File System Implementation (Part I)

Amir H. Payberah
amir@sics.se

Amirkabir University of Technology
(Tehran Polytechnic)

Motivation

Motivation

- The file system resides permanently on secondary storage.
- How to
  - structure file use
  - allocate disk space
  - recover free space
  - track the locations of data
  - interface other parts of the OS to secondary storage

File System Structure

File-System Structure

- Disk provides in-place rewrite and random access
  - I/O transfers performed in blocks of sectors (usually 512 bytes)

File-System Structure

- Disk provides in-place rewrite and random access
  - I/O transfers performed in blocks of sectors (usually 512 bytes)
- File system resides on secondary storage
  - User interface to storage, mapping logical to physical
  - Efficient and convenient access to disk

File-System Structure

- Disk provides in-place rewrite and random access
  - I/O transfers performed in blocks of sectors (usually 512 bytes)
- File system resides on secondary storage
  - User interface to storage, mapping logical to physical
  - Efficient and convenient access to disk
- File structure
  - Logical storage unit
  - Collection of related information

File-System Design Problems

- How the file system should look to the user?

File-System Design Problems

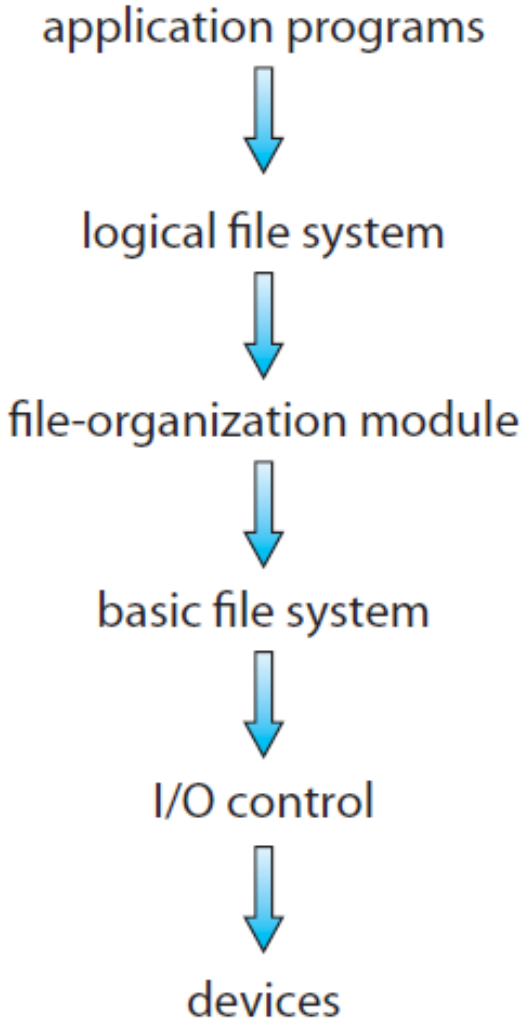
- How the file system should look to the user?
  - Defining a file and its attributes
  - The operations allowed on a file
  - The directory structure for organizing files

File-System Design Problems

- How the file system should look to the user?
  - Defining a file and its attributes
  - The operations allowed on a file
  - The directory structure for organizing files
- Algorithms and data structures to map the logical file system onto the physical secondary-storage devices.

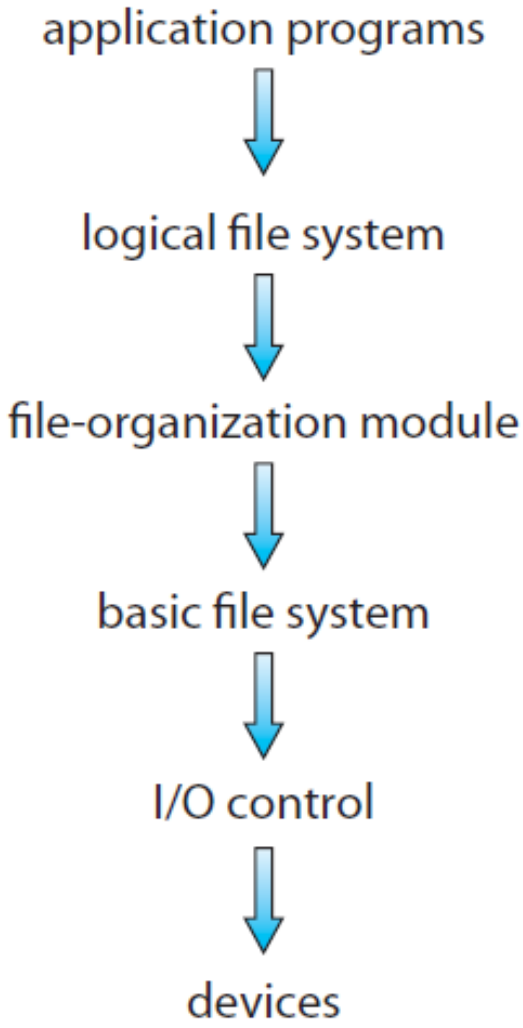
File System Layers (1/6)

- Different levels
- Each level uses the features of lower levels to create new features for use by higher levels.
- Reducing complexity and redundancy, but adds overhead and can decrease performance.



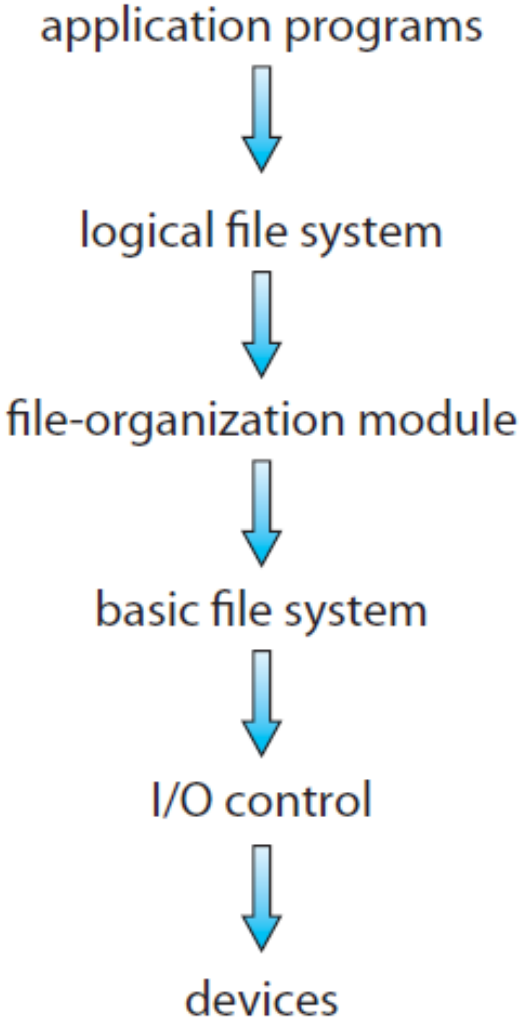
File System Layers (2/6)

- Device drivers manage I/O devices at the I/O control layer.
- Translates high-level commands to low-level hardware-specific instructions.



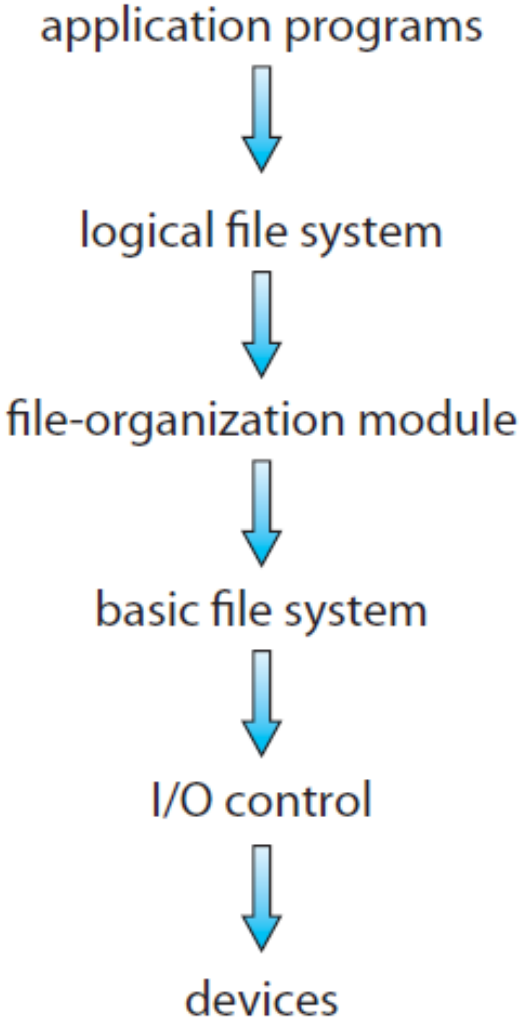
File System Layers (3/6)

- Basic file system translates given command like retrieve block 123 to device driver.



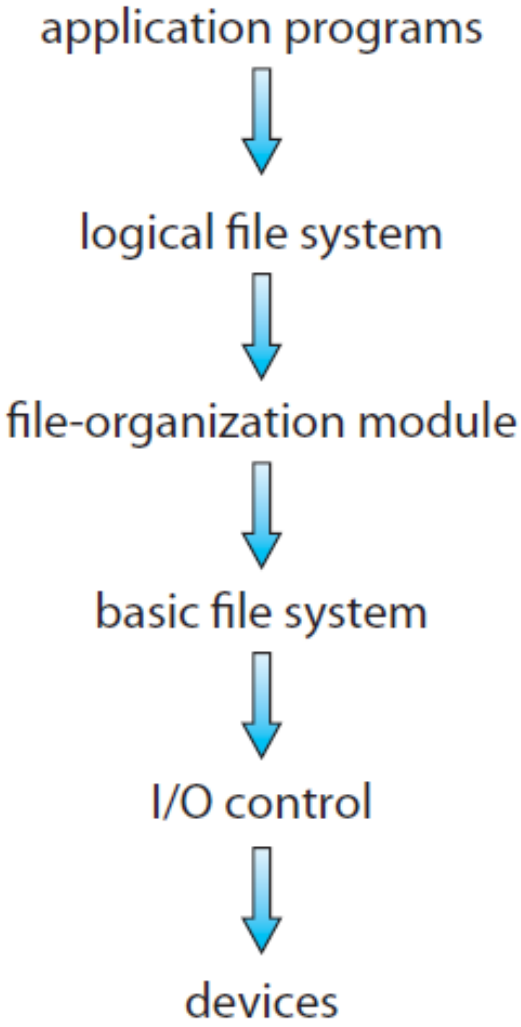
File System Layers (3/6)

- Basic file system translates given command like retrieve block 123 to device driver.
- Also manages memory buffers and caches (allocation, freeing, replacement)
  - Buffers hold data in transit
  - Caches hold frequently used data



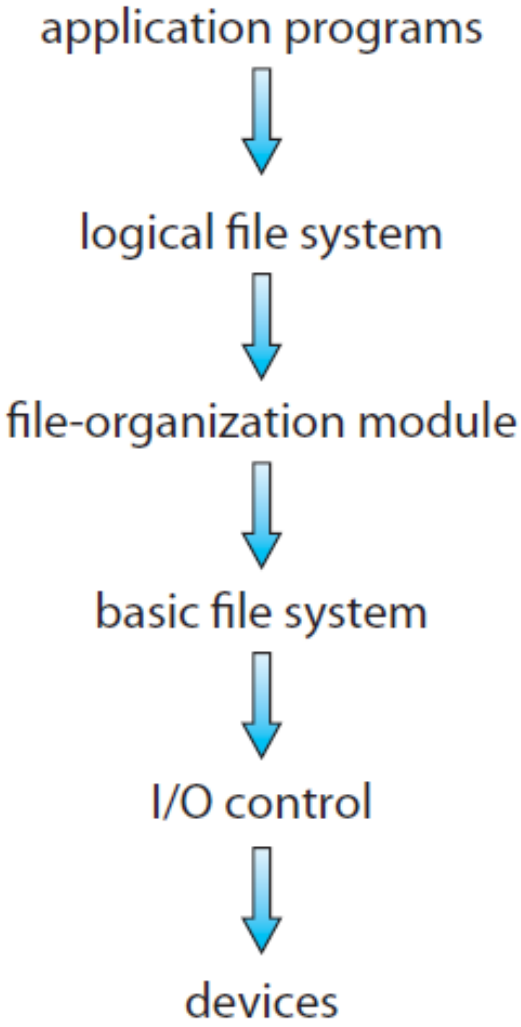
File System Layers (4/6)

- File organization understands files, logical address, and physical blocks.



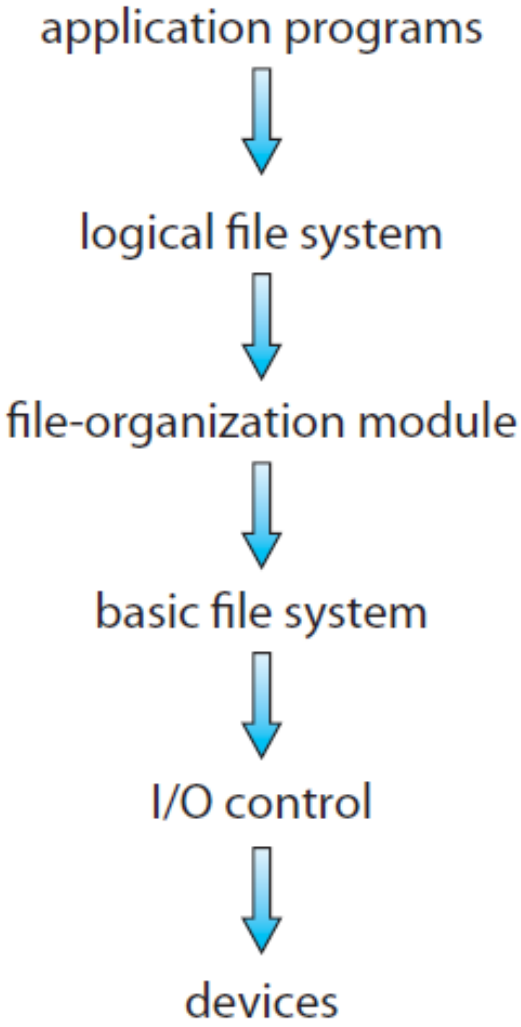
File System Layers (4/6)

- File organization understands files, logical address, and physical blocks.
- Translates logical block number to physical block number.



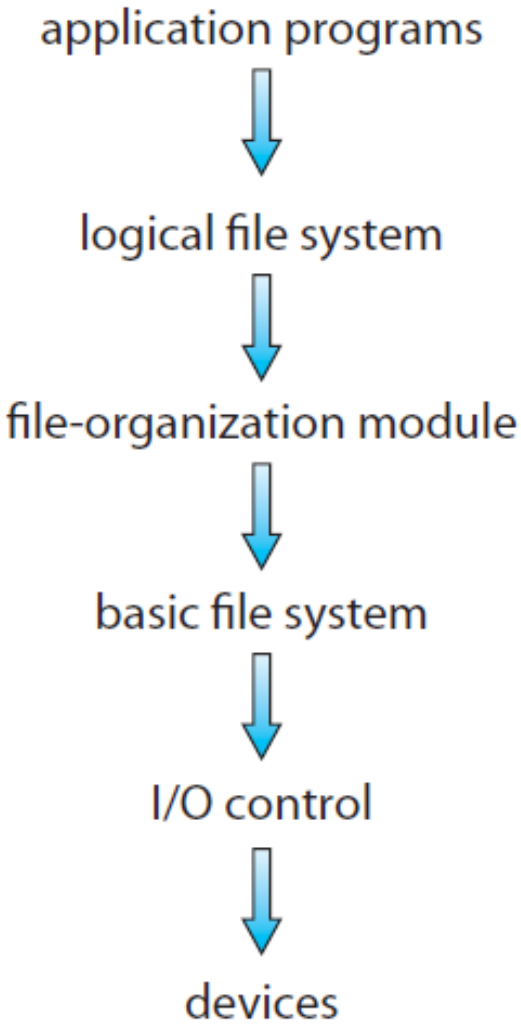
File System Layers (4/6)

- File organization understands files, logical address, and physical blocks.
- Translates logical block number to physical block number.
- Manages free space and disk allocation.



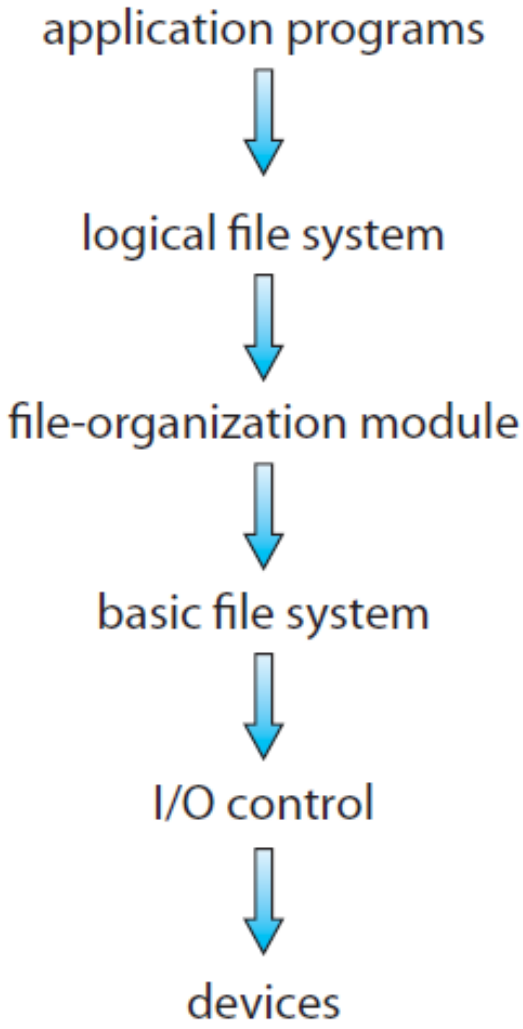
File System Layers (5/6)

- Logical file system manages metadata information.



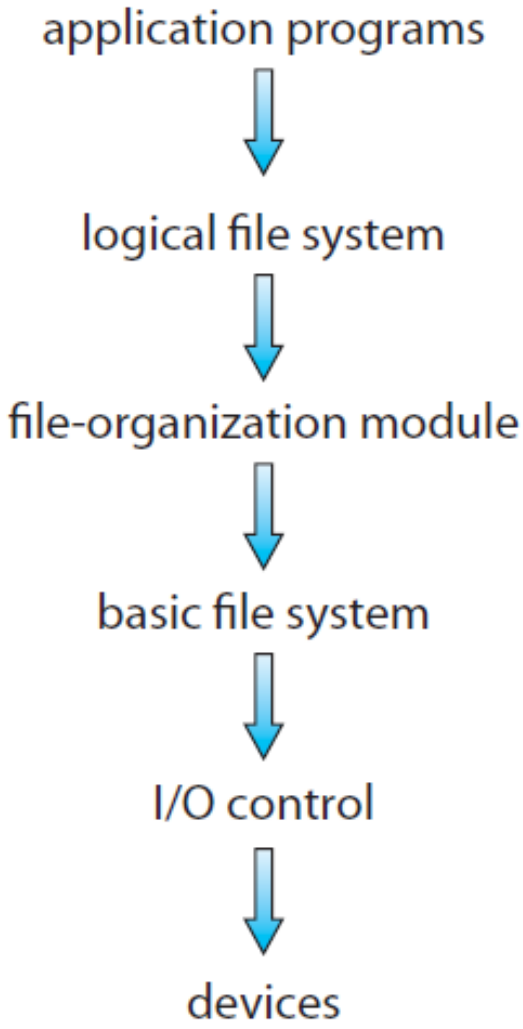
File System Layers (5/6)

- Logical file system manages metadata information.
- Translates file name into file number, file handle, location by maintaining file control blocks (inodes in Unix)



File System Layers (5/6)

- Logical file system manages metadata information.
- Translates file name into file number, file handle, location by maintaining file control blocks (inodes in Unix)
- Directory management
- Protection



File System Layers (6/6)

- Many file systems, sometimes many within an OS
- Each with its own format
  - CD-ROM: ISO 9660
  - Unix: UFS, FFS
  - Windows: FAT, FAT32, NTFS
  - Linux: more than 40 types, with extended file system (ext2, ext3, ext4)

File System Implementation

File-System Implementation

- Based on several on-disk and in-memory structures.

File-System Implementation

- Based on several on-disk and in-memory structures.

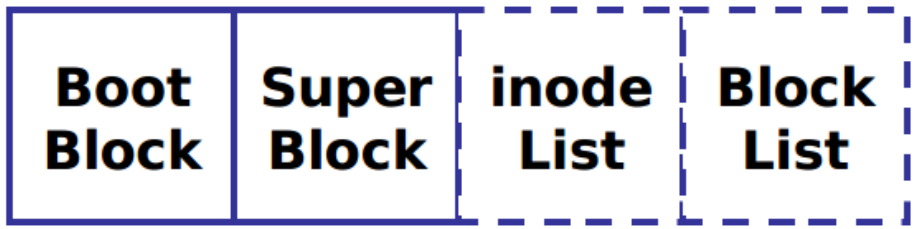
- On-disk
  - Boot control block (per volume)
  - Volume control block (per volume)
  - Directory structure (per file system)
  - File control block (per file)

File-System Implementation

- Based on several on-disk and in-memory structures.
- On-disk
  - Boot control block (per volume)
  - Volume control block (per volume)
  - Directory structure (per file system)
  - File control block (per file)
- In-memory
  - Mount table
  - Directory structure cache
  - The open-file table (system-wide and per process)
  - Buffers of the file-system blocks

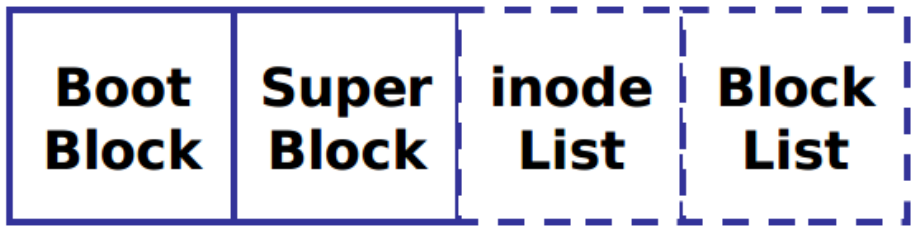
On-Disk File System Structures (1/2)

- Boot control block contains information needed by system to boot OS from that volume.



On-Disk File System Structures (1/2)

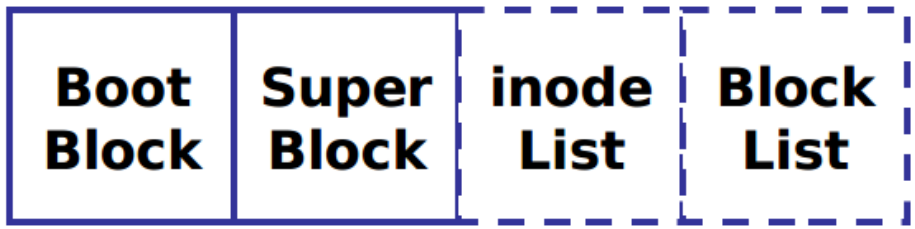
- Boot control block contains information needed by system to boot OS from that volume.
  - Needed if volume contains OS, usually first block of volume.
  - In UFS, it is called boot block, and in NTFS partition boot sector.



On-Disk File System Structures (1/2)

- Boot control block contains information needed by system to boot OS from that volume.
  - Needed if volume contains OS, usually first block of volume.
  - In UFS, it is called boot block, and in NTFS partition boot sector.

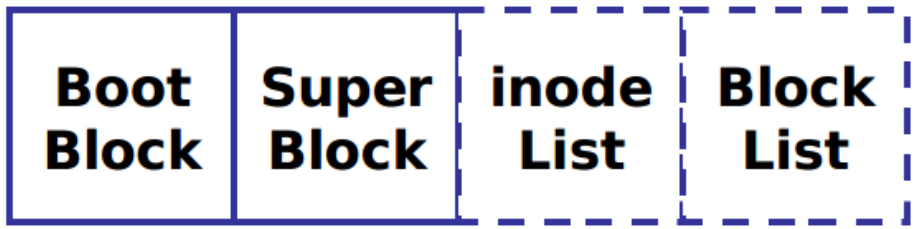
- Volume control block contains volume details.



On-Disk File System Structures (1/2)

- Boot control block contains information needed by system to boot OS from that volume.
  - Needed if volume contains OS, usually first block of volume.
  - In UFS, it is called boot block, and in NTFS partition boot sector.

- Volume control block contains volume details.
  - Total num. of blocks, num. of free blocks, block size, free block pointers or array
  - In UFS, it is called super block, and in NTFS master file table.

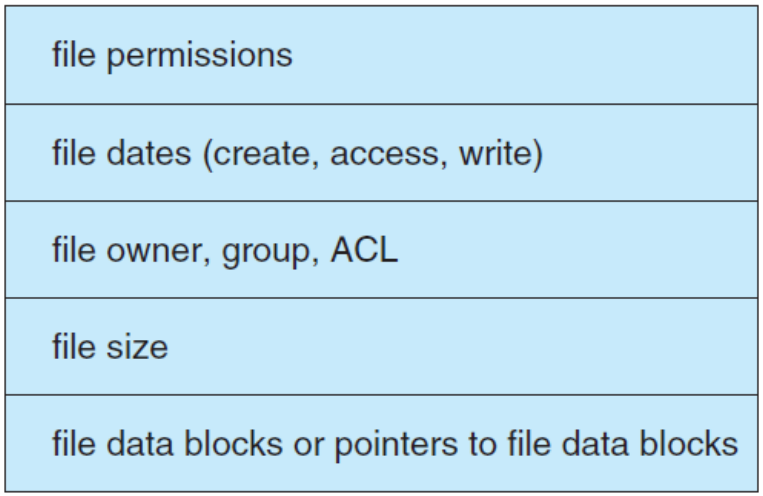


On-Disk File System Structures (2/2)

- Directory structure organizes the files.
  - In UFS, this includes file names and associated inode numbers.
  - In NTFS, it is stored in the master file table.

On-Disk File System Structures (2/2)

- Directory structure organizes the files.
  - In UFS, this includes file names and associated inode numbers.
  - In NTFS, it is stored in the master file table.
- File control block contains many details about the file.
  - In UFS, inode number, permissions, size, dates.
  - In NFTS stores into in master file table.



In-Memory File System Structures

- Mount table contains information about each mounted volume.

In-Memory File System Structures

- Mount table contains information about each mounted volume.
- Directory structure cache holds the directory information of recently accessed directories.

In-Memory File System Structures

- Mount table contains information about each mounted volume.
- Directory structure cache holds the directory information of recently accessed directories.
- System-wide open-file table contains a copy of the FCB of each open file.

In-Memory File System Structures

- Mount table contains information about each mounted volume.
- Directory structure cache holds the directory information of recently accessed directories.
- System-wide open-file table contains a copy of the FCB of each open file.
- Per-process open-file table contains a pointer to the appropriate entry in the system-wide open-file table.

In-Memory File System Structures

- Mount table contains information about each mounted volume.
- Directory structure cache holds the directory information of recently accessed directories.
- System-wide open-file table contains a copy of the FCB of each open file.
- Per-process open-file table contains a pointer to the appropriate entry in the system-wide open-file table.
- Buffers hold file-system blocks when they are being read from disk or written to disk.

Create a File

- A program calls the logical file system.

Create a File

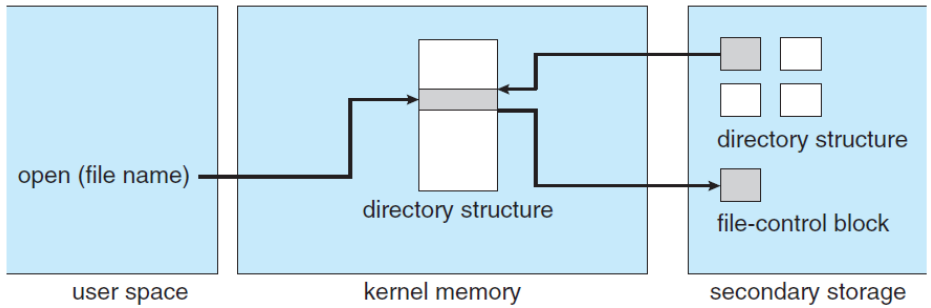
- A program calls the logical file system.
- The logical file system knows the format of the directory structures, and allocates a new FCB.

Create a File

- A program calls the logical file system.
- The logical file system knows the format of the directory structures, and allocates a new FCB.
- The system, then, reads the appropriate directory into memory, updates it with the new file name and FCB, and writes it back to the disk.

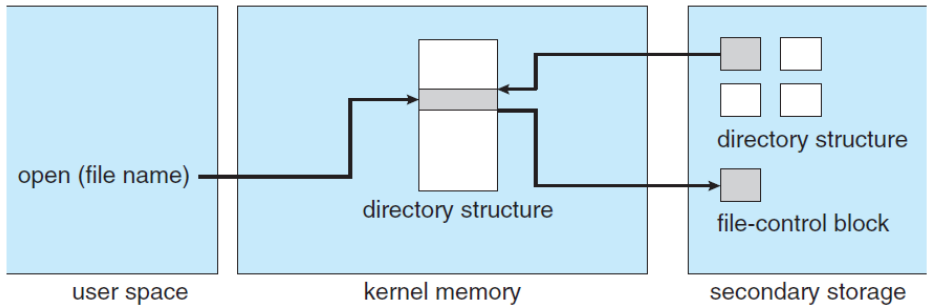
Open a File

- The file must be opened.
  - The `open()` passes a file name to the logical file system.



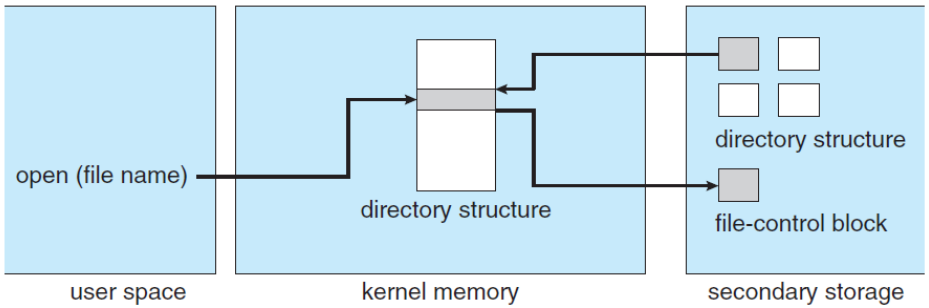
Open a File

- The file must be opened.
  - The `open()` passes a file name to the logical file system.
- The `open()` first searches the system-wide open-file: if the file is already in use by another process.



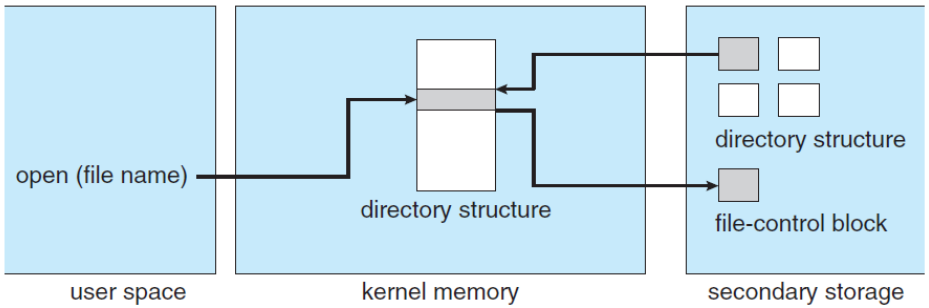
Open a File

- The file must be opened.
  - The `open()` passes a file name to the logical file system.
- The `open()` first searches the system-wide open-file: if the file is already in use by another process.
  - If yes: a per-process open-file table entry is created.



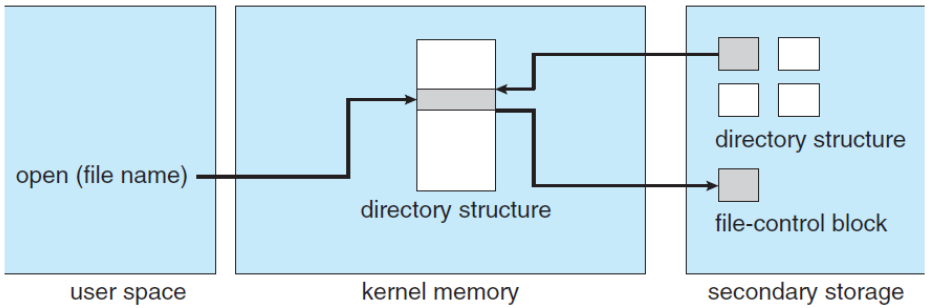
Open a File

- The file must be opened.
  - The `open()` passes a file name to the logical file system.
- The `open()` first searches the system-wide open-file: if the file is already in use by another process.
  - If yes: a per-process open-file table entry is created.
  - If no: the directory structure is searched for the given file name: once the file is found, the FCB is copied into a system-wide open-file table in memory.



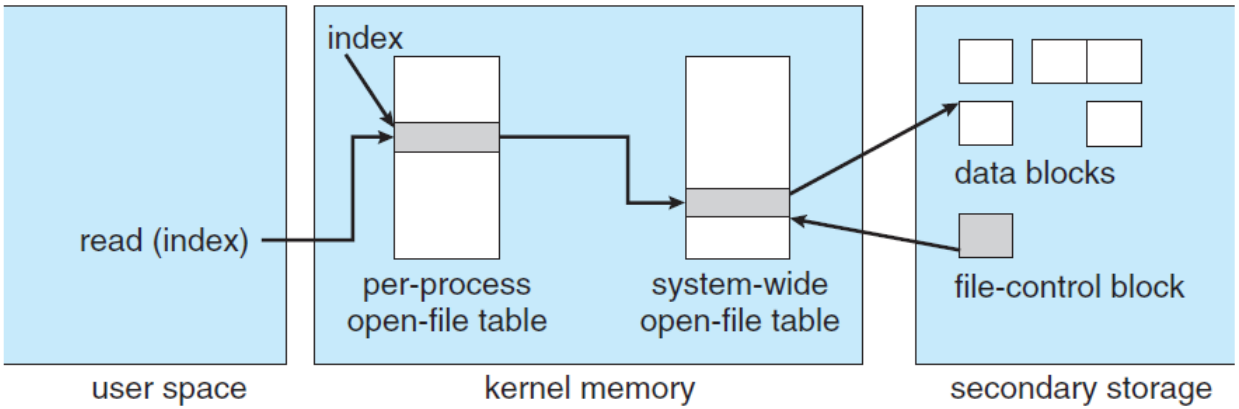
Open a File

- The file must be opened.
  - The `open()` passes a file name to the logical file system.
- The `open()` first searches the system-wide open-file: if the file is already in use by another process.
  - If yes: a per-process open-file table entry is created.
  - If no: the directory structure is searched for the given file name: once the file is found, the FCB is copied into a system-wide open-file table in memory.
- This table stores the FCB as well as the number of processes that have the file open.



Read From a File

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



Close a File

- When a process closes the file:
  - The per-process table entry is removed.
  - The system-wide entry's open count is decremented.

Close a File

- When a process closes the file:
  - The per-process table entry is removed.
  - The system-wide entry's open count is decremented.
- When all users that have opened the file close it, any updated meta-data is copied back to the disk-based directory structure, and the system-wide open-file table entry is removed.

Partitions and Mounting (1/2)

- Partition can be a volume containing a file system or raw.
  - Raw partition: just a sequence of blocks with no file system.

Partitions and Mounting (1/2)

- Partition can be a volume containing a file system or raw.
  - Raw partition: just a sequence of blocks with no file system.
- Boot block points to boot volume or boot loader.
  - Boot loader: knows enough about the file-system structure to be able to find and load the kernel and start it executing.
  - Dual-boot that allows to install multiple OS on a single system.

Partitions and Mounting (2/2)

- Root partition contains the OS
  - Mounted at boot time
  - Other partitions can hold other OSes, other file systems, or be raw
  - Other partitions can mount automatically or manually

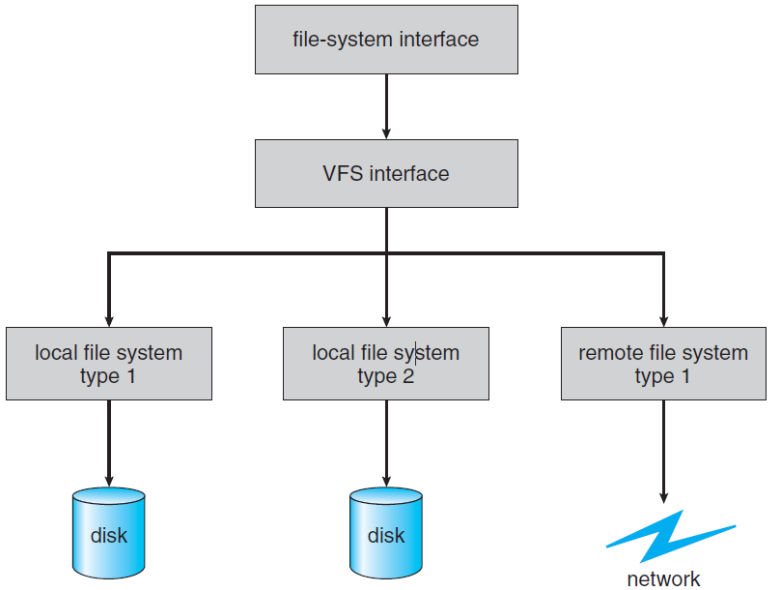
Partitions and Mounting (2/2)

- Root partition contains the OS
  - Mounted at boot time
  - Other partitions can hold other OSes, other file systems, or be raw
  - Other partitions can mount automatically or manually
- At mount time, file system consistency checked.
  - Is all metadata correct? if not, fix it, try again, if yes, add to mount table, allow access

Virtual File Systems

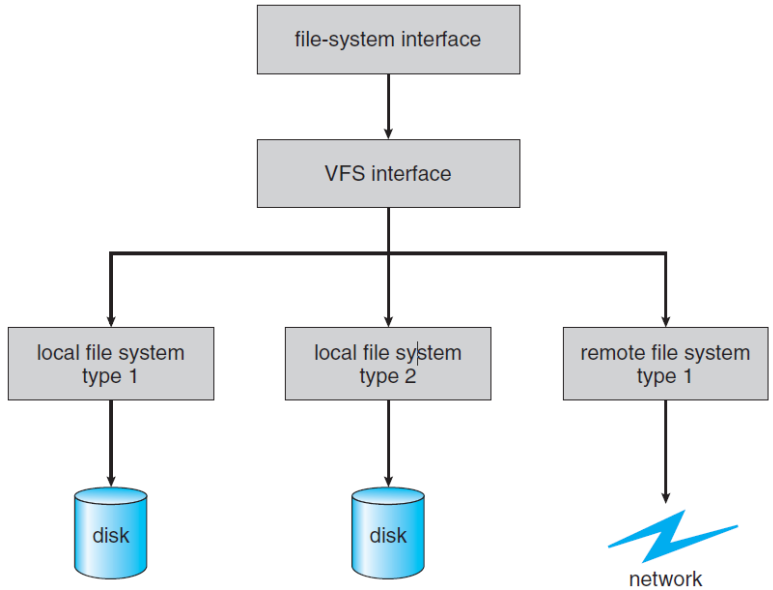
Virtual File Systems (1/2)

- Virtual File Systems (VFS) on Unix provide an object-oriented way of implementing file systems.



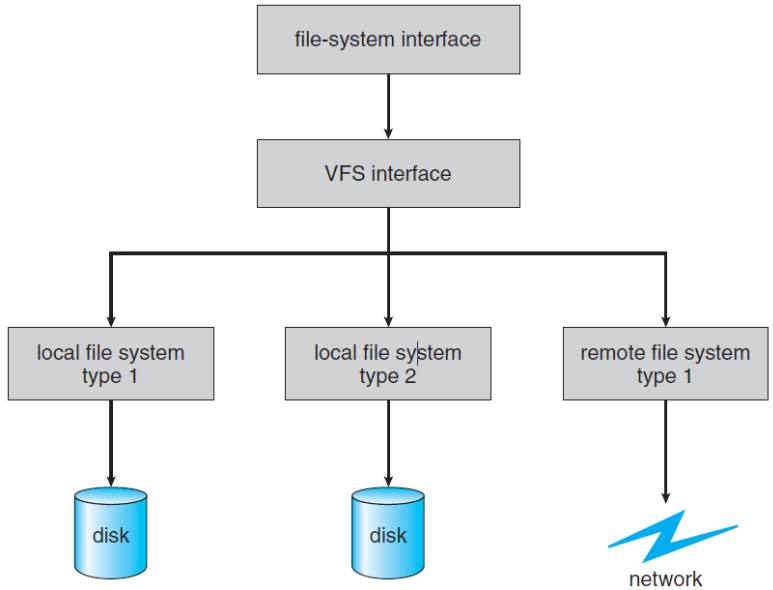
Virtual File Systems (1/2)

- Virtual File Systems (VFS) on Unix provide an object-oriented way of implementing file systems.
- VFS allows the same system call interface (the API) to be used for different types of file systems.



Virtual File Systems (1/2)

- Virtual File Systems (VFS) on Unix provide an object-oriented way of implementing file systems.
- VFS allows the same system call interface (the API) to be used for different types of file systems.
- The API is to the VFS interface, rather than any specific type of file system.



Virtual File Systems (2/2)

- VFS layer serves two important functions:

Virtual File Systems (2/2)

- VFS layer serves two important functions:
  1. It separates file-system-generic operations from their implementation, and allows transparent access to different types of file systems mounted locally.

Virtual File Systems (2/2)

- VFS layer serves two important functions:
  1. It separates file-system-generic operations from their implementation, and allows transparent access to different types of file systems mounted locally.
  2. It provides a mechanism for uniquely representing a file throughout a network.

Virtual File Systems (2/2)

- VFS layer serves two important functions:
  1. It separates file-system-generic operations from their implementation, and allows transparent access to different types of file systems mounted locally.
  2. It provides a mechanism for uniquely representing a file throughout a network.

- The VFS is based on a structure, called a vnode.

Virtual File Systems (2/2)

- VFS layer serves two important functions:
  1. It separates file-system-generic operations from their implementation, and allows transparent access to different types of file systems mounted locally.
  2. It provides a mechanism for uniquely representing a file throughout a network.

- The VFS is based on a structure, called a vnode.
  - Contains a numerical designator for a network-wide unique file.

Virtual File Systems (2/2)

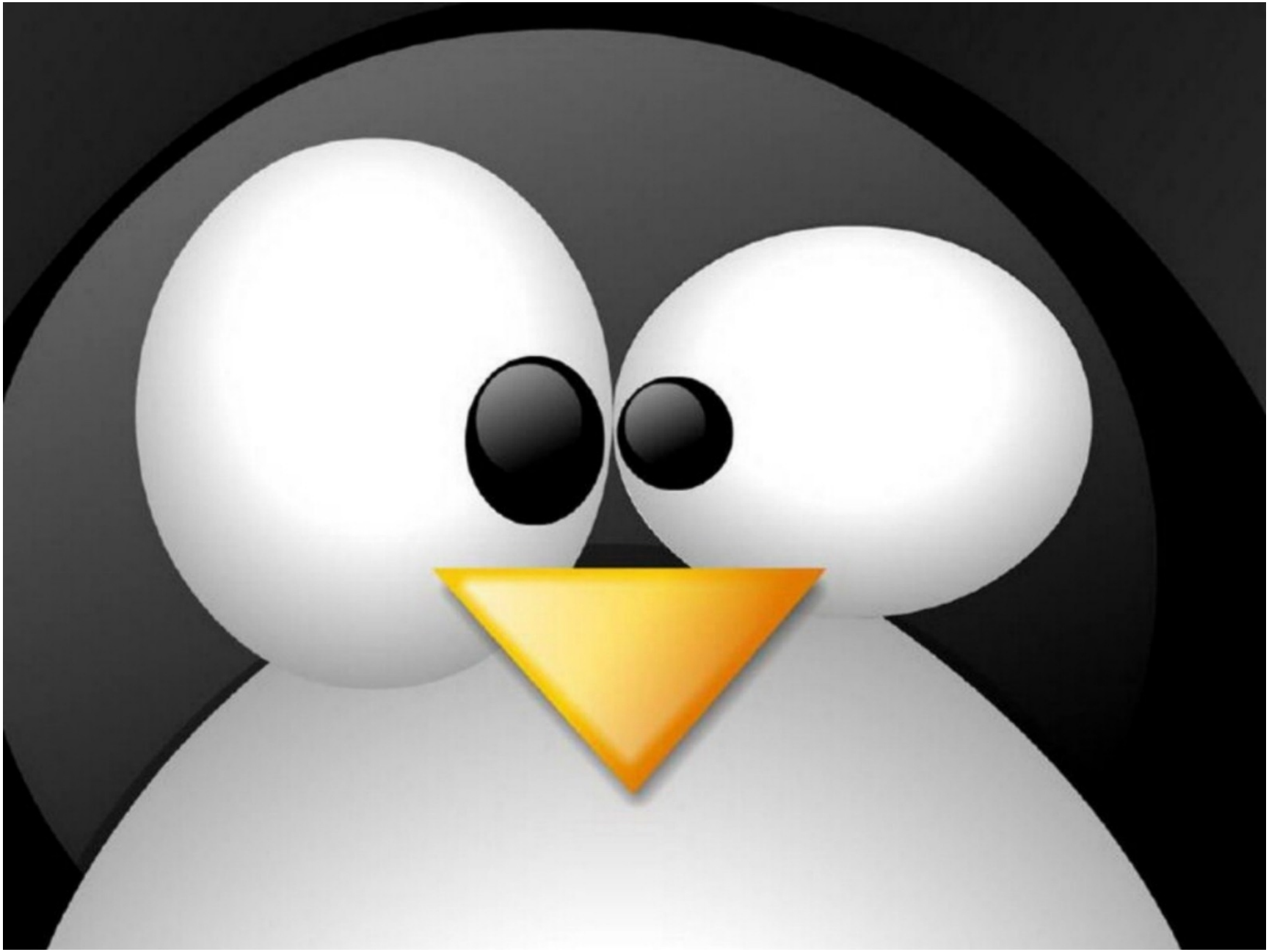
- VFS layer serves two important functions:
  1. It separates file-system-generic operations from their implementation, and allows transparent access to different types of file systems mounted locally.
  2. It provides a mechanism for uniquely representing a file throughout a network.

- The VFS is based on a structure, called a vnode.
  - Contains a numerical designator for a network-wide unique file.
  - Unix inodes are unique within only a single file system.

Virtual File Systems (2/2)

- VFS layer serves two important functions:
  1. It separates file-system-generic operations from their implementation, and allows transparent access to different types of file systems mounted locally.
  2. It provides a mechanism for uniquely representing a file throughout a network.

- The VFS is based on a structure, called a vnode.
  - Contains a numerical designator for a network-wide unique file.
  - Unix inodes are unique within only a single file system.
  - The kernel maintains one vnode structure for each active node.



VFS in Linux (1/2)

- The four main object types defined by the Linux VFS are:

VFS in Linux (1/2)

- The four main object types defined by the Linux VFS are:
  - The inode object: represents an individual file

VFS in Linux (1/2)

- The four main object types defined by the Linux VFS are:
  - The inode object: represents an individual file
  - The file object: represents an open file

VFS in Linux (1/2)

- The four main object types defined by the Linux VFS are:
  - The inode object: represents an individual file
  - The file object: represents an open file
  - The super block object: represents an entire file system

VFS in Linux (1/2)

- The four main object types defined by the Linux VFS are:
  - The inode object: represents an individual file
  - The file object: represents an open file
  - The super block object: represents an entire file system
  - The dentry object: represents an individual directory entry

VFS in Linux (2/2)

- VFS defines a set of operations on the objects that must be implemented.

VFS in Linux (2/2)

- VFS defines a set of operations on the objects that must be implemented.
- Every object has a pointer to a function table.

VFS in Linux (2/2)

- VFS defines a set of operations on the objects that must be implemented.
- Every object has a pointer to a function table.
  - Function table has addresses of routines to implement that function on that object.

VFS in Linux (2/2)

- VFS defines a set of operations on the objects that must be implemented.
- Every object has a pointer to a function table.
  - Function table has addresses of routines to implement that function on that object.
  - For example:
    `int open(...)`: open a file
    `int close(...)`: close an already-open file
    `ssize_t read(...)`: read from a file
    `ssize_t write(...)`: write to a file
    `int mmap(...)`: memory-map a file

Directory Implementation

Directory Implementation

- Linear list
- Hash table

Directory Implementation - Linear List

- Linear list of file names with pointer to the data blocks.

Directory Implementation - Linear List

- Linear list of file names with pointer to the data blocks.
- Simple to program.

Directory Implementation - Linear List

- Linear list of file names with pointer to the data blocks.
- Simple to program.
- Time-consuming to execute.

Directory Implementation - Linear List

- Linear list of file names with pointer to the data blocks.
- Simple to program.
- Time-consuming to execute.
- Linear search time.

Directory Implementation - Linear List

- Linear list of file names with pointer to the data blocks.
- Simple to program.
- Time-consuming to execute.
- Linear search time.
- Could keep ordered alphabetically via linked list or use B+ tree: binary search, but heavy

Directory Implementation - Hash Table

- Hash Table: linear list with hash data structure

Directory Implementation - Hash Table

- Hash Table: linear list with hash data structure
- Decreases directory search time

Directory Implementation - Hash Table

- Hash Table: linear list with hash data structure
- Decreases directory search time
- Collisions: situations where two file names hash to the same location

Directory Implementation - Hash Table

- Hash Table: linear list with hash data structure
- Decreases directory search time
- Collisions: situations where two file names hash to the same location
- Chained-overflow method.
  - Each hash entry can be a linked list instead of an individual value.

Allocation Methods

Allocation Methods

- How disk blocks are allocated to files?

Allocation Methods

- How disk blocks are allocated to files?
- Methods:
  - Contiguous allocation
  - Linked allocation
  - Indexed allocation

Contiguous Allocation

Contiguous Allocation (1/2)

- Contiguous allocation: each file occupies set of contiguous blocks.

Contiguous Allocation (1/2)

- Contiguous allocation: each file occupies set of contiguous blocks.
  - Best performance in most cases
  - Simple: only starting location (block number) and length (number of blocks) are required.

Contiguous Allocation (1/2)

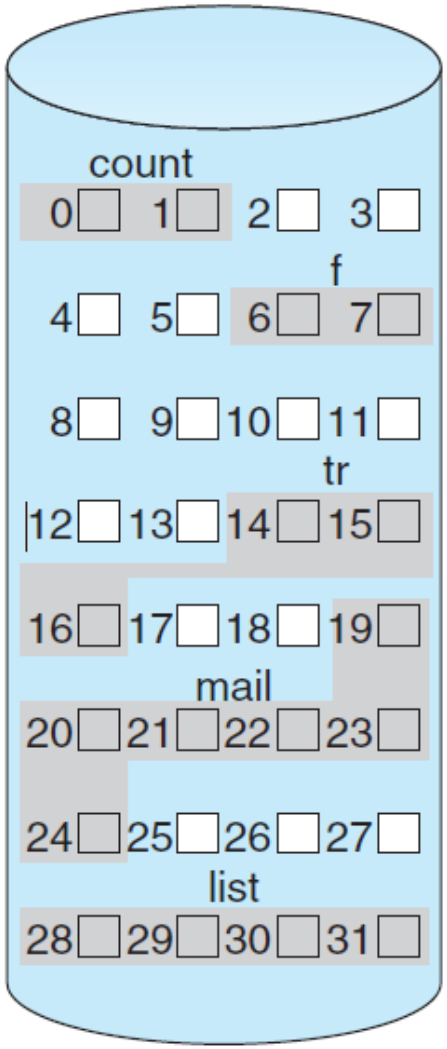
- Contiguous allocation: each file occupies set of contiguous blocks.
  - Best performance in most cases
  - Simple: only starting location (block number) and length (number of blocks) are required.
  - Supports both sequential and direct access.

Contiguous Allocation (1/2)

- Contiguous allocation: each file occupies set of contiguous blocks.
  - Best performance in most cases
  - Simple: only starting location (block number) and length (number of blocks) are required.
  - Supports both sequential and direct access.

- Allocation strategies like contiguous memory allocation:
  - First fit
  - Best fit
  - Worst fit

Contiguous Allocation (2/2)



directory

file	start	length
count	0	2
tr	14	3
mail	19	6
list	28	4
f	6	2

Contiguous Allocation Problems

- Finding space for file

Contiguous Allocation Problems

- Finding space for file
- External fragmentation

Contiguous Allocation Problems

- Finding space for file
- External fragmentation
- Need for compaction (fragmentation) off-line or on-line: lose of performance

Contiguous Allocation Problems

- Finding space for file
- External fragmentation
- Need for compaction (fragmentation) off-line or on-line: lose of performance
- Knowing file size

Extent-Based Systems

- A modified contiguous allocation scheme.
  - E.g., Veritas file system

Extent-Based Systems

- A modified contiguous allocation scheme.
  - E.g., Veritas file system
- Extent-based file systems allocate disk blocks in extents.

Extent-Based Systems

- A modified contiguous allocation scheme.
  - E.g., Veritas file system
- Extent-based file systems allocate disk blocks in extents.
- An extent is a contiguous block of disks.
  - Extents are allocated for file allocation.
  - A file consists of one or more extents.

Linked Allocation

Linked Allocation (1/2)

- Linked allocation: each file is a linked list of blocks.
  - Each block contains pointer to next block.
  - File ends at null pointer.

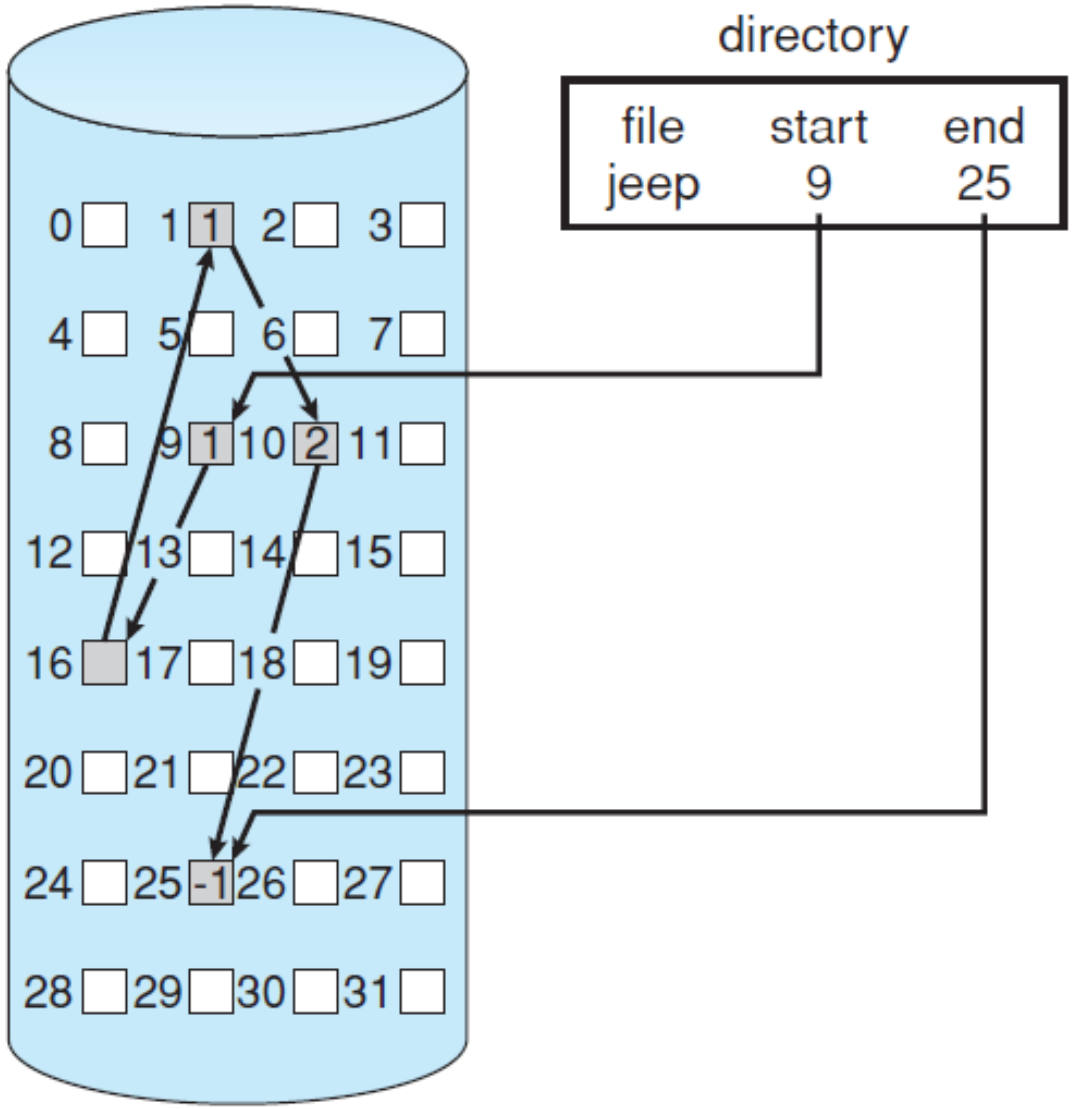
Linked Allocation (1/2)

- Linked allocation: each file is a linked list of blocks.
  - Each block contains pointer to next block.
  - File ends at null pointer.
- No external fragmentation, no compaction.

Linked Allocation (1/2)

- Linked allocation: each file is a linked list of blocks.
  - Each block contains pointer to next block.
  - File ends at null pointer.
- No external fragmentation, no compaction.
- Free space management system called when new block needed.

Linked Allocation (2/2)



Linked Allocation Problems

- Locating a block can take many I/Os and disk seeks.

Linked Allocation Problems

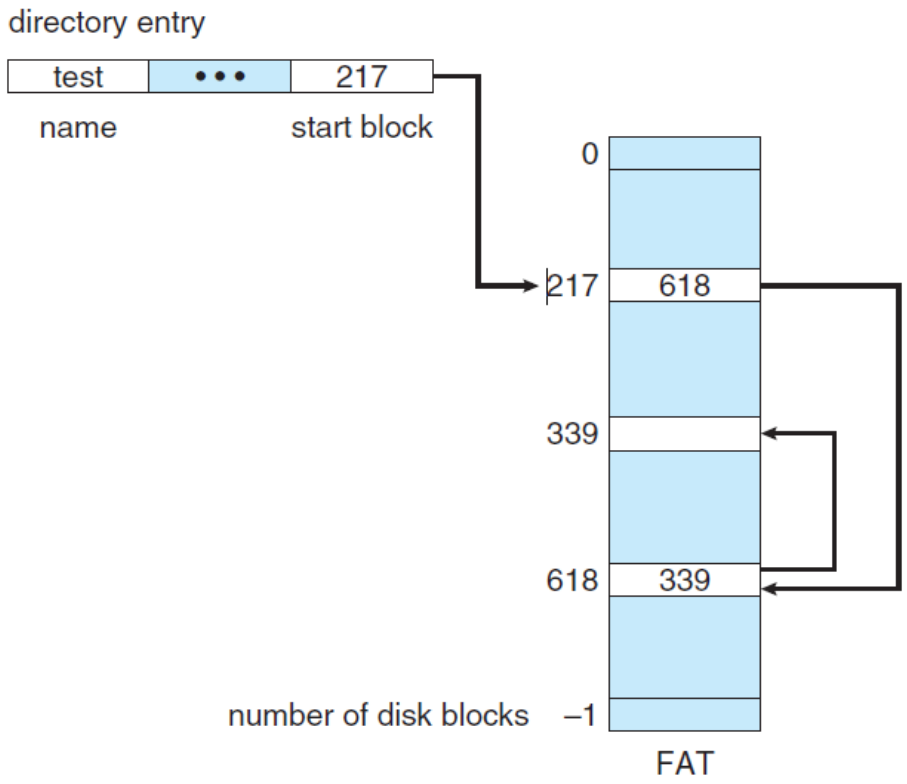
- Locating a block can take many I/Os and disk seeks.
- Reliability can be a problem.

Linked Allocation Problems

- Locating a block can take many I/Os and disk seeks.
- Reliability can be a problem.
- The space required for the pointers.
  - Efficiency can be improved by clustering blocks into groups but increases internal fragmentation.

File-Allocation Table (FAT)

- Beginning of volume has a table, indexed by block number.
- Much like a linked list, but faster on disk and cacheable.



Indexed Allocation

Indexed Allocation (1/2)

- Indexed allocation: each file has its own index block(s) of pointers to its data blocks.

Indexed Allocation (1/2)

- Indexed allocation: each file has its own index block(s) of pointers to its data blocks.
- Need index table

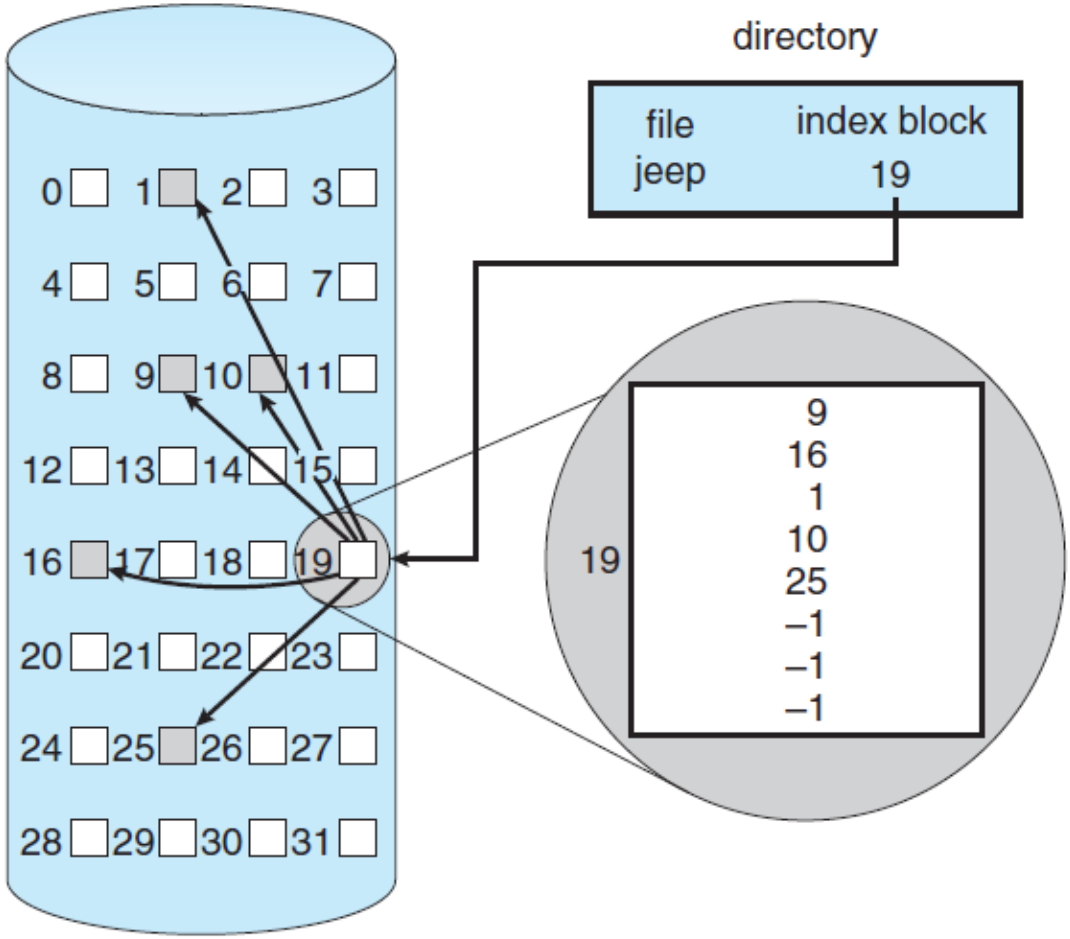
Indexed Allocation (1/2)

- Indexed allocation: each file has its own index block(s) of pointers to its data blocks.
- Need index table
- Random access

Indexed Allocation (1/2)

- Indexed allocation: each file has its own index block(s) of pointers to its data blocks.
- Need index table
- Random access
- Dynamic access without external fragmentation, but have overhead of index block

Indexed Allocation (2/2)



Indexed Allocation Problems

- Wasted space: overhead of the index blocks.
- For example, even with a file of only one or two blocks, we need an an entire index block.

Index Block Size

- How large the index block should be?

Index Block Size

- How large the index block should be?
- Keep the index block as small as possible.
  - We need a mechanism to hold pointers for large files.

Index Block Size

- How large the index block should be?
- Keep the index block as small as possible.
  - We need a mechanism to hold pointers for large files.
- Mechanisms for this purpose include the following:
  - Linked scheme
  - Multi-level index
  - Combined scheme

Linked Scheme

- Linked scheme: link blocks of index table (no limit on size)

Linked Scheme

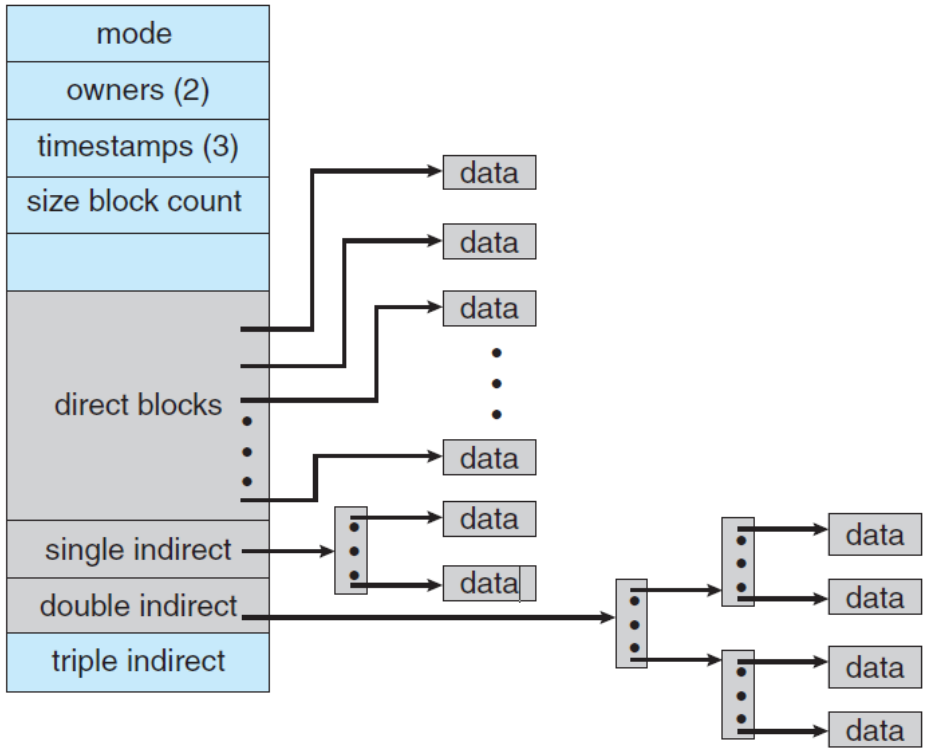
- Linked scheme: link blocks of index table (no limit on size)
- For example, an index block might contain a small header giving the name of the file and a set of the first 100 disk-block addresses.
- The next address is null or is a pointer to another index block.

Multi-Level Index

- Two-level index
- A first-level index block to point to a set of second-level index blocks, which in turn point to the file blocks.
- Could be continued to a third or fourth level.

Combined Scheme

- Combine scheme: used in Unix/Linux FS
- The first 12 pointers point to direct blocks
  - The data for small files do not need a separate index block.
- The next 3 pointers point to indirect blocks.
  - Single indirect
  - Double indirect
  - Triple indirect



Performance

- Best method depends on file access type.

Performance

- Best method depends on file access type.
- Contiguous is great for sequential and random.

Performance

- Best method depends on file access type.
- Contiguous is great for sequential and random.
- Linked is good for sequential, not random.

Performance

- Best method depends on file access type.
- Contiguous is great for sequential and random.
- Linked is good for sequential, not random.
- Indexed is more complex
  - Single block access could require 2 index block reads then data block read
  - Clustering can help improve throughput, reduce CPU overhead

Summary

Summary

- FS layers: device, I/O control, basic FS, file-organization, logical FS, application

Summary

- FS layers: device, I/O control, basic FS, file-organization, logical FS, application
- FS implementation:
  - On-disk structures: boot control block, volume control block, directory structure, and file control block
  - In-memory structures: mount table, directory structure, open-file tables, and buffers

Summary

- FS layers: device, I/O control, basic FS, file-organization, logical FS, application
- FS implementation:
  - On-disk structures: boot control block, volume control block, directory structure, and file control block
  - In-memory structures: mount table, directory structure, open-file tables, and buffers
- Virtual file system (VFS)

Summary

- FS layers: device, I/O control, basic FS, file-organization, logical FS, application
- FS implementation:
  - On-disk structures: boot control block, volume control block, directory structure, and file control block
  - In-memory structures: mount table, directory structure, open-file tables, and buffers
- Virtual file system (VFS)
- Directory implementation: linear list, and hash table

Summary

- FS layers: device, I/O control, basic FS, file-organization, logical FS, application
- FS implementation:
  - On-disk structures: boot control block, volume control block, directory structure, and file control block
  - In-memory structures: mount table, directory structure, open-file tables, and buffers
- Virtual file system (VFS)
- Directory implementation: linear list, and hash table
- Allocation methods: contiguous allocation, linked allocation, and indexed allocation

Questions?

Acknowledgements

Some slides were derived from Avi Silberschatz slides.