I/O Hardware: I/O devices

Input/output devices are the devices that are responsible for the input/output operations in a computer system.

Basically there are following two types of input/output devices:

- Block devices
- Character devices

Block Devices

A block device stores information in block with fixed-size and own-address.

It is possible to read/write each and every block independently in case of block device.

In case of disk, it is always possible to seek another cylinder and then wait for required block to rotate under head without mattering where the arm currently is. Therefore, disk is a block addressable device.

Character Devices

A character device accepts/delivers a stream of characters without regarding to any block structure.

Character device isn't addressable.

Character device doesn't have any seek operation.

There are too many character devices present in a computer system such as printer, mice, rats, network interfaces etc. These four are the common character devices.

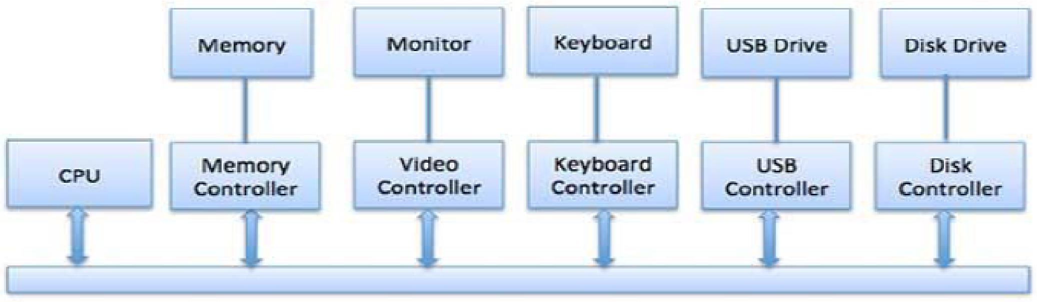
Device Controllers

Device drivers are software modules that can be plugged into an OS to handle a particular device. Operating System takes help from device drivers to handle all I/O devices.

The Device Controller works like an interface between a device and a device driver. I/O units (Keyboard, mouse, printer, etc.) typically consist of a mechanical component and an electronic component where electronic component is called the device controller.

There is always a device controller and a device driver for each device to communicate with the Operating Systems. A device controller may be able to handle multiple devices. As an interface its main task is to convert serial bit stream to block of bytes, perform error correction as necessary.

Any device connected to the computer is connected by a plug and socket, and the socket is connected to a device controller. Following is a model for connecting the CPU, memory, controllers, and I/O devices where CPU and device controllers all use a common bus for communication.



Synchronous vs asynchronous I/O

- **Synchronous I/O** − In this scheme CPU execution waits while I/O proceeds
- **Asynchronous I/O** − I/O proceeds concurrently with CPU execution

Communication to I/O Devices

The CPU must have a way to pass information to and from an I/O device. There are three approaches available to communicate with the CPU and Device.

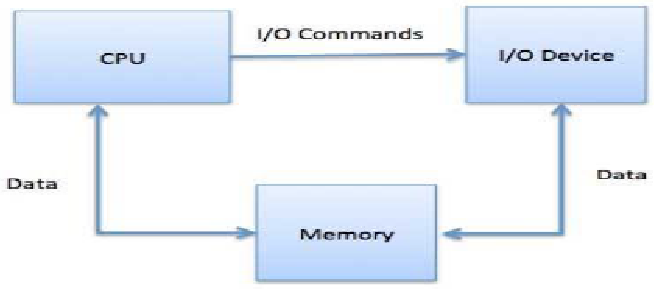
- Special Instruction I/O
- Memory-mapped I/O
- Direct memory access (DMA)

Special Instruction I/O

This uses CPU instructions that are specifically made for controlling I/O devices. These instructions typically allow data to be sent to an I/O device or read from an I/O device.

Memory-mapped I/O

When using memory-mapped I/O, the same address space is shared by memory and I/O devices. The device is connected directly to certain main memory locations so that I/O device can transfer block of data to/from memory without going through CPU.



While using memory mapped IO, OS allocates buffer in memory and informs I/O device to use that buffer to send data to the CPU. I/O device operates asynchronously with CPU, interrupts CPU when finished.

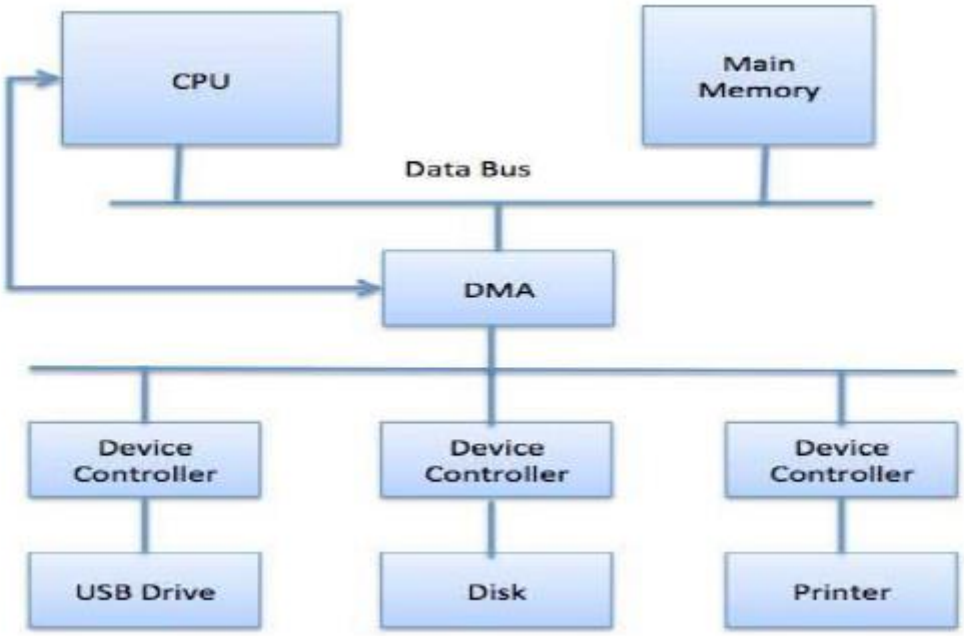
The advantage to this method is that every instruction which can access memory can be used to manipulate an I/O device. Memory mapped IO is used for most high-speed I/O devices like disks, communication interfaces.

Direct Memory Access (DMA)

Slow devices like keyboards will generate an interrupt to the main CPU after each byte is transferred. If a fast device such as a disk generated an interrupt for each byte, the operating system would spend most of its time handling these interrupts. So a typical computer uses direct memory access (DMA) hardware to reduce this overhead.

Direct Memory Access (DMA) means CPU grants I/O module authority to read from or write to memory without involvement. DMA module itself controls exchange of data between main memory and the I/O device. CPU is only involved at the beginning and end of the transfer and interrupted only after entire block has been transferred.

Direct Memory Access needs a special hardware called DMA controller (DMAC) that manages the data transfers and arbitrates access to the system bus. The controllers are programmed with source and destination pointers (where to read/write the data), counters to track the number of transferred bytes, and settings, which includes I/O and memory types, interrupts and states for the CPU cycles.



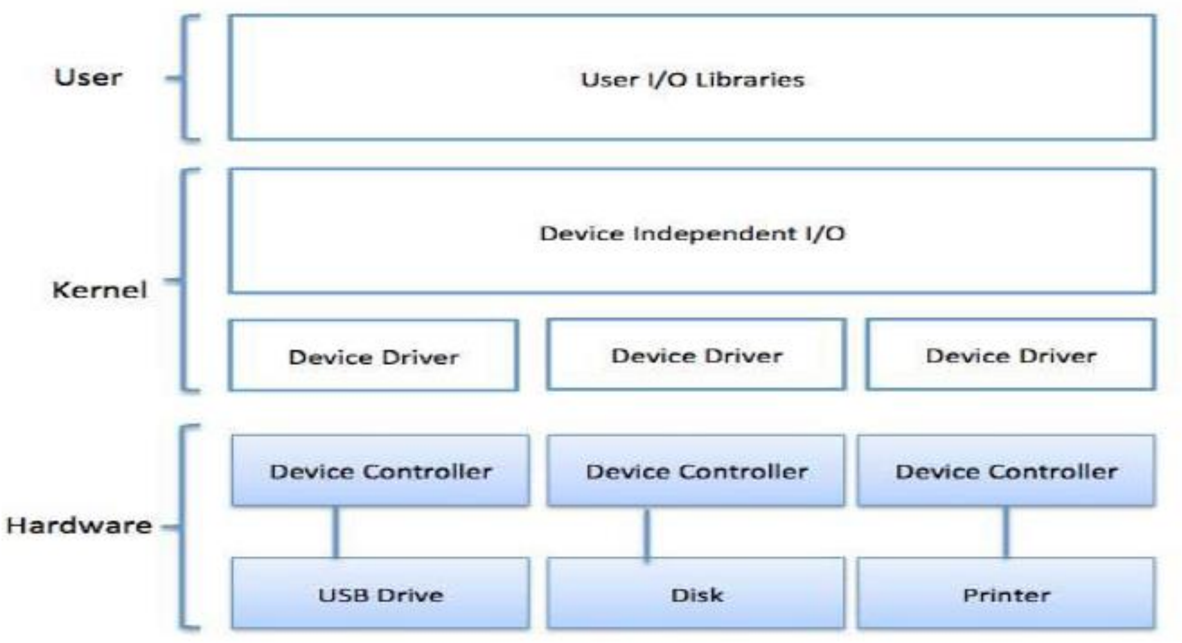
The operating system uses the DMA hardware as follows −

Step	Description
1	Device driver is instructed to transfer disk data to a buffer address X.
2	Device driver then instruct disk controller to transfer data to buffer.
3	Disk controller starts DMA transfer.
4	Disk controller sends each byte to DMA controller.
5	DMA controller transfers bytes to buffer, increases the memory address, decreases the counter C until C becomes zero.
6	When C becomes zero, DMA interrupts CPU to signal transfer completion.

I/O software is often organized in the following layers −

- **User Level Libraries** − This provides simple interface to the user program to perform input and output. For example, **stdio** is a library provided by C and C++ programming languages.
- **Kernel Level Modules** − This provides device driver to interact with the device controller and device independent I/O modules used by the device drivers.
- **Hardware** − This layer includes actual hardware and hardware controller which interact with the device drivers and makes hardware alive.

A key concept in the design of I/O software is that it should be device independent where it should be possible to write programs that can access any I/O device without having to specify the device in advance. For example, a program that reads a file as input should be able to read a file on a floppy disk, on a hard disk, or on a CD-ROM, without having to modify the program for each different device.



Device Drivers

Device drivers are software modules that can be plugged into an OS to handle a particular device. Operating System takes help from device drivers to handle all I/O devices. Device drivers encapsulate device-dependent code and implement a standard interface in such a way that code contains device-specific register reads/writes. Device driver, is generally written by the device's manufacturer and delivered along with the device on a CD-ROM.

A device driver performs the following jobs −

- To accept request from the device independent software above to it.
- Interact with the device controller to take and give I/O and perform required error handling
- Making sure that the request is executed successfully

How a device driver handles a request is as follows: Suppose a request comes to read a block N. If the driver is idle at the time a request arrives, it starts carrying out the request immediately. Otherwise, if the driver is already busy with some other request, it places the new request in the queue of pending requests.

Interrupt handlers

An interrupt handler, also known as an interrupt service routine or ISR, is a piece of software or more specifically a callback functions in an operating system or more specifically in a device driver, whose execution is triggered by the reception of an interrupt.

When the interrupt happens, the interrupt procedure does whatever it has to in order to handle the interrupt, updates data structures and wakes up process that was waiting for an interrupt to happen.

The interrupt mechanism accepts an address ─ a number that selects a specific interrupt handling routine/function from a small set. In most architecture, this address is an offset stored in a table called the interrupt vector table. This vector contains the memory addresses of specialized interrupt handlers.

Device-Independent I/O Software

The basic function of the device-independent software is to perform the I/O functions that are common to all devices and to provide a uniform interface to the user-level software. Though it is difficult to write completely device independent software but we can write some modules which are common among all the devices. Following is a list of functions of device-independent I/O Software −

- Uniform interfacing for device drivers
- Device naming - Mnemonic names mapped to Major and Minor device numbers
- Device protection
- Providing a device-independent block size
- Buffering because data coming off a device cannot be stored in final destination.
- Storage allocation on block devices
- Allocation and releasing dedicated devices
- Error Reporting

User-Space I/O Software

These are the libraries which provide richer and simplified interface to access the functionality of the kernel or ultimately interactive with the device drivers. Most of the user-level I/O software consists of library procedures with some exception like spooling system which is a way of dealing with dedicated I/O devices in a multiprogramming system.

I/O Libraries (e.g., stdio) are in user-space to provide an interface to the OS resident device-independent I/O SW. For example putchar(), getchar(), printf() and scanf() are example of user level I/O library stdio available in C programming.

Kernel I/O Subsystem

Kernel I/O Subsystem is responsible to provide many services related to I/O. Following are some of the services provided.

- **Scheduling** − Kernel schedules a set of I/O requests to determine a good order in which to execute them. When an application issues a blocking I/O system call, the request is placed on the queue for that device. The Kernel I/O scheduler rearranges the order of the queue to improve the overall system efficiency and the average response time experienced by the applications.
- **Buffering** − Kernel I/O Subsystem maintains a memory area known as **buffer** that stores data while they are transferred between two devices or between a device with an application operation. Buffering is done to cope with a speed mismatch between the producer and consumer of a data stream or to adapt between devices that have different data transfer sizes.
- **Caching** − Kernel maintains cache memory which is region of fast memory that holds copies of data. Access to the cached copy is more efficient than access to the original.
- **Spooling and Device Reservation** − A spool is a buffer that holds output for a device, such as a printer, that cannot accept interleaved data streams. The spooling system copies the queued spool files to the printer one at a time. In some operating systems, spooling is managed by a system daemon process. In other operating systems, it is handled by an in kernel thread.
- **Error Handling** − An operating system that uses protected memory can guard against many kinds of hardware and application errors.

Disk Scheduling Algorithms

Disk scheduling algorithms are used to allocate the services to the I/O requests on the disk . Since seeking disk requests is time consuming, disk scheduling algorithms try to minimize this latency. If desired disk drive or controller is available, request is served immediately. If busy, new request for service will be placed in the queue of pending requests. When one request is completed, the Operating System has to choose which pending request to service next. The OS relies on the type of algorithm it needs when dealing and choosing what particular disk request is to be processed next. The objective of using these algorithms is keeping Head movements to the amount as possible. The less the head to move, the faster the seek time will be. To see how it works, the different disk scheduling algorithms will be discussed and examples are also provided for better understanding on these different algorithms.

1. *First Come First Serve(FCFS)*

It is the simplest form of disk scheduling algorithms. The I/O requests are served or processes according to their arrival. The request arrives first will be accessed and served first. Since it follows the order of arrival, it causes the wild swings from the innermost to the outermost tracks of the disk and vice versa . The farther the location of the request being serviced by the read/write head from its current location, the higher the seek time will be.

Example: Given the following track requests in the disk queue, compute for the Total Head Movement (THM) of the read/write head :

95, 180, 34, 119, 11, 123, 62, 64

Consider that the read/write head is positioned at location 50. Prior to this track location 199 was serviced. Show the total head movement for a 200 track disk (0-199).

Solution:

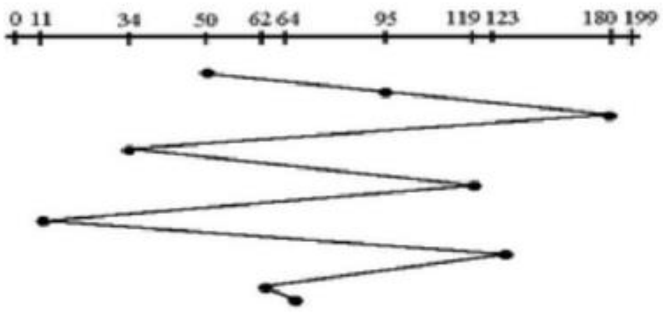


Fig. FCFS Representation

Total Head Movement Computation: (THM) =

(180 - 50) + (180-34) + (119-34) + (119-11) + (123-11) + (123-62) + (64-62) =

130 + 146 + 85 + 108 + 112 + 61 + 2 (THM) = 644 tracks

Assuming a seek rate of 5 milliseconds is given, we compute for the seek time using the formula: Seek Time = THM * Seek rate
=644 * 5 ms
Seek Time = 3,220 ms.

2. *Shortest Seek Time First(SSTF):*

This algorithm is based on the idea that that he R/W head should proceed to the track that is closest to its current position . The process would continue until all the track requests are taken care of. Using the same sets of example in FCFS the solution are as follows:

Solution:

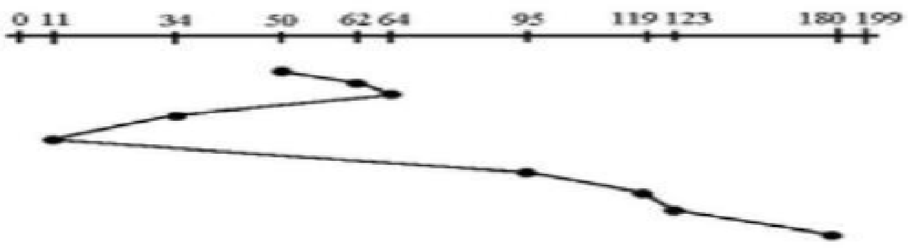


Fig. SSTF Representation

(THM) = (64-50) + (64-11) + (180-11) =

14 + 53 + 169 (THM) = 236 tracks

Seek Time = THM * Seek rate

= 236 * 5ms
Seek Time = 1,180 ms
In this algorithm, request is serviced according to the next shortest distance. Starting at 50, the next shortest distance would be 62 instead of 34 since it is only 12 tracks away from 62 and 16 tracks away from 34 . The process would continue up to the last track request. There are a total of 236 tracks and a seek time of 1,180 ms, which seems to be a better service compared with FCFS which there is a chance that starvation3 would take place. The reason for this is if there were lots of requests closed to each other, the other requests will never be handled since the distance will always be greater.

3. SCAN Scheduling Algorithm

This algorithm is performed by moving the R/W head back-and-forth to the innermost and outermost track. As it scans the tracks from end to end, it process all the requests found in the direction it is headed. This will ensure that all track requests, whether in the outermost, middle or innermost location, will be traversed by the access arm thereby finding all the requests. This is also known as the Elevator algorithm. Using the same sets of example in FCFS the solution are as follows:

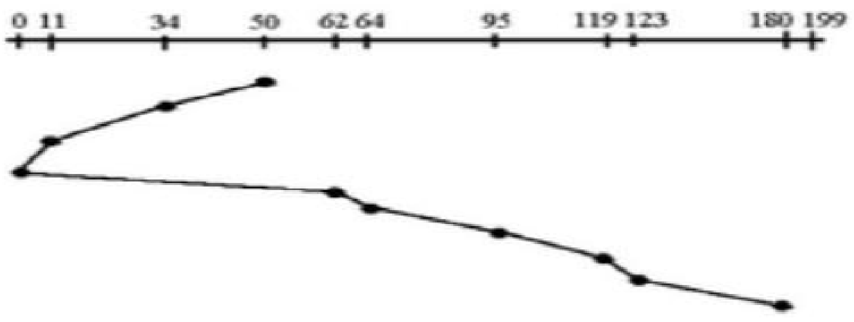


Fig. SCAN Representation

(THM) = (50-0) + (180-0)
= 50 + 180
(THM) = 230

*Seek Time = THM * Seek rate*
*= 230 * 5ms*
Seek Time = 1,150 ms

This algorithm works like an elevator does. In the algorithm example, it scans down towards the nearest end and when it reached the bottom it scans up servicing the requests that it did not get going down. If a request comes in after it has been scanned, it will not be serviced until the process comes back down or moves back up. This process moved a total of 230 tracks and a seek time of 1,150. This is optimal than the previous algorithm.

4 .Circular SCAN (C-SCAN)Algorithm

This algorithm is a modified version of the SCAN algorithm. C-SCAN sweeps the disk from end-to-end, but as soon it reaches one of the end tracks it then moves to the other end track without servicing any requesting location. As soon as it reaches the other end track it then starts servicing and grants requests headed to its direction. This algorithm improves the unfair situation of the end tracks against the middle tracks. Using the same sets of example in FCFS the solution are as follows:

Solution:

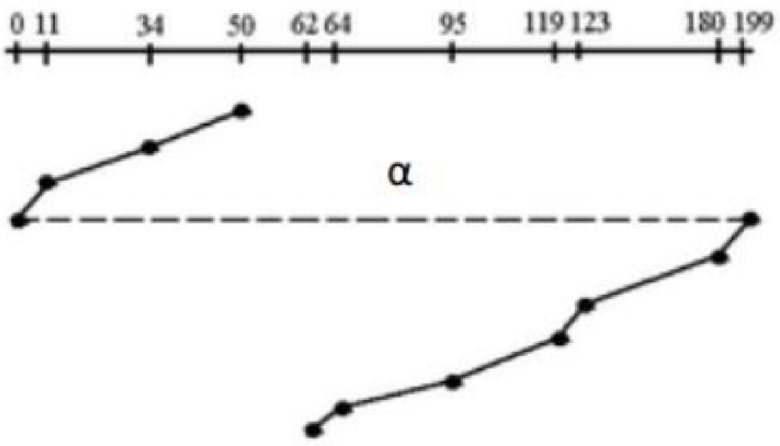


Fig. C-SCAN Representation

Notice that in this example an alpha3 symbol (α) was used to represent the dash line. This return sweeps is sometimes given a numerical value which is included in the computation of the THM . As analogy, this can be compared with the carriage return lever of a typewriter. Once it is pulled to the right most direction, it resets the typing point to the leftmost margin of the paper . A typist is not supposed to type during the movement of the carriage return lever because the line spacing is being adjusted . The frequent use of this lever consumes time, same with the time consumed when the R/W head is reset to its starting position.

Assume that in this example, α has a value of 20ms, the computation would be as follows: (THM) = (50-0) + (199-62) + α
= 50 + 137 + 20 (THM)

= 207 tracks

Seek Time = THM * Seek rate

= 187 * 5ms Seek Time = 935 ms .

The computation of the seek time excluded the alpha value because it is not an actual seek or search of a disk request but a reset of the access arm to the starting position .

DISK MANAGEMENT

The operating system is responsible for several aspects of disk management.

Disk Formatting

A new magnetic disk is a blank slate. It is just platters of a magnetic recording material. Before a disk can store data, it must be divided into sectors that the disk controller can read and write. This process is called low-level formatting (or **physical formatting).**

Low-level formatting fills the disk with a special data structure for each sector. The data structure for a sector consists of a header, a data area, and a trailer. The header and trailer contain information used by the disk controller, such as a sector number and an **error-correcting code** (ECC).

To use a disk to hold files, the operating system still needs to record its own data structures on the disk. It does so in two steps. The first step is to **partition** the disk into one or more groups of cylinders. The operating system can treat each partition as though it were a separate disk. For instance, one partition can hold a copy of the operating system's executable code, while another holds user files. After partitioning, the second step is **logical formatting** (or creation of a file system). In this step, the operating system stores the initial file-system data structures onto the disk.

Boot Block

When a computer is powered up or rebooted, it needs to have an initial program to run. This initial program is called bootstrap program. It initializes all aspects of the system (i.e. from CPU registers to device controllers and the contents of main memory) and then starts the operating system.

To do its job, the bootstrap program finds the operating system kernel on disk, loads that kernel into memory, and jumps to an initial address to begin the operating-system execution.

For most computers, the bootstrap is stored in read-only memory **(ROM).** This location is convenient, because ROM needs no initialization and is at a fixed location that the processor can start executing when powered up or reset. And since ROM is read only, it cannot be infected by a computer virus. The problem is that changing this bootstrap code requires changing the ROM hardware chips.

For this reason, most systems store a tiny bootstrap loader program in the boot ROM, whose only job is to bring in a full bootstrap program from disk. The full bootstrap program can be changed easily: A new version is simply written onto the disk. The full bootstrap program is stored in a partition (at a fixed location on the disk) is called **the boot blocks**. A disk that has a boot partition is called **a boot disk or system disk.**

Bad Blocks

Since disks have moving parts and small tolerances, they are prone to failure. Sometimes the failure is complete, and the disk needs to be replaced, and its contents restored from backup media to the new disk.

More frequently, one or more sectors become defective. Most disks even come from the factory with bad blocks. Depending on the disk and controller in use, these blocks are handled in a variety of ways.

The controller maintains a list of bad blocks on the disk. The list is initialized during the low-level format at the factory, and is updated over the life of the disk. The controller can be told to replace each bad sector logically with one of the spare sectors. This scheme is known as sector sparing or forwarding.

SWAP-SPACE MANAGEMENT

The swap-space management is a low-level task of the operating system. The main goal for the design and implementation of swap space is to provide the best throughput for the virtual-memory system.

Swap-Space Use

Swap space is used in various ways by different operating systems depending on the implemented memory-management algorithms.

Those systems are implemented swapping, they may use swap space to hold the entire process image, including the code and data segments. The amount of swap space needed on a system can vary depending on the amount of physical memory,

Swap-Space Location

A swap space can reside in two places: Swap space can be carved out of the normal file system, or it can be in a separate disk partition.

If the swap space is simply a large file within the file system, normal file-system routines can be used to create it, name it, and allocate its space. This approach is easy to implement and is also inefficient.

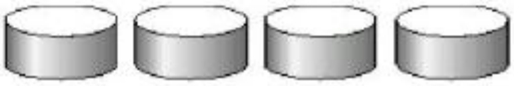
Alternatively, swap space can be created in a separate disk partition. No file system or directory structure is placed on this space. A separate swap-space storage manager is used to allocate and deallocate the blocks. This manager uses algorithms optimized for speed and storage efficiency.

RAID STRUCTURE

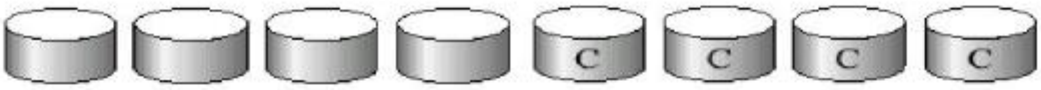
A Redundant Array of Inexpensive Disks(RAID) may be used to increase disk reliability. RAID may be implemented in hardware or in the operating system.

The RAID consists of seven levels, zero through six. These levels designate different design architectures that share three common characteristics:

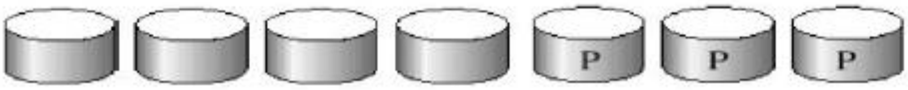
- RAID is a set of physical disk drives viewed by the operating system as a single logical drive.
- Data are distributed across the physical drives of an array in a scheme known as striping, described subsequently.
- Redundant disk capacity is used to store parity information, which guarantees data recoverability in case of a disk failure.



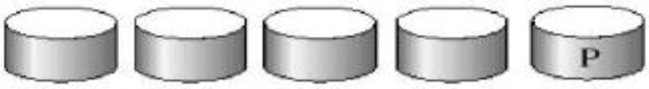
(a) RAID 0: non-redundant striping



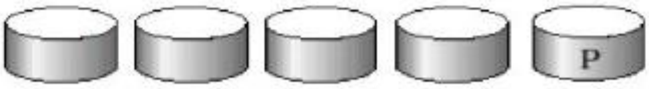
(b) RAID 1: mirrored disks



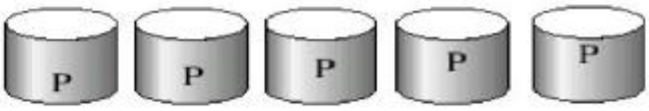
(c) RAID 2: memory-style error-correcting codes



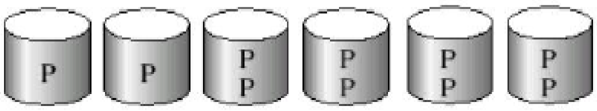
(d) RAID 3: bit-interleaved Parity



(e) RAID 4: block-interleaved parity



(f) RAID 5: block-Interleaved distributed parity



(g) RAID 6: P + Q redundancy

(RAID levels)

(Here *P* indicates error-correcting bits and C indicates a second copy of the data)

The RAID levels are described as follows:

- **RAID Level 0:** RAID level 0 refers to disk arrays with striping at the level of blocks, but without any redundancy (such as parity bits). Figure(a) shows an array of size 4.
- **RAID Level 1:** RAID level 1 refers to disk mirroring. Figure (b) shows a mirrored organization that holds four disks' worth of data.
- **RAID Level 2:** RAID level 2 is also known as **memory-style error-correcting code (ECC) organization.** Each byte in a memory system may have a parity bit associated with it that records whether the numbers of bits in the byte set to 1 is even (parity=O) or odd (parity=l). The idea of ECC can be used directly in disk arrays via striping of bytes across disks.
- **RAID level 3:** RAID level **3**, or **bit-interleaved parity organization**, improves on level 2 by noting that, disk controllers can detect whether a sector has been read correctly, so a single parity bit can be used for error correction, as well as for detection. The idea is as follows. If one of the sectors gets damaged, we know exactly which sector it is, and, for each bit in the sector, we can figure out whether it is a 1 or a 0 by computing the parity of the corresponding bits from sectors in the other disks. If the parity of the remaining bits is equal to the stored parity, the missing bit is 0; otherwise, it is 1.
- **RAID Level 4: RAID level 4 or block-interleaved parity organization** uses block-level striping, as in RAID 0 and in addition keeps a parity block on a separate disk for corresponding blocks from N other disks. This scheme is shown pictorially in Figure(e). If one of the disks fails, the parity block can be used with the corresponding blocks from the other disks to restore the blocks of the failed disk.
- **RAID level 5: RAID level 5 or block-interleaved distributed parity** is similar as level 4 but level 5 spreading data and parity among all N + 1 disks, rather than storing data in N disks and parity in one disk. For each block, one of the disks stores the parity, and the others store data. By spreading the parity across all the disks in the set, RAID 5 avoids the potential overuse of a single parity disk that can occur with RAID 4.
- **RAID Level 6:** RAID level 6 (is also called the P+Q redundancy scheme) is much like RAID level 5, but stores extra redundant information to guard against multiple disk failures. Instead of using parity, error-correcting codes such as the **Reed-Solomon codes** are used.