UNIT IV

Deadlocks: System Model, deadlock characterization, Methods of handling Deadlocks, Deadlock prevention, Detection and Avoidance, Recovery from deadlock.

Mass-storage structure: Overview of Mass-storage structure, Disk structure, Disk attachment, Disk scheduling, Swap-space management, RAID structure, Stable-storage implementation.

File system Interface: The concept of a file, Access Methods, Directory and Disk structure, File system mounting, File sharing, Protection.

File system Implementation: File-system structure, File-system Implementation, Directory Implementation, Allocation Methods, Free-Space management.

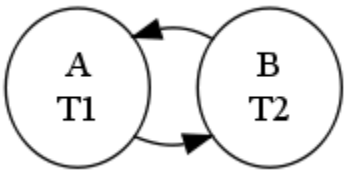
DEADLOCKS

Definition

A set of two or more processes are deadlocked if they are blocked (i.e., in the waiting state) each holding a resource and waiting to acquire a resource held by another process in the set.

or

A process is deadlocked if it is waiting for an event which is never going to happen.



Example:

- a system has two tape drives
- two processes are deadlocked if each holds one tape drive and has requested the other

Example: semaphores A and B, each initialized to 1:

```
P_0           P_1
---           ---
A.wait();     B.wait();
B.wait();     A.wait();
```

```
A.signal();  B.signal();
B.signal();  A.signal();
```

Deadlock depends on the dynamics of the execution.
Illustrates that it is difficult to identify and test for deadlocks which may occur only under certain circumstances.

System model:

- resource types: R_1, R_2, ..., R_n
- each resource R has W_i instances
- each process utilizes a resource as follows:

```
// request (e.g., open() system call)
// use
// release (e.g., close() system call)
```

Any instance of a resource type can be used to satisfy a request of that resource.

Conditions Necessary for Deadlock

All of the following four necessary conditions must hold simultaneously for deadlock to occur:

- **mutual exclusion:** only one process can use a resource at a time.
- **hold and wait:** a process holding at least one resource is waiting to acquire additional resources which are currently held by other processes.
- **no preemption:** a resource can only be released voluntarily by the process holding it.
- **circular wait:** a cycle of process requests exists (i.e., P_0 is waiting for a resource hold by P_1 who is waiting for a resource held by P_j ... who is waiting for a resource held by $P_{(n-1)}$ which is waiting for a resource held by P_n which is waiting for a resource held by P_0).

Circular wait implies the hold and wait condition. Therefore, these conditions are not completely independent.

Resource Allocation Graph Syntax

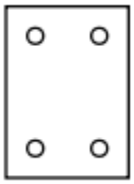
A resource allocation graph contains a set of vertices V and a set of edges E.

V is partitioned into two types:

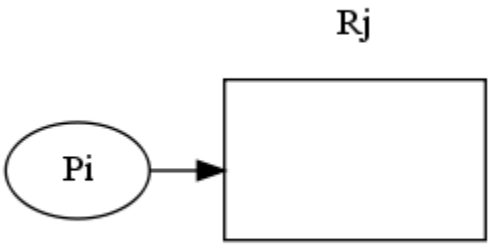
- $P = \{P_1, P_2, \ldots, P_n\}$ is the set of all processes.
- $R = \{R_1, R_2, \ldots, R_m\}$ is the set of all resources.

A *request* is represented by a directed edge from P_i to R_j.
An *assignment* is represented by a directed edge from R_j to P_i.

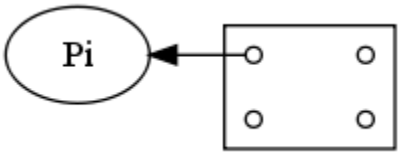
- resource type with four instances:



- P_i requests an instance of R_j

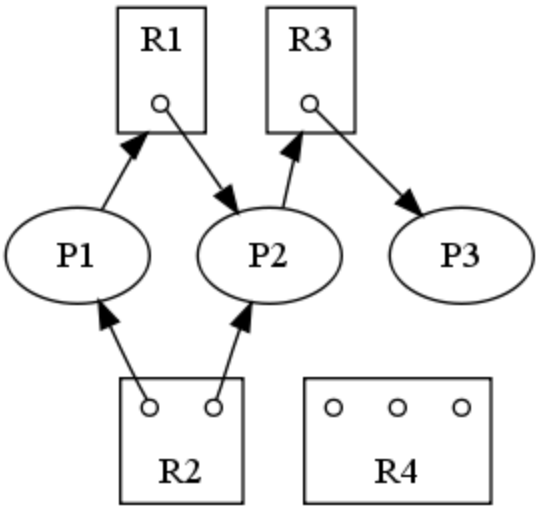


- P_i is holding an instance of R_j



Sample Resource Allocation Graphs

- **resource allocation graph without deadlock:**
    - P_1 wants a resource held by P_2
    - no process is requesting an instance of R_4



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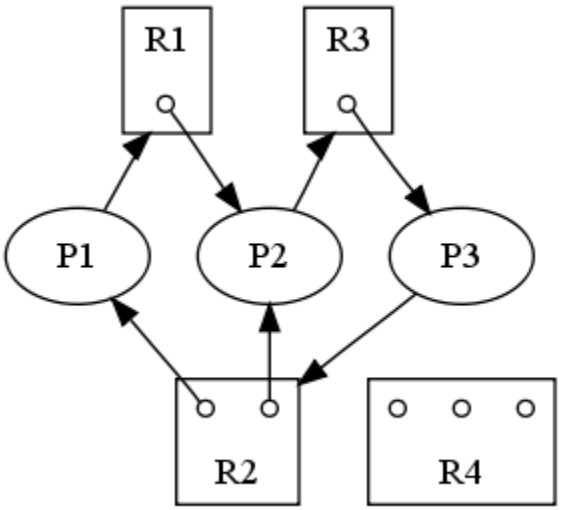
- **resource allocation graph with a cycle and deadlock:**



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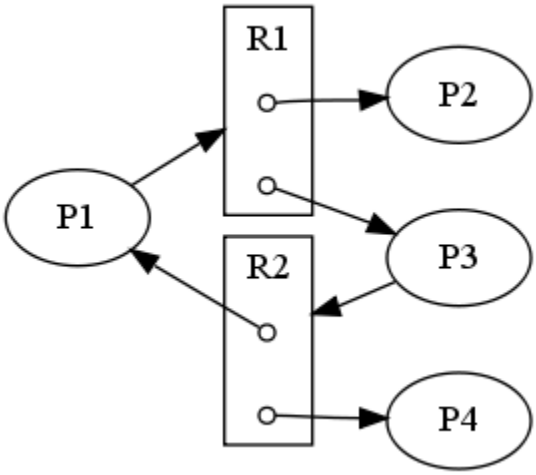
- **resource allocation graph with a cycle but no deadlock:**



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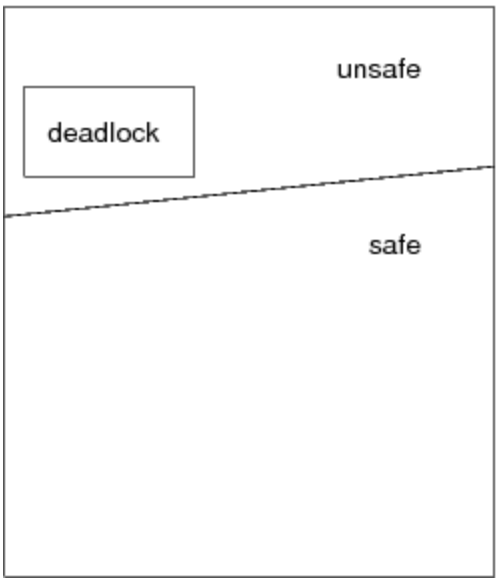
Possibility of Deadlock



If a resource allocation graph contains no cycles, then no process is deadlocked.

If a resource allocation graph contains a cycle, then a deadlock may exist.

Therefore, a cycle means deadlock is *possible*, but not necessarily *present*.

A cycle is not sufficient proof of the presence of deadlock. A cycle is a *necessary* condition for deadlock, but not a *sufficient* condition for deadlock.

Resource Allocation Graph Summary

- if a resource allocation graph does not contain a cycle, then there is absolutely no possibility of deadlock
- if a resource allocation graph contains a cycle, then there is the possibility of deadlock
- if each resource type has exactly one instance, then a cycle implies that deadlock has occurred
- if the cycle involves only a set of resource types, each of which has only a single instance, then a deadlock has occurred
- if all instances of a resource are allocated to a process in a cycle, then there is deadlock

Methods for Handling Deadlock

The following are methods for addressing the possibility of deadlock:

- ensure that the system never enters a deadlocked state:
  - deadlock prevention
  - deadlock avoidance
- deadlock detection and recovery: allow the system to enter a deadlocked state, then deal with and eliminate the problem
- ignore the problem: approached used by many operating systems including UNIX and Windows, and the Java VM

Deadlock Prevention

Restrain the ways resource requests are made so to prevent one of the four conditions necessary for deadlock.

- **prevent mutual exclusion**
  - use only sharable resources (e.g., a read-only file)
  - impossible for practical systems

- **prevent hold and wait**
  - methods
    - preallocate
      - do not pick up one chopstick if you cannot pick up the other
      - for a process that copies data from DVD drive to a file on disk and then prints it from there:
        1. request DVD drive
        2. request disk file
        3. request printer
      - all system calls requesting resources must proceed all other system calls

    - a process can request resources only when it has none
        1. request DVD drive and disk file
        2. release DVD drive and disk file
        3. request disk file and printer (no guarantee data will still be there)

4. release disk file and printer

inefficient
starvation possible

prevent no preemption (i.e., allow preemption, and permit the OS to take away resources from a process)

when a process must wait, it must release its resources
some resources cannot be feasibly preempted (e.g., printers, tape drives)

prevent circular wait

impose a total ordering on resources
only allow requests in an increasing order

Usually a deadlock prevention approach is simply unreasonable.

Deadlock Avoidance

This requires that the system has some information available up front. Each process declares the maximum number of resources of each type which it may need. Dynamically examine the resource allocation state to ensure that there can never be a circular-wait condition.

The system's resource-allocation state is defined by the number of available and allocated resources, and the maximum possible demands of the processes. When a process requests an available resource, the system must decide if immediate allocation leaves the system in a *safe state*.

The system is in a safe state if there exists a safe sequence of all processes:

Sequence < P_1, P_2, ... P_n > is safe for the current allocation state if, for each P_i, the resources which P_i can still request can be satisfied by

- the currently available resources plus

- the resources held by all of the P_j's, where $j < i$.

If the system is in a safe state, there can be no deadlock. If the system is in an unsafe state, there is the *possibility* of deadlock.

Example: consider a system with 12 magnetic tapes and 3 processes (P_0, P_1, and P_2):

available = 3			
Process	**Maximum Needs**	**Holding**	**Needs**
P_0	10	5	5
P_1	4	2	2
P_2	9	2	7

Is the system in a safe state? If so, which sequence satisfies the safety criteria?

available = 2			
Process	**Maximum Needs**	**Holding**	**Needs**
P_0	10	5	5
P_1	4	2	2
P_2	9	3	6

Is the system in a safe state? If so, which sequence satisfies the safety criteria?

In this scheme, a process which requests a resource that is currently available, may still have to wait. Thus, resource utilization may be lower than it would otherwise be.

Deadlock Avoidance Algorithms

Two deadlock avoidance algorithms:

- resource-allocation graph algorithm
- Banker's algorithm

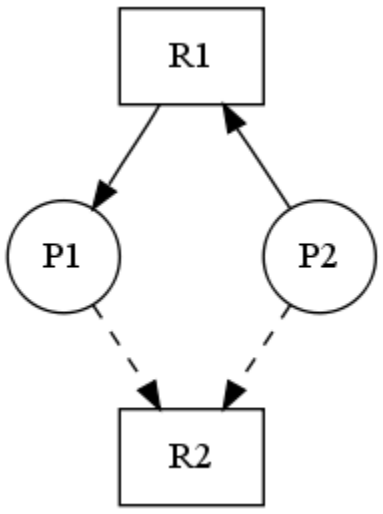
Resource-allocation graph algorithm

- only applicable when we only have 1 instance of each resource type
- claim edge (dotted edge), like a *future* request edge
- when a process requests a resource, the claim edge is converted to a request edge
- when a process releases a resource, the assignment edge is converted to a claim edge
- cycle detection: $O(n^2)$

Banker's Algorithm

- a classic deadlock avoidance algorithm
- more general than resource-allocation graph algorithm (handles multiple instances of each resource type), but
- is less efficient

Resource-allocations graphs for deadlock avoidance



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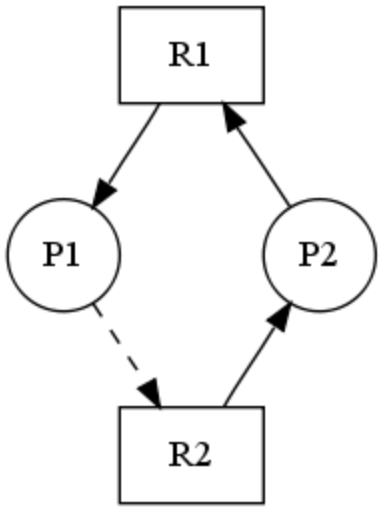

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Banker's Algorithm

We call Banker's algorithm when a request for R is made. Let `n` be the number of processes in the system, and `m` be the number of resource types.

Define:

- `available[m]`: the number of units of R currently unallocated (e.g., `available[3] = 2`)
- `max[n][m]`: describes the maximum demands of each process (e.g., `max[3][1] = 2`)
- `allocation[n][m]`: describes the current allocation status (e.g., `allocation[5][1] = 3`)
- `need[n][m]`: describes the *remaining* possible need (i.e., `need[i][j] = max[i][j] - allocation[i][j]`)

Resource-request algorithm:

Define:

- `request[n][m]`: describes the current outstanding requests of all processes (e.g., `request[2][1] = 3`)

1. If `request[i][j] <= need[i][j]`, to to step 2; otherwise, raise an error condition.
2. If `request[i][j] > available[j]`, then the process must wait.
3. Otherwise, *pretend* to allocate the requested resources to P_i :

```
4.       available[j] = available[j] - request[i][j]
5.       allocation[i][j] = allocation[i][j] +
   request[i][j]
         need[i][j] = need[i][j] - request[i][j]
```

Once the resources are *allocated*, check to see if the system state is safe. If unsafe, the process must wait and the old resource-allocated state is restored.

Safety algorithm (to check for a safe state):

1. Let `work` be an integer array of length `m`, initialized to `available`.
   Let `finish` be a boolean array of length `n`, initialized to `false`.

2. Find an `i` such that both:
   - `finish[i] == false`
   - `need[i] <= work`

   If no such `i` exists, go to step 4

3. ```
   work = work + allocation[i];
   finish[i] = true;
   ```
   Go to step 2

4. If `finish[i] == true` for all `i`, then the system is in a safe state, otherwise unsafe.

Run-time complexity: $\boldsymbol{O(m \times n^2)}$.

Example: consider a system with 5 processes (P_0 ... P_4) and 3 resources types (`A(10) B(5) C(7)`)

resource-allocation state at time t_0:

Process	**Allocation**			**Max**			**Need**			**Available**		
	A	B	C	A	B	C	A	B	C	A	B	C
P_0	0	1	0	7	5	3	7	4	3	3	3	2
P_1	2	0	0	3	2	2	1	2	2			
P_2	3	0	2	9	0	2	6	0	0			
   ```

P_3	2	1	1	2	2	2	0	1	1
P_4	0	0	2	4	3	3	4	3	1

Is the system in a safe state? If so, which sequence satisfies the safety criteria?

`< P1, P3, P4, P2, P0 >`

Now suppose, P_1 requests an additional instance of A and 2 more instances of type C.

```
request[1] = (1,0,2)
```

1. check if `request[1] <= need[i]` (yes)
2. check if `request[1] <= available[i]` (yes)
3. do pretend updates to the state

Process	Allocation			Max			Need			Available		
	A	B	C	A	B	C	A	B	C	A	B	C
P_0	0	1	0	7	5	3	7	4	3	3	3	2
P_1	3	0	2	3	2	2	0	2	0			
P_2	3	0	2	9	0	2	6	0	0			
P_3	2	1	1	2	2	2	0	1	1			
P_4	0	0	2	4	3	3	4	3	1			

Is the system in a safe state? If so, which sequence satisfies the safety criteria?

<P_1, P_3, P_4, P_0, P_2>

Hence, we immediately grant the request.

Will a request of (3,3,0) by P_4 be granted?

Will a request of (0,2,0) by P_0 be granted?

Deadlock Detection

- requires an algorithm which examines the state of the system to determine whether a deadlock has occurred
- requires overhead
  - run-time cost of maintaining necessary information and executing the detection algorithm

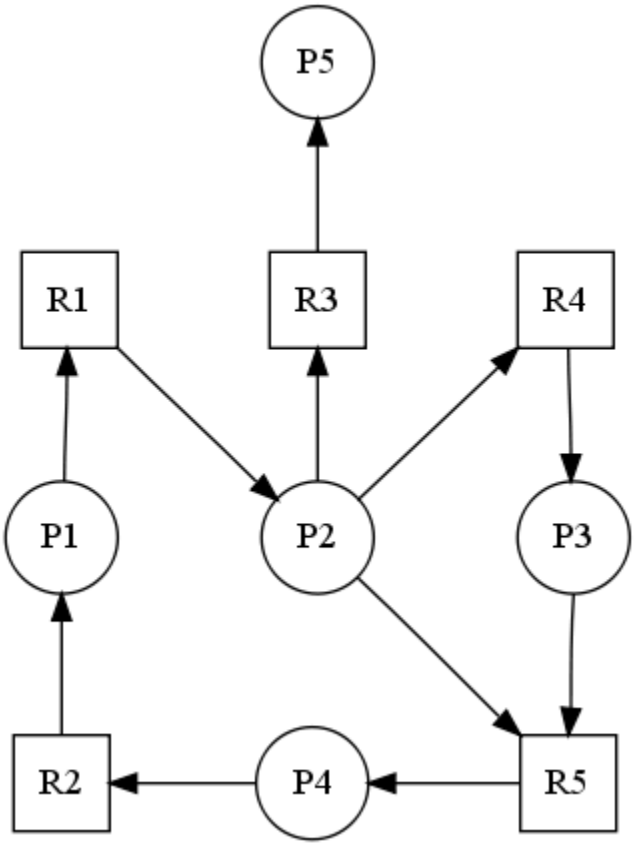
- potential losses inherent in recovering from deadlock

Single instance of each resource type

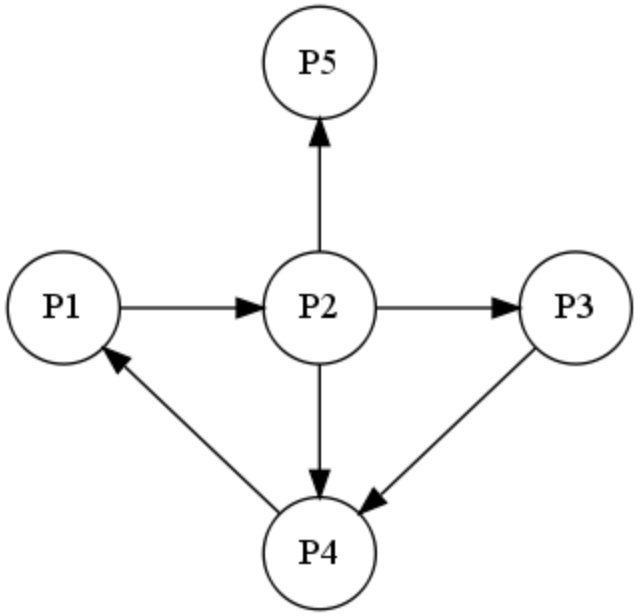
- wait-graph
- $P_i \rightarrow P_j = P_i > R_q$ and $R_q \rightarrow P_j$
- detect cycle: ***O*(*n*²)**
- overhead: maintain the graph + invoke algorithm

Resource-allocations graphs for deadlock detection

resource-allocation graph:



corresponding wait-for graph:



(regenerated from [OSC8] Fig. 7.8 on p. 302)

Multiple instances of a resource type: use an algorithm similar to Banker's, which simply investigates *every* possible allocation sequence for the processes which remain to be completed.

Define:

- `available[m]`
- `allocation[n][m]`
- `request[n][m]`
  with their usual semantics.

Algorithm:

1. Let `work` be an integer array of length `m`, initialized to `available`.

   Let finish be a boolean array of length `n`.

   For all `i`, if `allocation[i] != 0`, then `finish[i] = false;`
   Otherwise `finish[i] = true`.

2. Find an `i` such that both
   - `finish[i] == false //` P_i is currently *not* involved in a deadlock

- `request[i] <= work`

If no such `i` exists, go to step 4

3. // reclaim the resources of process P_i
   ```
   work = work + allocation[i];
   finish[i] = true;
   ```
   Go to step 2

4. If `finish[i] == false` for some `i`,
   Then the system is in a deadlocked state.
   Moreover, if `finish[i] == false`, then process P_i is deadlocked.

Run-time complexity: $\boldsymbol{O(m \times n^2)}$.

Example: consider a system with 5 processes (P_0 .. P_4) and 3 resources types (`A(7) B(2) C(6)`)

resource-allocation state at time t_0:

Process	**Allocation**			**Request**			**Available**		
	A	B	C	A	B	C	A	B	C
P_0	0	1	0	0	0	0	0	0	0
P_1	2	0	0	2	0	2			
P_2	3	0	3	0	0	0			
P_3	2	1	1	1	0	0			
P_4	0	0	2	0	0	2			

Is the system in a deadlocked state?

If not, which sequence results in `finish[i] == true` for all `i` ?

< P_0, P_2, P_3, P_1, P_4 >

Now suppose, P_2 requests an additional instance of `C`:

Process	**Allocation**			**Request**			**Available**		
	A	B	C	A	B	C	A	B	C

P_0	0	1	0	0	0	0	0	0	0
P_1	2	0	0	2	0	2			
P_2	3	0	3	0	0	1			
P_3	2	1	1	1	0	0			
P_4	0	0	2	0	0	2			

Is the system in a deadlocked state? Yes.

If not, which sequence results in `finish[i] == true` for all `i` ?

Although we can reclaim the resources held by P_0, the number of available resources is insufficient to fulfill the requests of the other processes.

Thus, a deadlock exists, consisting of processes P_1, P_2, P_3, and P_4.

When should we invoke the detection algorithm? Depends on:

- how *often* is a deadlock likely to occur
- how *many* processes will be affected by deadlock when it happens

If deadlocks occur frequently, then the algorithm should be invoked frequently.

Deadlocks only occur when some process makes a request which cannot be granted (if this request is the completes a chain of waiting processes).

- **Extreme:** invoke the algorithm every time a request is denied
- **Alternative**: invoke the algorithm at less frequent time intervals:
  - once per hour
  - whenever CPU utilization < 40%
  - disadvantage: cannot determine exactly which process 'caused' the deadlock

Deadlock Recovery

How to deal with deadlock:

- inform operator and let them decide how to deal with it manually
- let the system *recover* from the deadlock automatically:

    - abort or more of the deadlocked processes to break the circular wait
    - preempt some resources from one or more of the processes to break the circular wait

Process termination

Aborting a process is not easy; involves clean-up (e.g., file, printer).

- abort all deadlocked processes (disadvantage: wasteful)
- abort one process at a time until the circular wait is eliminated
    - disadvantage: lot of overhead; must re-run algorithm after each kill
    - how to determine which process to terminate? minimize cost
        - priority of the process
        - how long has it executed? how much more time does it need?
        - how many and what type of resources has the process used?
        - how many more resources will the process need to complete?
        - how many processes will need to be terminated?
        - is the process interactive or batch?

Resource Preemption

Incrementally preempt and re-allocate resources until the circular wait is broken.

- selecting a victim (see above)
- rollback: what should be done with process which lost the resource?
  clearly it cannot continue; must rollback to a safe state (???)
  => total rollback
- starvation: pick victim only small (finite) number of times; use number of rollbacks in decision

Mass-Storage Structure

10.1 Overview of Mass-Storage Structure

10.1.1 Magnetic Disks

- Traditional magnetic disks have the following basic structure:
  - One or more ***platters*** in the form of disks covered with magnetic media. ***Hard disk*** platters are made of rigid metal, while "***floppy***" disks are made of more flexible plastic.
  - Each platter has two working ***surfaces.*** Older hard disk drives would sometimes not use the very top or bottom surface of a stack of platters, as these surfaces were more susceptible to potential damage.
  - Each working surface is divided into a number of concentric rings called ***tracks.*** The collection of all tracks that are the same distance from the edge of the platter, (i.e. all tracks immediately above one another in the following diagram) is called a ***cylinder***.
  - Each track is further divided into ***sectors,*** traditionally containing 512 bytes of data each, although some modern disks occasionally use larger sector sizes. (Sectors also include a header and a trailer, including checksum information among other things. Larger sector sizes reduce the fraction of the disk consumed by headers and trailers, but increase internal fragmentation and the amount of disk that must be marked bad in the case of errors.)
  - The data on a hard drive is read by read-write ***heads.*** The standard configuration (shown below) uses one head per surface, each on a separate ***arm***, and controlled by a common ***arm assembly*** which moves all heads simultaneously from one cylinder to another. (Other configurations, including independent read-write heads, may speed up disk access, but involve serious technical difficulties.)
  - The storage capacity of a traditional disk drive is equal to the number of heads (i.e. the number of working surfaces), times the number of tracks per surface, times the number of sectors per track, times the number of bytes per sector. A particular physical block of data is specified by providing the head-sector-cylinder number at which it is located.

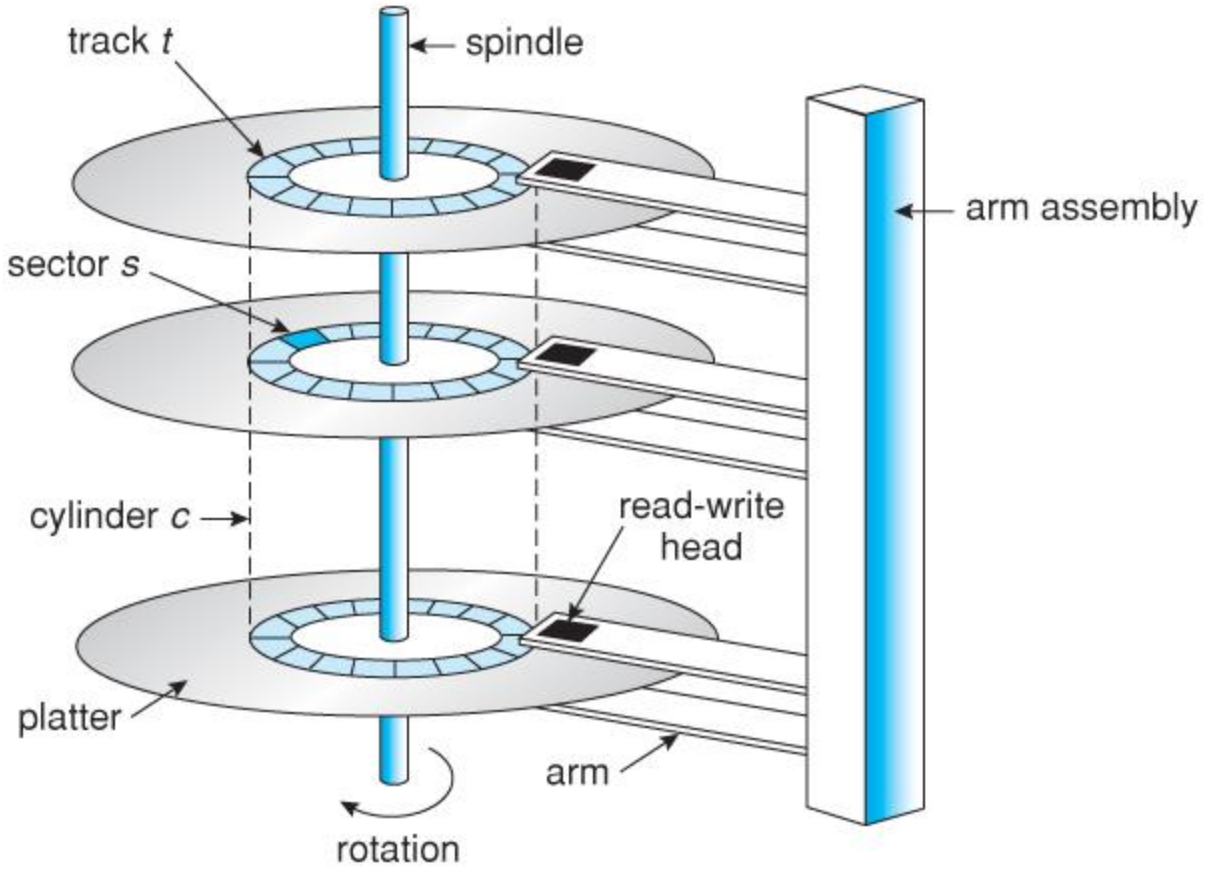


Figure 10.1 - Moving-head disk mechanism.

- In operation the disk rotates at high speed, such as 7200 rpm (120 revolutions per second.) The rate at which data can be transferred from the disk to the computer is composed of several steps:
  - The ***positioning time***, a.k.a. the ***seek time*** or ***random access time*** is the time required to move the heads from one cylinder to another, and for the heads to settle down after the move. This is typically the slowest step in the process and the predominant bottleneck to overall transfer rates.
  - The ***rotational latency*** is the amount of time required for the desired sector to rotate around and come under the read-write head.This can range anywhere from zero to one full revolution, and on the average will equal one-half revolution. This is another physical step and is usually the second slowest step behind seek time. (For a disk rotating at 7200 rpm, the average rotational latency would be 1/2 revolution / 120 revolutions per second, or just over 4 milliseconds, a long time by computer standards.
  - The ***transfer rate***, which is the time required to move the data electronically from the disk to the computer. (Some authors may

also use the term transfer rate to refer to the overall transfer rate, including seek time and rotational latency as well as the electronic data transfer rate.)

- Disk heads "fly" over the surface on a very thin cushion of air. If they should accidentally contact the disk, then a ***head crash*** occurs, which may or may not permanently damage the disk or even destroy it completely. For this reason it is normal to ***park*** the disk heads when turning a computer off, which means to move the heads off the disk or to an area of the disk where there is no data stored.
- Floppy disks are normally ***removable***. Hard drives can also be removable, and some are even ***hot-swappable***, meaning they can be removed while the computer is running, and a new hard drive inserted in their place.
- Disk drives are connected to the computer via a cable known as the ***I/O Bus.*** Some of the common interface formats include Enhanced Integrated Drive Electronics, EIDE; Advanced Technology Attachment, ATA; Serial ATA, SATA, Universal Serial Bus, USB; Fiber Channel, FC, and Small Computer Systems Interface, SCSI.
- The ***host controller*** is at the computer end of the I/O bus, and the ***disk controller*** is built into the disk itself. The CPU issues commands to the host controller via I/O ports. Data is transferred between the magnetic surface and onboard ***cache*** by the disk controller, and then the data is transferred from that cache to the host controller and the motherboard memory at electronic speeds.

10.1.2 Solid-State Disks - New

- As technologies improve and economics change, old technologies are often used in different ways. One example of this is the increasing used of ***solid state disks, or SSDs.***
- SSDs use memory technology as a small fast hard disk. Specific implementations may use either flash memory or DRAM chips protected by a battery to sustain the information through power cycles.
- Because SSDs have no moving parts they are much faster than traditional hard drives, and certain problems such as the scheduling of disk accesses simply do not apply.
- However SSDs also have their weaknesses: They are more expensive than hard drives, generally not as large, and may have shorter life spans.
- SSDs are especially useful as a high-speed cache of hard-disk information that must be accessed quickly. One example is to store filesystem meta-data, e.g. directory and inode information, that must be accessed quickly and often. Another variation is a boot disk containing

the OS and some application executables, but no vital user data. SSDs are also used in laptops to make them smaller, faster, and lighter.
- Because SSDs are so much faster than traditional hard disks, the throughput of the bus can become a limiting factor, causing some SSDs to be connected directly to the system PCI bus for example.

10.1.3 Magnetic Tapes - was 12.1.2

- Magnetic tapes were once used for common secondary storage before the days of hard disk drives, but today are used primarily for backups.
- Accessing a particular spot on a magnetic tape can be slow, but once reading or writing commences, access speeds are comparable to disk drives.
- Capacities of tape drives can range from 20 to 200 GB, and compression can double that capacity.

10.2 Disk Structure

- The traditional head-sector-cylinder, HSC numbers are mapped to linear block addresses by numbering the first sector on the first head on the outermost track as sector 0. Numbering proceeds with the rest of the sectors on that same track, and then the rest of the tracks on the same cylinder before proceeding through the rest of the cylinders to the center of the disk. In modern practice these linear block addresses are used in place of the HSC numbers for a variety of reasons:
    1. The linear length of tracks near the outer edge of the disk is much longer than for those tracks located near the center, and therefore it is possible to squeeze many more sectors onto outer tracks than onto inner ones.
    2. All disks have some bad sectors, and therefore disks maintain a few spare sectors that can be used in place of the bad ones. The mapping of spare sectors to bad sectors in managed internally to the disk controller.
    3. Modern hard drives can have thousands of cylinders, and hundreds of sectors per track on their outermost tracks. These numbers exceed the range of HSC numbers for many (older) operating systems, and therefore disks can be configured for any convenient combination of HSC values that falls within the total number of sectors physically on the drive.
- There is a limit to how closely packed individual bits can be placed on a physical media, but that limit is growing increasingly more packed as technological advances are made.
- Modern disks pack many more sectors into outer cylinders than inner ones, using one of two approaches:

    - With ***Constant Linear Velocity, CLV,*** the density of bits is uniform from cylinder to cylinder. Because there are more sectors in outer cylinders, the disk spins slower when reading those cylinders, causing the rate of bits passing under the read-write head to remain constant. This is the approach used by modern CDs and DVDs.
    - With ***Constant Angular Velocity, CAV,*** the disk rotates at a constant angular speed, with the bit density decreasing on outer cylinders. (These disks would have a constant number of sectors per track on all cylinders.)

10.3 Disk Attachment

Disk drives can be attached either directly to a particular host (a local disk) or to a network.

10.3.1 Host-Attached Storage

- Local disks are accessed through I/O Ports as described earlier.
- The most common interfaces are IDE or ATA, each of which allow up to two drives per host controller.
- SATA is similar with simpler cabling.
- High end workstations or other systems in need of larger number of disks typically use SCSI disks:
    - The SCSI standard supports up to 16 ***targets*** on each SCSI bus, one of which is generally the host adapter and the other 15 of which can be disk or tape drives.
    - A SCSI target is usually a single drive, but the standard also supports up to 8 ***units*** within each target. These would generally be used for accessing individual disks within a RAID array. (See below.)
    - The SCSI standard also supports multiple host adapters in a single computer, i.e. multiple SCSI busses.
    - Modern advancements in SCSI include "fast" and "wide" versions, as well as SCSI-2.
    - SCSI cables may be either 50 or 68 conductors. SCSI devices may be external as well as internal.
    - See wikipedia for more information on the SCSI interface.
- FC is a high-speed serial architecture that can operate over optical fiber or four-conductor copper wires, and has two variants:
    - A large switched fabric having a 24-bit address space. This variant allows for multiple devices and multiple hosts to interconnect, forming

the basis for the ***storage-area networks, SANs,*** to be discussed in a future section.
    - The ***arbitrated loop, FC-AL,*** that can address up to 126 devices (drives and controllers.)

10.3.2 Network-Attached Storage

- Network attached storage connects storage devices to computers using a remote procedure call, RPC, interface, typically with something like NFS filesystem mounts. This is convenient for allowing several computers in a group common access and naming conventions for shared storage.
- NAS can be implemented using SCSI cabling, or ***ISCSI*** uses Internet protocols and standard network connections, allowing long-distance remote access to shared files.
- NAS allows computers to easily share data storage, but tends to be less efficient than standard host-attached storage.

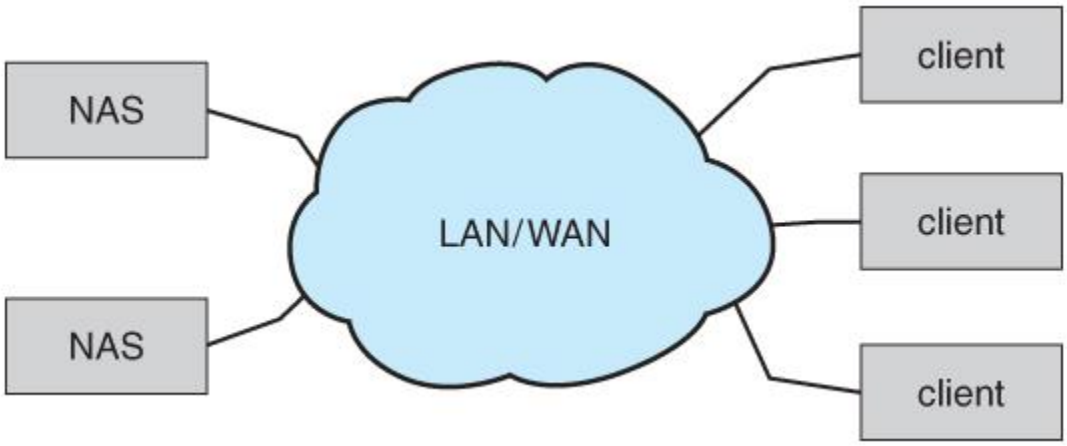


Figure 10.2 - Network-attached storage.

10.3.3 Storage-Area Network

- A ***Storage-Area Network, SAN,*** connects computers and storage devices in a network, using storage protocols instead of network protocols.
- One advantage of this is that storage access does not tie up regular networking bandwidth.
- SAN is very flexible and dynamic, allowing hosts and devices to attach and detach on the fly.
- SAN is also controllable, allowing restricted access to certain hosts and devices.

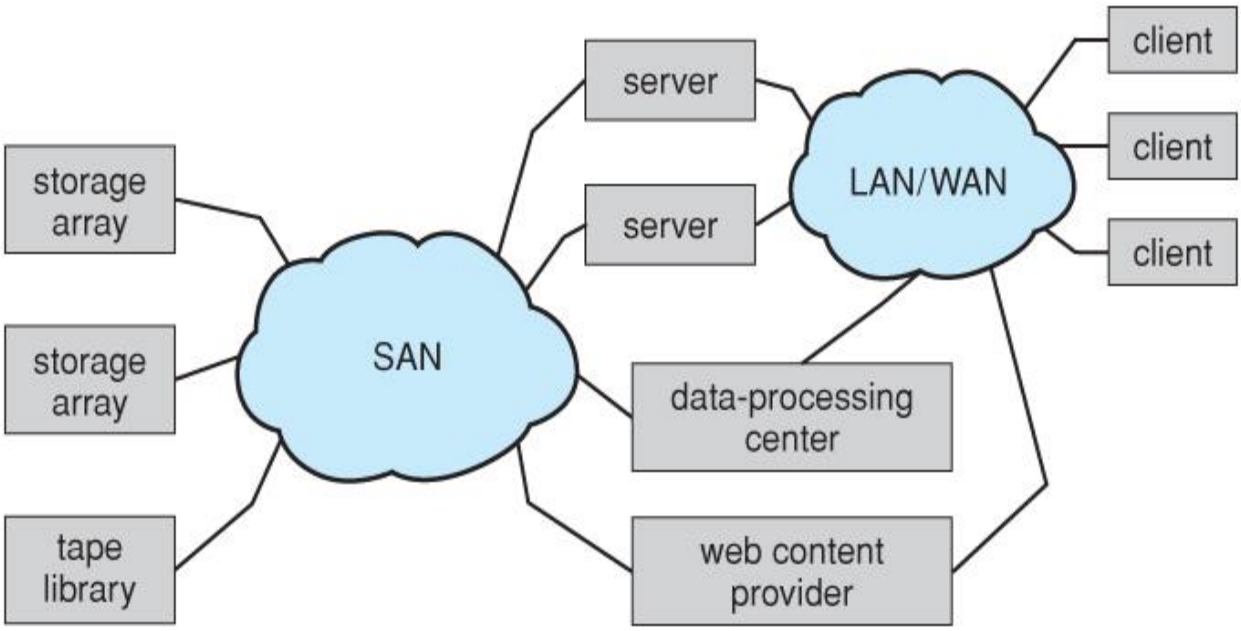


Figure 10.3 - Storage-area network.

10.4 Disk Scheduling

- As mentioned earlier, disk transfer speeds are limited primarily by ***seek times*** and ***rotational latency.*** When multiple requests are to be processed there is also some inherent delay in waiting for other requests to be processed.
- *Bandwidth* is measured by the amount of data transferred divided by the total amount of time from the first request being made to the last transfer being completed, (for a series of disk requests.)
- Both bandwidth and access time can be improved by processing requests in a good order.
- Disk requests include the disk address, memory address, number of sectors to transfer, and whether the request is for reading or writing.

10.4.1 FCFS Scheduling

- ***First-Come First-Serve*** is simple and intrinsically fair, but not very efficient. Consider in the following sequence the wild swing from cylinder 122 to 14 and then back to 124:

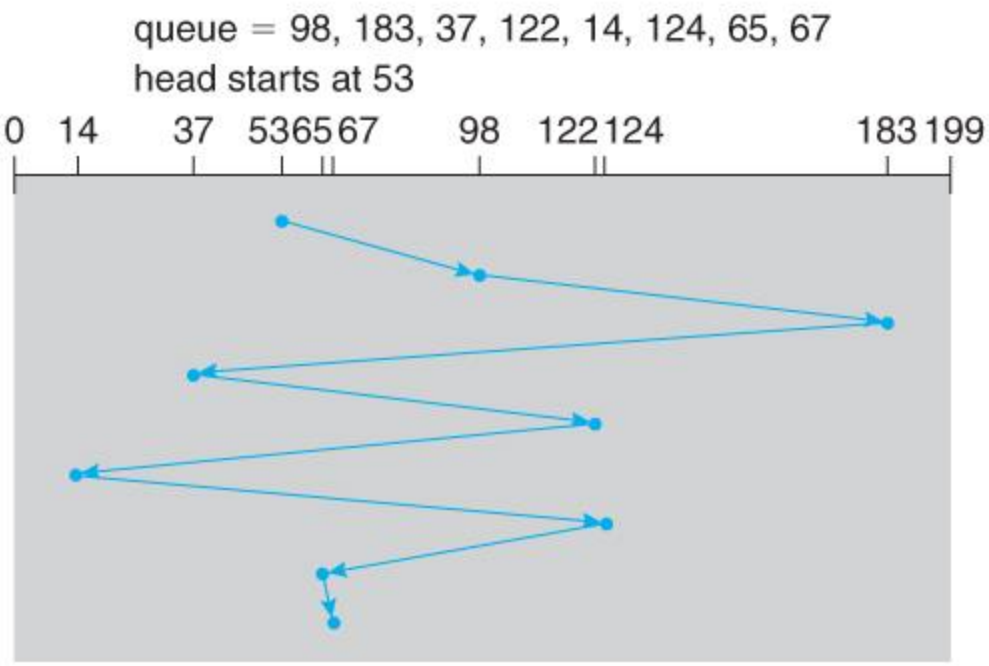


Figure 10.4 - FCFS disk scheduling.

10.4.2 SSTF Scheduling

- ***Shortest Seek Time First*** scheduling is more efficient, but may lead to starvation if a constant stream of requests arrives for the same general area of the disk.
- SSTF reduces the total head movement to 236 cylinders, down from 640 required for the same set of requests under FCFS. Note, however that the distance could be reduced still further to 208 by starting with 37 and then 14 first before processing the rest of the requests.

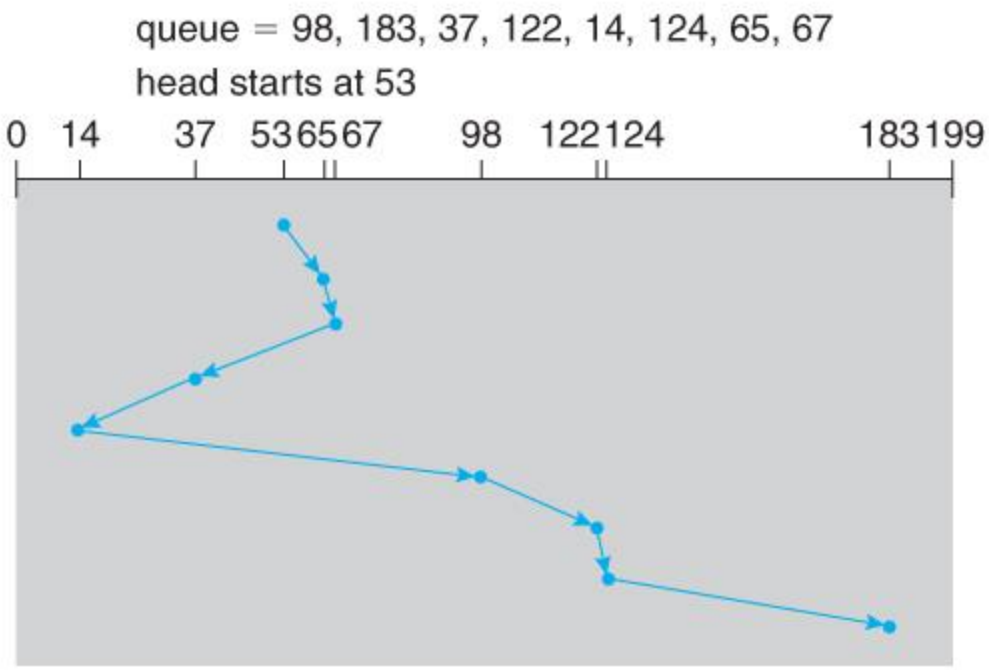


Figure 10.5 - SSTF disk scheduling.

10.4.3 SCAN Scheduling

- The ***SCAN*** algorithm, a.k.a. the ***elevator*** algorithm moves back and forth from one end of the disk to the other, similarly to an elevator processing requests in a tall building.

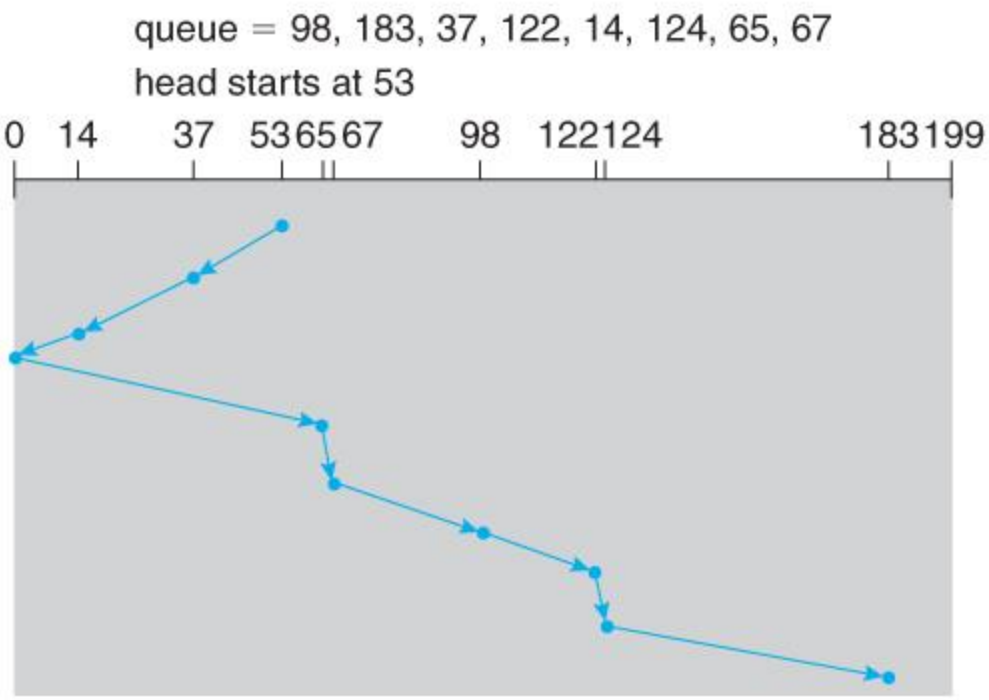


Figure 10.6 - SCAN disk scheduling.

- Under the SCAN algorithm, If a request arrives just ahead of the moving head then it will be processed right away, but if it arrives just after the head has passed, then it will have to wait for the head to pass going the other way on the return trip. This leads to a fairly wide variation in access times which can be improved upon.
- Consider, for example, when the head reaches the high end of the disk: Requests with high cylinder numbers just missed the passing head, which means they are all fairly recent requests, whereas requests with low numbers may have been waiting for a much longer time. Making the return scan from high to low then ends up accessing recent requests first and making older requests wait that much longer.

10.4.4 C-SCAN Scheduling

- The ***Circular-SCAN*** algorithm improves upon SCAN by treating all requests in a circular queue fashion - Once the head reaches the end of the disk, it returns to the other end without processing any requests, and then starts again from the beginning of the disk:

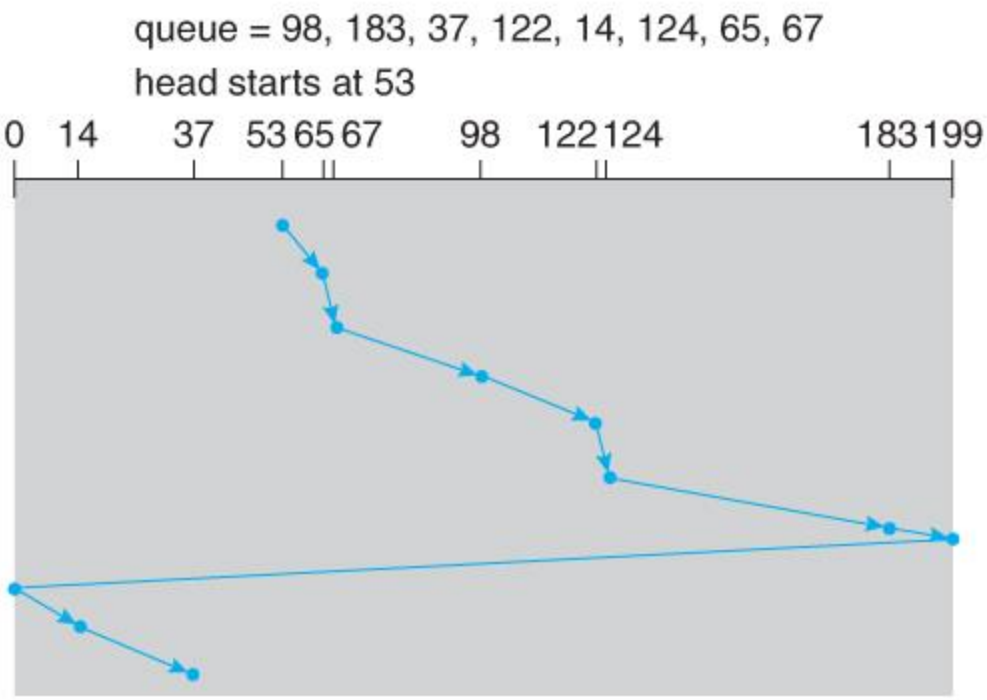


Figure 10.7 - C-SCAN disk scheduling.

12.4.5 LOOK Scheduling

- ***LOOK*** scheduling improves upon SCAN by looking ahead at the queue of pending requests, and not moving the heads any farther towards the end of the disk than is necessary. The following diagram illustrates the circular form of LOOK:

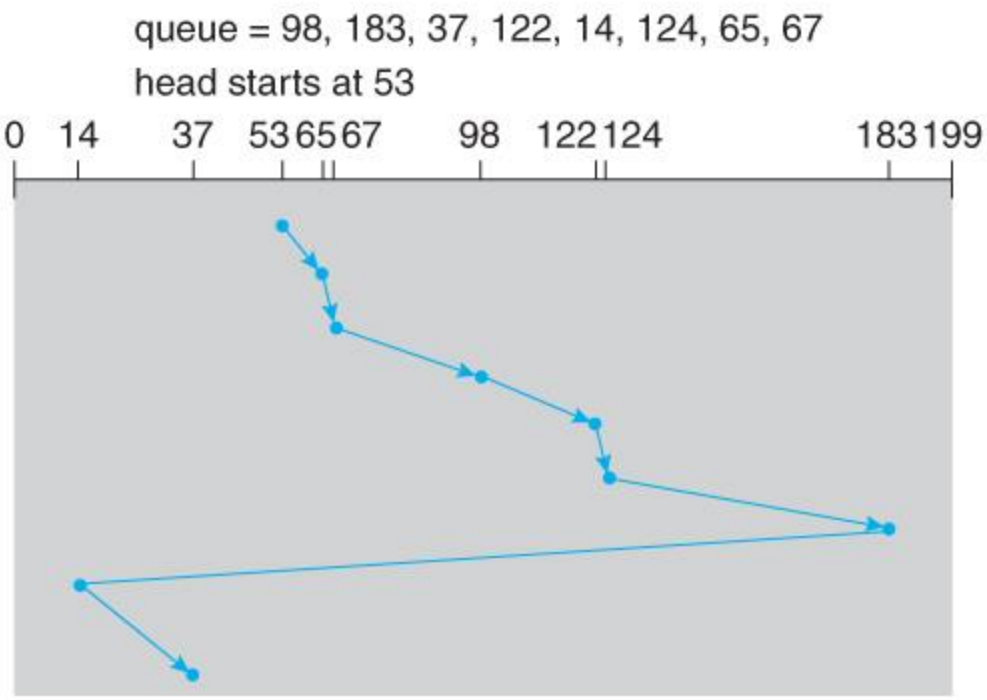


Figure 10.8 - C-LOOK disk scheduling.

10.4.6 Selection of a Disk-Scheduling Algorithm

- With very low loads all algorithms are equal, since there will normally only be one request to process at a time.
- For slightly larger loads, SSTF offers better performance than FCFS, but may lead to starvation when loads become heavy enough.
- For busier systems, SCAN and LOOK algorithms eliminate starvation problems.
- The actual optimal algorithm may be something even more complex than those discussed here, but the incremental improvements are generally not worth the additional overhead.
- Some improvement to overall filesystem access times can be made by intelligent placement of directory and/or inode information. If those structures are placed in the middle of the disk instead of at the beginning of the disk, then the maximum distance from those structures to data blocks is reduced to only one-half of the disk size. If those structures can be further distributed and furthermore have their data blocks stored as close as possible to the corresponding directory structures, then that reduces still further the overall time to find the disk block numbers and then access the corresponding data blocks.
- On modern disks the rotational latency can be almost as significant as the seek time, however it is not within the OSes control to account for that, because

modern disks do not reveal their internal sector mapping schemes,
(particularly when bad blocks have been remapped to spare sectors.)

- Some disk manufacturers provide for disk scheduling algorithms directly on their disk controllers, (which do know the actual geometry of the disk as well as any remapping), so that if a series of requests are sent from the computer to the controller then those requests can be processed in an optimal order.
- Unfortunately there are some considerations that the OS must take into account that are beyond the abilities of the on-board disk-scheduling algorithms, such as priorities of some requests over others, or the need to process certain requests in a particular order. For this reason OSes may elect to spoon-feed requests to the disk controller one at a time in certain situations.

10.6 Swap-Space Management

- Modern systems typically swap out pages as needed, rather than swapping out entire processes. Hence the swapping system is part of the virtual memory management system.
- Managing swap space is obviously an important task for modern OSes.

10.6.1 Swap-Space Use

- The amount of swap space needed by an OS varies greatly according to how it is used. Some systems require an amount equal to physical RAM; some want a multiple of that; some want an amount equal to the amount by which virtual memory exceeds physical RAM, and some systems use little or none at all!
- Some systems support multiple swap spaces on separate disks in order to speed up the virtual memory system.

10.6.2 Swap-Space Location

Swap space can be physically located in one of two locations:

- As a large file which is part of the regular filesystem. This is easy to implement, but inefficient. Not only must the swap space be accessed through the directory system, the file is also subject to fragmentation issues. Caching the block location helps in finding the physical blocks, but that is not a complete fix.

- As a raw partition, possibly on a separate or little-used disk. This allows the OS more control over swap space management, which is usually faster and more efficient. Fragmentation of swap space is generally not a big issue, as the space is re-initialized every time the system is rebooted. The downside of keeping swap space on a raw partition is that it can only be grown by repartitioning the hard drive.

12.6.3 Swap-Space Management: An Example

- Historically OSes swapped out entire processes as needed. Modern systems swap out only individual pages, and only as needed. (For example process code blocks and other blocks that have not been changed since they were originally loaded are normally just freed from the virtual memory system rather than copying them to swap space, because it is faster to go find them again in the filesystem and read them back in from there than to write them out to swap space and then read them back.)
- In the mapping system shown below for Linux systems, a map of swap space is kept in memory, where each entry corresponds to a 4K block in the swap space. Zeros indicate free slots and non-zeros refer to how many processes have a mapping to that particular block (>1 for shared pages only.)

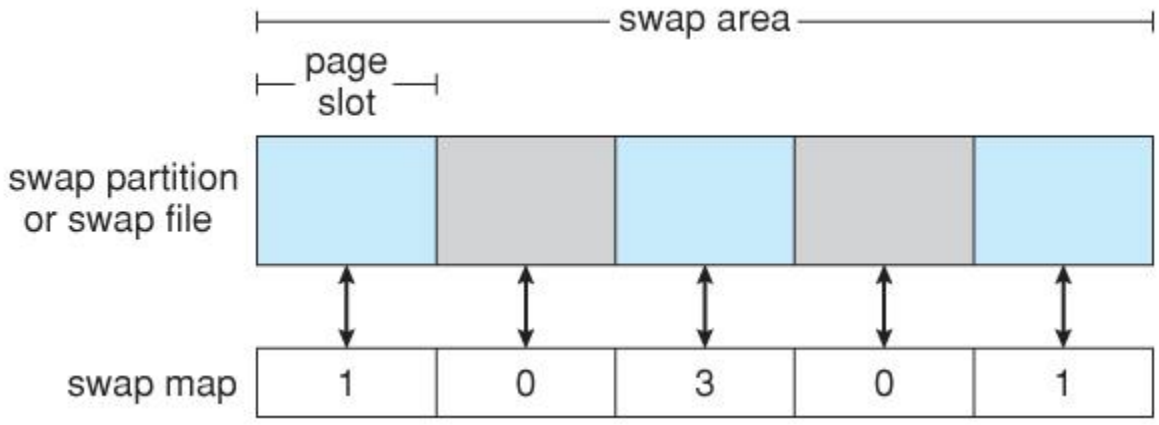


Figure 10.10 - The data structures for swapping on Linux systems.

10.7 RAID Structure

- The general idea behind RAID is to employ a group of hard drives together with some form of duplication, either to increase reliability or to speed up operations, (or sometimes both.)
- ***RAID*** originally stood for ***Redundant Array of Inexpensive Disks,*** and was designed to use a bunch of cheap small disks in place of one or two larger more expensive ones. Today RAID systems employ large possibly expensive disks as their components, switching the definition to ***Independent*** disks.

10.7.1 Improvement of Reliability via Redundancy

- The more disks a system has, the greater the likelihood that one of them will go bad at any given time. Hence increasing disks on a system actually ***decreases*** the **Mean Time To Failure, MTTF** of the system.
- If, however, the same data was copied onto multiple disks, then the data would not be lost unless **both** (or all) copies of the data were damaged simultaneously, which is a **MUCH** lower probability than for a single disk going bad. More specifically, the second disk would have to go bad before the first disk was repaired, which brings the **Mean Time To Repair** into play. For example if two disks were involved, each with a MTTF of 100,000 hours and a MTTR of 10 hours, then the **Mean Time to Data Loss** would be 500 * 10^6 hours, or 57,000 years!
- This is the basic idea behind disk ***mirroring***, in which a system contains identical data on two or more disks.
    - Note that a power failure during a write operation could cause both disks to contain corrupt data, if both disks were writing simultaneously at the time of the power failure. One solution is to write to the two disks in series, so that they will not both become corrupted (at least not in the same way) by a power failure. And alternate solution involves non-volatile RAM as a write cache, which is not lost in the event of a power failure and which is protected by error-correcting codes.

10.7.2 Improvement in Performance via Parallelism

- There is also a performance benefit to mirroring, particularly with respect to reads. Since every block of data is duplicated on multiple disks, read operations can be satisfied from any available copy, and multiple disks can be reading different data blocks simultaneously in parallel. (Writes could possibly be sped up as well through careful scheduling algorithms, but it would be complicated in practice.)

- Another way of improving disk access time is with ***striping***, which basically means spreading data out across multiple disks that can be accessed simultaneously.
    - With ***bit-level striping*** the bits of each byte are striped across multiple disks. For example if 8 disks were involved, then each 8-bit byte would be read in parallel by 8 heads on separate disks. A single disk read would access 8 * 512 bytes = 4K worth of data in the time normally required to read 512 bytes. Similarly if 4 disks were involved, then two bits of each byte could be stored on each disk, for 2K worth of disk access per read or write operation.
    - *Block-level striping* spreads a filesystem across multiple disks on a block-by-block basis, so if block N were located on disk 0, then block N + 1 would be on disk 1, and so on. This is particularly useful when filesystems are accessed in ***clusters*** of physical blocks. Other striping possibilities exist, with block-level striping being the most common.

10.7.3 RAID Levels

- Mirroring provides reliability but is expensive; Striping improves performance, but does not improve reliability. Accordingly there are a number of different schemes that combine the principals of mirroring and striping in different ways, in order to balance reliability versus performance versus cost. These are described by different ***RAID levels***, as follows: (In the diagram that follows, "C" indicates a copy, and "P" indicates parity, i.e. checksum bits.)
    1. *Raid Level 0* - This level includes striping only, with no mirroring.
    2. *Raid Level 1* - This level includes mirroring only, no striping.
    3. *Raid Level 2* - This level stores error-correcting codes on additional disks, allowing for any damaged data to be reconstructed by subtraction from the remaining undamaged data. Note that this scheme requires only three extra disks to protect 4 disks worth of data, as opposed to full mirroring. (The number of disks required is a function of the error-correcting algorithms, and the means by which the particular bad bit(s) is(are) identified.)
    4. *Raid Level 3* - This level is similar to level 2, except that it takes advantage of the fact that each disk is still doing its own error-detection, so that when an error occurs, there is no question about which disk in the array has the bad data. As a result a single parity bit is all that is needed to recover the lost data from an array of disks. Level 3 also includes striping, which improves performance. The downside with the parity

approach is that every disk must take part in every disk access, and the parity bits must be constantly calculated and checked, reducing performance. Hardware-level parity calculations and NVRAM cache can help with both of those issues. In practice level 3 is greatly preferred over level 2.

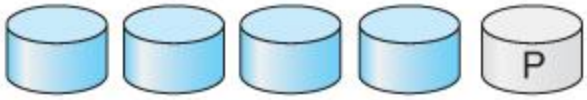
5. *Raid Level 4* - This level is similar to level 3, employing block-level striping instead of bit-level striping. The benefits are that multiple blocks can be read independently, and changes to a block only require writing two blocks (data and parity) rather than involving all disks. Note that new disks can be added seamlessly to the system provided they are initialized to all zeros, as this does not affect the parity results.
6. *Raid Level 5* - This level is similar to level 4, except the parity blocks are distributed over all disks, thereby more evenly balancing the load on the system. For any given block on the disk(s), one of the disks will hold the parity information for that block and the other N-1 disks will hold the data. Note that the same disk cannot hold both data and parity for the same block, as both would be lost in the event of a disk crash.
7. *Raid Level 6* - This level extends raid level 5 by storing multiple bits of error-recovery codes, (such as the ***Reed-Solomon codes***), for each bit position of data, rather than a single parity bit. In the example shown below 2 bits of ECC are stored for every 4 bits of data, allowing data recovery in the face of up to two simultaneous disk failures. Note that this still involves only 50% increase in storage needs, as opposed to 100% for simple mirroring which could only tolerate a single 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.

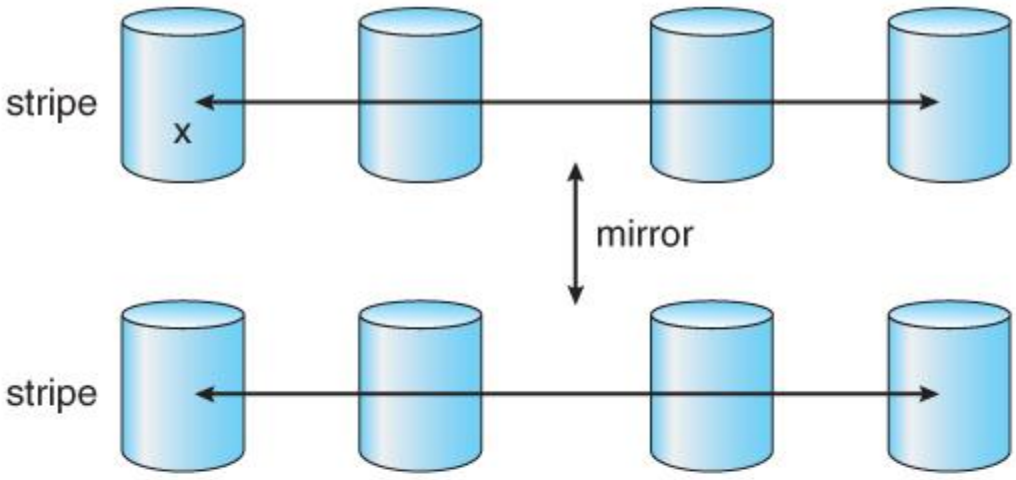
(f) RAID 5: block-interleaved distributed parity.

(g) RAID 6: P + Q redundancy.

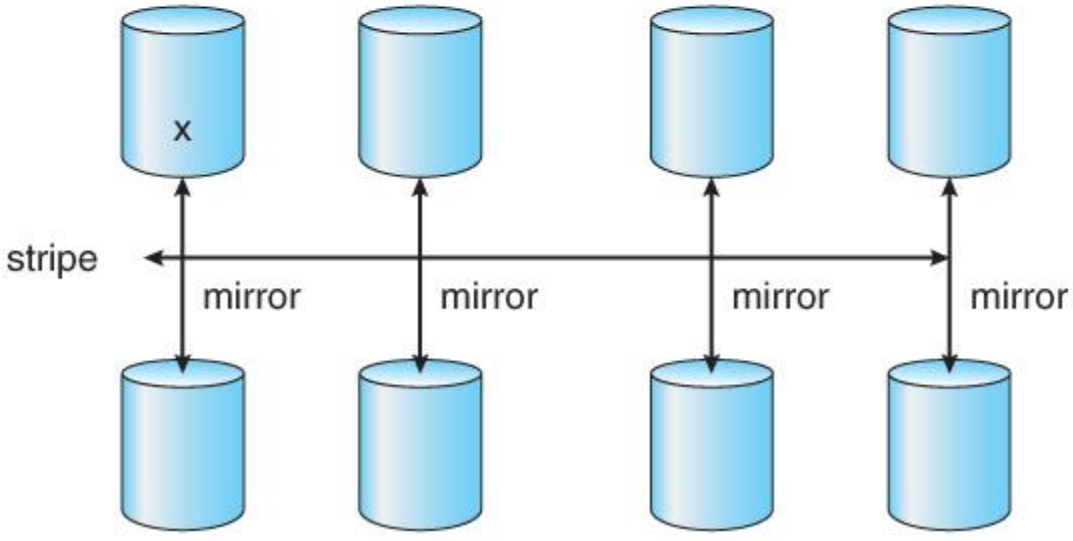
Figure 10.11 - RAID levels.

- There are also two RAID levels which combine RAID levels 0 and 1 (striping and mirroring) in different combinations, designed to provide both performance and reliability at the expense of increased cost.
    - **RAID level 0 + 1** disks are first striped, and then the striped disks mirrored to another set. This level generally provides better performance than RAID level 5.
    - **RAID level 1 + 0** mirrors disks in pairs, and then stripes the mirrored pairs. The storage capacity, performance, etc. are all the same, but there is an advantage to this approach in the event of multiple disk failures, as illustrated below:.
        - In diagram (a) below, the 8 disks have been divided into two sets of four, each of which is striped, and then one stripe set is used to mirror the other set.
            - If a single disk fails, it wipes out the entire stripe set, but the system can keep on functioning using the remaining set.
            - However if a second disk from the other stripe set now fails, then the entire system is lost, as a result of two disk failures.
        - In diagram (b), the same 8 disks are divided into four sets of two, each of which is mirrored, and then the file system is striped across the four sets of mirrored disks.
            - If a single disk fails, then that mirror set is reduced to a single disk, but the system rolls on, and the other three mirror sets continue mirroring.
            - Now if a second disk fails, (that is not the mirror of the already failed disk), then another one of the mirror sets is reduced to a single disk, but the system can continue without data loss.
            - In fact the second arrangement could handle as many as four simultaneously failed disks, as long as no two of them were from the same mirror pair.

- See the wikipedia article on nested raid levels for more information.
- Here's a better explanation: http://www.storagereview.com/guide2000/ref/hdd/perf/raid/levels/multXY.html



a) RAID 0 + 1 with a single disk failure.



b) RAID 1 + 0 with a single disk failure.

Figure 10.12 - RAID 0 + 1 and 1 + 0

10.7.4 Selecting a RAID Level

- Trade-offs in selecting the optimal RAID level for a particular application include cost, volume of data, need for reliability, need for performance, and

rebuild time, the latter of which can affect the likelihood that a second disk will fail while the first failed disk is being rebuilt.

- Other decisions include how many disks are involved in a RAID set and how many disks to protect with a single parity bit. More disks in the set increases performance but increases cost. Protecting more disks per parity bit saves cost, but increases the likelihood that a second disk will fail before the first bad disk is repaired.

10.7.5 Extensions

- RAID concepts have been extended to tape drives (e.g. striping tapes for faster backups or parity checking tapes for reliability), and for broadcasting of data.

10.7.6 Problems with RAID

- RAID protects against physical errors, but not against any number of bugs or other errors that could write erroneous data.
- ZFS adds an extra level of protection by including data block checksums in all inodes along with the pointers to the data blocks. If data are mirrored and one copy has the correct checksum and the other does not, then the data with the bad checksum will be replaced with a copy of the data with the good checksum. This increases reliability greatly over RAID alone, at a cost of a performance hit that is acceptable because ZFS is so fast to begin with.

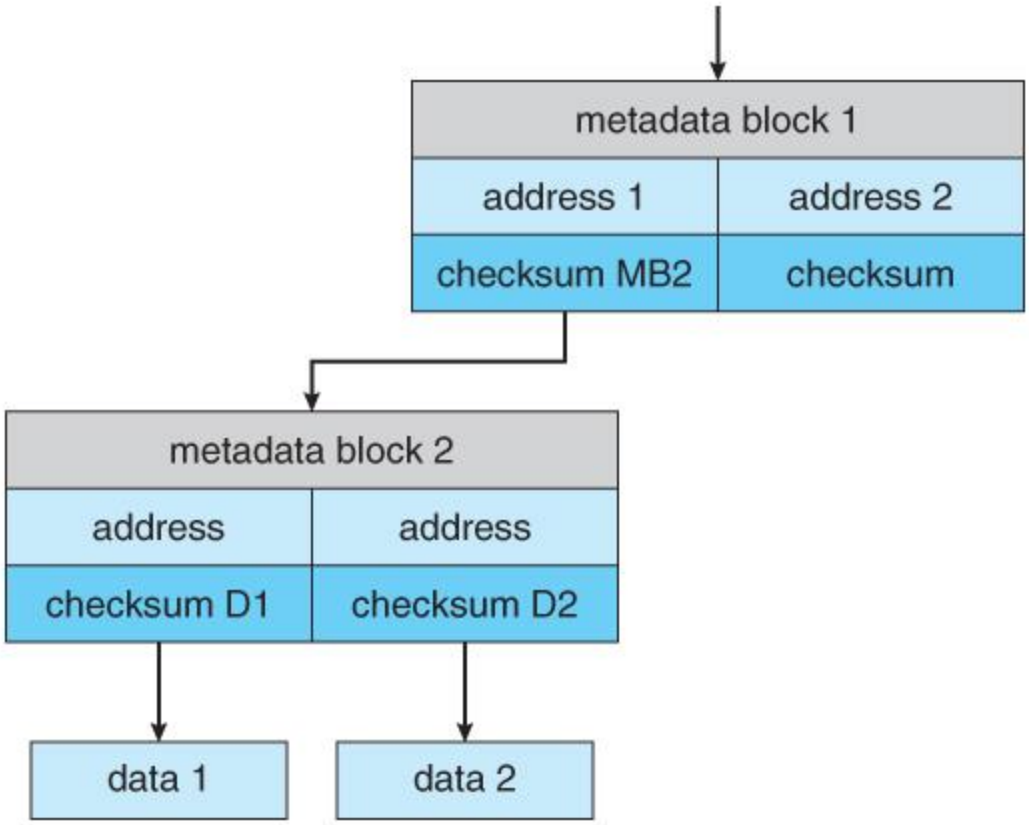


Figure 10.13 - ZFS checksums all metadata and data.

- Another problem with traditional filesystems is that the sizes are fixed, and relatively difficult to change. Where RAID sets are involved it becomes even harder to adjust filesystem sizes, because a filesystem cannot span across multiple filesystems.
- ZFS solves these problems by pooling RAID sets, and by dynamically allocating space to filesystems as needed. Filesystem sizes can be limited by quotas, and space can also be reserved to guarantee that a filesystem will be able to grow later, but these parameters can be changed at any time by the filesystem's owner. Otherwise filesystems grow and shrink dynamically as needed.

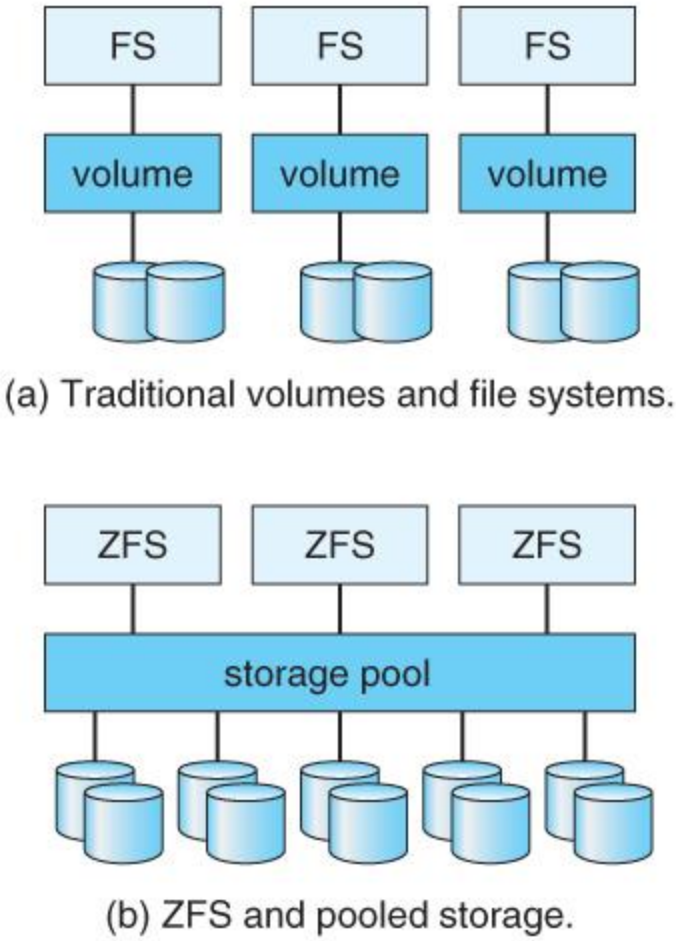


Figure 10.14 - (a) Traditional volumes and file systems. (b) a ZFS pool and file systems.

10.8 Stable-Storage Implementation (Optional)

- The concept of stable storage (first presented in chapter 6) involves a storage medium in which data is ***never*** lost, even in the face of equipment failure in the middle of a write operation.
- To implement this requires two (or more) copies of the data, with separate failure modes.
- An attempted disk write results in one of three possible outcomes:
    1. The data is successfully and completely written.
    2. The data is partially written, but not completely. The last block written may be garbled.
    3. No writing takes place at all.
- Whenever an equipment failure occurs during a write, the system must detect it, and return the system back to a consistent state. To do this requires two physical blocks for every logical block, and the following procedure:

1. Write the data to the first physical block.
2. After step 1 had completed, then write the data to the second physical block.
3. Declare the operation complete only after both physical writes have completed successfully.

- During recovery the pair of blocks is examined.
    - If both blocks are identical and there is no sign of damage, then no further action is necessary.
    - If one block contains a detectable error but the other does not, then the damaged block is replaced with the good copy. (This will either undo the operation or complete the operation, depending on which block is damaged and which is undamaged.)
    - If neither block shows damage but the data in the blocks differ, then replace the data in the first block with the data in the second block. (Undo the operation.)

Because the sequence of operations described above is slow, stable storage usually includes NVRAM as a cache, and declares a write operation complete once it has been written to the NVRAM.

File-System Interface

10.1 File Concept

10.1.1 File Attributes

- Different OSes keep track of different file attributes, including:
  - **Name** - Some systems give special significance to names, and particularly extensions (.exe, .txt, etc.), and some do not. Some extensions may be of significance to the OS (.exe), and others only to certain applications (.jpg)
  - **Identifier** (e.g. inode number)
  - **Type** - Text, executable, other binary, etc.
  - **Location** - on the hard drive.
  - **Size**
  - **Protection**
  - **Time & Date**
  - **User ID**

10.1.2 File Operations

- The file ADT supports many common operations:
  - Creating a file
  - Writing a file
  - Reading a file
  - Repositioning within a file
  - Deleting a file
  - Truncating a file.
- Most OSes require that files be ***opened*** before access and ***closed*** after all access is complete. Normally the programmer must open and close files explicitly, but some rare systems open the file automatically at first access. Information about currently open files is stored in an ***open file table***, containing for example:
  - **File pointer** - records the current position in the file, for the next read or write access.
  - **File-open count** - How many times has the current file been opened (simultaneously by different processes) and not yet closed? When this counter reaches zero the file can be removed from the table.
  - **Disk location of the file.**
  - **Access rights**

- Some systems provide support for ***file locking.***
  - A ***shared lock*** is for reading only.
  - A ***exclusive lock*** is for writing as well as reading.
  - An ***advisory lock*** is informational only, and not enforced. (A "Keep Out" sign, which may be ignored.)
  - A ***mandatory lock*** is enforced. (A truly locked door.)
  - UNIX used advisory locks, and Windows uses mandatory locks.

10.1.3 File Types

- Windows (and some other systems) use special file extensions to indicate the type of each file:

file type	usual extension	function
executable	exe, com, bin or none	ready-to-run machine-language program
object	obj, o	compiled, machine language, not linked
source code	c, cc, java, perl, asm	source code in various languages
batch	bat, sh	commands to the command interpreter
markup	xml, html, tex	textual data, documents
word processor	xml, rtf, docx	various word-processor formats
library	lib, a, so, dll	libraries of routines for programmers
print or view	gif, pdf, jpg	ASCII or binary file in a format for printing or viewing
archive	rar, zip, tar	related files grouped into one file, sometimes compressed, for archiving or storage
multimedia	mpeg, mov, mp3, mp4, avi	binary file containing audio or A/V information

Common file types

- Macintosh stores a creator attribute for each file, according to the program that first created it with the create( ) system call.
- UNIX stores magic numbers at the beginning of certain files. (Experiment with the "file" command, especially in directories such as /bin and /dev)

10.1.4 File Structure

- Some files contain an internal structure, which may or may not be known to the OS.
- For the OS to support particular file formats increases the size and complexity of the OS.
- UNIX treats all files as sequences of bytes, with no further consideration of the internal structure. (With the exception of executable binary programs, which it must know how to load and find the first executable statement, etc.)
- Macintosh files have two ***forks*** - a ***resource fork***, and a ***data fork***. The resource fork contains information relating to the UI, such as icons and button images, and can be modified independently of the data fork, which contains the code or data as appropriate.

10.1.5 Internal File Structure

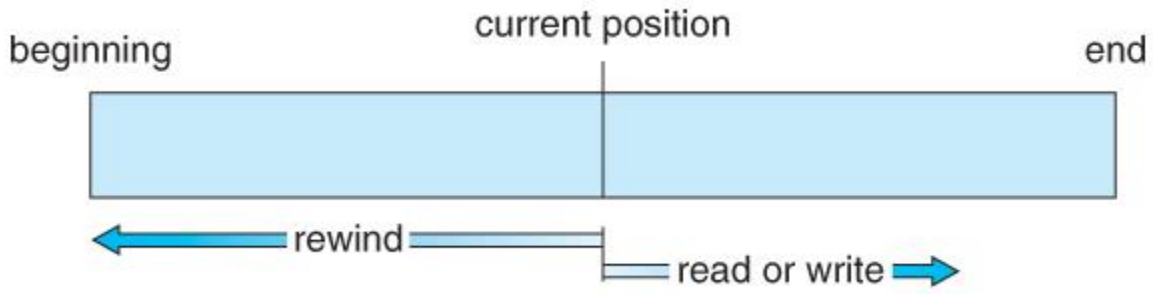
- Disk files are accessed in units of physical blocks, typically 512 bytes or some power-of-two multiple thereof. (Larger physical disks use larger block sizes, to keep the range of block numbers within the range of a 32-bit integer.)
- Internally files are organized in units of logical units, which may be as small as a single byte, or may be a larger size corresponding to some data record or structure size.
- The number of logical units which fit into one physical block determines its ***packing***, and has an impact on the amount of internal fragmentation (wasted space) that occurs.
- As a general rule, half a physical block is wasted for each file, and the larger the block sizes the more space is lost to internal fragmentation.

10.2 Access Methods

10.2.1 Sequential Access

- A sequential access file emulates magnetic tape operation, and generally supports a few operations:

- read next - read a record and advance the tape to the next position.
- write next - write a record and advance the tape to the next position.
- rewind
- skip n records - May or may not be supported. N may be limited to positive numbers, or may be limited to +/- 1.



Sequential-access file

10.2.2 Direct Access

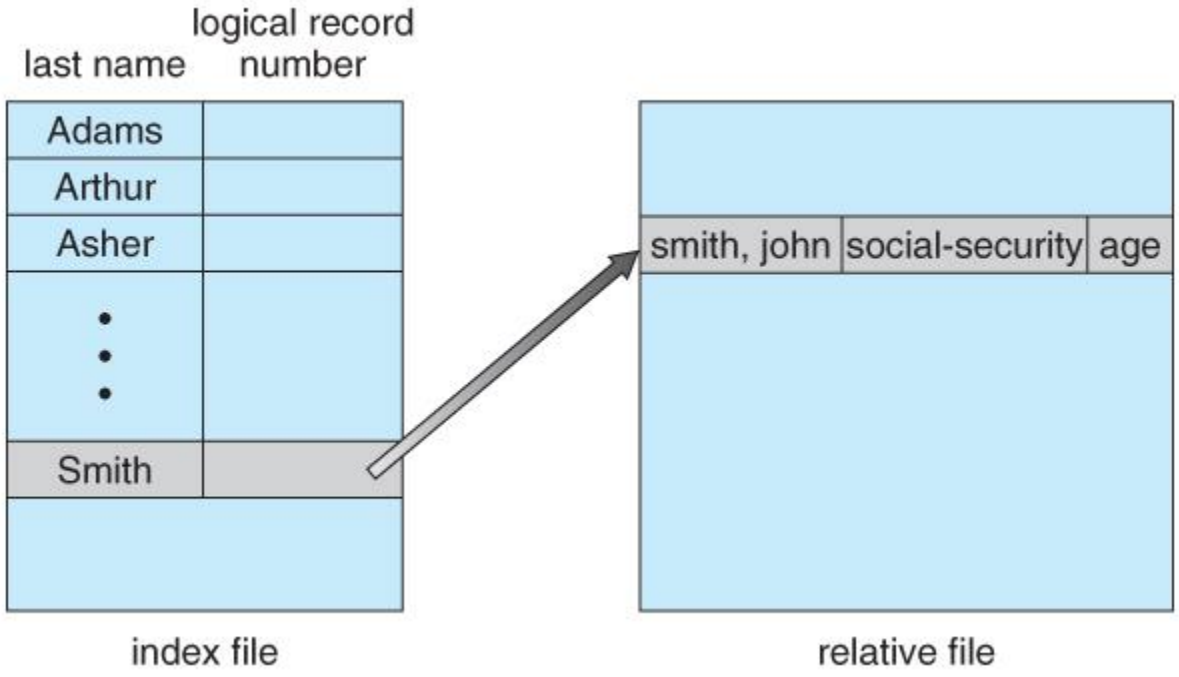
- Jump to any record and read that record. Operations supported include:
  - read n - read record number n. (Note an argument is now required.)
  - write n - write record number n. (Note an argument is now required.)
  - jump to record n - could be 0 or the end of file.
  - Query current record - used to return back to this record later.
  - Sequential access can be easily emulated using direct access. The inverse is complicated and inefficient.

sequential access	implementation for direct access
reset	cp = 0;
read_next	read cp ; cp = cp + 1;
write_next	write cp; cp = cp + 1;

Simulation of sequential access on a direct access file

10.2.3 Other Access Methods

- An indexed access scheme can be easily built on top of a direct access system. Very large files may require a multi-tiered indexing scheme, i.e. indexes of indexes.

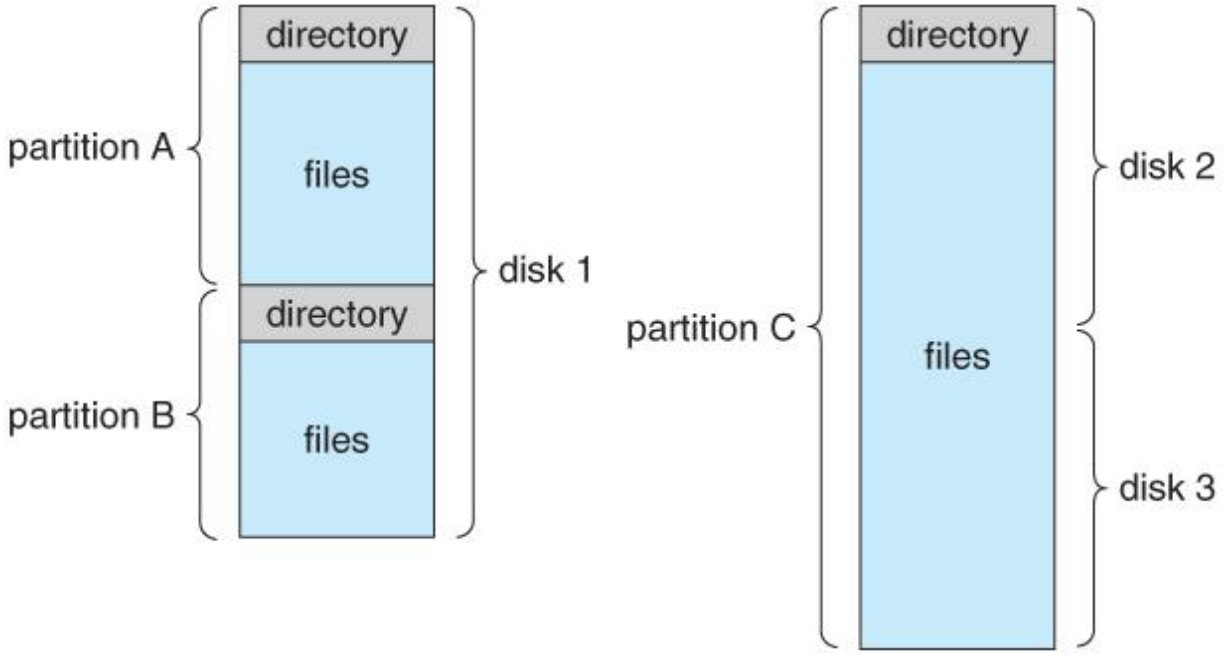


Example of index and relative files

10.3 Directory Structure

10.3.1 Storage Structure

- A disk can be used in its entirety for a file system.
- Alternatively a physical disk can be broken up into multiple ***partitions, slices, or mini-disks***, each of which becomes a virtual disk and can have its own filesystem. (or be used for raw storage, swap space, etc.)
- Or, multiple physical disks can be combined into one ***volume***, i.e. a larger virtual disk, with its own filesystem spanning the physical disks.



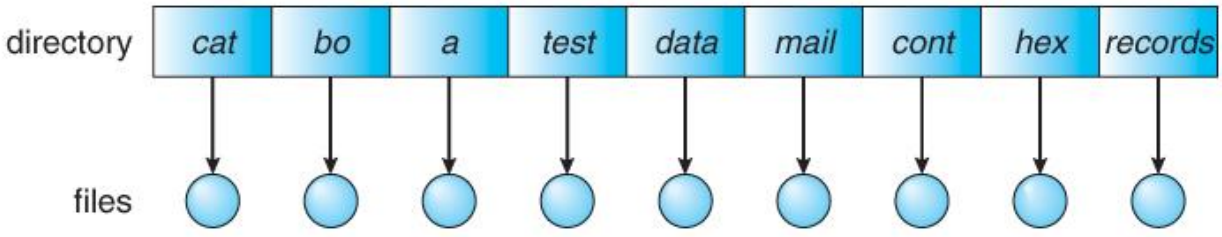
A typical file system organization

10.3.2 Directory Overview

- Directory operations to be supported include:
  - Search for a file
  - Create a file - add to the directory
  - Delete a file - erase from the directory
  - List a directory - possibly ordered in different ways.
  - Rename a file - may change sorting order
  - Traverse the file system.

10.3.3. Single-Level Directory

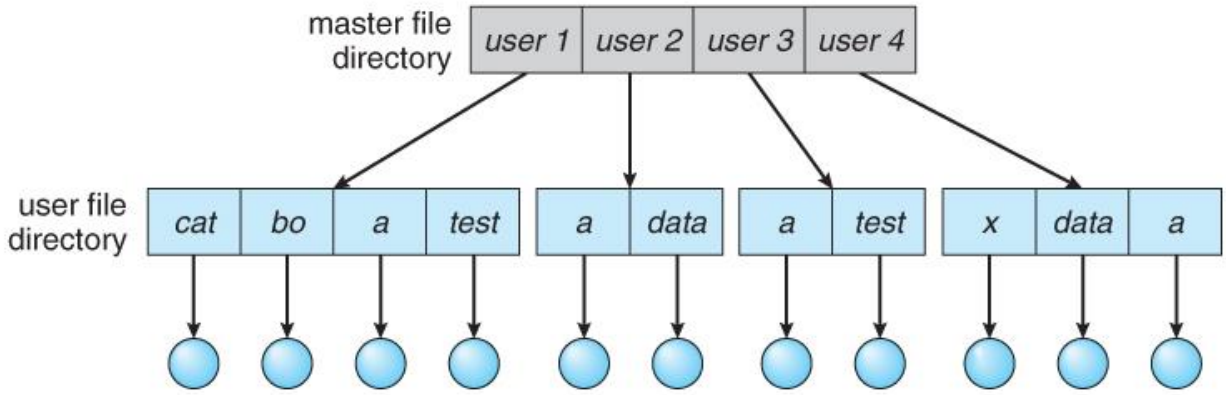
- Simple to implement, but each file must have a unique name.



Single-level directory

10.3.4 Two-Level Directory

- Each user gets their own directory space.
- File names only need to be unique within a given user's directory.
- A master file directory is used to keep track of each users directory, and must be maintained when users are added to or removed from the system.
- A separate directory is generally needed for system (executable) files.
- Systems may or may not allow users to access other directories besides their own
    - If access to other directories is allowed, then provision must be made to specify the directory being accessed.
    - If access is denied, then special consideration must be made for users to run programs located in system directories. A ***search path*** is the list of directories in which to search for executable programs, and can be set uniquely for each user.

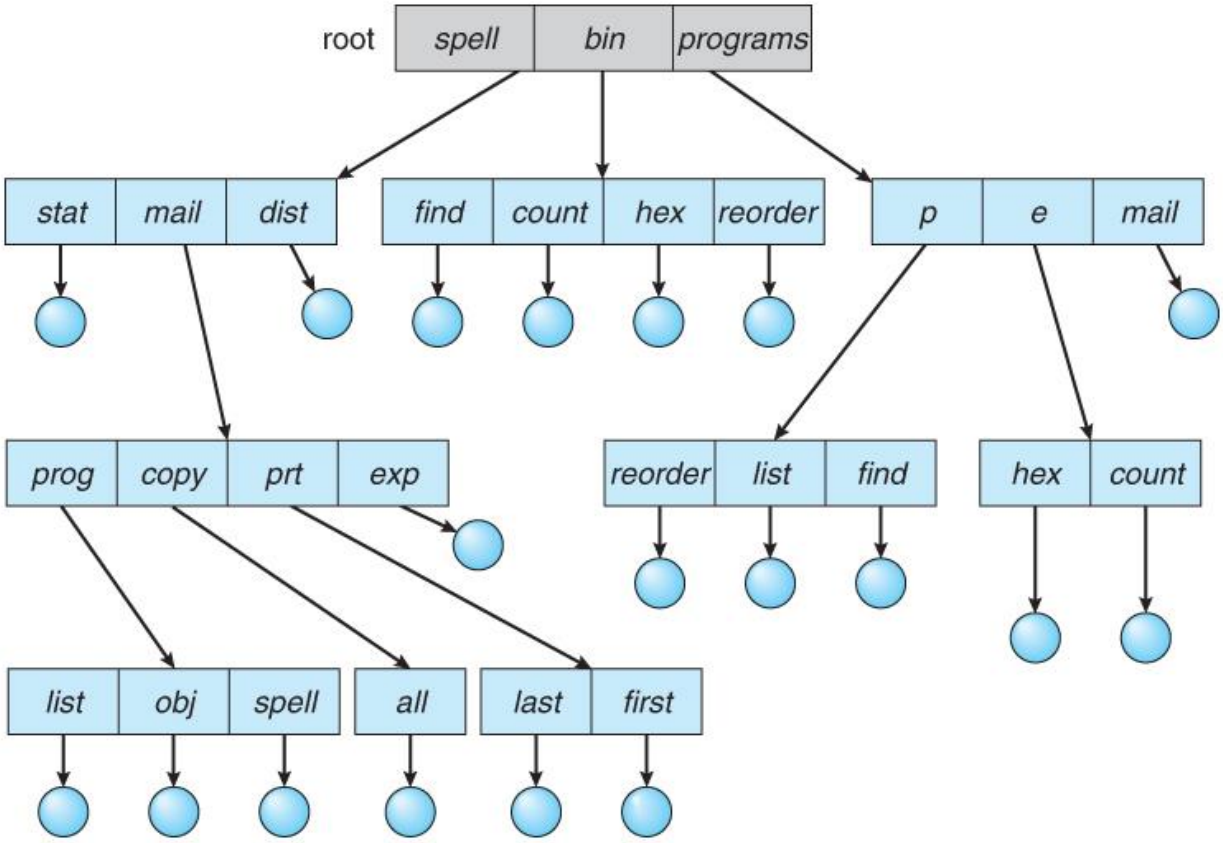


Two level directory structure

10.3.5 Tree-Structured Directories

- An obvious extension to the two-tiered directory structure, and the one with which we are all most familiar.
- Each user / process has the concept of a ***current directory*** from which all (relative) searches take place.
- Files may be accessed using either absolute pathnames (relative to the root of the tree) or relative pathnames (relative to the current directory.)
- Directories are stored the same as any other file in the system, except there is a bit that identifies them as directories, and they have some special structure that the OS understands.

- One question for consideration is whether or not to allow the removal of directories that are not empty - Windows requires that directories be emptied first, and UNIX provides an option for deleting entire sub-trees.

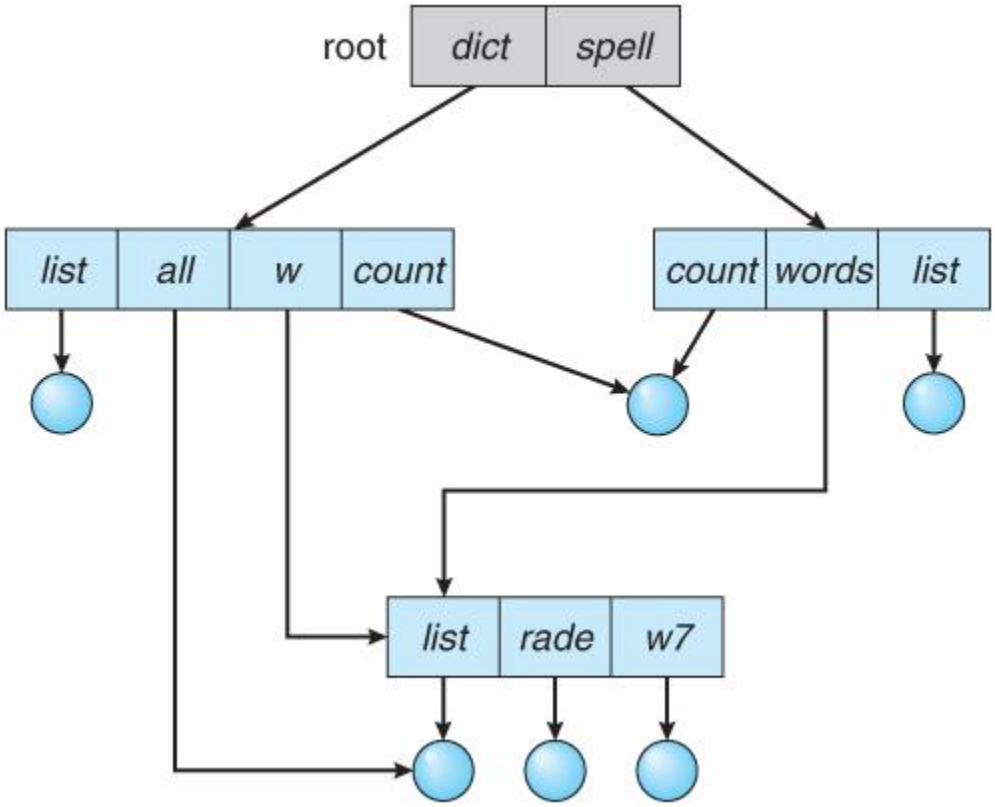


Tree-structured directory structure

10.3.6 Acyclic-Graph Directories

- When the same files need to be accessed in more than one place in the directory structure (e.g. because they are being shared by more than one user / process), it can be useful to provide an acyclic-graph structure. (Note the ***directed*** arcs from parent to child.)
- UNIX provides two types of ***links*** for implementing the acyclic-graph structure. (See "man ln" for more details.)
    - A ***hard link*** (usually just called a link) involves multiple directory entries that both refer to the same file. Hard links are only valid for ordinary files in the same filesystem.
    - A ***symbolic link***, that involves a special file, containing information about where to find the linked file. Symbolic links may be used to link directories and/or files in other filesystems, as well as ordinary files in the current filesystem.

- Windows only supports symbolic links, termed ***shortcuts.***
- Hard links require a ***reference count***, or ***link count*** for each file, keeping track of how many directory entries are currently referring to this file. Whenever one of the references is removed the link count is reduced, and when it reaches zero, the disk space can be reclaimed.
- For symbolic links there is some question as to what to do with the symbolic links when the original file is moved or deleted:
    - One option is to find all the symbolic links and adjust them also.
    - Another is to leave the symbolic links dangling, and discover that they are no longer valid the next time they are used.
    - What if the original file is removed, and replaced with another file having the same name before the symbolic link is next used?

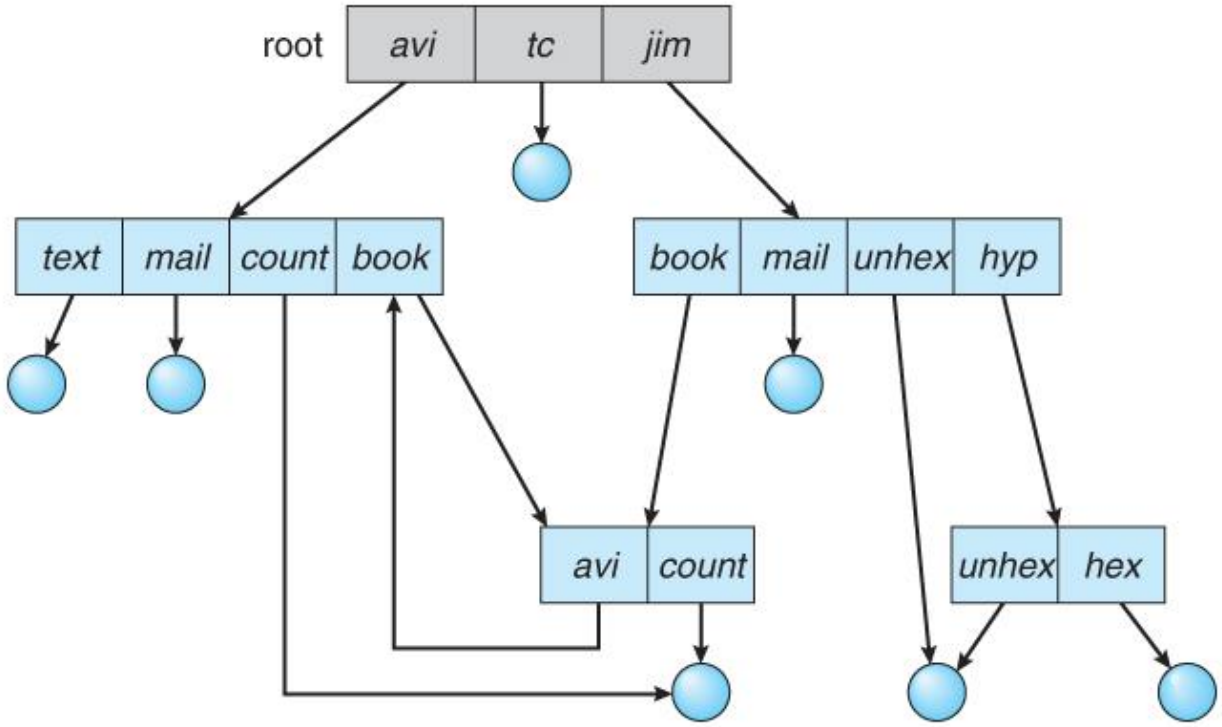


Acyclic-Graph directory structure

10.3.7 General Graph Directory

- If cycles are allowed in the graphs, then several problems can arise:
    - Search algorithms can go into infinite loops. One solution is to not follow links in search algorithms. (Or not to follow symbolic links, and to only allow symbolic links to refer to directories.)

- Sub-trees can become disconnected from the rest of the tree and still not have their reference counts reduced to zero. Periodic garbage collection is required to detect and resolve this problem. (chkdsk in DOS and fsck in UNIX search for these problems, among others, even though cycles are not supposed to be allowed in either system. Disconnected disk blocks that are not marked as free are added back to the file systems with made-up file names, and can usually be safely deleted.)



General graph directory

10.4 File-System Mounting

- The basic idea behind mounting file systems is to combine multiple file systems into one large tree structure.
- The mount command is given a filesystem to mount and a ***mount point*** (directory) on which to attach it.
- Once a file system is mounted onto a mount point, any further references to that directory actually refer to the root of the mounted file system.
- Any files (or sub-directories) that had been stored in the mount point directory prior to mounting the new filesystem are now hidden by the mounted filesystem, and are no longer available. For this reason some systems only allow mounting onto empty directories.

- Filesystems can only be mounted by root, unless root has previously configured certain filesystems to be mountable onto certain pre-determined mount points. (E.g. root may allow users to mount floppy filesystems to /mnt or something like it.) Anyone can run the mount command to see what filesystems are currently mounted.
- Filesystems may be mounted read-only, or have other restrictions imposed.

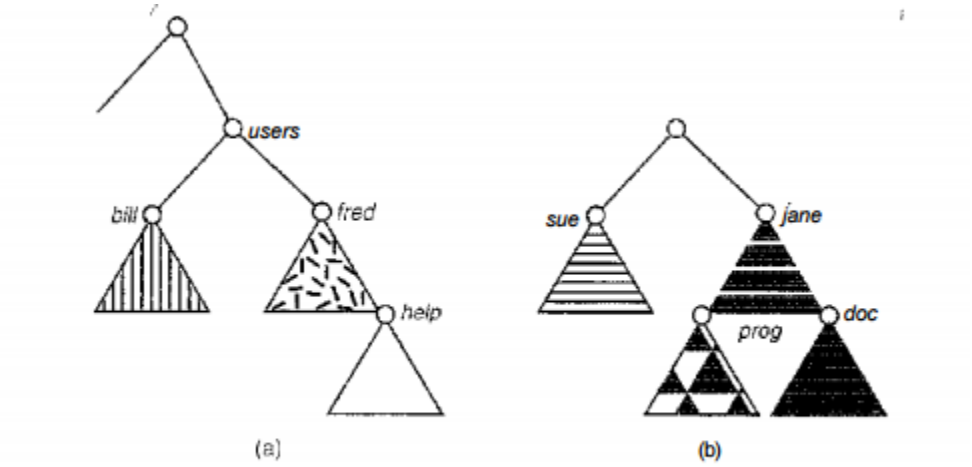
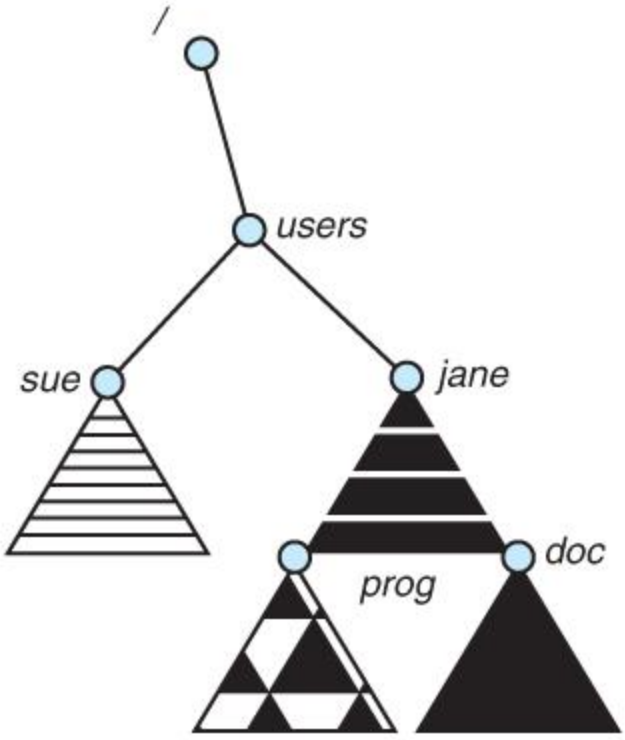


Figure 10.12 File system. (a) Existing system. (b) Unmounted volume.



Mount point

- The traditional Windows OS runs an extended two-tier directory structure, where the first tier of the structure separates volumes by drive letters, and a tree structure is implemented below that level.
- Macintosh runs a similar system, where each new volume that is found is automatically mounted and added to the desktop when it is found.
- More recent Windows systems allow filesystems to be mounted to any directory in the filesystem, much like UNIX.

10.5 File Sharing

10.5.1 Multiple Users

- On a multi-user system, more information needs to be stored for each file:
  - The owner (user) who owns the file, and who can control its access.
  - The group of other user IDs that may have some special access to the file.
  - What access rights are afforded to the owner (**U**ser), the **G**roup, and to the rest of the world (the universe, a.k.a. **O**thers.)

- Some systems have more complicated access control, allowing or denying specific accesses to specifically named users or groups.

10.5.2 Remote File Systems

- The advent of the Internet introduces issues for accessing files stored on remote computers
  - The original method was ftp, allowing individual files to be transported across systems as needed. Ftp can be either account and password controlled, or ***anonymous***, not requiring any user name or password.
  - Various forms of ***distributed file systems*** allow remote file systems to be mounted onto a local directory structure, and accessed using normal file access commands. (The actual files are still transported across the network as needed, possibly using ftp as the underlying transport mechanism.)
  - The WWW has made it easy once again to access files on remote systems without mounting their filesystems, generally using (anonymous) ftp as the underlying file transport mechanism.

10.5.2.1 The Client-Server Model

- When one computer system remotely mounts a filesystem that is physically located on another system, the system which physically owns the files acts as a ***server***, and the system which mounts them is the ***client.***
- User IDs and group IDs must be consistent across both systems for the system to work properly. (I.e. this is most applicable across multiple computers managed by the same organization, shared by a common group of users.)
- The same computer can be both a client and a server. (E.g. cross-linked file systems.)
- There are a number of security concerns involved in this model:
  - Servers commonly restrict mount permission to certain trusted systems only. Spoofing (a computer pretending to be a different computer) is a potential security risk.
  - Servers may restrict remote access to read-only.
  - Servers restrict which filesystems may be remotely mounted. Generally the information within those subsystems is limited, relatively public, and protected by frequent backups.

- The NFS (Network File System) is a classic example of such a system.

10.5.2.2 Distributed Information Systems

- The ***Domain Name System, DNS,*** provides for a unique naming system across all of the Internet.
- Domain names are maintained by the ***Network Information System, NIS***, which unfortunately has several security issues. NIS+ is a more secure version, but has not yet gained the same widespread acceptance as NIS.
- Microsoft's ***Common Internet File System, CIFS***, establishes a ***network login*** for each user on a networked system with shared file access. Older Windows systems used ***domains***, and newer systems (XP, 2000), use ***active directories.*** User names must match across the network for this system to be valid.
- A newer approach is the ***Lightweight Directory-Access Protocol, LDAP,*** which provides a ***secure single sign-on*** for all users to access all resources on a network. This is a secure system which is gaining in popularity, and which has the maintenance advantage of combining authorization information in one central location.

10.5.2.3 Failure Modes

- When a local disk file is unavailable, the result is generally known immediately, and is generally non-recoverable. The only reasonable response is for the response to fail.
- However when a remote file is unavailable, there are many possible reasons, and whether or not it is unrecoverable is not readily apparent. Hence most remote access systems allow for blocking or delayed response, in the hopes that the remote system (or the network) will come back up eventually.

10.5.3 Consistency Semantics

- ***Consistency Semantics*** deals with the consistency between the views of shared files on a networked system. When one user changes the file, when do other users see the changes?
- At first glance this appears to have all of the synchronization issues discussed in Chapter 6. Unfortunately the long delays involved in network operations prohibit the use of atomic operations as discussed in that chapter.

10.5.3.1 UNIX Semantics

- The UNIX file system uses the following semantics:
  - Writes to an open file are immediately visible to any other user who has the file open.
  - One implementation uses a shared location pointer, which is adjusted for all sharing users.
- The file is associated with a single exclusive physical resource, which may delay some accesses.

10.5.3.2 Session Semantics

- The Andrew File System, AFS uses the following semantics:
  - Writes to an open file are not immediately visible to other users.
  - When a file is closed, any changes made become available only to users who open the file at a later time.
- According to these semantics, a file can be associated with multiple (possibly different) views. Almost no constraints are imposed on scheduling accesses. No user is delayed in reading or writing their personal copy of the file.
- AFS file systems may be accessible by systems around the world. Access control is maintained through (somewhat) complicated access control lists, which may grant access to the entire world (literally) or to specifically named users accessing the files from specifically named remote environments.

10.5.3.3 Immutable-Shared-Files Semantics

- Under this system, when a file is declared as ***shared*** by its creator, it becomes immutable and the name cannot be re-used for any other resource. Hence it becomes read-only, and shared access is simple.

10.6 Protection

- Files must be kept safe for reliability (against accidental damage), and protection (against deliberate malicious access.) The former is usually managed with backup copies. This section discusses the latter.
- One simple protection scheme is to remove all access to a file. However this makes the file unusable, so some sort of controlled access must be arranged.

10.6.1 Types of Access

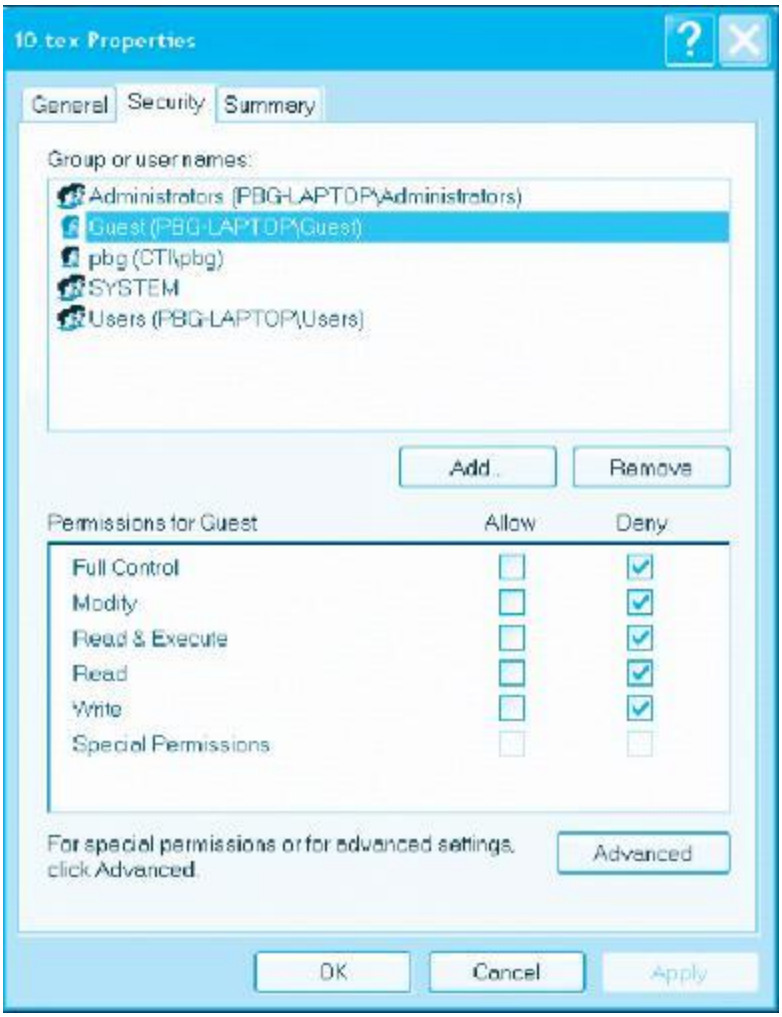
- The following low-level operations are often controlled:
  - Read - View the contents of the file
  - Write - Change the contents of the file.
  - Execute - Load the file onto the CPU and follow the instructions contained therein.
  - Append - Add to the end of an existing file.
  - Delete - Remove a file from the system.
  - List -View the name and other attributes of files on the system.
- Higher-level operations, such as copy, can generally be performed through combinations of the above.

10.6.2 Access Control

- One approach is to have complicated ***Access Control Lists, ACL,*** which specify exactly what access is allowed or denied for specific users or groups.
  - The AFS uses this system for distributed access.
  - Control is very finely adjustable, but may be complicated, particularly when the specific users involved are unknown. (AFS allows some wild cards, so for example all users on a certain remote system may be trusted, or a given username may be trusted when accessing from any remote system.)
- UNIX uses a set of 9 access control bits, in three groups of three. These correspond to R, W, and X permissions for each of the Owner, Group, and Others. (See "man chmod" for full details.) The RWX bits control the following privileges for ordinary files and directories:

bit	Files	Directories
R	Read (view) file contents.	Read directory contents. Required to get a listing of the directory.
W	Write (change) file contents.	Change directory contents. Required to create or delete files.
X	Execute file contents as a program.	Access detailed directory information. Required to get a long listing, or to access any specific file in the directory. Note that if a user has X but not R permissions on a directory, they can still access specific files, but only if they already know the name of the file they are trying to access.

- In addition there are some special bits that can also be applied:
  - The set user ID (SUID) bit and/or the set group ID (SGID) bits applied to executable files temporarily change the identity of whoever runs the program to match that of the owner / group of the executable program. This allows users running specific programs to have access to files (***while running that program***) to which they would normally be unable to access. Setting of these two bits is usually restricted to root, and must be done with caution, as it introduces a potential security leak.
  - The sticky bit on a directory modifies write permission, allowing users to only delete files for which they are the owner. This allows everyone to create files in /tmp, for example, but to only delete files which they have created, and not anyone else's.
  - The SUID, SGID, and sticky bits are indicated with an S, S, and T in the positions for execute permission for the user, group, and others, respectively. If the letter is lower case, (s, s, t), then the corresponding execute permission is not also given. If it is upper case, (S, S, T), then the coresponding execute permission IS given.
  - The numeric form of chmod is needed to set these advanced bits.



windows XP access control list management

- Windows adjusts files access through a simple GUI:

Figure 10.15

10.6.3 Other Protection Approaches and Issues

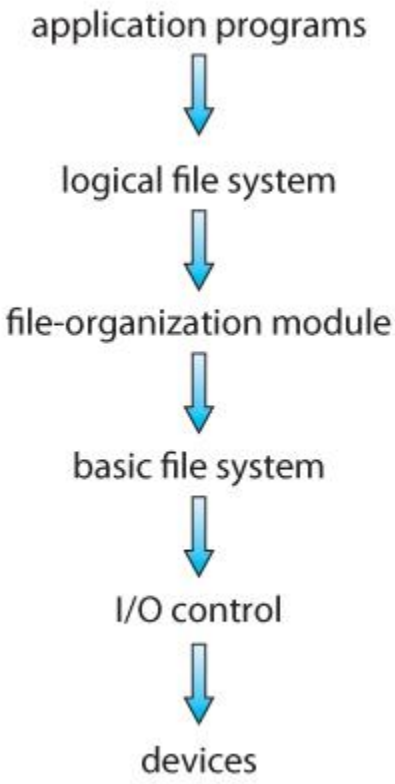
- Some systems can apply passwords, either to individual files, or to specific sub-directories, or to the entire system. There is a trade-off between the number of passwords that must be maintained (and remembered by the users) and the amount of information that is vulnerable to a lost or forgotten password.
- Older systems which did not originally have multi-user file access permissions (DOS and older versions of Mac) must now be ***retrofitted*** if they are to share files on a network.
- Access to a file requires access to all the files along its path as well. In a cyclic directory structure, users may have different access to the same file accessed through different paths.
- Sometimes just the knowledge of the existence of a file of a certain name is a security (or privacy) concern. Hence the distinction between the R and X bits on UNIX directories.

File-System Implementation

11.1 File-System Structure

- Hard disks have two important properties that make them suitable for secondary storage of files in file systems: (1) Blocks of data can be rewritten in place, and (2) they are direct access, allowing any block of data to be accessed with only (relatively) minor movements of the disk heads and rotational latency. (See Chapter 12)
- Disks are usually accessed in physical blocks, rather than a byte at a time. Block sizes may range from 512 bytes to 4K or larger.
- File systems organize storage on disk drives, and can be viewed as a layered design:
    - At the lowest layer are the physical devices, consisting of the magnetic media, motors & controls, and the electronics connected to them and controlling them. Modern disk put more and more of the electronic controls directly on the disk drive itself, leaving relatively little work for the disk controller card to perform.
    - ***I/O Control*** consists of ***device drivers***, special software programs (often written in assembly) which communicate with the devices by reading and writing special codes directly to and from memory addresses corresponding to the controller card's registers. Each controller card (device) on a system has a different set of addresses (registers, a.k.a. ***ports***) that it listens to, and a unique set of command codes and results codes that it understands.
    - The ***basic file system*** level works directly with the device drivers in terms of retrieving and storing raw blocks of data, without any consideration for what is in each block. Depending on the system, blocks may be referred to with a single block number, (e.g. block # 234234), or with head-sector-cylinder combinations.
    - The ***file organization module*** knows about files and their logical blocks, and how they map to physical blocks on the disk. In addition to translating from logical to physical blocks, the file organization module also maintains the list of free blocks, and allocates free blocks to files as needed.
    - The ***logical file system*** deals with all of the meta data associated with a file (UID, GID, mode, dates, etc), i.e. everything about the file except the data itself. This level manages the directory structure and the mapping of file names to ***file control blocks, FCBs***, which contain all of the meta data as well as block number information for finding the data on the disk.

- The layered approach to file systems means that much of the code can be used uniformly for a wide variety of different file systems, and only certain layers need to be filesystem specific. Common file systems in use include the UNIX file system, UFS, the Berkeley Fast File System, FFS, Windows systems FAT, FAT32, NTFS, CD-ROM systems ISO 9660, and for Linux the extended file systems ext2 and ext3 (among 40 others supported.)



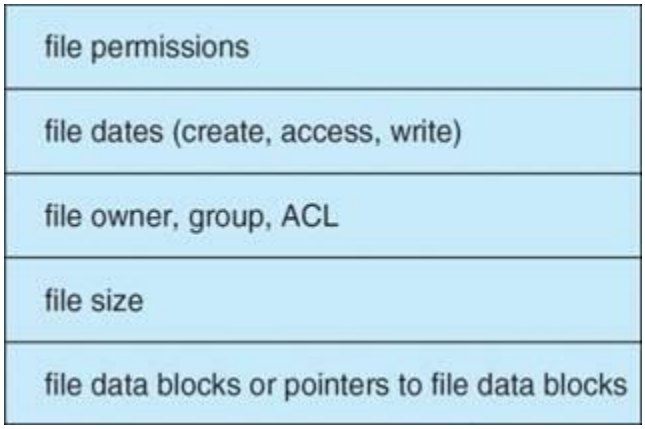
Layered file system

11.2 File-System Implementation

11.2.1 Overview

- File systems store several important data structures on the disk:
  - A ***boot-control bloc*k**, (per volume) a.k.a. the ***boot block*** in UNIX or the ***partition boot sector*** in Windows contains information about how to boot the system off of this disk. This will generally be the first sector of the volume if there is a bootable system loaded on that volume, or the block will be left vacant otherwise.

- A ***volume control block,*** (per volume) a.k.a. the ***master file table*** in UNIX or the ***superblock*** in Windows, which contains information such as the partition table, number of blocks on each filesystem, and pointers to free blocks and free FCB blocks.
- A directory structure (per file system), containing file names and pointers to corresponding FCBs. UNIX uses inode numbers, and NTFS uses a ***master file table.***
- The ***File Control Block, FCB,*** (per file) containing details about ownership, size, permissions, dates, etc. UNIX stores this information in inodes, and NTFS in the master file table as a relational database structure.

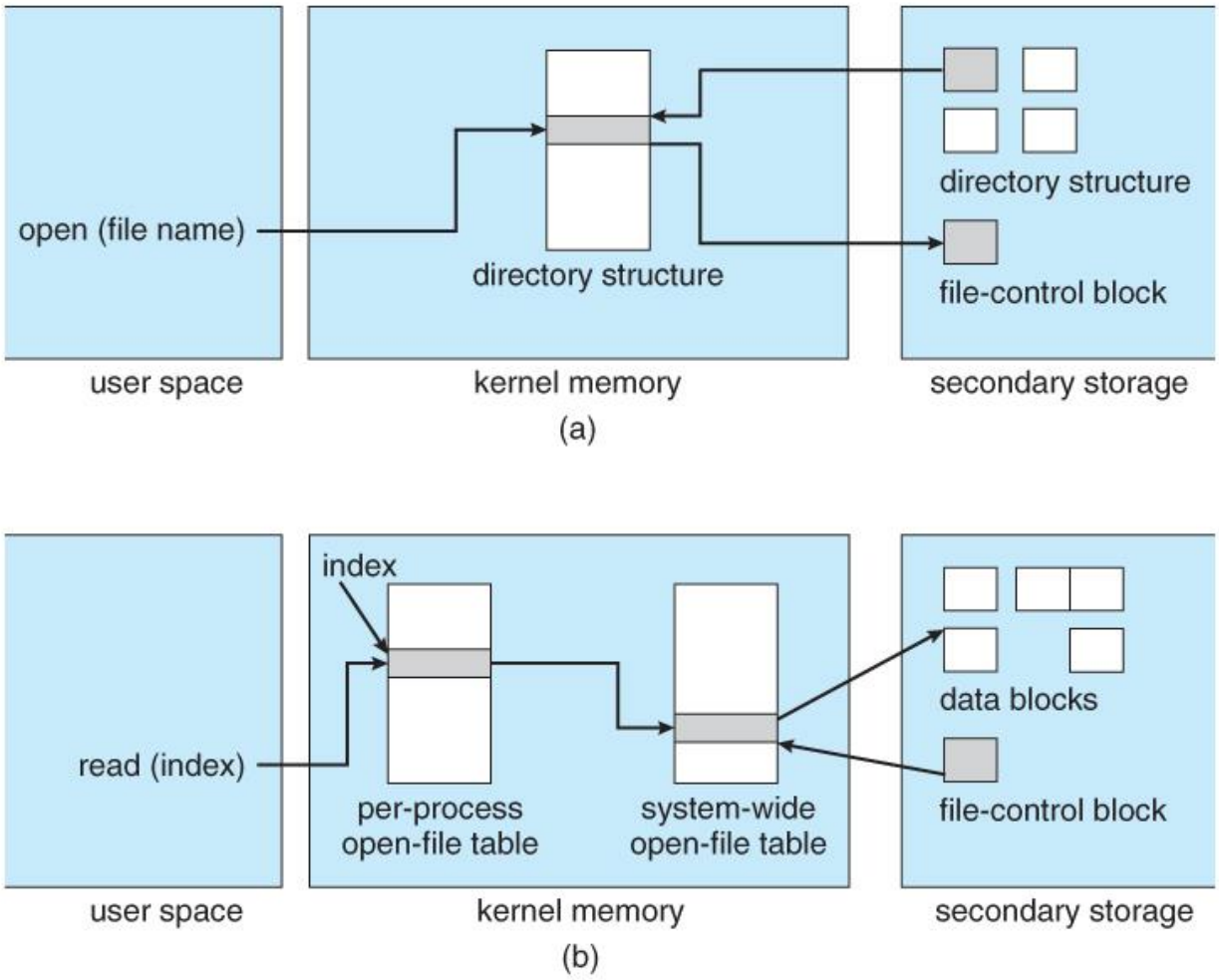


A typical file-control block

- There are also several key data structures stored in memory:
  - An in-memory mount table.
  - An in-memory directory cache of recently accessed directory information.
  - ***A system-wide open file table***, containing a copy of the FCB for every currently open file in the system, as well as some other related information.
  - ***A per-process open file table,*** containing a pointer to the system open file table as well as some other information. (For example the current file position pointer may be either here or in the system file table, depending on the implementation and whether the file is being shared or not.)
- Figure 11.3 illustrates some of the interactions of file system components when files are created and/or used:
  - When a new file is created, a new FCB is allocated and filled out with important information regarding the new file. The

appropriate directory is modified with the new file name and FCB information.

- When a file is accessed during a program, the open( ) system call reads in the FCB information from disk, and stores it in the system-wide open file table. An entry is added to the per-process open file table referencing the system-wide table, and an index into the per-process table is returned by the open( ) system call. UNIX refers to this index as a ***file descriptor***, and Windows refers to it as a ***file handle***.
- If another process already has a file open when a new request comes in for the same file, and it is sharable, then a counter in the system-wide table is incremented and the per-process table is adjusted to point to the existing entry in the system-wide table.
- When a file is closed, the per-process table entry is freed, and the counter in the system-wide table is decremented. If that counter reaches zero, then the system wide table is also freed. Any data currently stored in memory cache for this file is written out to disk if necessary.



In-memory file-system structures (a)File open (b) file read

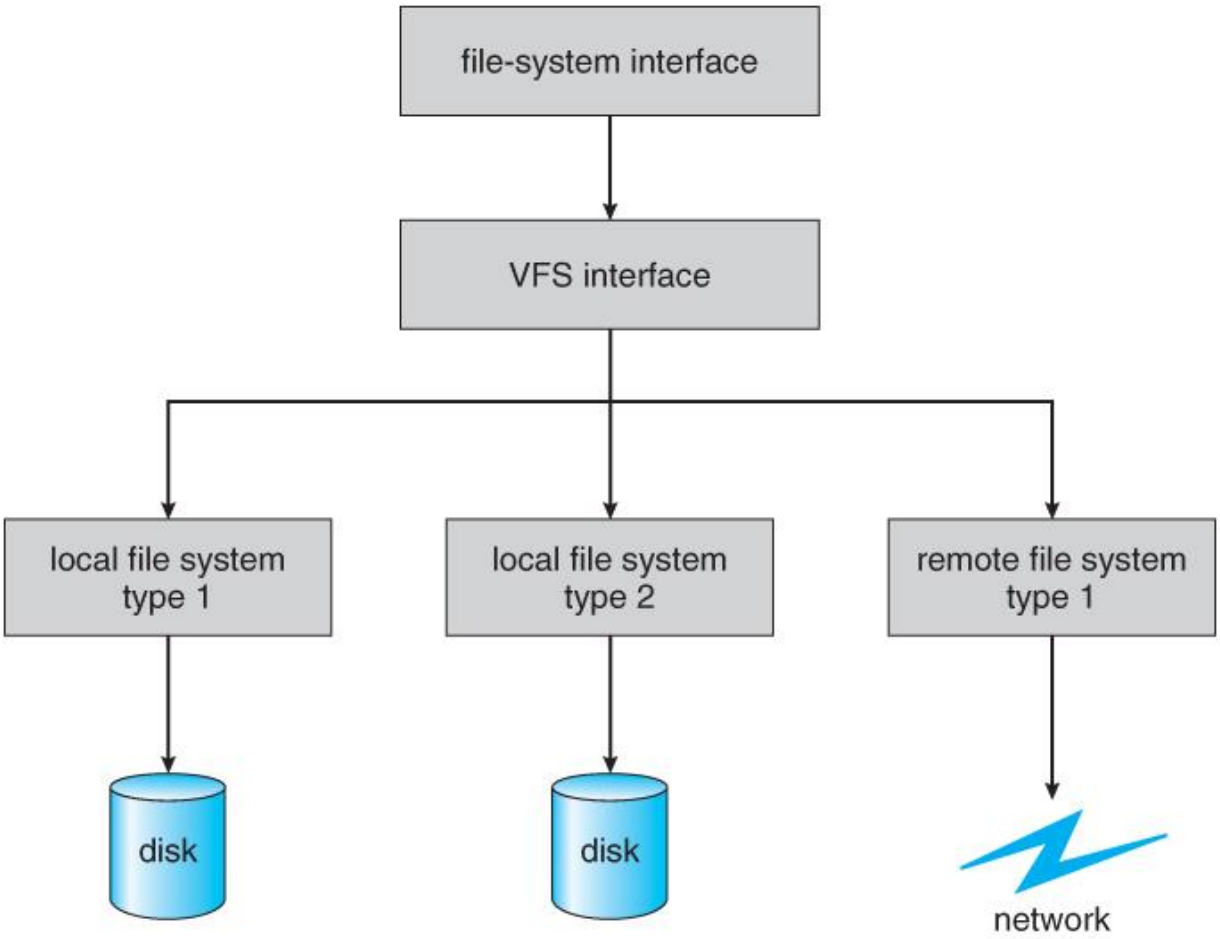
11.2.2 Partitions and Mounting

- Physical disks are commonly divided into smaller units called partitions. They can also be combined into larger units, but that is most commonly done for RAID installations and is left for later chapters.
- Partitions can either be used as raw devices (with no structure imposed upon them), or they can be formatted to hold a filesystem (i.e. populated with FCBs and initial directory structures as appropriate.) Raw partitions are generally used for swap space, and may also be used for certain programs such as databases that choose to manage their own disk storage system. Partitions containing filesystems can generally only be accessed using the file system structure by ordinary users, but can often be accessed as a raw device also by root.

- The boot block is accessed as part of a raw partition, by the boot program prior to any operating system being loaded. Modern boot programs understand multiple OSes and filesystem formats, and can give the user a choice of which of several available systems to boot.
- The ***root partition*** contains the OS kernel and at least the key portions of the OS needed to complete the boot process. At boot time the root partition is mounted, and control is transferred from the boot program to the kernel found there. (Older systems required that the root partition lie completely within the first 1024 cylinders of the disk, because that was as far as the boot program could reach. Once the kernel had control, then it could access partitions beyond the 1024 cylinder boundary.)
- Continuing with the boot process, additional filesystems get mounted, adding their information into the appropriate mount table structure. As a part of the mounting process the file systems may be checked for errors or inconsistencies, either because they are flagged as not having been closed properly the last time they were used, or just for general principals. Filesystems may be mounted either automatically or manually. In UNIX a mount point is indicated by setting a flag in the in-memory copy of the inode, so all future references to that inode get re-directed to the root directory of the mounted filesystem.

11.2.3 Virtual File Systems

- ***Virtual File Systems, VFS***, provide a common interface to multiple different filesystem types. In addition, it provides for a unique identifier (vnode) for files across the entire space, including across all filesystems of different types. (UNIX inodes are unique only across a single filesystem, and certainly do not carry across networked file systems.)
- The VFS in Linux is based upon four key object types:
    - The ***inode*** object, representing an individual file
    - The ***file*** object, representing an open file.
    - The ***superblock*** object, representing a filesystem.
    - The ***dentry*** object, representing a directory entry.
- Linux VFS provides a set of common functionalities for each filesystem, using function pointers accessed through a table. The same functionality is accessed through the same table position for all filesystem types, though the actual functions pointed to by the pointers may be filesystem-specific. See /usr/include/linux/fs.h for full details. Common operations provided include open( ), read( ), write( ), and mmap( ).



Schematic view of virtual file system

11.3 Directory Implementation

- Directories need to be fast to search, insert, and delete, with a minimum of wasted disk space.

11.3.1 Linear List

- A linear list is the simplest and easiest directory structure to set up, but it does have some drawbacks.
- Finding a file (or verifying one does not already exist upon creation) requires a linear search.
- Deletions can be done by moving all entries, flagging an entry as deleted, or by moving the last entry into the newly vacant position.
- Sorting the list makes searches faster, at the expense of more complex insertions and deletions.

- A linked list makes insertions and deletions into a sorted list easier, with overhead for the links.
- More complex data structures, such as B-trees, could also be considered.

11.3.2 Hash Table

- A hash table can also be used to speed up searches.
- Hash tables are generally implemented ***in addition to*** a linear or other structure

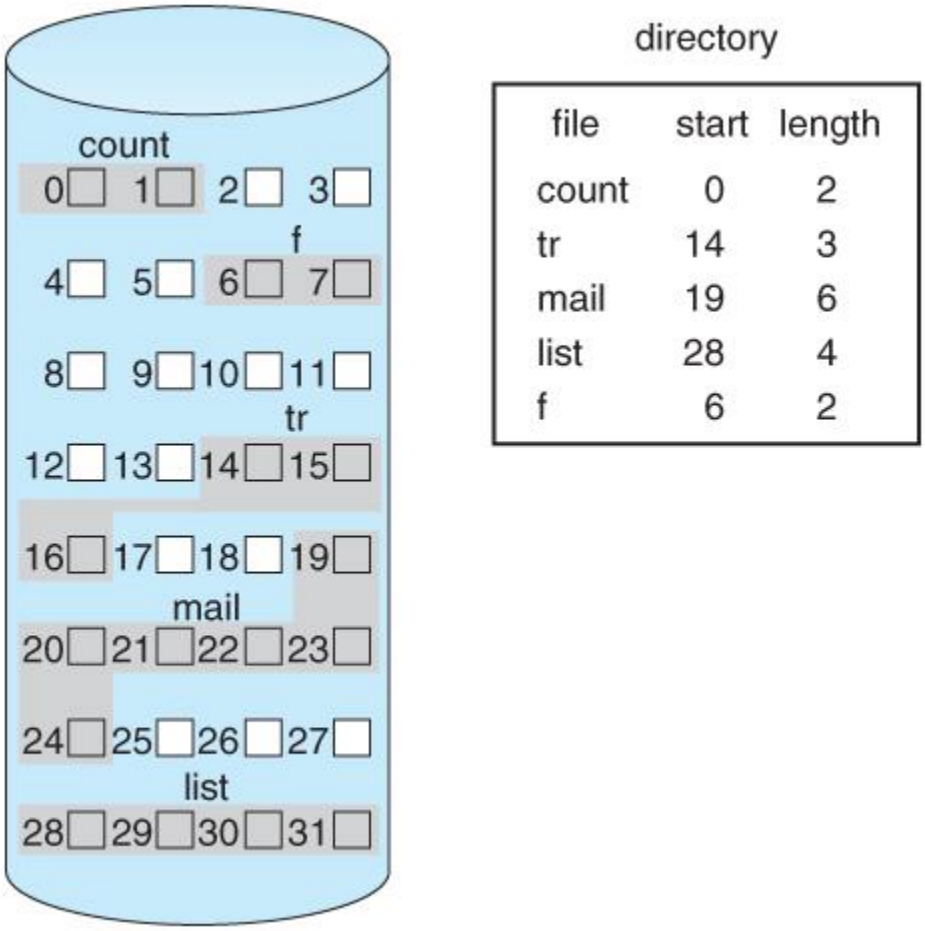
11.4 Allocation Methods

- There are three major methods of storing files on disks: contiguous, linked, and indexed.

11.4.1 Contiguous Allocation

- ***Contiguous Allocation*** requires that all blocks of a file be kept together contiguously.
- Performance is very fast, because reading successive blocks of the same file generally requires no movement of the disk heads, or at most one small step to the next adjacent cylinder.
- Storage allocation involves the same issues discussed earlier for the allocation of contiguous blocks of memory (first fit, best fit, fragmentation problems, etc.) The distinction is that the high time penalty required for moving the disk heads from spot to spot may now justify the benefits of keeping files contiguously when possible.
- (Even file systems that do not by default store files contiguously can benefit from certain utilities that compact the disk and make all files contiguous in the process.)
- Problems can arise when files grow, or if the exact size of a file is unknown at creation time:
    - Over-estimation of the file's final size increases external fragmentation and wastes disk space.
    - Under-estimation may require that a file be moved or a process aborted if the file grows beyond its originally allocated space.
    - If a file grows slowly over a long time period and the total final space must be allocated initially, then a lot of space becomes unusable before the file fills the space.
- A variation is to allocate file space in large contiguous chunks, called ***extents.*** When a file outgrows its original extent, then an additional one is allocated. (For example an extent may be the size of a

complete track or even cylinder, aligned on an appropriate track or cylinder boundary.) The high-performance files system Veritas uses extents to optimize performance.

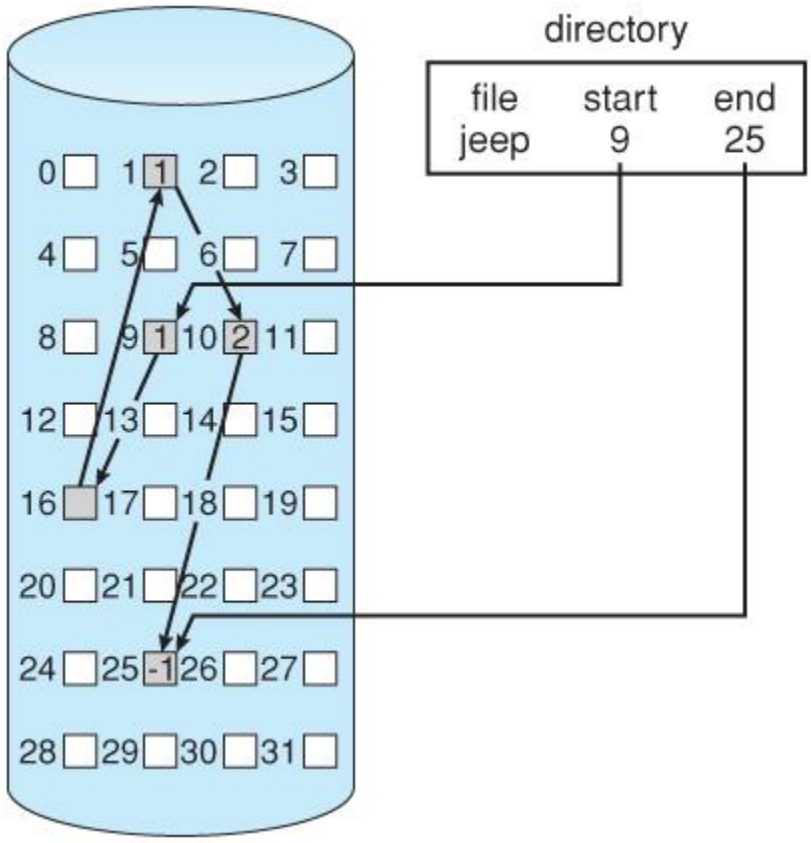


Contiguous allocation of disk space

11.4.2 Linked Allocation

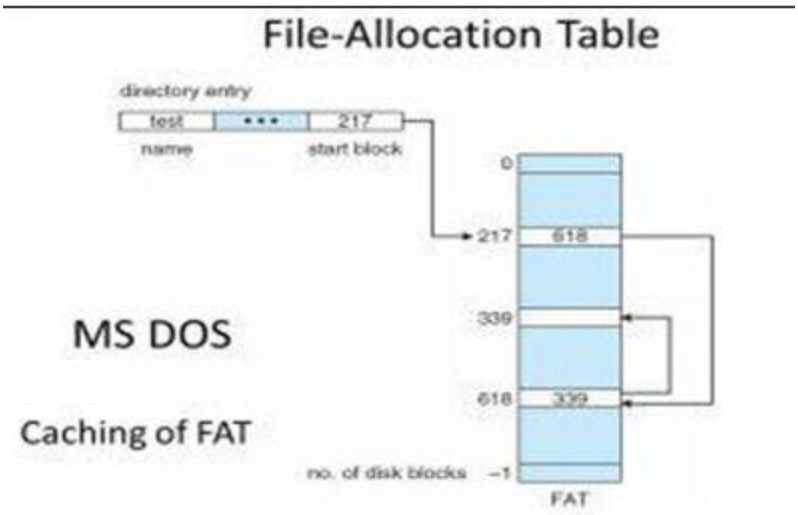
- Disk files can be stored as linked lists, with the expense of the storage space consumed by each link. (E.g. a block may be 508 bytes instead of 512.)
- Linked allocation involves no external fragmentation, does not require pre-known file sizes, and allows files to grow dynamically at any time.
- Unfortunately linked allocation is only efficient for sequential access files, as random access requires starting at the beginning of the list for each new location access.
- Allocating ***clusters*** of blocks reduces the space wasted by pointers, at the cost of internal fragmentation.

- Another big problem with linked allocation is reliability if a pointer is lost or damaged. Doubly linked lists provide some protection, at the cost of additional overhead and wasted space.



Linked allocation of disk space

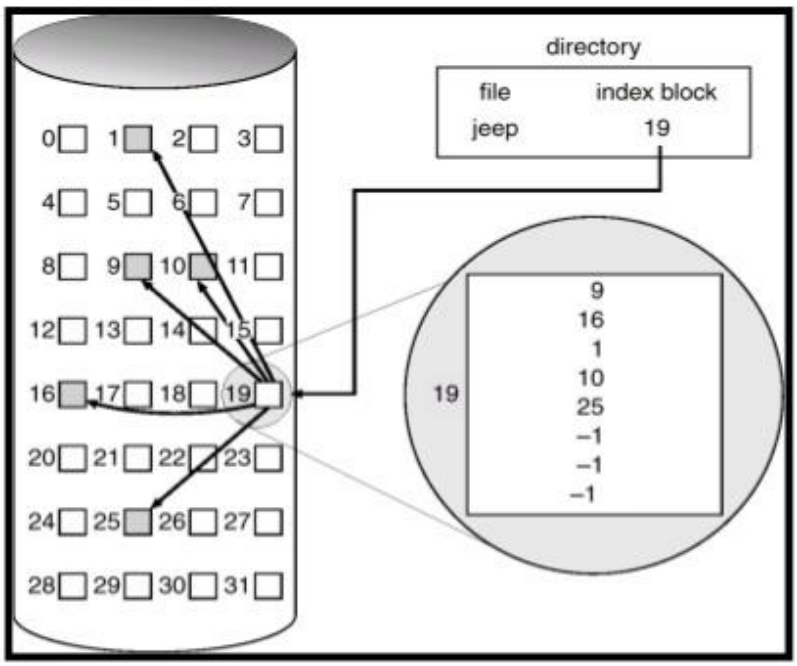
- The ***File Allocation Table, FAT,*** used by DOS is a variation of linked allocation, where all the links are stored in a separate table at the beginning of the disk. The benefit of this approach is that the FAT table can be cached in memory, greatly improving random access speeds.



11.4.3 Indexed Allocation

- ***Indexed Allocation*** combines all of the indexes for accessing each file into a common block (for that file), as opposed to spreading them all over the disk or storing them in a FAT table.

Example of Indexed Allocation



- Some disk space is wasted (relative to linked lists or FAT tables) because an entire index block must be allocated for each file, regardless of how many data blocks the file contains. This leads to questions of how big the index block should be, and how it should be implemented. There are several approaches:
    - **Linked Scheme -** An index block is one disk block, which can be read and written in a single disk operation. The first index block contains some header information, the first N block addresses, and if necessary a pointer to additional linked index blocks.
    - **Multi-Level Index -** The first index block contains a set of pointers to secondary index blocks, which in turn contain pointers to the actual data blocks.
    - **Combined Scheme -** This is the scheme used in UNIX inodes, in which the first 12 or so data block pointers are stored directly in the inode, and then singly, doubly, and triply indirect pointers provide access to more data blocks as needed. (See below.) The advantage of this scheme is that for small files (which many are), the data blocks are readily accessible (up to 48K with 4K block

sizes); files up to about 4144K (using 4K blocks) are accessible with only a single indirect block (which can be cached), and huge files are still accessible using a relatively small number of disk accesses (larger in theory than can be addressed by a 32-bit address, which is why some systems have moved to 64-bit file pointers.)

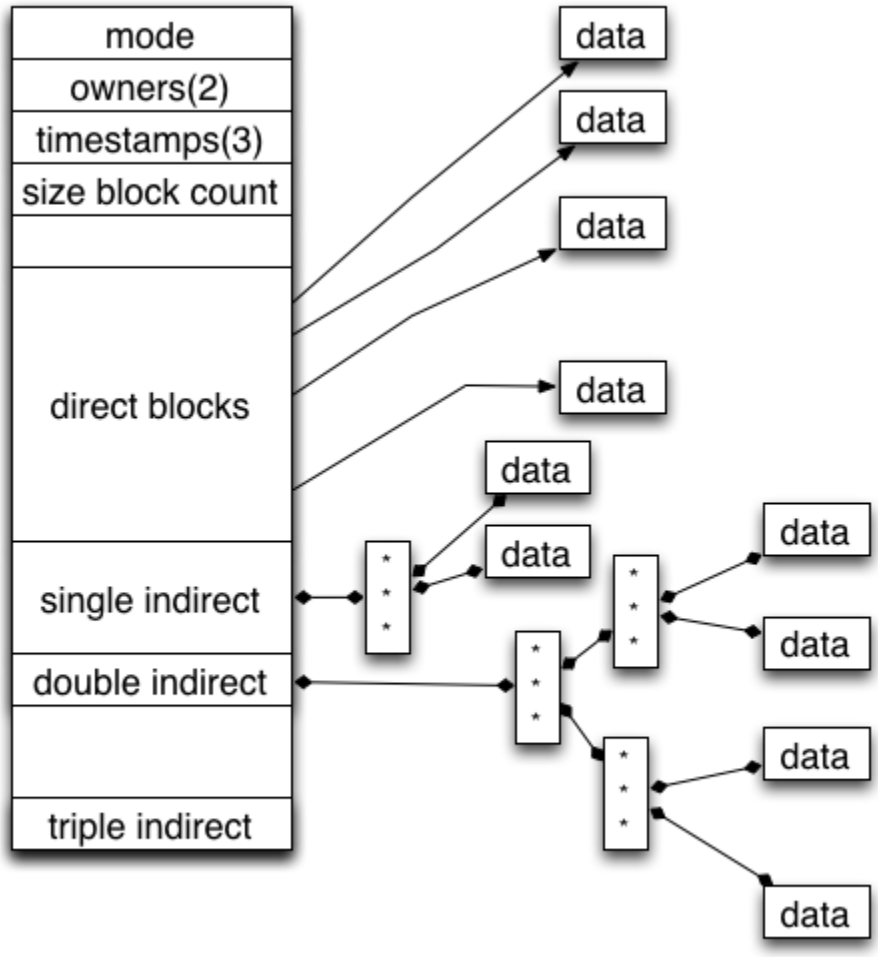


Figure 12.9 UNIX inode

11.4.4 Performance

- The optimal allocation method is different for sequential access files than for random access files, and is also different for small files than for large files.
- Some systems support more than one allocation method, which may require specifying how the file is to be used (sequential or random access) at the time it is allocated. Such systems also provide conversion utilities.

- Some systems have been known to use contiguous access for small files, and automatically switch to an indexed scheme when file sizes surpass a certain threshold.
- And of course some systems adjust their allocation schemes (e.g. block sizes) to best match the characteristics of the hardware for optimum performance.

11.5 Free-Space Management

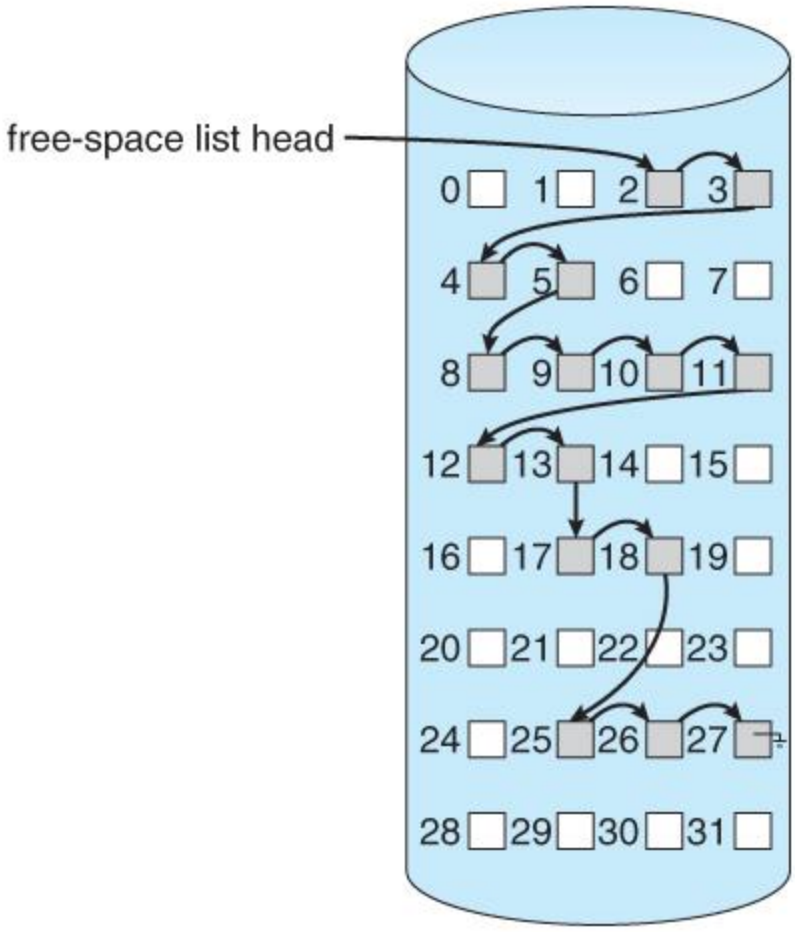
- Another important aspect of disk management is keeping track of and allocating free space.

11.5.1 Bit Vector

- One simple approach is to use a ***bit vector***, in which each bit represents a disk block, set to 1 if free or 0 if allocated.
- Fast algorithms exist for quickly finding contiguous blocks of a given size
- The down side is that a 40GB disk requires over 5MB just to store the bitmap. (For example.)

11.5.2 Linked List

- A linked list can also be used to keep track of all free blocks.
- Traversing the list and/or finding a contiguous block of a given size are not easy, but fortunately are not frequently needed operations. Generally the system just adds and removes single blocks from the beginning of the list.
- The FAT table keeps track of the free list as just one more linked list on the table.



11.5.3 Grouping

- A variation on linked list free lists is to use links of blocks of indices of free blocks. If a block holds up to N addresses, then the first block in the linked-list contains up to N-1 addresses of free blocks and a pointer to the next block of free addresses.

11.5.4 Counting

- When there are multiple contiguous blocks of free space then the system can keep track of the starting address of the group and the number of contiguous free blocks. As long as the average length of a contiguous group of free blocks is greater than two this offers a savings in space needed for the free list. (Similar to compression techniques used for graphics images when a group of pixels all the same color is encountered.)

11.5.5 Space Maps (New)

- Sun's ZFS file system was designed for HUGE numbers and sizes of files, directories, and even file systems.
- The resulting data structures could be VERY inefficient if not implemented carefully. For example, freeing up a 1 GB file on a 1 TB file system could involve updating thousands of blocks of free list bit maps if the file was spread across the disk.
- ZFS uses a combination of techniques, starting with dividing the disk up into (hundreds of) ***metaslabs*** of a manageable size, each having their own space map.
- Free blocks are managed using the counting technique, but rather than write the information to a table, it is recorded in a log-structured transaction record. Adjacent free blocks are also coalesced into a larger single free block.
- An in-memory space map is constructed using a balanced tree data structure, constructed from the log data.
- The combination of the in-memory tree and the on-disk log provide for very fast and efficient management of these very large files and free blocks.