I/O Systems

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I/O Devices

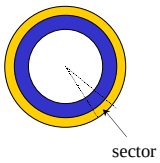
- Typically, IO devices generate an interrupt when something happens
- Three alternatives:
  - Raise an interrupt for every byte transferred from/to the I/O device
  - Do block transfers to memory (direct memory access or DMA) and raise interrupt when transfer is done
  - Bitmap display – CPU writes to video memory what should be displayed, display reads video memory, illuminating pixels
    - Done at user-level without kernel intervention

Performance issues

- Terminals, modems are connected to computers via serial lines
  - Raise an interrupt for every character
  - CPU could get swamped due to "overhead" of handling each byte
  - Example: 10 terminals connect at 9600 baud (about 1KB/s)
    - 10 thousand interrupts per second
    - If each interrupt takes 1 us to handle, load = 0.01 secs = 1%
    - If each interrupt takes 100 us to handle, CPU is loaded
- Block device performance depends
  - Overhead to initiate a request
  - Latency of performing a 1 byte transfer (dominates cost of small I/Os)
  - Bandwidth of I/O transfer once started (dominates cost of large transfers)

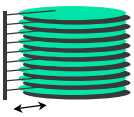
Disk organization

- Disk surface
  - Circular disk coated with magnetic material
- Tracks
  - Concentric rings around disk surface, bits laid out serially along each track
- Sectors
  - Each track is split into arc of track (min unit of transfer)



More on disks

- Magnetic disks come organized in a disk pack
- Cylinder
  - Certain track of the platter
- Disk arm
  - Seek to the right cylinder
- Disk is constantly spinning
- Disk operation is in radial coordinates (track #, sector #)



Disk performance

- Seek
  - Max seek cost is typically 10 ms
  - Average seek cost is typically 3-4 ms
- Rotational delay
  - Wait for a sector to rotate underneath the heads
  - Typically 8.3 – 5.0 ms (7,200 – 12,000RPM) or ½ rotation takes **4.15-2.5ms**
- Transfer bytes
  - Average transfer bandwidth (**15-50 Mbytes/sec**)
- Performance of transferring 1 Kbytes
  - Seek (4 ms) + half rotational delay (3 ms) + transfer (0.04 ms)
  - Total time is 7.04 ms or **140 Kbytes/sec**!

Disk Performance

- Depends on locality of access
  - If reading next sector *immediately* after reading previous sector, no need to wait
  - If reading next sector after a small delay, need to wait for disk to finish the current rotation (assuming no **track buffers**)
  - If track buffers, next access within the same track is fast
- If random place in same cylinder
  - No seek needed
  - Just rotational delay (3ms)
  - Transfer (0.04 ms)
  - Total time is 3.04ms or about 330 KB/sec
- If random place in same cylinder, but read 10KB instead
  - Rotational delay (3ms) + Transfer (0.4ms)
  - Total time is 3.4ms or about 3MB/sec

Bandwidth w/ seek & rotation

Block Size (Kbytes)	% of Disk Transfer Bandwidth
1Kbytes	0.5%
8Kbytes	3.7%
256Kbytes	55%
1Mbytes	83%
2Mbytes	90%

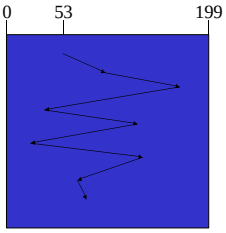
- Seek time and rotational latency dominates the cost of small reads
  - A lot of disk transfer bandwidth is wasted
  - Need algorithms to reduce seek time
- There are more sectors on outer tracks than inner tracks
  - For example, reading outer tracks could be 40MB/sec, while reading inner tracks could be 25MB/sec

Disk Performance Optimizations

- Minimize seek and rotational latency by putting related data together
- Always read/write large amounts of data
- If there are multiple requests, adaptively schedule the requests
- Use multiple arms? Use multiple disks?
  - Can we improve both bandwidth and latency?

Scheduling Disk Requests

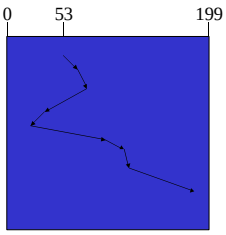
- Method FIFO
  - First come first serve
- Pros
  - Fairness among requests
  - In the order applications expect
- Cons
  - Arrival may be on random spots on the disk (long seeks)
  - Consider files accessed at a server – merging accesses from different users
  - Wild swings can happen



98, 183, 37, 122, 14, 124, 65, 67

SSTF (Shortest Seek Time First)

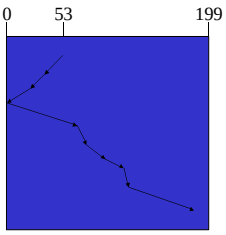
- Method
  - Pick the one closest on disk
- Pros
  - Try to minimize seek time
- Cons
  - Starvation
- Extension:
  - SATF – shortest access time first
  - Include rotational cost
  - Can we implement this??



98, 183, 37, 122, 14, 124, 65, 67
(65, 67, 37, 14, 98, 122, 124, 183)

Elevator (SCAN)

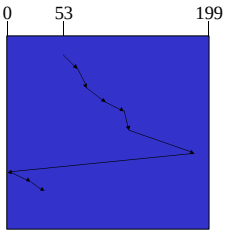
- Method
  - Take the closest request in the direction of travel
  - Real implementations do not go to the end
- Pros
  - Bounded time for each request
- Cons
  - Request at the other end will take a while



98, 183, 37, 122, 14, 124, 65, 67
(37, 14, 65, 67, 98, 122, 124, 183)

C-SCAN (Circular SCAN)

- Method
  - Like SCAN
  - But, wrap around
  - Real implementation doesn't go to the end
- Pros
  - Uniform service time
- Cons
  - Do nothing on the return



98, 183, 37, 122, 14, 124, 65, 67
(65, 67, 98, 122, 124, 183, 14, 37)

Disk caching

- Method
  - Disk controller has a piece of RAM to cache recently accessed blocks
    - IBM Ultra160 SCSI has 16MB
    - Some of the RAM space stores "firmware" (an OS)
  - Blocks are replaced usually in LRU order
- Pros
  - Good for reads if you have locality
- Cons
  - Expensive
  - Need to deal with reliable writes

Disk Technology Trends

- Disks are getting cheaper ($/MB)
  - About a factor of 2 per year since 1991
- Disk data is getting denser
  - More bits/square inch
  - Tracks are closer together
  - Doubles density every 18 months
  - Head close to surface
- Disks are getting smaller for similar capacity
  - Spin faster, less rotational delay, higher bandwidth
  - Less distance for head to travel (faster seeks)
  - Lighter weight (for portables)

Announcements

- Paper reviews for the week after spring break:
  - A fast file system for Unix (Monday: 3/22)
  - Log Structured File Systems (Wednesday: 3/24)

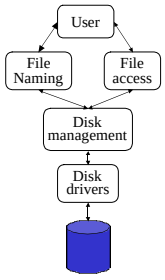
Upcoming lectures

- Implementing file system abstraction

Physical Reality (Disks)	File System Abstraction
sector oriented	byte oriented
physical sector #'s	named files
no protection	users protected from each other
data might be corrupted if machine crashes	robust to machine failures

File System Components

- Disk management
  - Arrange collection of disk sectors into files
- Naming
  - User gives file name, not track or sector number, to locate data
- Protection
  - Keep information secure
- Reliability/durability
  - When system crashes, lose stuff in memory, but want files to be durable



File usage patterns

- How do users access files?
  - Sequential: bytes read in order
  - Random: read/write element out of middle of arrays
  - Content-based access: find me next byte starting with “CS422”
- How are files used?
  - Most files are small
  - Large files account for most of the bytes transferred
  - Large files use up most of the disk space
- Bad news
  - Need everything to be efficient

Data structures for Disks

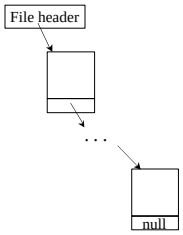
- A file header for each file (part of the file meta-data)
  - Disk sectors associated with each file
- A data structure to represent free space on disk
  - Bit map
    - 1 bit per block (or sector)
    - blocks numbered in cylinder-major order, why?
    - How much space does a bitmap need for a 4G disk?
  - Linked list
- Caching: keep most recently accessed blocks in memory

Approach 1: Contiguous allocation

- Request in advance for the size of the file
- Search bit map or linked list to locate a space
- File header
  - first sector in file
  - number of sectors
- Pros
  - Fast sequential access
  - Easy random access
- Cons
  - External fragmentation
  - Hard to grow files

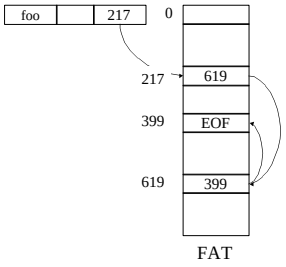
Approach 2: Linked files

- File header points to 1st block on disk
- A block points to the next
- Pros
  - Can grow files dynamically
  - Free list is similar to a file
  - No waste of space
- Cons
  - Sequential access: slow
  - random access: horrible
  - unreliable: losing a block means losing the rest



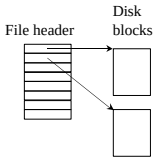
Approach 3: File Allocation Table

- FAT Approach (used by MSDOS)
  - A section of disk for each partition is reserved
  - One entry for each block
  - A file is a linked list of blocks
  - A directory entry points to the 1st block of the file
- Pros
  - Simple
  - Improved random access
- Cons
  - Always go to FAT

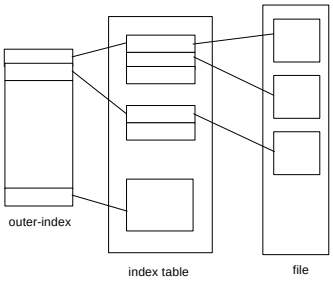


Approach 4: Indexed files

- Used in Nachos
- User declares max size
- A file header holds an array of pointers to point to disk blocks
- Pros
  - Can grow up to a limit
  - Random access is faster
  - No external fragmentation
- Cons
  - Clumsy to grow beyond the limit
  - File headers typically need to be of fixed size

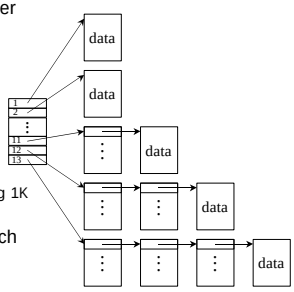


Multi-level indexed files



Combined Scheme (Unix 4.1)

- 13 Pointers in a header
  - 10 direct pointers
  - 11: 1-level indirect
  - 12: 2-level indirect
  - 13: 3-level indirect
- Pros & Cons
  - In favor of small files
  - Can grow
  - Limit is 16G (assuming 1K blocks)
- What happens to reach block 23, 5, 340?



File header storage

- Where is file header stored on disk?
  - In (early) Unix & DOS FAT file systems, special array in outermost cylinders
- Unix refers to file by index into array --- tells it where to find the file header
  - "i-node" --- file header; "i-number" --- index into the array
- Original Unix file header organization:
  - header not anywhere near the data blocks. To read a small file, seek to get header, seek back to data.
  - fixed size, set when disk is formatted.

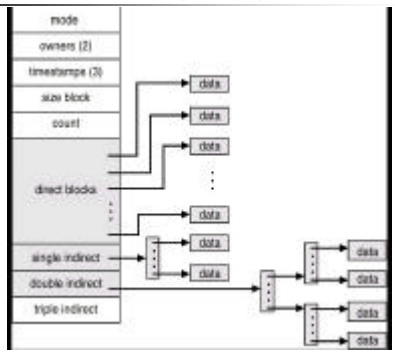
File header storage (cont'd)

- Why not put headers near data?
  - Reliability: whatever happens to the data, you can find all of the files.
  - Unix BSD 4.2 puts portion of the file header array on each cylinder. For small directories, can fit all data, file headers, etc. in same cylinder ➔ no seeks!
  - File headers are much smaller than a whole block (a few hundred bytes), so multiple file headers fetched from disk at same time.
- Q: do you ever look at a file header without reading the file?
  - Yes! Reading the header is 4 times more common than reading the file (e.g., ls, make).

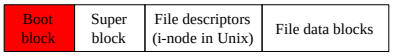
File attributes

- **Name**
- **Type** – needed for systems that support different types.
- **Location** – pointer to file blocks on device.
- **Size** – current file size.
- **Protection** – controls who can do reading, writing, executing.
- **Time**, **date**, **and user identification** – data for protection, security, and usage monitoring.
- Information about files are stored at:
  - Directory (typically contains just the name)
  - File-headers (typically contains all other file attributes)

Unix file header (I-node)



Disk Layout



- Superblock defines a file system
  - size of the file system
  - size of the file descriptor area
  - free list pointer, or pointer to bitmap
  - location of the file descriptor of the root directory
  - other meta-data such as permission and various times