File System Implementation

Operating Systems
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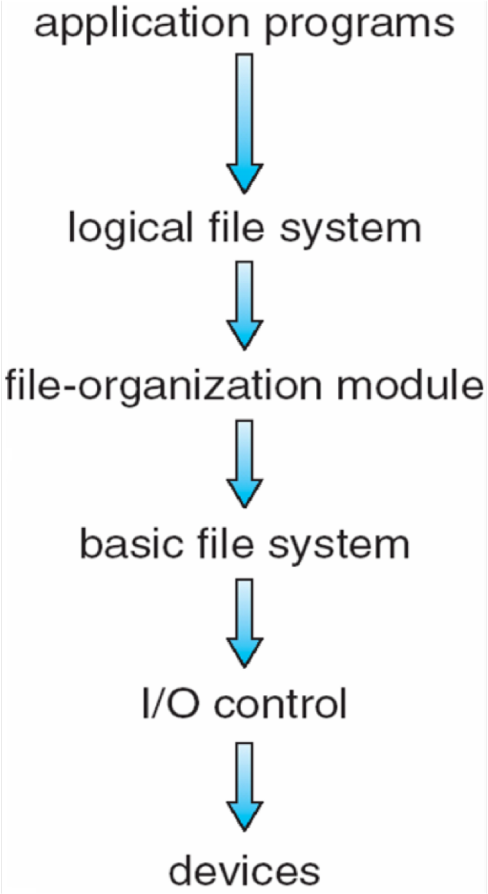
Review

- File system
- File operations
  - Create, open, read/write, close
- Directory structure
  - Single level, two-level, tree, acyclic-graph, general graph

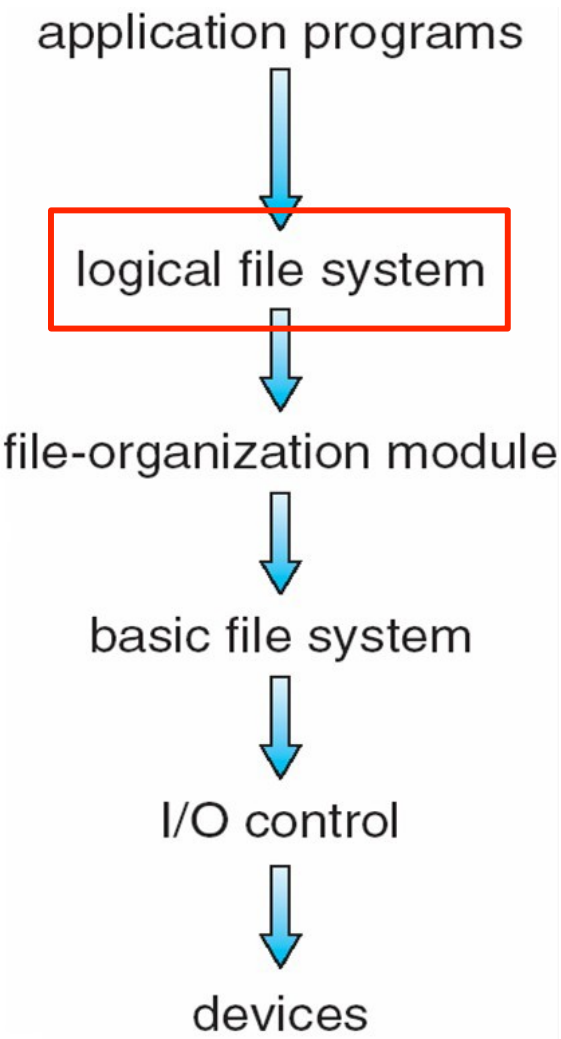
File-System Structure

- File is a logical storage unit for a collection of related information
- There are many file systems; OS may support several **simultaneously**
  - Linux has Ext2/3/4, Reiser FS/4, Btrfs…
  - Windows has FAT, FAT32, NTFS…
  - new ones still arriving – ZFS, GoogleFS, Oracle ASM, FUSE
- File system resides on **secondary storage** (disks)
  - disk driver provides interfaces to read/write disk blocks
  - **fs provides user/program interface to storage, mapping logical to physical**
    - file control block – storage structure consisting of information about a file
- File system is usually implemented and organized into **layers**

Layered File System

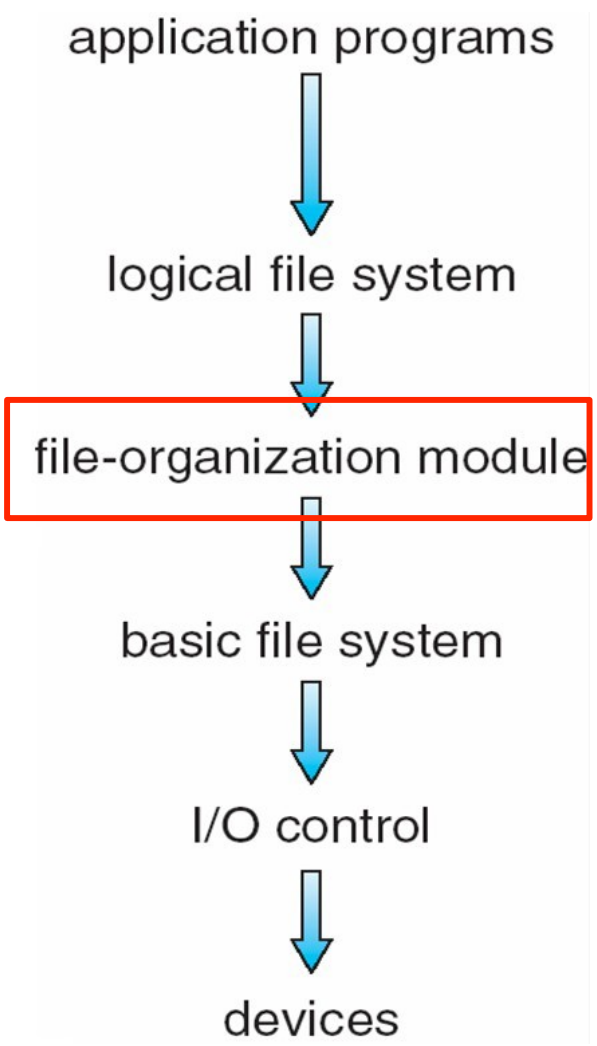


File System Implementation



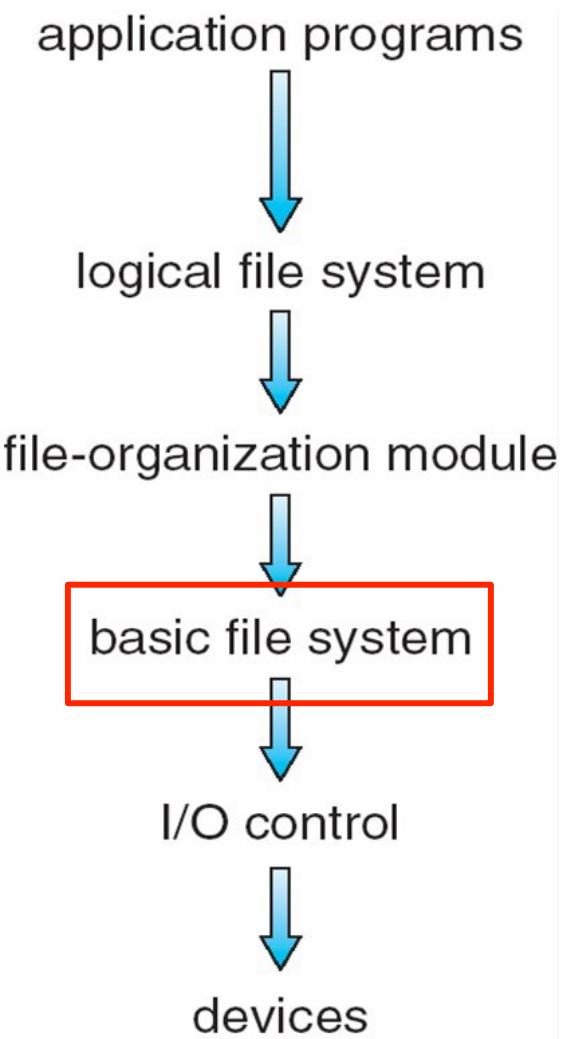
- Logical file system
- Keep all the meta-data necessary for the file system
  - i.e., everything but file content
- It stores the directory structure
- It stores a data structure that stores the file description (File Control Block - FCB)
  - Name, ownership, permissions
  - Reference count, time stamps, pointers to other FCBs
  - Pointers to data blocks on disk
- Input from above:
  - Open/Read/Write filepath
- Output to below:
  - Read/Write logical blocks

File System Implementation



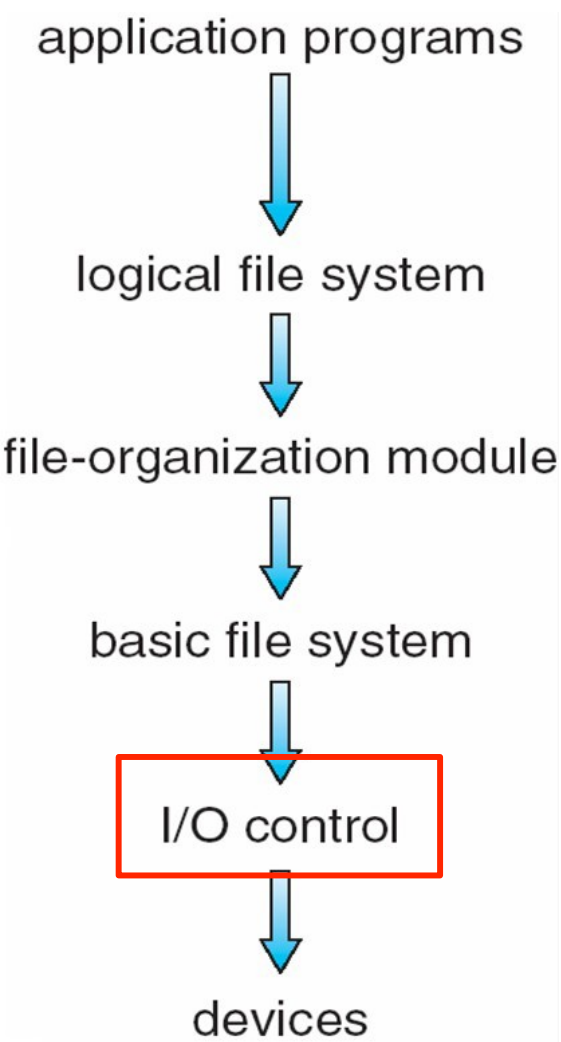
- File-organization module
- Knows about logical file blocks (from 0 to N) and corresponding physical file blocks: it performs translation
- It also manages free space
- Input from above:
  - Read logical block 3
  - Write logical block 17
- Output below:
  - Read physical block 43
  - Write physical block 421

File System Implementation



- Basic file system
- Allocates/maintains various buffers that contain file-system, directory, and data blocks
- These buffers are caches and are used for enhancing performance
- Input from above:
  - Read physical block #43
  - Write physical block #421
- Output below:
  - Read physical block #43
  - Write physical block #421

File System Implementation



- I/O Control
- Device drivers and interrupt handlers
- Input from above:
  - Read physical block #43
  - Write physical block #124
- Output below:
  - Writes into device controller's memory to enact disk reads and writes
  - React to relevant interrupts

Layered File System

- Layering useful for **reducing complexity** and redundancy, but adds overhead and can **decrease performance**
  - Translates file name into file number, file handle, location by maintaining file control blocks (**inodes** in UNIX)
  - Logical layers can be implemented by any coding method according to OS designer

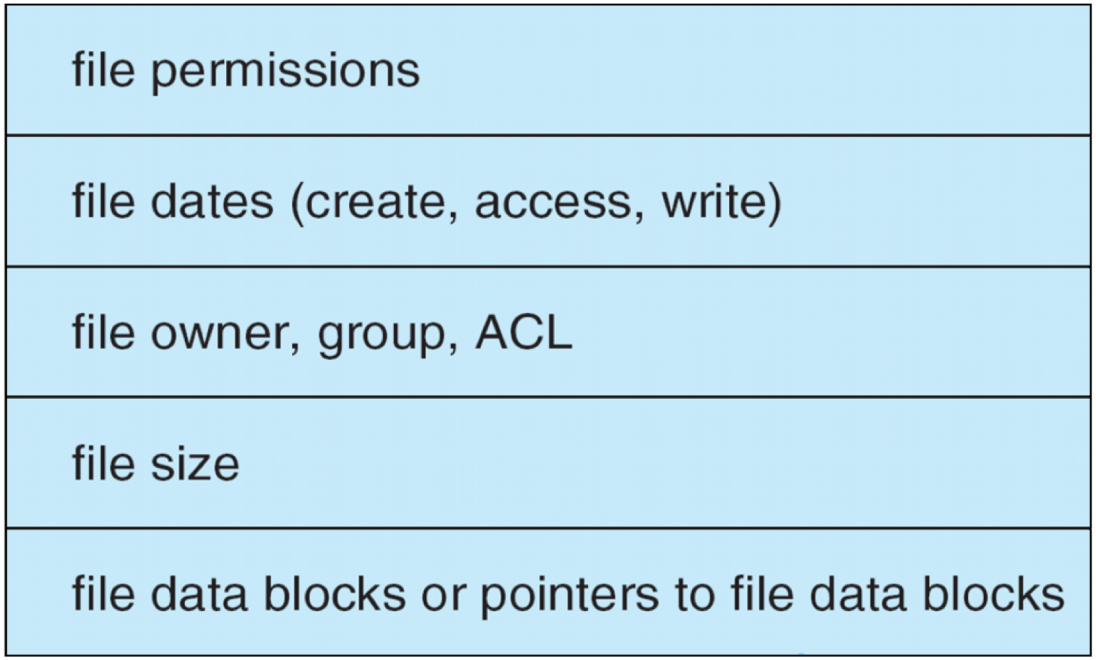
File Systems

- Most OSes support many file systems
  - e.g., the ISO 9660 file system standard for CD-ROM
- UNIX:
  - UFS (UNIX FS), based on BFFS (Berkeley Fast FS)
- Windows:
  - FAT, FAT32, and NTFS
- Basic Linux supports 40+ file systems
  - Standard: ext2 and ext3 (Extended FS)
- An active area of research and development
  - Distributed File Systems
    - Not new, but still a lot of activity
  - High-Performance File Systems
  - The Google File System

File System Data Structures

- The file system comprises data structures
- On-disk structures:
  - An optional boot control block
    - First block of a volume that stores an OS
    - boot block in UFS, partition boot sector in NTFS
  - A volume control block
    - Contains the number of blocks in the volume, block size, free-block count, free-block pointers, free-FCB count, FCB-pointers
    - superblock in UFS, master file table in NTFS
  - A directory
    - File names associated with an ID, FCB pointers
  - A per-file File Control Block (FCB)
    - In NTFS, the FCB is a row in a relational database
- In-memory structures:
  - A mount table with one entry per mounted volume
  - A directory cache for fast path translation (performance)
  - A global open-file table
  - A per-process open-file table
  - Various buffers holding disk blocks "in transit" (performance)

A Typical File Control Block



File Creation

- application process requests the creation of a new file
- logical file system allocates a new FCB, i.e., inode structure
- appropriate directory is updated with the new file name and FCB

Operations - open()

- search **System-Wide Open-File Table** to see if file is currently in use
  - if it is, create a Per-Process Open-File table entry pointing to the existing System-Wide Open-File Table
  - if it is not, search the directory for the file name; once found, load the **FCB** from disk to memory and place it in the System-Wide Open-File Table
- make an entry in the **Per-Process Open-File Table**, with pointers to the entry in the **System-Wide Open-File Table** and other fields which include a pointer to the current location in the file and the access mode in which the file is open

Operations - open()

- increment the open count in the System-Wide Open-File Table
- returns a pointer to the appropriate entry in the Per-Process Open-File Table
- all subsequent operations are performed with **this pointer**
- process closes file -> Per-Process Open-File Table entry is removed; **open count decremented**
- all processes close file -> copy in-memory directory information to disk and System-Wide Open-File Table is removed from memory

Unix (UFS)

- System-Wide Open-File Table holds inodes (index node) for files, directories, devices, and network connections
- inode numbering system is only unique within a given file system

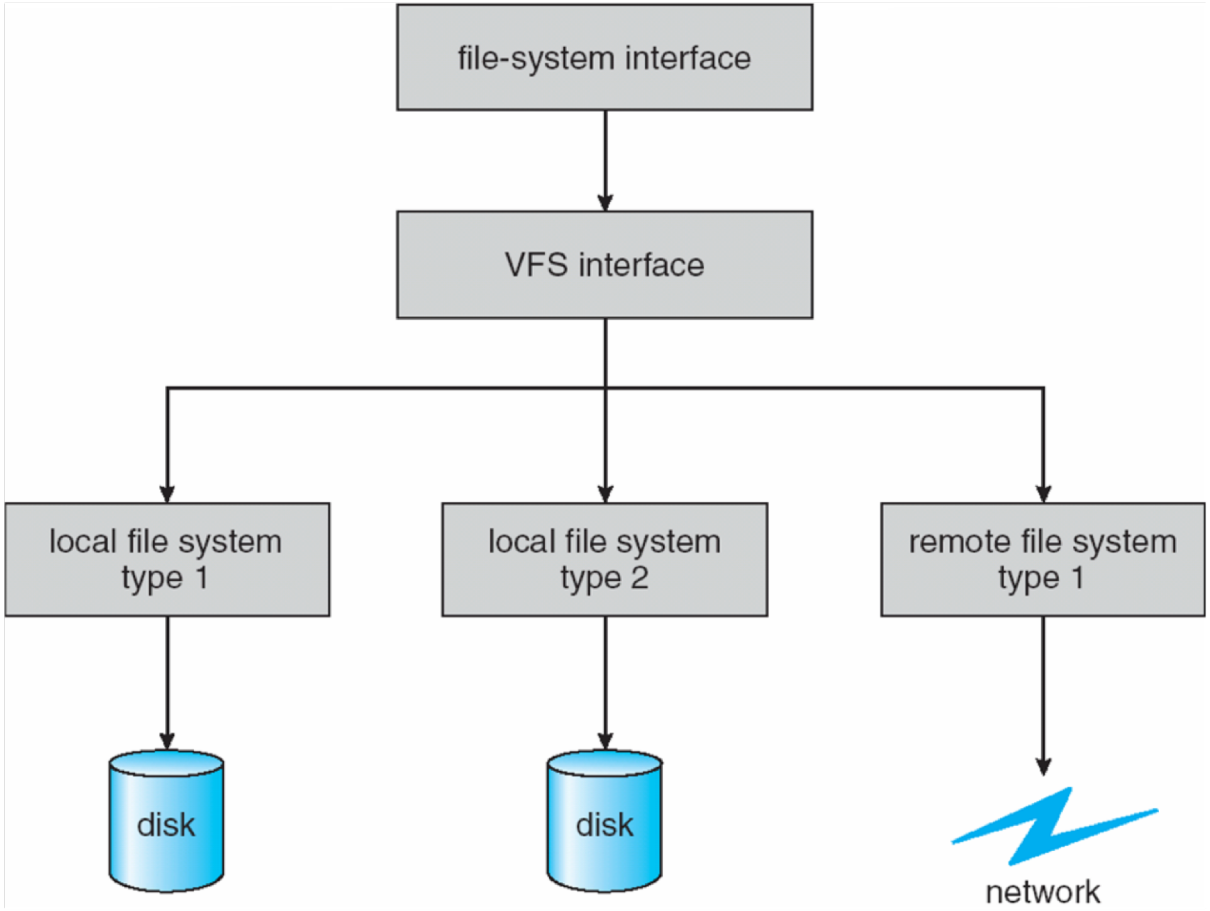
Mounting File Systems

- Boot Block – series of sequential blocks containing a memory image of a program, call the boot loader, that locates and mounts the root partition; the partition contains the kernel; the boot loader locates, loads, and starts the kernel executing
- In-memory mount table – external file systems must be mounted on devices, the mount table records the mount points, types of file systems mounted, and an access path to the desired file system
- Unix – the in-memory mount table contains a pointer to the **superblock** of the file system on that device

Virtual File Systems

- VFS provides an object-oriented way of implementing file systems
  - OS defines a common interface for FS, all FSes implement them
  - System call is implemented based on this common interface
    - it allows the same syscall API to be used for different types of FS
- VFS separates FS generic operations from implementation details
  - implementation can be one of many FS types, or network file system
  - OS can dispatches syscalls to appropriate FS implementation routines

Virtual File System



Virtual File System Example

- Linux defines four **VFS object types**:
  - **superblock**: defines the file system type, size, status, and other metadata
  - **inode**: contains metadata about a **file** (location, access mode, owners…)
  - **dentry**: associates names to inodes, and the directory layout
  - **file**: actual data of the file
- VFS defines set of operations on the objects that must be implemented
  - the set of operations is saved in a function table

```
struct file_operations {
        struct module *owner;
        loff_t (*llseek) (struct file *, loff_t, int);
        ssize_t (*read) (struct file *, char __user *, size_t, loff_t
        ssize_t (*write) (struct file *, const char __user *, size_t,
        ssize_t (*read_iter) (struct kiocb *, struct iov_iter *);
        ssize_t (*write_iter) (struct kiocb *, struct iov_iter *);
        int (*iopoll)(struct kiocb *kiocb, bool spin);
        int (*iterate) (struct file *, struct dir_context *);
        int (*iterate_shared) (struct file *, struct dir_context *);
        __poll_t (*poll) (struct file *, struct poll_table_struct *);
        long (*unlocked_ioctl) (struct file *, unsigned int, unsigned
        long (*compat_ioctl) (struct file *, unsigned int, unsigned lo
        int (*mmap) (struct file *, struct vm_area_struct *);
        unsigned long mmap_supported_flags;
        int (*open) (struct inode *, struct file *);
        int (*flush) (struct file *, fl_owner_t id);
        int (*release) (struct inode *, struct file *);
```

VFS Implementation

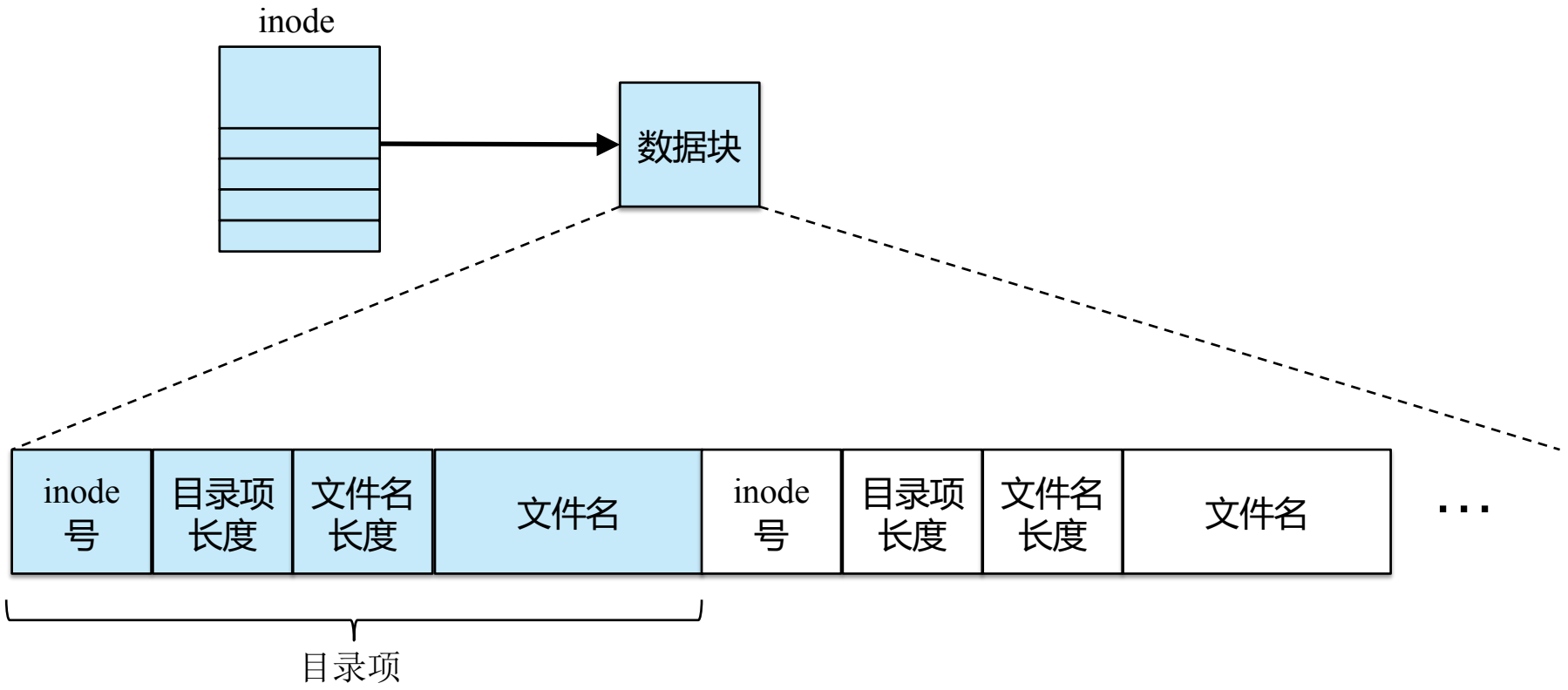
- Write syscall → vfs_write → indirect call → ext4_file_write_iter

```
ssize_t vfs_write(struct file *file, const char __user *buf, si
{
        ssize_t ret;

        if (!(file->f_mode & FMODE_WRITE))
                return -EBADF;
        if (!(file->f_mode & FMODE_CAN_WRITE))
                return -EINVAL;
        if (unlikely(!access_ok(buf, count)))
                return -EFAULT;

        ret = rw_verify_area(WRITE, file, pos, count);
        if (ret)
                return ret;
        if (count > MAX_RW_COUNT)
                count =  MAX_RW_COUNT;
        file_start_write(file);
        if (file->f_op->write)
                ret = file->f_op->write(file, buf, count, pos);
        else if (file->f_op->write_iter)
                ret = new_sync_write(file, buf, count, pos);
        else
                ret = -EINVAL;
        if (ret > 0) {
                fsnotify_modify(file);
                add_wchar(current, ret);
        }
        inc_syscw(current);
        file_end_write(file);
        return ret;
}
```

```
const struct file_operations ext4_file_operations = {
        .llseek         = ext4_llseek,
        .read_iter      = ext4_file_read_iter,
        .write_iter     = ext4_file_write_iter,
        .iopoll         = iomap_dio_iopoll,
        .unlocked_ioctl = ext4_ioctl,
#ifdef CONFIG_COMPAT
        .compat_ioctl   = ext4_compat_ioctl,
#endif
        .mmap           = ext4_file_mmap,
        .mmap_supported_flags = MAP_SYNC,
        .open           = ext4_file_open,
        .release        = ext4_release_file,
```

Directory Implementation

- Directory is a special file
  - Store the mapping from file name to inode



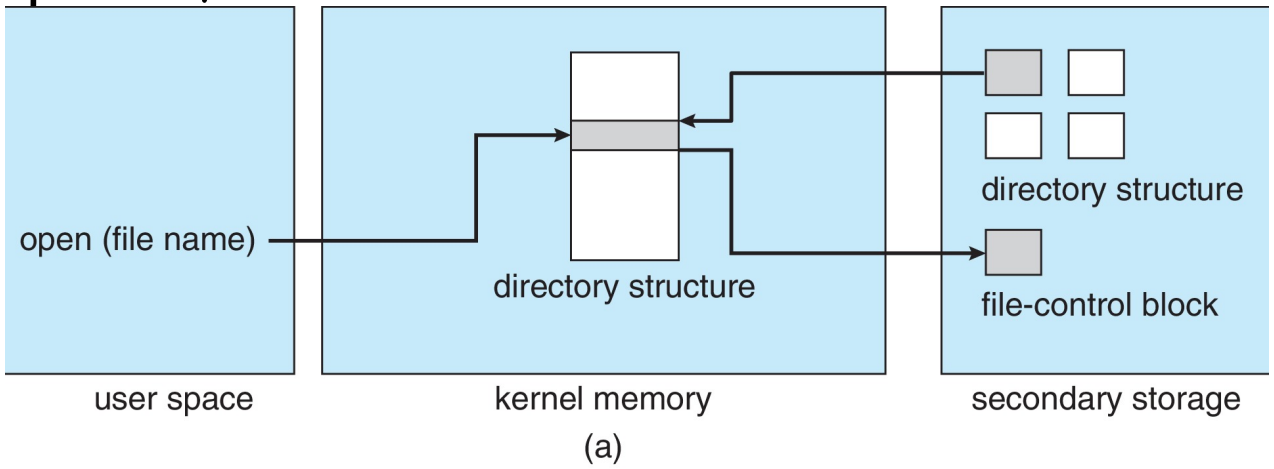

```
struct ext2_dir_entry {
        __le32  inode;                  /* Inode number */
        __le16  rec_len;                /* Directory entry length */
        __le16  name_len;               /* Name length */
        char    name[];                 /* File name, up to EXT2_NAME_LEN */
};
```

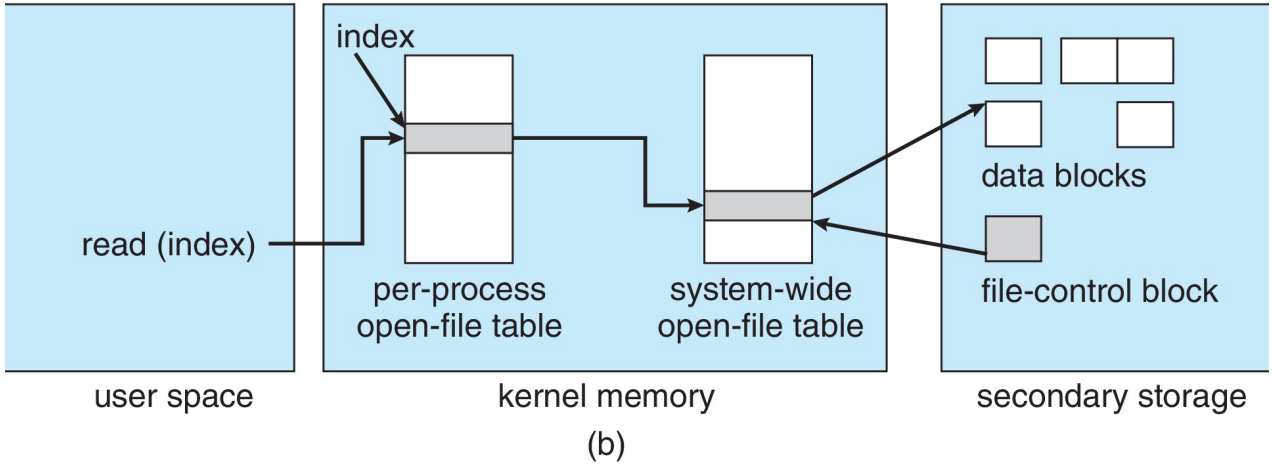
Directory Implementation

- **Linear list of file names** with pointer to the file metadata
  - simple to program, but **time-consuming to search** (e.g., linear search)
    - could keep files ordered alphabetically via linked list or use B+ tree
- **Hash table**: linear list with hash data structure to reduce search time
  - collisions are possible: two or more file names hash to the same location

Directory-Revisit open/read

- Unix – directories are treated as files containing special data
- Windows – directories differently from files;
  - they require a separate set of systems calls to create, manipulate, etc



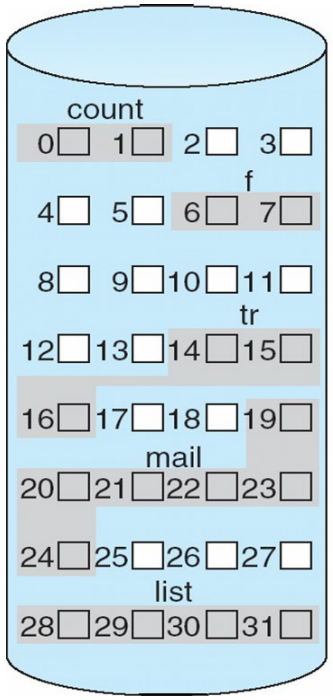


Disk Block Allocation

- **Files** need to be allocated with disk blocks to store data
  - different allocation strategies have different complexity and performance
- Many allocation strategies:
  - contiguous
  - linked
  - indexed
  - …

Contiguous Allocation

- Each file is in a set of contiguous blocks
  - Good because sequential access causes little disk head movement, and thus shorten seek times
- The directory keeps track of each file as the address of its first block and of its length in blocks



directory

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

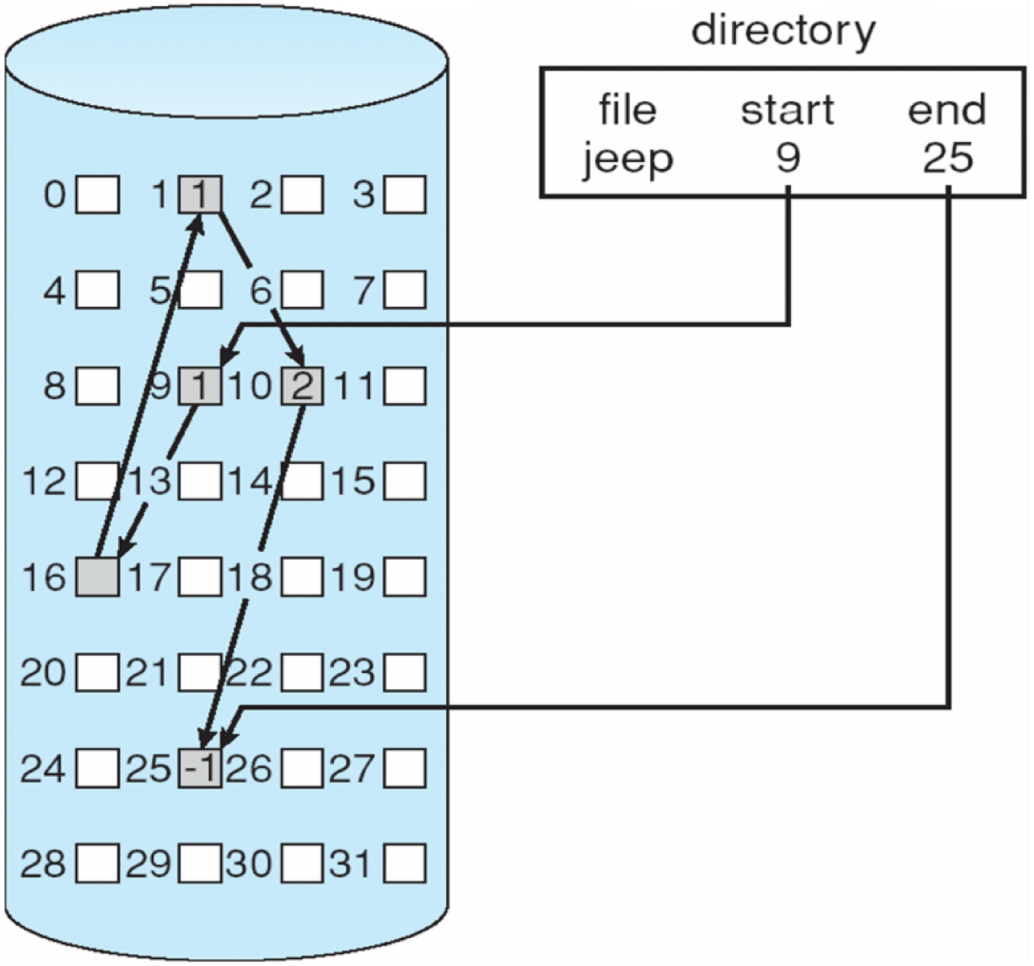
Contiguous Allocation

- Can be difficult to find free space
  - Best Fit, First Fit, etc.
- External fragmentation
  - With a big disk, perhaps we don't care
  - Compaction/defrag
    - Expensive but doable
- Difficult to have files grow
  - Copies to bigger holes under the hood?
    - High overhead
  - Ask users to specify maximum file sizes?
    - Inconvenient
    - High internal fragmentation
  - Create a linked list of file chunks
    - Called an extent

Linked Allocation

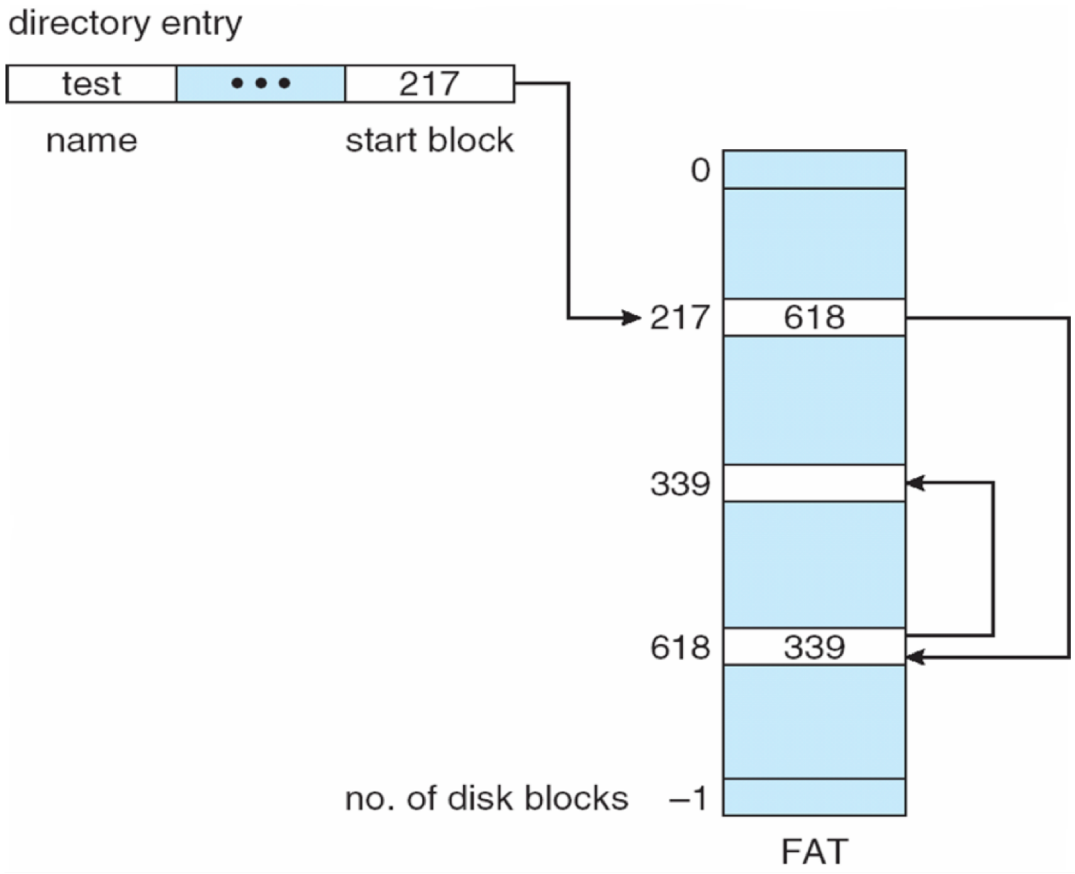
- Linked allocation: each file is a linked list of disk blocks
  - each block contains pointer to next block, file ends at nil pointer
  - blocks may be scattered anywhere on the disk (no external fragmentation, no compaction)
  - Disadvantages
    - locating a file block can take many I/Os and disk seeks
    - Pointer size: 4 of 512 bytes are used for pointer - 0.78% space is wasted
    - Reliability: what about the pointer has corrupted!
  - Improvements: cluster the blocks - like 4 blocks
  - however, has internal fragmentation

Linked Allocation



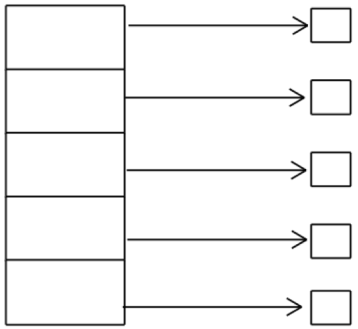
File-Allocation Table (FAT): MS-DOS

- FAT (File Allocation Table) uses linked allocation



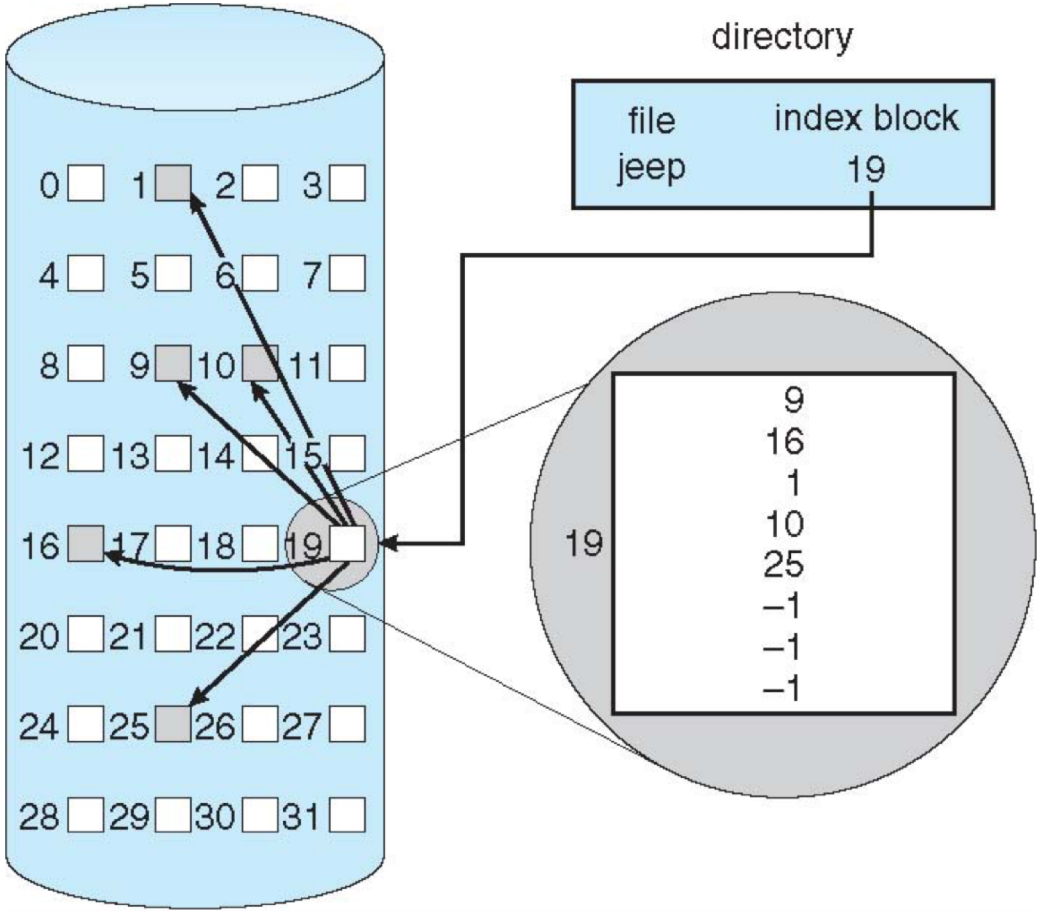
Indexed Allocation

- Indexed allocation: each file has its own **index blocks of pointers to its data blocks**
  - index table provides **random access** to file data blocks
  - no **external fragmentation**, but overhead of index blocks
  - allows **holes** in the file
  - Index block needs space - waste for small files



index table

Indexed Allocation



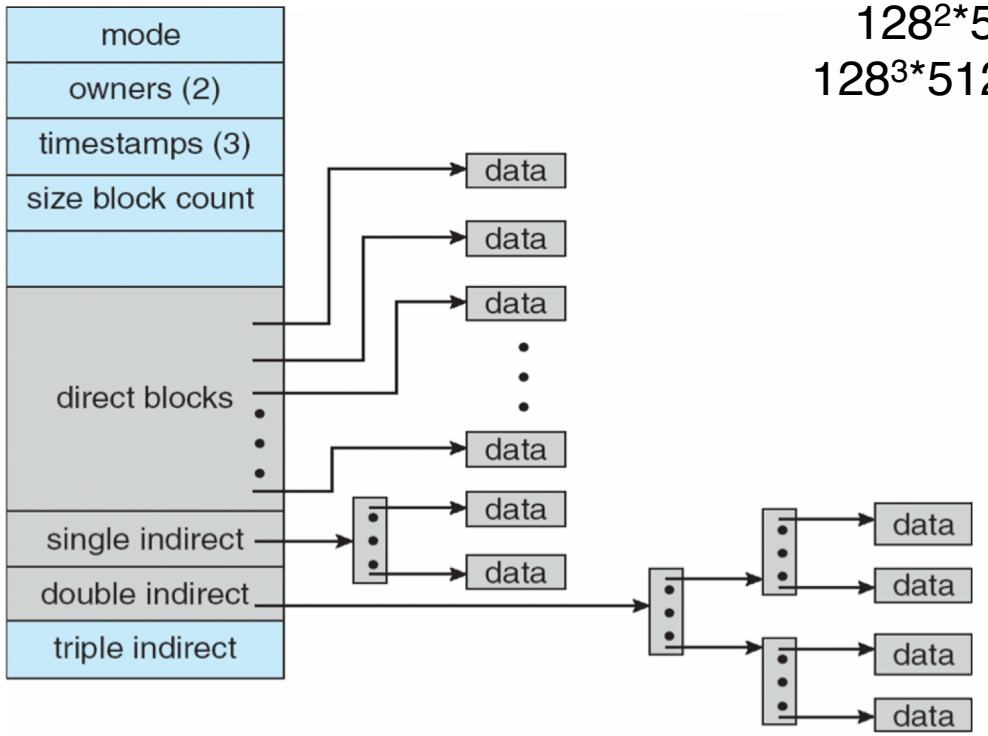
Indexed Allocation

- Need a method to allocate index blocks - cannot too big or too small
  - linked index blocks: link index blocks to support huge file
  - multiple-level index blocks (e.g., 2-level)

Indexed Allocation

- Combined scheme
- The UNIX FCB: the inode (index node)
  - First 15 pointers are in inode
    - Direct block: first 12 pointers
    - Indirect block: next 3 pointers
- Check ext2_inode

Block size = 512 bytes
Pointer = 4 bytes
Max file size =
$12*512 +$
$128*512 +$
$128^2*512 +$
128^3*512 bytes



Allocation Methods

- Best allocation method depends on file access type
  - **contiguous** is great for **sequential** and **random**
  - **linked** is good for **sequential**, not random
  - **indexed** (combined) is more complex
    - single block access may require 2 index block reads then data block read
    - clustering can help improve throughput, reduce CPU overhead
    - cluster is a set of contiguous blocks
- Disk I/O is slow, reduce as many disk I/Os as possible
  - Intel Core i7 extreme edition 990x (2011) at 3.46Ghz = 159,000 MIPS
  - typical disk drive at 250 I/Os per second
    - 159,000 MIPS / 250 = 630 million instructions during one disk I/O
  - fast SSD drives provide 60,000 IOPS
    - 159,000 MIPS / 60,000 = 2.65 millions instructions during one disk I/O

Free-Space Management

- File system maintains free-space list to track available blocks/clusters
  - The space of deleted files should be reclaimed
- Many allocation methods:
  - bit vector or bit map
  - linked free space
  - ...

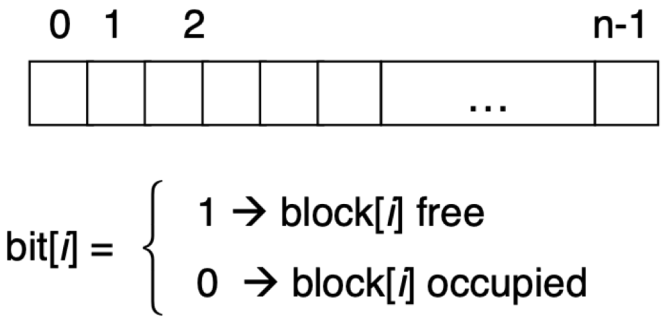
Bitmap Free-Space Management

- Use one bit for each block, track its allocation status
  - relatively easy to find contiguous blocks
  - bit map requires extra space
    - example: block size = 4KB = 2^{12} bytes

      disk size = 2^{40} bytes (1 terabyte)

      n = $2^{40}/2^{12} = 2^{28}$ bits (or 256 MB)

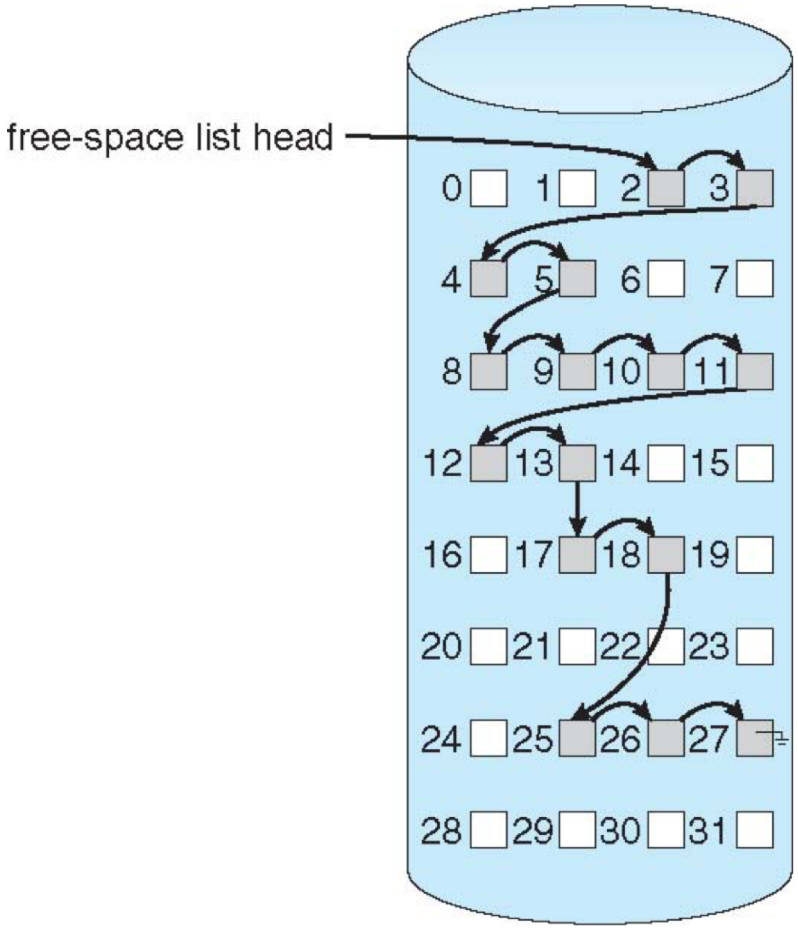
      if clusters of 4 blocks -> 64MB of memory



Linked Free Space

- Keep free blocks in linked list
  - no waste of space, just use the memory in the free block for pointers
  - cannot get contiguous space easily
  - Usually no need to traverse the entire list: return the first one

Linked Free Space



Grouping and Counting

- Simple linked list of free-space is inefficient
  - one extra disk I/O to allocate one free block (disk I/O is extremely slow)
    - allocating **multiple free blocks** require traverse the list
  - difficult to allocate contiguous free blocks
- **Grouping**: use indexes to group free blocks
  - store address of **n-1** free blocks in the **first free block**, plus a pointer to the next **index block**
  - allocating **multiple free blocks does not need to traverse the list**
- **Counting**: a link of clusters (starting block + # of contiguous blocks)
  - space is frequently contiguously used and freed
  - in link node, keep address of first free block and # of following free blocks

File System Performance

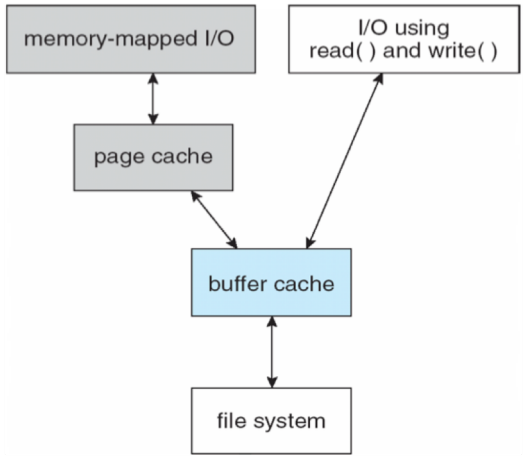
- File system efficiency and performance dependent on:
  - disk allocation and directory algorithms
  - types of data kept in file's directory entry
  - pre-allocation or as-needed allocation of metadata structures
  - fixed-size or varying-size data structures

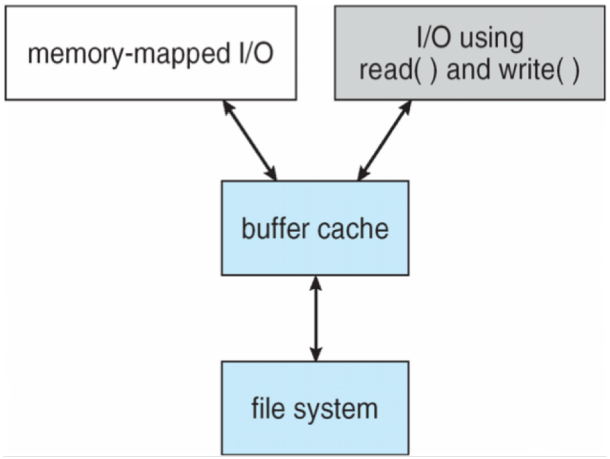
File System Performance

- To improve file system performance:
  - keeping **data and metadata close together**
  - use cache: separate section of main memory for frequently used blocks
  - use **asynchronous writes**, it can be buffered/cached, thus faster
    - cannot cache synchronous write, writes must hit disk before return
    - synchronous writes sometimes requested by apps or needed by OS
  - **free-behind and read-ahead**: techniques to optimize sequential access - remove the previous page from the buffer, read multiple pages ahead
  - **Reads frequently slower than write**: really?

Page Cache

- OS has different levels of cache:
  - a **page cache** caches pages for MMIO, such as memory mapped files
  - file systems uses **buffer** (disk) **cache** for disk I/O
    - memory mapped I/O may be cached twice in the system
- A unified buffer cache uses the same page cache to cache both memory-mapped pages and disk I/O to avoid double caching





Recovery

- File system needs consistency checking to ensure consistency
  - compares data in directory with some metadata on disk for consistency
  - fs recovery can be slow and sometimes fails
- File system recovery methods
  - backup
  - log-structured file system

Log Structured File Systems

- In LSFS, metadata for updates sequentially written to a **circular log**
  - once changes written to the log, it is committed, and syscall can return
    - log can be located on the other disk/partition
  - meanwhile, log entries are replayed on the file system to actually update it
    - when a transaction is replayed, it is removed from the log
    - a log is circular, but un-committed entries will not be overwritten
    - garbage collection can reclaim/compact log entries
  - upon system crash, only need to replay transactions existing in the log

Takeaway

- File system layers
- File system implementation
  - On-disk structure, in-memory structure
  - inode
- File creation(), open()
- VFS
- Directory Implementation
- Allocation Methods
  - Contiguous, linked, indexed
- Free-Space Management