File Systems

Operating System Design – MOSIG 1

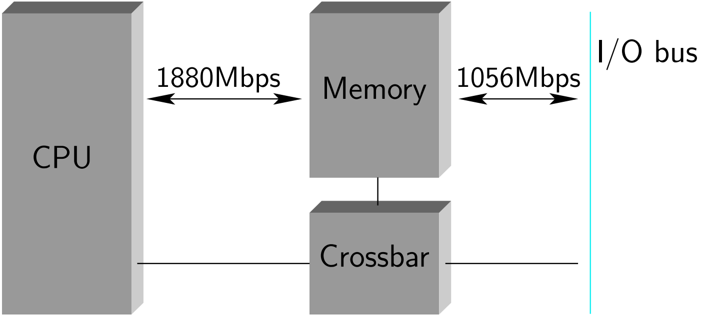
Instructor: Arnaud Legrand
Class Assistants: Benjamin Negrevergne, Sascha Hunold

November 24, 2010

Outline

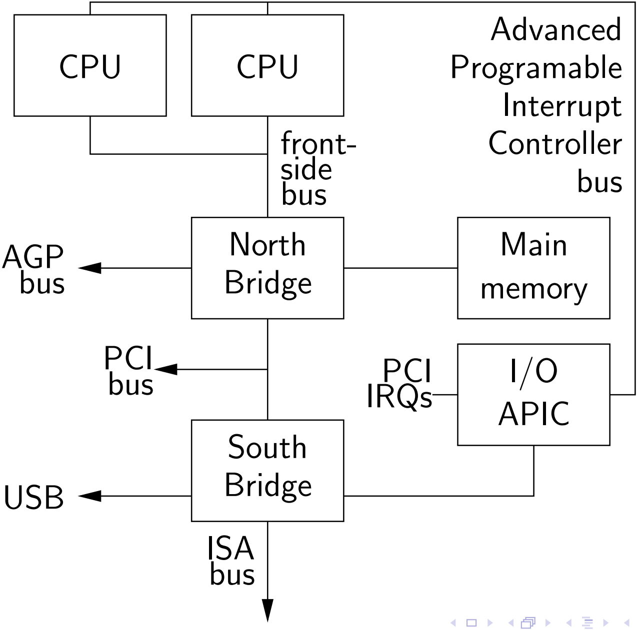
Outline

Memory and I/O buses



- **CPU accesses physical memory over a bus**
- **Devices access memory over I/O bus with DMA**
- **Devices can appear to be a region of memory**

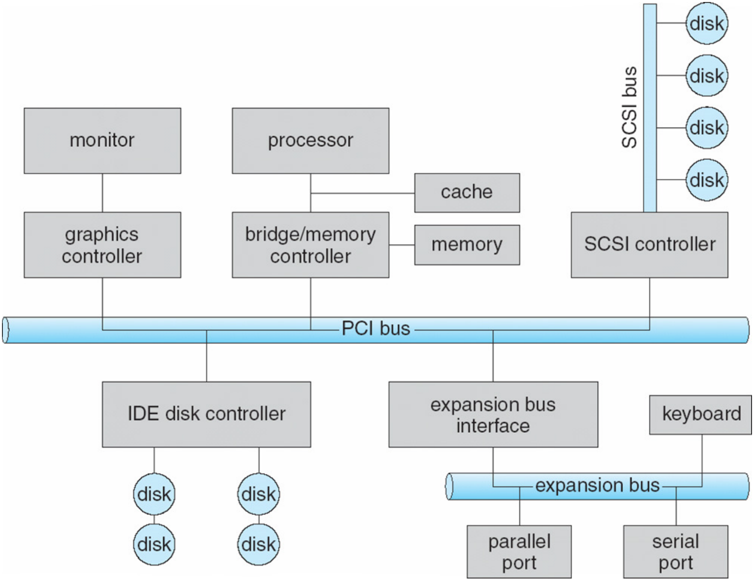
Realistic PC architecture



What is memory?

- **SRAM – Static RAM**
  - Like two NOT gates circularly wired input-to-output
  - 4–6 transistors per bit, actively holds its value
  - Very fast, used to cache slower memory
- **DRAM – Dynamic RAM**
  - A capacitor + gate, holds charge to indicate bit value
  - 1 transistor per bit – extremely dense storage
  - Charge leaks—need slow comparator to decide if bit 1 or 0
  - Must re-write charge after reading, and periodically refresh
- **VRAM – "Video RAM"**
  - Dual ported, can write while someone else reads

What is I/O bus? E.g., PCI

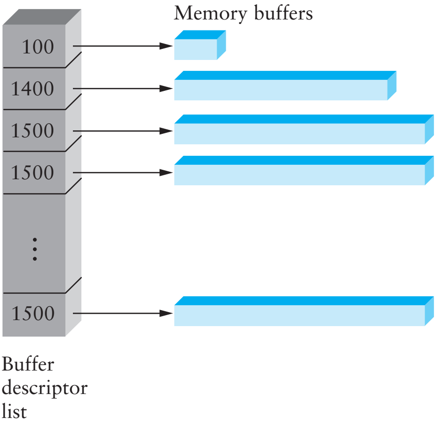


Outline

Communicating with a device

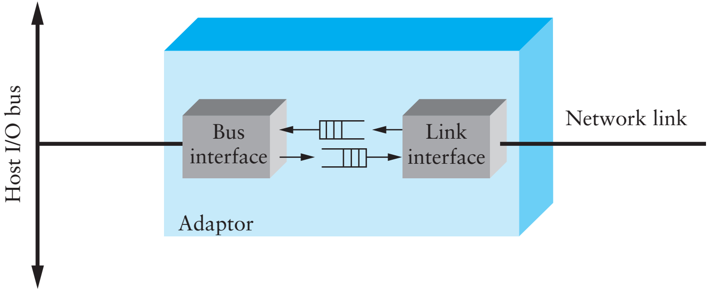
- **Memory-mapped device registers**
  - Certain *physical* addresses correspond to device registers
  - Load/store gets status/sends instructions – not real memory
- **Device memory – device may have memory OS can write to directly on other side of I/O bus**
- **Special I/O instructions**
  - Some CPUs (e.g., x86) have special I/O instructions
  - Like load & store, but asserts special I/O pin on CPU
  - OS can allow user-mode access to I/O ports with finer granularity than page
- **DMA – place instructions to card in main memory**
  - Typically then need to "poke" card by writing to register
  - Overlaps unrelated computation with moving data over (typically slower than memory) I/O bus

DMA buffers



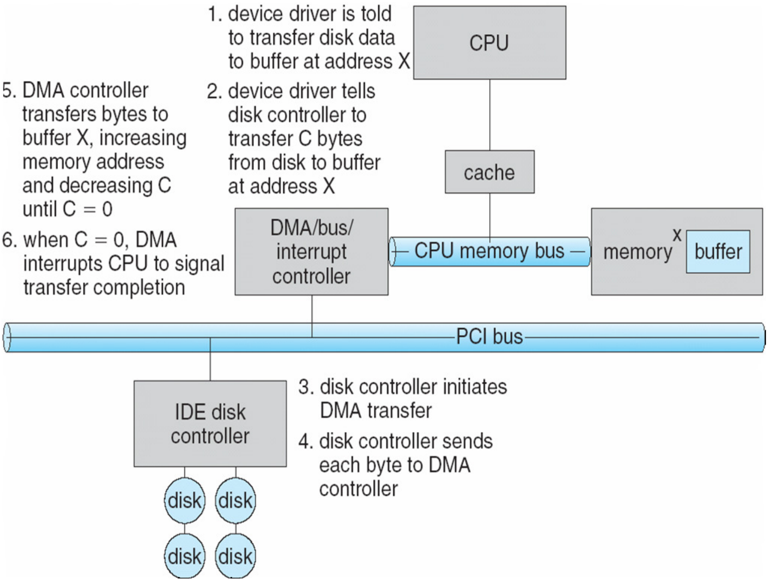
- **Include list of buffer locations in main memory**
- **Card reads list then accesses buffers (w. DMA)**
  - Descriptions sometimes allow for scatter/gather I/O

Example: Network Interface Card



- **Link interface talks to wire/fiber/antenna**
  - Typically does framing, link-layer CRC
- **FIFOs on card provide small amount of buffering**
- **Bus interface logic uses DMA to move packets to and from buffers in main memory**

Example: IDE disk read w. DMA



Driver architecture

- **Device driver provides several entry points to kernel**
  - Reset, ioctl, output, interrupt, read, write, strategy ...
- **How should driver synchronize with card?**
  - E.g., Need to know when transmit buffers free or packets arrive
  - Need to know when disk request complete
- **One approach: Polling**
  - Sent a packet? Loop asking card when buffer is free
  - Waiting to receive? Keep asking card if it has packet
  - Disk I/O? Keep looping until disk ready bit set
- **Disadvantages of polling?**

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- **Disadvantages of polling?**
  - Can't use CPU for anything else while polling
  - Or schedule poll in future and do something else, but then high latency to receive packet or process disk block

Interrupt driven devices

- **Instead, ask card to interrupt CPU on events**
  - Interrupt handler runs at high priority
  - Asks card what happened (xmit buffer free, new packet)
  - This is what most general-purpose OSes do
- **Bad under high network packet arrival rate**
  - Packets can arrive faster than OS can process them
  - Interrupts are very expensive (context switch)
  - Interrupt handlers have high priority
  - In worst case, can spend 100% of time in interrupt handler and never make any progress – *receive livelock*
  - Best: Adaptive switching between interrupts and polling
- **Very good for disk requests**
- **Rest of today: Disks (network devices in 1.5 weeks)**

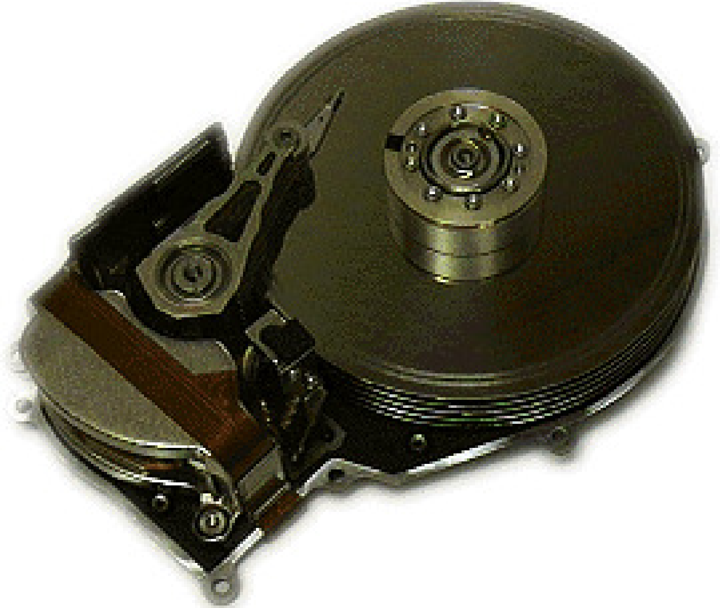
Outline

Anatomy of a disk

- **Stack of magnetic platters**
  - Rotate together on a central spindle @3,600-15,000 RPM
  - Drive speed drifts slowly over time
  - Can't predict rotational position after 100-200 revolutions
- **Disk arm assembly**
  - Arms rotate around pivot, all move together
  - Pivot offers some resistance to linear shocks
  - Arms contain disk heads–one for each recording surface
  - Heads read and write data to platters

Disk

Disk

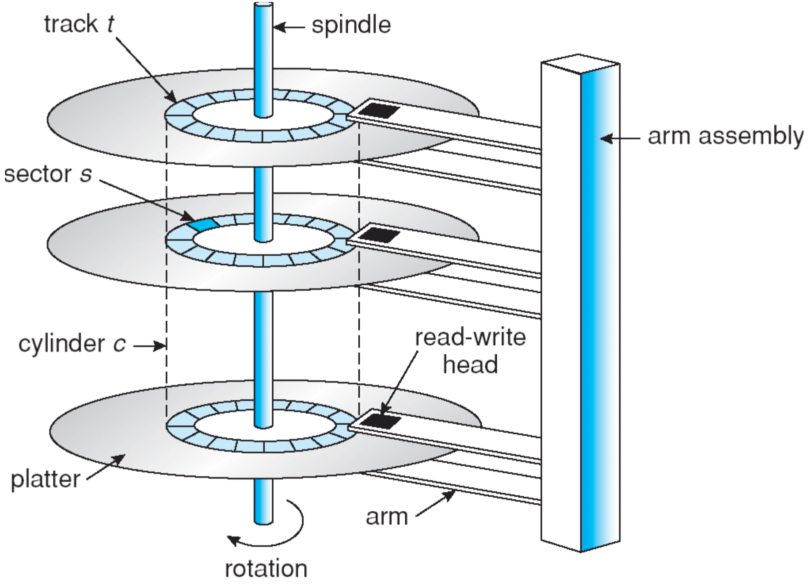


Disk

Storage on a magnetic platter

- **Platters divided into concentric tracks**
- **A stack of tracks of fixed radius is a cylinder**
- **Heads record and sense data along cylinders**
  - Significant fractions of encoded stream for error correction
- **Generally only one head active at a time**
  - Disks usually have one set of read-write circuitry
  - Must worry about cross-talk between channels
  - Hard to keep multiple heads exactly aligned

Cylinders, tracks, & sectors



Disk positioning system

- **Move head to specific track and keep it there**
  - Resist physical socks, imperfect tracks, etc.
- **Seek time depends on:**
  - Inertial power of the arm actuator motor
  - Distance between outer-disk recording radius and inner-disk recording radius (data-band)
  - Depends on platter-size
- **A seek consists of up to four phases:**
  - *speedup*–accelerate arm to max speed or half way point
  - *coast*–at max speed (for long seeks)
  - *slowdown*–stops arm near destination
  - *settle*–adjusts head to actual desired track
- **Very short seeks dominated by settle time (∼1 ms)**
- **Short (200-400 cyl.) seeks dominated by speedup**
  - Accelerations of 40g

Seek details

- **Head switches comparable to short seeks**
  - May also require head adjustment
  - Settles take longer for writes than for reads – Why?

Seek details

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  - May also require head adjustment
  - Settles take longer for writes than for reads
    If read strays from track, catch error with checksum, retry
    If write strays, you've just clobbered some other track
- **Disk keeps table of pivot motor power**
  - Maps seek distance to power and time
  - Disk interpolates over entries in table
  - Table set by periodic "thermal recalibration"
  - But, e.g., ∼500 ms recalibration every ∼25 min bad for AV
- **"Average seek time" quoted can be many things**
  - Time to seek 1/3 disk, 1/3 time to seek whole disk

Sectors

- **Bits are grouped into sectors: generally 512 bytes + overhead information**
  - Error Correcting Codes
  - Servo fields to properly position the head
- **Disk interface presents linear array of sectors**
  - Also 512 bytes, written atomically (even if power failure)
- **Disk maps logical sector #s to physical sectors**
  - *Zoning*–puts more sectors on longer tracks
  - *Track and Cylinder skewing*–sector 0 pos. varies by track (why?)
  - *Sparing*–flawed sectors remapped elsewhere
- **OS doesn't know logical to physical sector mapping**
  - Larger logical sector # difference means larger seek
  - Highly non-linear relationship (*and* depends on zone)
  - OS has no info on rotational positions
  - Can empirically build table to estimate times

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    (known head and cylinder switch time $\leadsto$ sequential access speed optimization)
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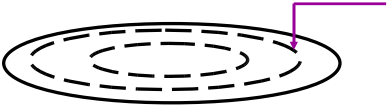
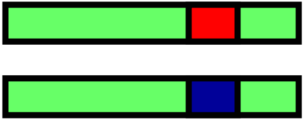
Disk review

- **Disk reads/writes in terms of sectors, not bytes**
  - Read/write single sector or adjacent groups (cluster)



- **How to write a single byte? "Read-modify-write"**
  - Read in sector containing the byte
  - Modify that byte
  - Write entire sector back to disk
  - Key: if cached, don't need to read in



- **Sector = unit of atomicity.**
  - Sector write done completely, even if crash in middle (disk saves up enough momentum to complete)

- **Larger atomic units have to be synthesized by OS**

Disk interface

- **Controls hardware, mediates access**
- **Computer, disk often connected by bus (e.g., SCSI)**
  - Multiple devices may contentd for bus
- **Possible disk/interface features:**
- **Disconnect from bus during requests**
- **Command queuing: Give disk multiple requests**
  - Disk can schedule them using rotational information
- **Disk cache used for read-ahead**
  - Otherwise, sequential reads would incur whole revolution
  - Cross track boundaries? Can't stop a head-switch
- **Some disks support write caching**
  - But data not stable—not suitable for all requests

Disk performance

- **Placement & ordering of requests a huge issue**
  - Sequential I/O much, much faster than random
  - Long seeks much slower than short ones
  - Power might fail any time, leaving inconsistent state
- **Must be careful about order for crashes**
  - More on this in next lecture
- **Try to achieve contiguous accesses where possible**
  - E.g., make big chunks of individual files contiguous
- **Try to order requests to minimize seek times**
  - OS can only do this if it has a multiple requests to order
  - Requires disk I/O concurrency
  - High-performance apps try to maximize I/O concurrency
- **Next: How to schedule concurrent requests**

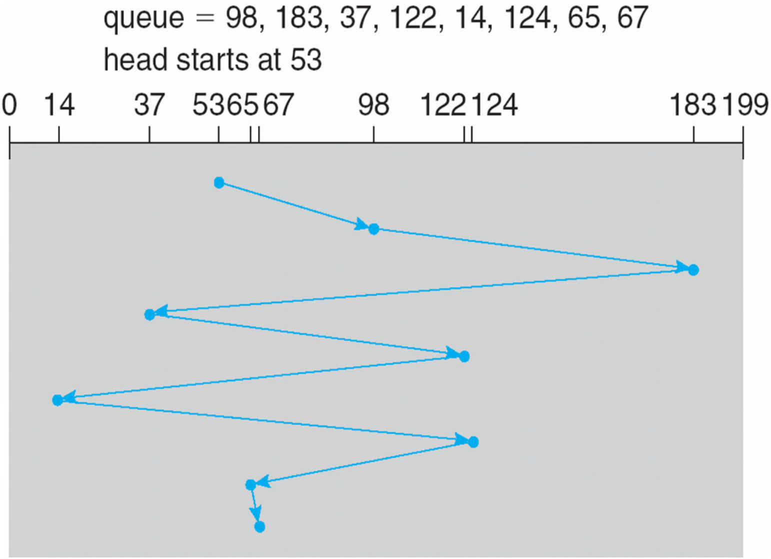
Scheduling: FCFS

- **"First Come First Served"**
  - Process disk requests in the order they are received
- **Advantages**
- **Disadvantages**

Scheduling: FCFS

- **“First Come First Served”**
  - Process disk requests in the order they are received
- **Advantages**
  - Easy to implement
  - Good fairness
- **Disadvantages**
  - Cannot exploit request locality
  - Increases average latency, decreasing throughput

FCFS example



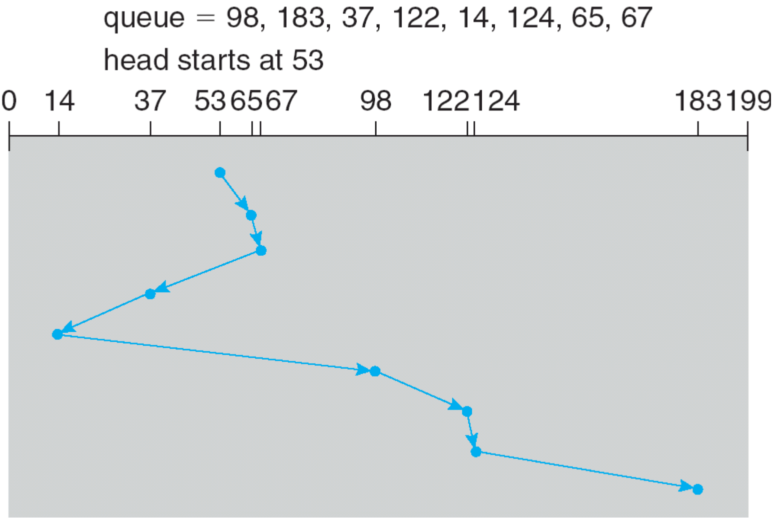
Shortest positioning time first (SPTF)

- **Shortest positioning time first (SPTF)**
  - Always pick request with shortest seek time
- **Advantages**
- **Disadvantages**
- **Improvement**

Shortest positioning time first (SPTF)

- **Shortest positioning time first (SPTF)**
  - Always pick request with shortest seek time
- **Advantages**
  - Exploits locality of disk requests
  - Higher throughput
- **Disadvantages**
  - Starvation
  - Don't always know what request will be fastest
- **Improvement: Aged SPTF**
  - Give older requests higher priority
  - Adjust "effective" seek time with weighting factor: $T_{\text{eff}} = T_{\text{pos}} - W \cdot T_{\text{wait}}$
- **Also called Shortest Seek Time First (SSTF)**

SPTF example



“Elevator” scheduling (SCAN)

- **Sweep across disk, servicing all requests passed**
  - Like SPTF, but next seek must be in same direction
  - Switch directions only if no further requests
- **Advantages**
- **Disadvantages**

"Elevator" scheduling (SCAN)

- **Sweep across disk, servicing all requests passed**
  - Like SPTF, but next seek must be in same direction
  - Switch directions only if no further requests
- **Advantages**
  - Takes advantage of locality
  - Bounded waiting
- **Disadvantages**
  - Cylinders in the middle get better service
  - Might miss locality SPTF could exploit
- **CSCAN: Only sweep in one direction**
  Very commonly used algorithm in Unix
- **Also called LOOK/CLOOK in textbook**
  - (Textbook uses [C]SCAN to mean scan entire disk uselessly)

Outline

Flash memory

- **Today, people increasingly using flash memory**
- **Completely solid state (no moving parts)**
  - Remembers data by storing charge
  - Lower power consumption and heat
  - No mechanical seek times to worry about
- **Limited # overwrites possible**
  - Blocks wear out after 10,000 (MLC) – 100,000 (SLC) erases
  - Requires *flash translation layer* (FTL) to provide *wear leveling*, so repeated writes to logical block don't wear out physical block
  - FTL can seriously impact performance
  - In particular, random writes *very* expensive [Birrell]
- **Limited durability**
  - Charge wears out over time
  - Turn off device for a year, you can easily lose data

Disk vs. Memory

	Disk	MLC NAND Flash	DRAM
Smallest write	sector	sector	byte
Atomic write	sector	sector	byte/word
Random read	8 ms	75 μs	50 ns
Random write	8 ms	300 μs*	50 ns
Sequential read	100 MB/s	250 MB/s	$>$ 1 GB/s
Sequential write	100 MB/s	170 MB/s*	$>$ 1 GB/s
Cost	$.08–1/GB	$3/GB	$10-25/GB
Persistence	Non-volatile	Non-volatile	Volatile

*Flash write performance degrades over time

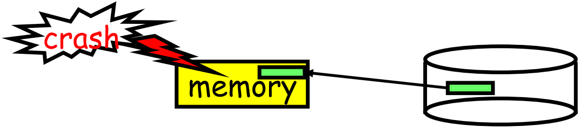
Outline

File system fun

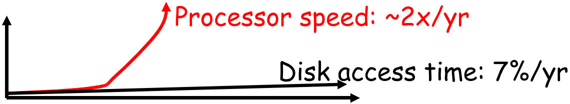
- **File systems = the hardest part of OS**
  - More papers on FSes than any other single topic
- **Main tasks of file system:**
  - Don't go away (ever)
  - Associate bytes with name (files)
  - Associate names with each other (directories)
  - Can implement file systems on disk, over network, in memory, in non-volatile ram (NVRAM), on tape, w/ paper.
  - We'll focus on disk and generalize later
- **Today: files, directories, and a bit of performance**

The medium is the message

- **Disk = First thing we've seen that doesn't go away**



  - So: Where all important state ultimately resides
- **Slow (ms access vs ns for memory)**

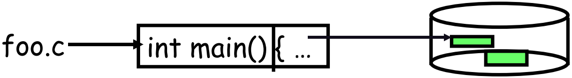


- **Huge (100–1,000x bigger than memory)**
  - How to organize large collection of ad hoc information?
  - Taxonomies! (Basically FS = general way to make these)

Outline

Files: named bytes on disk

- **File abstraction:**
  - User's view: named sequence of bytes



  - FS's view: collection of disk blocks
  - File system's job: translate name & offset to disk blocks:

{file, offset} ⟶ FS ⟶ disk address

- **File operations:**
  - Create a file, delete a file
  - Read from file, write to file
  - Repositionning withing a file
  - Truncating a file, append, rename, . . .
- **File meta-informations** (size, owner, access rights, timestamps, . . .)
- **Want: operations to have as few disk accesses as possible & have minimal space overhead**

What's hard about grouping blocks?

- **Like page tables, file system meta data are simply data structures used to construct mappings**
  - Page table: map virtual page # to physical page #

    23 ⟶ Page table ⟶ 33
  - File meta data: map byte offset to disk block address

    418 ⟶ Unix **inode** ⟶ 8003121
  - Directory: map name to disk address or file #

    foo.c ⟶ directory ⟶ 44
- **Inode stores meta-information (not name!) and file bytes location.**

FS vs. VM

- **In both settings, want location transparency**
- **In some ways, FS has easier job than than VM:**
  - CPU time to do FS mappings not a big deal (= no TLB)
  - Page tables deal with sparse address spaces and random access, files often denser $(0 \ldots \mathrm{filesize} - 1)$ & ∼sequentially accessed
- **In some ways FS's problem is harder:**
  - Each layer of translation = potential disk access
  - Space a huge premium! (But disk is huge?!?!) Reason? Cache space never enough; amount of data you can get in one fetch never enough
  - Range very extreme: Many files <10 KB, some files many GB

Outline

Some working intuitions

- **FS performance dominated by # of disk accesses**
  - Each access costs ~10 milliseconds
  - Touch the disk 100 extra times = 1 *second*
  - Can easily do 100s of millions of ALU ops in same time
- **Access cost dominated by movement, not transfer:**

  seek time + **rotational delay** + # bytes/disk-bw

  - Can get 50x the data for only ~3% more overhead
  - 1 sector: 10ms + 8ms + 10μs $(= 512\,\mathrm{B}/(50\,\mathrm{MB/s}))$ ≈ 18ms
  - 50 sectors: 10ms + 8ms + .5ms = 18.5ms
- **Observations that might be helpful:**
  - All blocks in file tend to be used together, sequentially
  - All files in a directory tend to be used together
  - All names in a directory tend to be used together

Common addressing patterns

- **Sequential:**
  - File data processed in sequential order
  - By far the most common mode
  - Example: editor writes out new file, compiler reads in file, etc
- **Random access:**
  - Address any block in file directly without passing through predecessors
  - Examples: data set for demand paging, databases
- **Keyed access**
  - Search for block with particular values
  - Examples: associative data base, index
  - Usually not provided by OS

Problem: how to track file's data

- **Disk management:**
  - Need to keep track of where file contents are on disk
  - Must be able to use this to map byte offset to disk block
  - Structure tracking a file's sectors is called an index node or **inode**
  - File descriptors must be stored on disk, too
- **Things to keep in mind while designing file structure:**
  - Most files are small
  - Much of the disk is allocated to large files
  - Many of the I/O operations are made to large files
  - Want good sequential and good random access
    (what do these require?)

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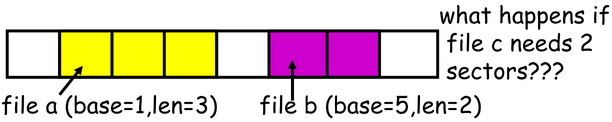
- **Just like VM: good data structures**
  - Arrays, linked list, trees (of arrays), hash tables.

Straw man: contiguous allocation

- **"Extent-based": allocate files like segmented memory**
  - When creating a file, make the user specify pre-specify its length and allocate all space at once
  - Inode contents: location and size



- **Example: IBM OS/360**
- **Pros?**
- **Cons? (What VM scheme does this correspond to?)**

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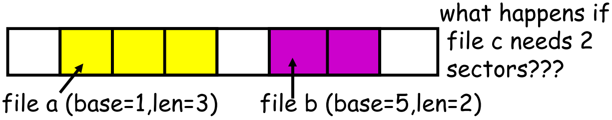
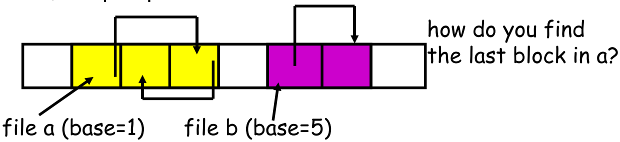


- **Example: IBM OS/360**
- **Pros?**
  - Simple, fast access, both sequential and random
- **Cons? (What VM scheme does this correspond to?)**
  - External fragmentation

Linked files

- **Basically a linked list on disk.**
  - Keep a linked list of all free blocks
  - Inode contents: a pointer to file's first block
  - In each block, keep a pointer to the next one



- **Examples (sort-of): Alto, TOPS-10, DOS FAT**
- **Pros?**
- **Cons?**

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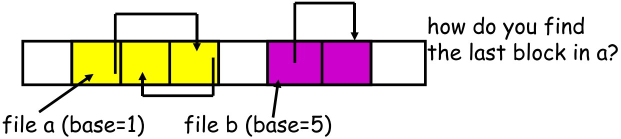
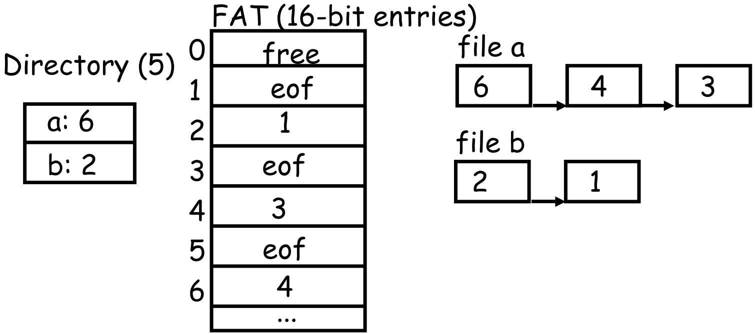


- **Examples (sort-of): Alto, TOPS-10, DOS FAT**
- **Pros?**
  - Easy dynamic growth & sequential access, no fragmentation
- **Cons?**
  - Linked lists on disk a bad idea because of access times
  - Pointers take up room in block, skewing alignment
  - If one pointer is ever damaged, the rest of the file is lost.

Example: DOS FS (simplified)

- **Uses linked files. Cute: links reside in fixed-sized "file allocation table" (FAT) rather than in the blocks.**



- **Still do pointer chasing, but can cache entire FAT so can be cheap compared to disk access**

FAT discussion

- **Entry size = 16 bits**
  - What's the maximum size of the FAT?
  - Given a 512 byte block, what's the maximum size of FS?
  - One attack: go to bigger blocks. Pros? Cons?
- **Space overhead of FAT is trivial:**
  - 2 bytes / 512 byte block = $\sim 0.4\%$ (Compare to Unix)
- **Reliability: how to protect against errors?**
  - Create duplicate copies of FAT on disk.
  - State duplication a very common theme in reliability
- **Bootstrapping: where is root directory?**
  - Fixed location on disk:

FAT	(opt) FAT	root dir	...

FAT discussion

- **Entry size = 16 bits**
  - What's the maximum size of the FAT? 65,536 entries
  - Given a 512 byte block, what's the maximum size of FS? 32 MB
  - One attack: go to bigger blocks. Pros? Cons?
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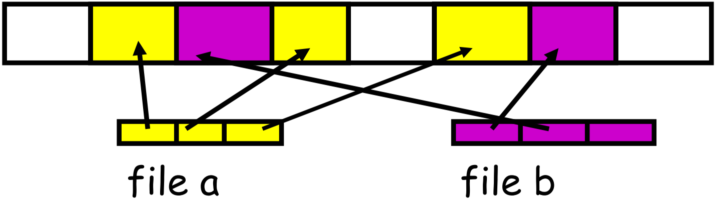
Indexed files

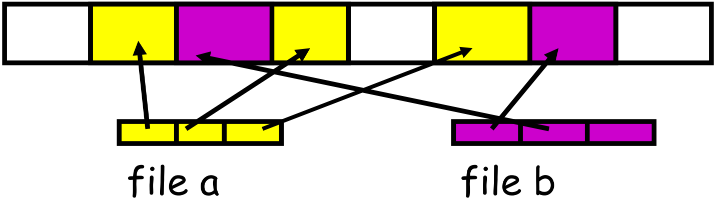
- **Each file has an array holding all of it's block pointers**
  - Just like a page table, so will have similar issues
  - Max file size fixed by array's size (static or dynamic?)
  - Allocate array to hold file's block pointers on file creation
  - Allocate actual blocks on demand using free list



- **Pros?**
- **Cons?**

Indexed files

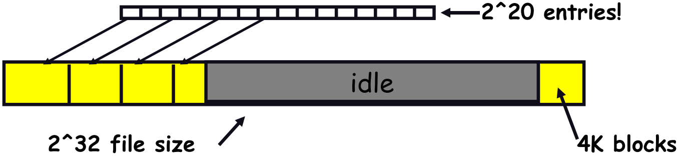
- **Each file has an array holding all of it's block pointers**
  - Just like a page table, so will have similar issues
  - Max file size fixed by array's size (static or dynamic?)
  - Allocate array to hold file's block pointers on file creation
  - Allocate actual blocks on demand using free list



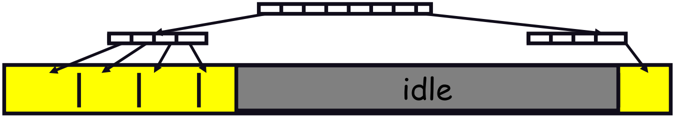
- **Pros?**
  - Both sequential and random access easy
- **Cons?**
  - Mapping table requires large chunk of contiguous space
    ...Same problem we were trying to solve initially

Indexed files

- **Issues same as in page tables**

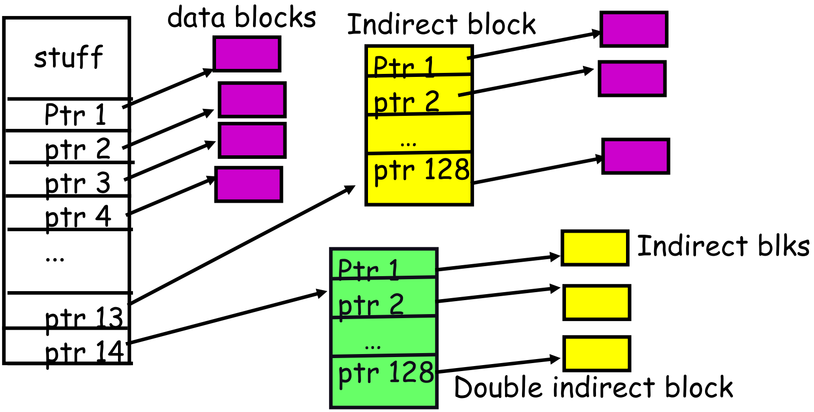


  - Large possible file size = lots of unused entries
  - Large actual size? table needs large contiguous disk chunk
- **Solve identically: small regions with index array, this array with another array, . . . Downside?**



Multi-level indexed files (old BSD FS)

- **inode = 14 block pointers + "stuff" (meta-informations)**



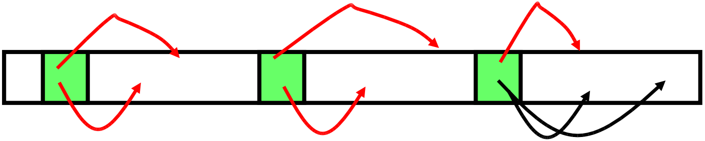
Old BSD FS discussion

- **Pros:**
  - Simple, easy to build, fast access to small files
  - Maximum file length fixed, but large.
- **Cons:**
  - What is the worst case # of accesses?
  - What is the worst-case space overhead? (e.g., 13 block file)
- **An empirical problem:**
  - Because you allocate blocks by taking them off unordered freelist, meta data and data get strewn across disk

More about inodes

- **Inodes are stored in a fixed-size array**
  - Size of array fixed when disk is initialized; can't be changed
  - Lives in known location, originally at one side of disk:

  - Now is smeared across it (why?)



  - The index of an inode in the inode array called an i-number
  - Internally, the OS refers to files by inumber
  - When file is opened, inode brought in memory
  - Written back when modified and file closed or time elapses

Outline

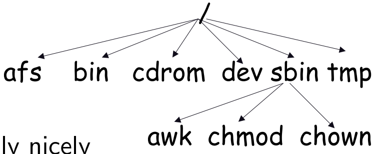
Directories

- **Problem:**
  - "Spend all day generating data, come back the next morning, want to use it." F. Corbato, on why files/dirs invented.
- **Approach 0: Have users remember where on disk their files are**
  - (E.g., like remembering your social security or bank account #)
- **Yuck. People want human digestible names**
  - We use directories to map names to file blocks
- **Next: What is in a directory and why?**

A short history of directories

- **Approach 1: Single directory for entire system**
  - Put directory at known location on disk
  - Directory contains $\langle \text{name}, \text{inumber} \rangle$ pairs
  - If one user uses a name, no one else can
  - Many ancient personal computers work this way
- **Approach 2: Single directory for each user**
  - Still clumsy, and `ls` on 10,000 files is a real pain
- **Approach 3: Hierarchical name spaces**
  - Allow directory to map names to files *or other dirs*
  - File system forms a tree (or graph, if links allowed)
  - Large name spaces tend to be hierarchical (ip addresses, domain names, scoping in programming languages, etc.)

Hierarchical Unix



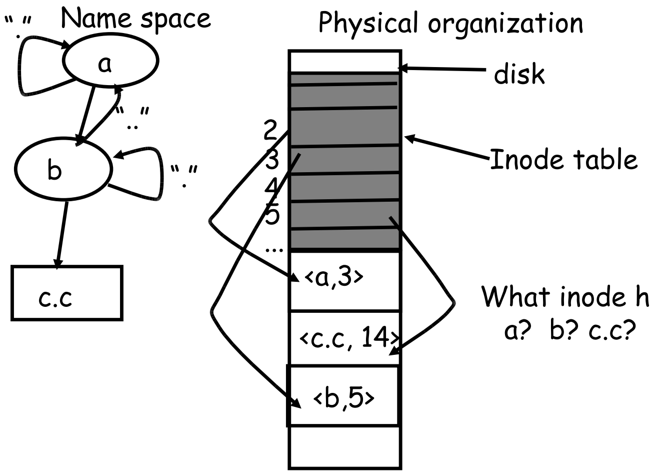
- **Used since CTSS (1960s)**
  - Unix picked up and used really nicely
- **Directories stored on disk just like regular files**
  - Inode contains special flag bit set dir
  - User's can read just like any other file
  - Only special programs can write (why?)
  - Inodes at fixed disk location
  - File pointed to by the index may be another directory
  - Makes FS into hierarchical tree (what needed to make a DAG?)
- **Simple, plus speeding up file ops speeds up dir ops!**

⟨name,inode#⟩
⟨afs,1021⟩
⟨tmp,1020⟩
⟨bin,1022⟩
⟨cdrom,4123⟩
⟨dev,1001⟩
⟨sbin,1011⟩
⋮

Naming magic

- **Bootstrapping: Where do you start looking?**
  - Root directory always inode #2 (0 and 1 historically reserved)
- **Special names:**
  - Root directory: "/"
  - Current directory: "`.`"
  - Parent directory: "`..`"
- **Special names not implemented in FS:**
  - User's home directory: "$\sim$"
  - Globbing: "`foo.*`" expands to all files starting "`foo.`"
- **Using the given names, only need two operations to navigate the entire name space:**
  - `cd` *name*: move into (change context to) directory *name*
  - `ls` : enumerate all names in current directory (context)

Unix example: /a/b/c.c



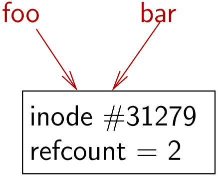
What inode holds file for a? b? c.c?

Default context: working directory

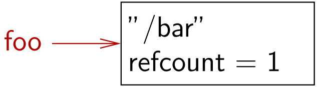
- **Cumbersome to constantly specify full path names**
  - In Unix, each process associated with a "current working directory"
  - File names that do not begin with "/" are assumed to be relative to the working directory, otherwise translation happens as before
- **Shells track a default list of active contexts**
  - A "search path" for programs you run
  - Given a search path $A : B : C$, a shell will check in A, then check in B, then check in C
  - Can escape using explicit paths: "./foo"

Hard and soft links (synonyms)

- **More than one dir entry can refer to a given file**
  - Unix stores count of pointers ("hard links") to inode
  - To make: "`ln foo bar`" creates a synonym (`bar`) for *file* `foo`



- **Soft links = synonyms for names**
  - Point to a file (or dir) *name*, but object can be deleted from underneath it (or never even exist).
  - Unix implements like directories: inode has special "sym link" bit set and contains pointed to name

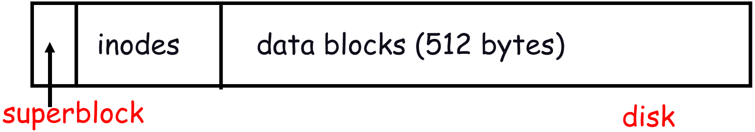


  - To make: "`ln -sf bar baz`
  - When the file system encounters a symbolic link it automatically translates it (if possible).

Outline

Case study: speeding up FS

- **Original Unix FS: Simple and elegant:**



- **Components:**
  - Data blocks
  - Inodes (directories represented as files)
  - Hard links
  - Superblock. (specifies number of blks in FS, counts of max # of files, pointer to head of free list)
- **Problem: slow**
  - Only gets 20Kb/sec (2% of disk maximum) even for sequential disk transfers!

A plethora of performance costs

- **Blocks too small (512 bytes)**
  - File index too large
  - Too many layers of mapping indirection
  - Transfer rate low (get one block at time)
- **Sucky clustering of related objects:**
  - Consecutive file blocks not close together
  - Inodes far from data blocks
  - Inodes for directory not close together
  - Poor enumeration performance: e.g., “`ls`”, “`grep foo *.c`”
- **Next: how FFS fixes these problems (to a degree)**

Problem: Internal fragmentation

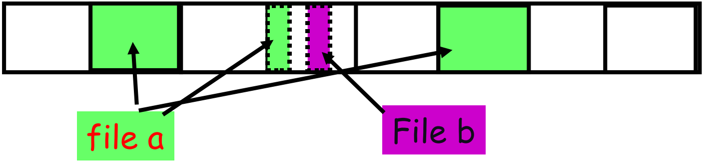
- **Block size was to small in Unix FS**
- **Why not just make bigger?**

Block size	space wasted	file bandwidth
512	6.9%	2.6%
1024	11.8%	3.3%
2048	22.4%	6.4%
4096	45.6%	12.0%
1MB	99.0%	97.2%

- **Bigger block increases bandwidth, but how to deal with wastage ("internal fragmentation")?**
  - Use idea from malloc: split unused portion.

Solution: fragments

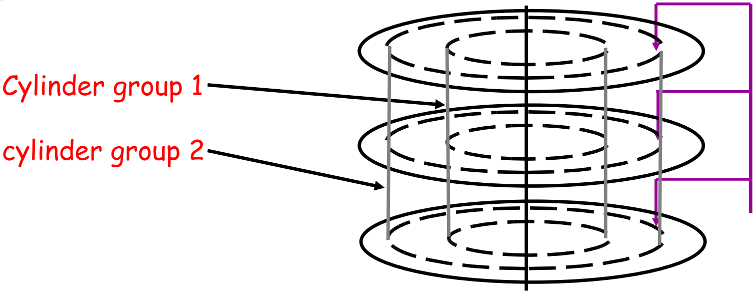
- **BSD FFS:**
  - Has large block size (4096 or 8192)
  - Allow large blocks to be chopped into small ones ("fragments")
  - Used for little files and pieces at the ends of files



- **Best way to eliminate internal fragmentation?**
  - Variable sized splits of course
  - Why does FFS use fixed-sized fragments (1024, 2048)?

Clustering related objects in FFS

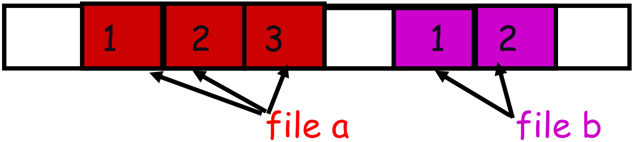
- **Group 1 or more consecutive cylinders into a "cylinder group"**



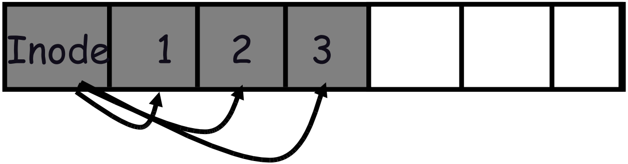
  - Key: can access any block in a cylinder without performing a seek. Next fastest place is adjacent cylinder.
  - Tries to put everything related in same cylinder group
  - Tries to put everything not related in different group (?!)

Clustering in FFS

- **Tries to put sequential blocks in adjacent sectors**
  - (Access one block, probably access next)



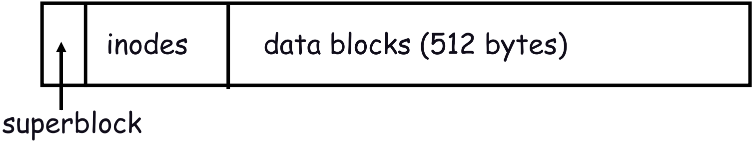
- **Tries to keep inode in same cylinder as file data:**
  - (If you look at inode, most likely will look at data too)



- **Tries to keep all inodes in a dir in same cylinder group**
  - Access one name, frequently access many, e.g., "`ls -l`"

What does a cyl. group look like?

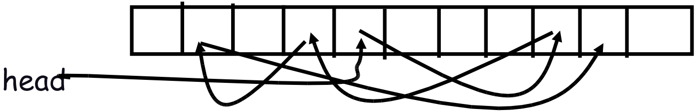
- **Basically a mini-Unix file system:**



- **How how to ensure there's space for related stuff?**
  - Place different directories in different cylinder groups
  - Keep a "free space reserve" so can allocate near existing things
  - When file grows too big (1MB) send its remainder to different cylinder group.

Finding space for related objs

- **Old Unix (& dos): Linked list of free blocks**
  - Just take a block off of the head. Easy.



  - Bad: free list gets jumbled over time. Finding adjacent blocks hard and slow
- **FFS: switch to bit-map of free blocks**
  - 1010101111111000001111111000101100
  - Easier to find contiguous blocks.
  - Small, so usually keep entire thing in memory
  - Key: keep a reserve of free blocks. Makes finding a close block easier

Using a bitmap

- **Usually keep entire bitmap in memory:**
  - 4G disk / 4K byte blocks. How big is map?
- **Allocate block close to block x?**
  - Check for blocks near bmap[x/32]
  - If disk almost empty, will likely find one near
  - As disk becomes full, search becomes more expensive and less effective.
- **Trade space for time (search time, file access time)**
- **Keep a reserve (e.g, 10%) of disk always free, ideally scattered across disk**
  - Don't tell users (`df` $\rightarrow$ 110% full)
  - With 10% free, can almost always find one of them free

So what did we gain?

- **Performance improvements:**
  - Able to get 20-40% of disk bandwidth for large files
  - 10-20x original Unix file system!
  - Better small file performance (why?)
- **Is this the best we can do? No.**
- **Block based rather than extent based**
  - Name contiguous blocks with single pointer and length
  - (Linux ext2fs)
- **Writes of meta data done synchronously**
  - Really hurts small file performance
  - Make asynchronous with write-ordering ("soft updates") or logging (the episode file system, ∼LFS)
  - Play with semantics (/tmp file systems)

Other hacks

- **Obvious:**
  - Big file cache.
- **Fact: no rotation delay if get whole track.**
  - How to use?
- **Fact: transfer cost negligible.**
  - Recall: Can get 50x the data for only $\sim$3% more overhead
  - 1 sector: 10ms + 8ms + 10μs $(= 512\,\mathrm{B}/(50\,\mathrm{MB/s}))$ $\approx$ 18ms
  - 50 sectors: 10ms + 8ms + .5ms = 18.5ms
  - How to use?
- **Fact: if transfer huge, seek + rotation negligible**
  - How to use ?

Other hacks

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  - Big file cache.
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  - How to use?
- **Fact: if transfer huge, seek + rotation negligible**
  - How to use ?

Use read ahead + cluster read/write (hoard data, write out MB at a time)

Outline

Fixing corruption – fsck

- **Must run FS check (fsck) program after crash**
- **Summary info usually bad after crash**
  - Scan to check free block map, block/inode counts
- **System may have corrupt inodes (not simple crash)**
  - Bad block numbers, cross-allocation, etc.
  - Do sanity check, clear inodes with garbage
- **Fields in inodes may be wrong**
  - Count number of directory entries to verify link count, if no entries but count $\neq 0$, move to `lost+found`
  - Make sure size and used data counts match blocks
- **Directories may be bad**
  - Holes illegal, "." and ". ." must be valid, . . .
  - All directories must be reachable

Crash recovery permeates FS code

- **Have to ensure fsck can recover file system**
- **Example: Suppose all data written asynchronously**
- **Delete/truncate a file, append to other file, crash**
  - New file may reuse block from old
  - Old inode may not be updated
  - Cross-allocation!
  - Often inode with older mtime wrong, but can't be sure
- **Append to file, allocate indirect block, crash**
  - Inode points to indirect block
  - But indirect block may contain garbage

Ordering of updates

- **Must be careful about order of updates**
  - Write new inode to disk before directory entry
  - Remove directory name before deallocating inode
  - Write cleared inode to disk before updating CG free map
- **Solution: Many metadata updates synchronous**
  - Doing one write at a time ensures ordering
  - Of course, this hurts performance
  - E.g., untar much slower than disk bandwidth
- **Note: Cannot update buffers on the disk queue**
  - E.g., say you make two updates to same directory block
  - But crash recovery requires first to be synchronous
  - Must wait for first write to complete before doing second

Performance vs. consistency

- **FFS crash recoverability comes at huge cost**
  - Makes tasks such as untar easily 10-20 times slower
  - All because you *might* lose power or reboot at any time
- **Even while slowing ordinary usage, recovery slow**
  - If fsck takes one minute, then disks get $10\times$ bigger ...
- **One solution: battery-backed RAM**
  - Expensive (requires specialized hardware)
  - Often don't learn battery has died until too late
  - A pain if computer dies (can't just move disk)
  - If OS bug causes crash, RAM might be garbage
- **Better solution: Advanced file system techniques**
  - Topic of rest of lecture

Outline

First attempt: Ordered updates

- **Must follow three rules in ordering updates:**
  1. Never write pointer before initializing the structure it points to
  2. Never reuse a resource before nullifying all pointers to it
  3. Never clear last pointer to live resource before setting new one
- **If you do this, file system will be recoverable**
- **Moreover, can recover quickly**
  - Might leak free disk space, but otherwise correct
  - So start running after reboot, scavenge for space in background
- **How to achieve?**
  - Keep a partial order on buffered blocks

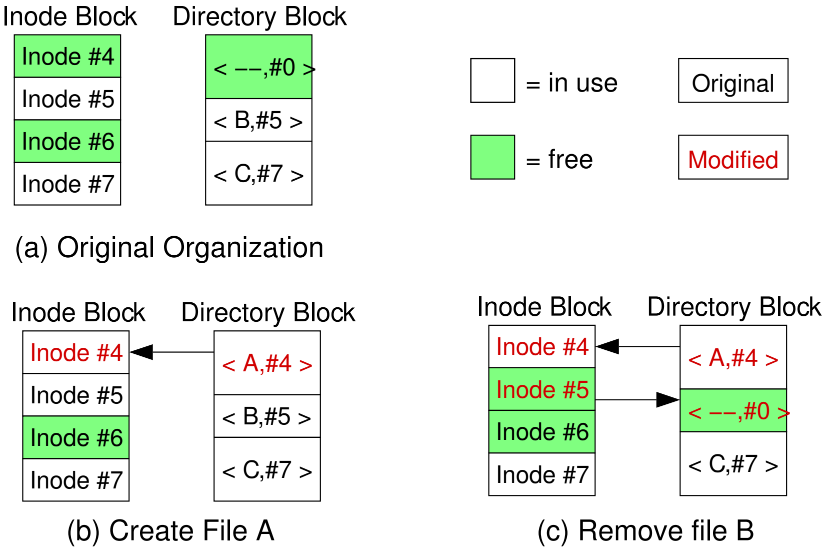
Ordered updates (continued)

- **Example: Create file A**
  - Block X contains an inode
  - Block Y contains a directory block
  - Create file A in inode block X, dir block Y
- **We say $Y \rightarrow X$, pronounced "Y depends on X"**
  - Means Y cannot be written before X is written
  - X is called the depend*ee*, Y the depend*er*
- **Can delay both writes, so long as order preserved**
  - Say you create a second file B in blocks X and Y
  - Only have to write each out once for both creates

Problem: Cyclic dependencies

- **Suppose you create file A, unlink file B**
  - Both files in same directory block & inode block
- **Can't write directory until inode A initialized**
  - Otherwise, after crash directory will point to bogus inode
  - Worse yet, same inode # might be re-allocated
  - So could end up with file name A being an unrelated file
- **Can't write inode block until dir entry B cleared**
  - Otherwise, B could end up with too small a link count
  - File could be deleted while links to it still exist
- **Otherwise, fsck has to be very slow**
  - Check every directory entry and inode link count

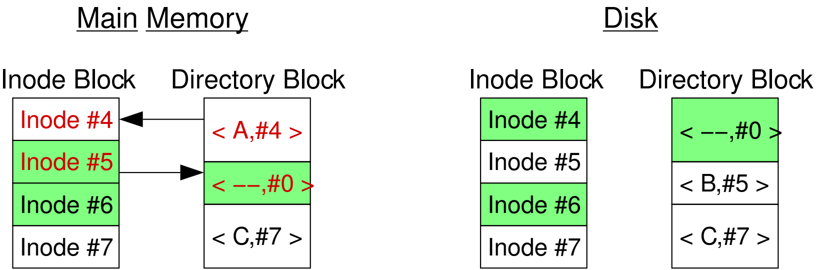
Cyclic dependencies illustrated



More problems

- **Crash might occur between ordered but related writes**
  - E.g., summary information wrong after block freed
- **Block aging**
  - Block that always has dependency will never get written back
- **Solution: "Soft updates" [Ganger]**
  - Write blocks in any order
  - But keep track of dependencies
  - When writing a block, temporarily roll back any changes you can't yet commit to disk

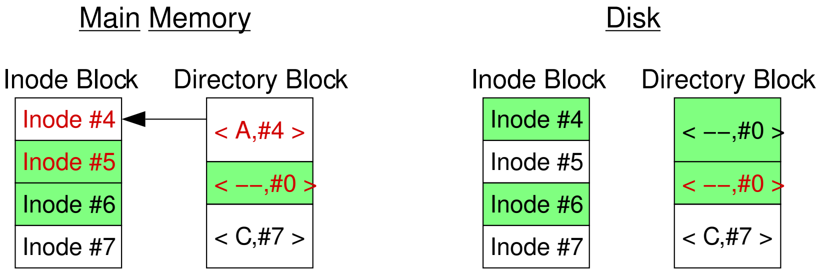
Breaking dependencies w. rollback



(a) After Metadata Updates

- **Now say we decide to write directory block. . .**
- **Can't write file name *A* to disk—has dependee**

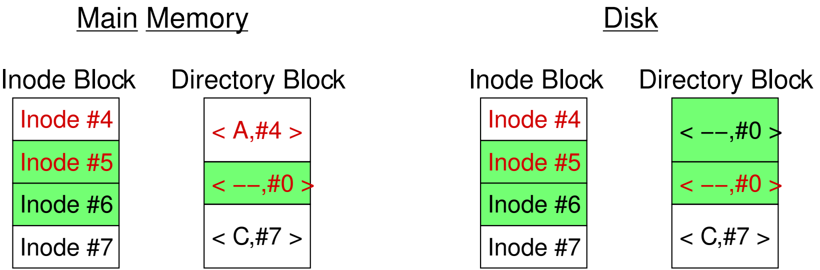
Breaking dependencies w. rollback



(b) Safe Version of Directory Block Written

- **Undo file *A* before writing dir block to disk**
  - Even though we just wrote it, directory block still
- **But now inode block has no dependees**
  - Can safely write inode block to disk as-is. . .

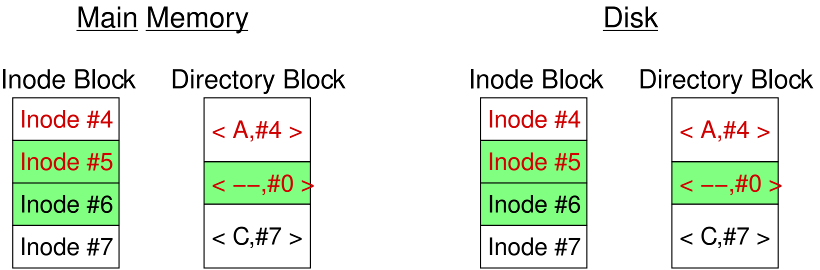
Breaking dependencies w. rollback



(c) Inode Block Written

- **Now inode block clean (same in memory as on disk)**
- **But have to write directory block a second time. . .**

Breaking dependencies w. rollback



(d) Directory Block Written

- **All data stably on disk**
- **Crash at any point would have been safe**

Soft updates

- **Structure for each updated field or pointer, contains:**
  - old value
  - new value
  - list of updates on which this update depends (*dependees*)
- **Can write blocks in any order**
  - But must temporarily undo updates with pending dependencies
  - Must lock rolled-back version so applications don't see it
  - Choose ordering based on disk arm scheduling
- **Some dependencies better handled by postponing in-memory updates**
  - E.g., when freeing block (e.g., because file truncated), just mark block free in bitmap after block pointer cleared on disk

Simple example

- **Say you create a zero-length file A**
- **Depender: Directory entry for A**
  - Can't be written untill dependees on disk
- **Dependees:**
  - Inode – must be initialized before dir entry written
  - Bitmap – must mark inode allocated before dir entry written
- **Old value: empty directory entry**
- **New value:** $\langle \text{filename } A, \text{inode } \# \rangle$
- **Can write directory block to disk any time**
  - Must substitute old value until inode & bitmap updated on disk
  - Once dir block on disk contains A, file fully created
  - Crash before A on disk, worst case might leak the inode

Operations requiring soft updates (1)

1. **Block allocation**
   - Must write the disk block, the free map, & a pointer
   - Disk block & free map must be written before pointer
   - Use Undo/redo on pointer (& possibly file size)
2. **Block deallocation**
   - Must write the cleared pointer & free map
   - Just update free map after pointer written to disk
   - Or just immediately update free map if pointer not on disk

- **Say you quickly append block to file then truncate**
  - You will know pointer to block not written because of the allocated dependency structure
  - So both operations together require no disk I/O!

Operations requiring soft updates (2)

3. **Link addition (see simple example)**
   - Must write the directory entry, inode, & free map (if new inode)
   - Inode and free map must be written before dir entry
   - Use undo/redo on i# in dir entry (ignore entries w. i# 0)
4. **Link removal**
   - Must write directory entry, inode & free map (if nlinks==0)
   - Must decrement nlinks only after pointer cleared
   - Clear directory entry immediately
   - Decrement in-memory nlinks once pointer written
   - If directory entry was never written, decrement immediately (again will know by presence of dependency structure)

- **Note: Quick create/delete requires no disk I/O**

Soft update issues

- **fsync – sycall to flush file changes to disk**
  - Must also flush directory entries, parent directories, etc.
- **unmount – flush all changes to disk on shutdown**
  - Some buffers must be flushed multiple times to get clean
- **Deleting large directory trees frighteningly fast**
  - *unlink* syscall returns even if inode/indir block not cached!
  - Dependencies allocated faster than blocks written
  - Cap # dependencies allocated to avoid exhausting memory
- **Useless write-backs**
  - Syncer flushes dirty buffers to disk every 30 seconds
  - Writing all at once means many dependencies unsatisfied
  - Fix syncer to write blocks one at a time
  - Fix LRU buffer eviction to know about dependencies

Soft updates fsck

- **Split into foreground and background parts**
- **Foreground must be done before remounting FS**
  - Need to make sure per-cylinder summary info makes sense
  - Recompute free block/inode counts from bitmaps – very fast
  - Will leave FS consistent, but might leak disk space
- **Background does traditional fsck operations**
  - Do after mounting to recuperate free space
  - Can be using the file system while this is happening
  - Must be done in forground after a media failure
- **Difference from traditional FFS fsck:**
  - May have many, many inodes with non-zero link counts
  - Don't stick them all in lost+found (unless media failure)

Outline

An alternative: Journaling

- **Reserve a portion of disk for write-ahead log**
  - Write any metadata operation first to log, then to disk
  - After crash/reboot, re-play the log (efficient)
  - May re-do already committed change, but won't miss anything
- **Performance advantage:**
  - Log is consecutive portion of disk
  - Multiple log writes very fast (at disk b/w)
  - Consider updates committed when written to log
- **Example: delete directory tree**
  - Record all freed blocks, changed directory entries in log
  - Return control to user
  - Write out changed directories, bitmaps, etc. in background (sort for good disk arm scheduling)

Journaling details

- **Must find oldest relevant log entry**
  - Otherwise, redundant and slow to replay whole log
- **Use checkpoints**
  - Once all records up to log entry N have been processed and affected blocks stably committed to disk...
  - Record N to disk either in reserved checkpoint location, or in checkpoint log record
  - Never need to go back before most recent checkpointed N
- **Must also find end of log**
  - Typically circular buffer; don't play old records out of order
  - Can include begin transaction/end transaction records
  - Also typically have checksum in case some sectors bad

Journaling vs. soft updates

- **Both much better than FFS alone**
- **Some limitations of soft updates**
  - Very specific to FFS data structures (E.g., couldn't easily complex data structures like B-trees in XFS—even directory rename not quite right)
  - Metadata updates may proceed out of order (E.g., create A, create B, crash—maybe only B exists after reboot)
  - Still need slow background fsck to reclaim space
- **Some limitations of journaling**
  - Disk write required for every metadata operation (whereas create-then-delete might require no I/O w. soft updates)
  - Possible contention for end of log on multi-processor
  - *fsync* must sync other operations' metadata to log, too