveis, temos  $p1 = 8, p2 = 8, p3 = 8, offset = 10 \gg 34 = 34$

Considere um disco com as seguintes características: 10000 rpm, 512 bytes per sector, 200 sectors por pista, com tempo médio de seek de 4.9ms. Nestas condições, quanto tempo em média demoraria a leitura de um bloco de 8KB contíguos no disco?

10000 rpm = 10000 / 60 rps 200 \* (512 \* 2<sup>9</sup>) = 102400 B/track

Trot = 1 / (2 \* (10000 / 60)) = 0.003s

Ttransf = size to transfer / (rps \* tracksize) =

Byte que usa  $8KB = 2^{13}$  / ((10000 / 60) \* 102400 = 0,00048s

Total = Tseek + Trot + Ttransf = 0,00838s

**EN 2017/2018**

Que vantagens pode ter um sistema operativo que use preemptive multitasking? Um SO que usa preemptão maximiza o uso de recursos do processador, uma vez que pode executar muitos processos simultaneamente e garante mais flexibilidade na escolha de quais executar, dada a prioridade de cada.

No contexto do escalonamento de processos explique sucintamente as funções do long-term scheduler e do short-term scheduler.

O LTS seleciona o processo da waiting list e carrega-o em memória. O STS seleciona o processo da ready queue a ser executado quando o CPU fica inativo.

Suponha que pretende aumentar a performance do seu sistema através da utilização de RAID1 ou RAID5. Qual deles escolheria para cada um dos cenários

aj) Bases de dados transacional com milhares de actualizações por segundo: RAID1, dado que permite leituras e escritas em paralelo, duplicando as esc. sem penalização. O desempenho de L e E é excelente, crucial para uma DB.

bj) Web server com conteúdos estáticos.

RAID5, dado que os dados e paridade são distribuídos em todos os discos, acelerando as operações de L, útil para conteúdos estáticos. Operações de E têm pior desempenho, mas isso é menos significativo neste contexto.

Made by

