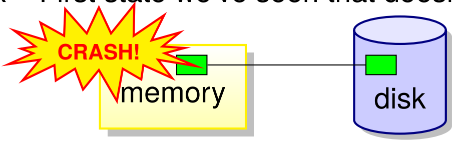
File system fun

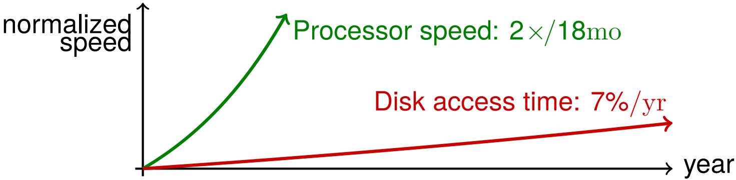
- File systems: traditionally hardest part of OS
  - More papers on FSes than any other single topic
- Main tasks of file system:
  - Don't go away (ever)
  - Associate bytes with name (files)
  - Associate names with each other (directories)
  - Can implement file systems on disk, over network, in memory, 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

Why disks are different

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



  - So: Where all important state ultimately resides
- Slow (milliseconds access vs. nanoseconds 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)

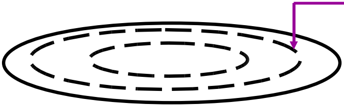
Disk vs. Memory

	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	$0.04/GB	$0.65/GB	$10/GiB
Persistence	Non-volatile	Non-volatile	Volatile

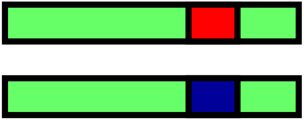
*Flash write performance degrades over time

Disk review

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



- 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.

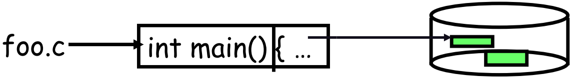
  - Sector write done completely, even if crash in middle (disk saves up enough momentum to complete)
- Larger atomic units have to be synthesized by OS

Some useful trends

- Disk bandwidth and cost/bit improving exponentially
  - Similar to CPU speed, memory size, etc.
- Seek time and rotational delay improving *very* slowly
  - Why? require moving physical object (disk arm)
- Disk accesses a huge system bottleneck & getting worse
  - Bandwidth increase lets system (pre-)fetch large chunks for about the same cost as small chunk.
  - Trade bandwidth for latency if you can get lots of related stuff.
  - How to get related stuff? Cluster together on disk
- Desktop memory size increasing faster than typical workloads
  - More and more of workload fits in file cache
  - Disk traffic changes: mostly writes and new data
  - Doesn't necessarily apply to big server-side jobs

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 operations:
  - Create a file, delete a file
  - Read from file, write to file
- Want: operations to have as few disk accesses as possible & have minimal space overhead (group related things)

What’s hard about grouping blocks?

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

  - File metadata: map byte offset to disk block address

  - Directory: map name to disk address or file #

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 ($0 \ldots \text{filesize} - 1$), $\sim$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

Some working intuitions

- FS performance dominated by # of disk accesses
  - Say each access costs $\sim$10 milliseconds
  - Touch the disk 100 extra times = 1 *second*
  - Can do a *billion* ALU ops in same time!
- Access cost dominated by movement, not transfer:

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

  - 1 sector: 5ms + 4ms + 5μs ($\approx 512\,\mathrm{B}/(100\,\mathrm{MB/s})$) $\approx$ 9ms
  - 50 sectors: 5ms + 4ms + .25ms = 9.25ms
  - Can get 50x the data for only $\sim$3% more overhead!
- 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

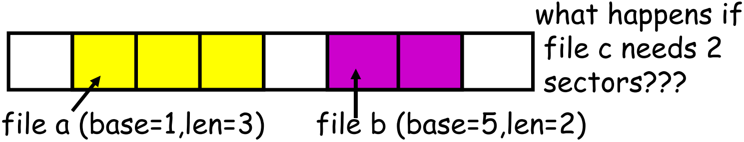
- Sequential:
  - File data processed in sequential order
  - By far the most common mode
  - Example: editor writes out new file, compiler reads in file, etc
- Random access:
  - Address any block in file directly without passing through predecessors
  - Examples: data set for demand paging, databases
- 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*
  - Inodes 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?)

Straw man: contiguous allocation

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



- Example: IBM OS/360
- Pros?
- Cons? (Think of corresponding VM scheme)

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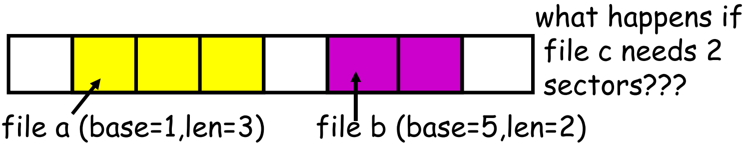
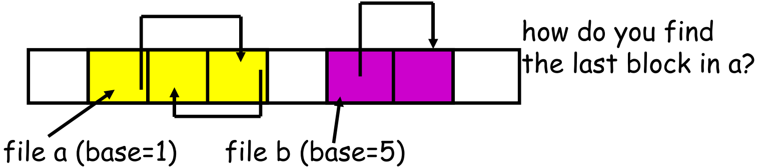


- Example: IBM OS/360
- Pros?
  - Simple, fast access, both sequential and random
- Cons? (Think of corresponding VM scheme)
  - External fragmentation

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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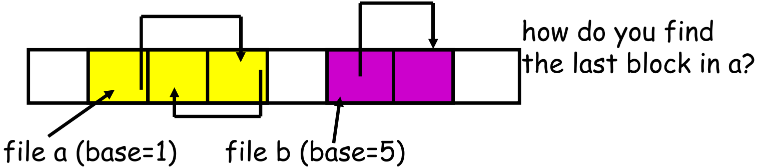


- Examples (sort-of): Alto, TOPS-10, DOS FAT
- Pros?
  - Easy dynamic growth & sequential access, no fragmentation
- Cons?
  - Linked lists on disk a bad idea because of access times
  - Pointers take up room in block, skewing alignment

Example: DOS FS (simplified)

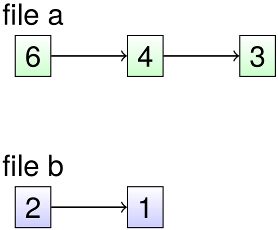
- Uses linked files. Cute: links reside in fixed-sized “file allocation table” (FAT) rather than in the blocks.

Directory (5)

a: 6
b: 2

FAT (16-bit entries)

0	free
1	eof
2	1
3	eof
4	3
5	eof
6	4
	. . .



- 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 solution: 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:

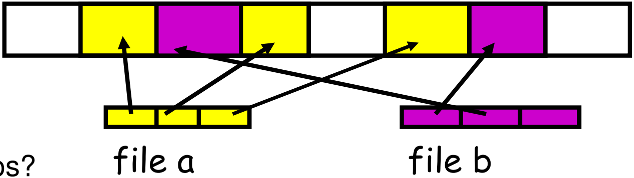
FAT discussion

- 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 MiB
  - One solution: 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	...

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

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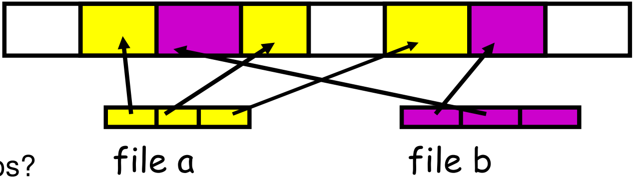
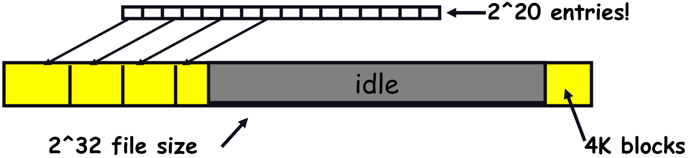


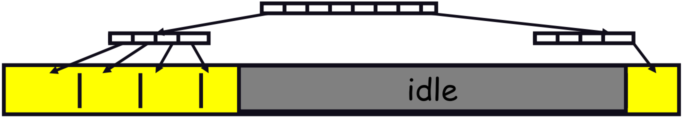
- Pros?
  - Both sequential and random access easy
- Cons?
  - Mapping table requires large chunk of contiguous space
    . . . Same problem we were trying to solve initially

Indexed files

- Issues same as in page tables

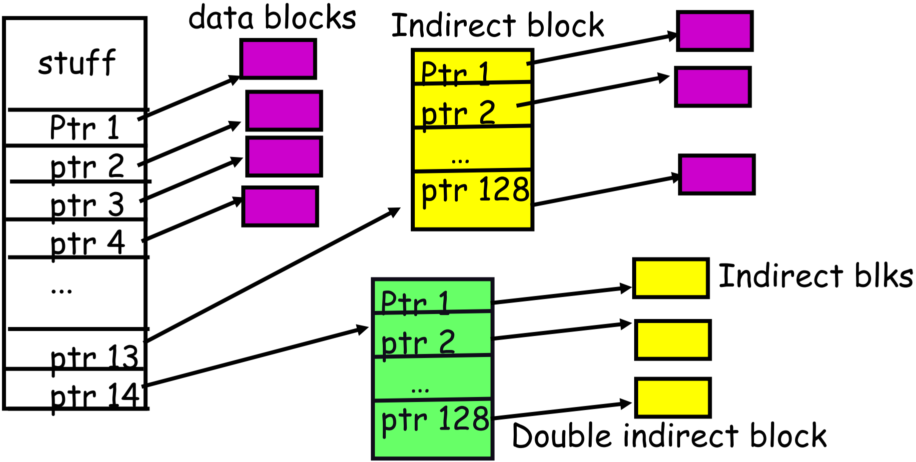


  - Large possible file size = lots of unused entries
  - Large actual size? table needs large contiguous disk chunk
- Solve identically: small regions with index array, this array with another array, . . . Downside?



Multi-level indexed files (old BSD FS)

- Solve problem of first block access slow
- inode = 14 block pointers + “stuff”

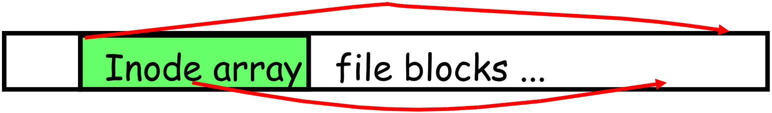


Old BSD FS discussion

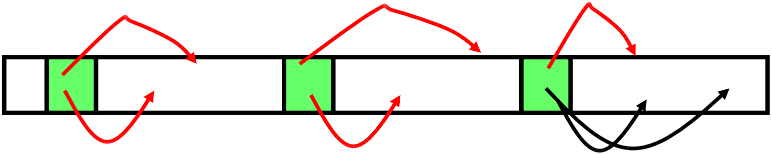
- Pros:
  - Simple, easy to build, fast access to small files
  - Maximum file length fixed, but large.
- Cons:
  - What is the worst case # of accesses?
  - What is the worst-case space overhead? (e.g., 13 block file)
- An empirical problem:
  - Because you allocate blocks by taking them off unordered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

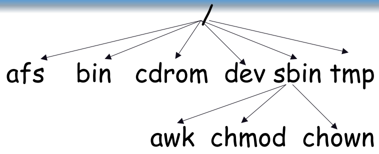
Directories

- 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



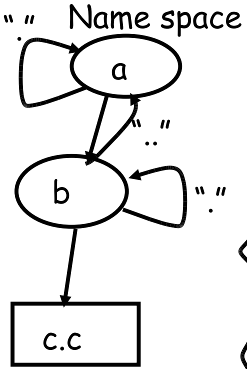
- Used since CTSS (1960s)
  - Unix picked up and used really nicely
- Directories stored on disk just like regular files
  - Special inode type byte set to directory
  - User's can read just like any other file
  - Only special syscalls can write (why?)
  - Inodes at fixed disk location
  - File pointed 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!

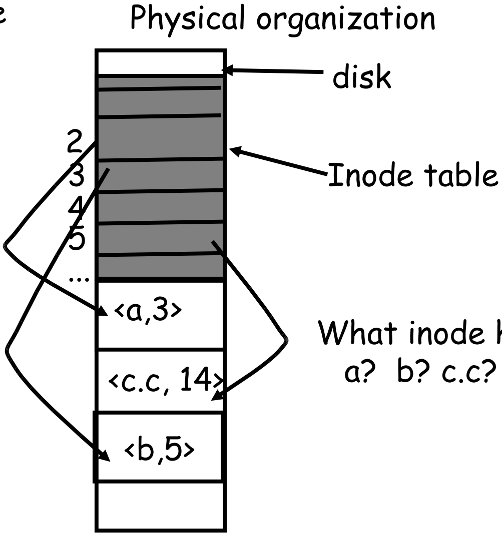
<name,inode#>
<afs,1021>
<tmp,1020>
<bin,1022>
<cdrom,4123>
<dev,1001>
<sbin,1011>
⋮

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`





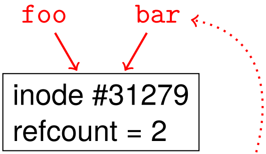
What inode holds file for
a? b? c.c?

Default context: working directory

- Cumbersome to constantly specify full path names
  - In Unix, each process associated with a "current working directory" (cwd)
  - File names not beginning with "/" are assumed to be relative to cwd; otherwise translation happens as before
  - Editorial: root, cwd should be regular fds (like stdin, stdout, ...) with *openat* syscall instead of *open*
- 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"
- Example of locality

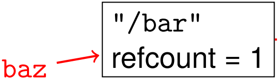
Hard and soft links (synonyms)

- 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/symbolic 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 “symlink” bit set and contains name of link target

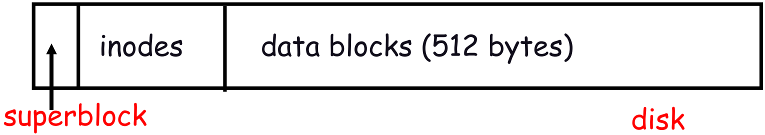
```
ln -s /bar baz
```



  - When the file system encounters a symbolic link it automatically translates it (if possible).

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)
- Poor 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`"
- Usability problems
  - 14-character file names a pain
  - Can't atomically update file in crash-proof way
- Next: how FFS fixes these (to a degree) [McKusic]

Problem: Internal fragmentation

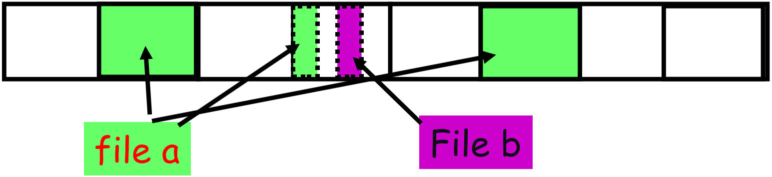
- Block size was too small in Unix FS
- Why not just make block size bigger?

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

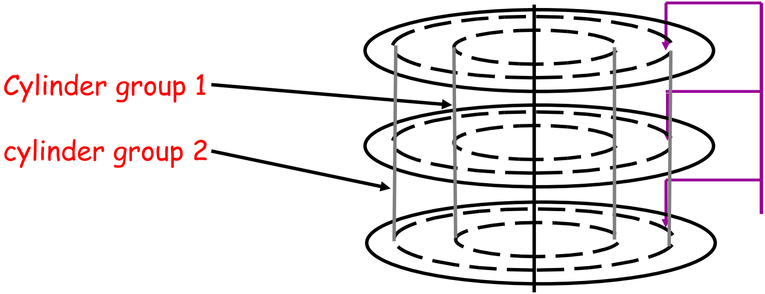
- BSD FFS:
  - Has large block size (4096 or 8192)
  - Allow large blocks to be chopped into small ones (“fragments”)
  - Used for little files and pieces at the ends of files



- 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

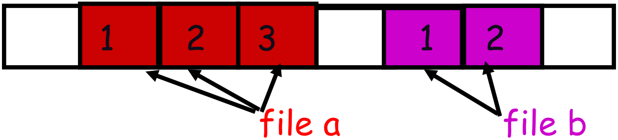
- Group 1 or more consecutive cylinders into a "*cylinder group*"



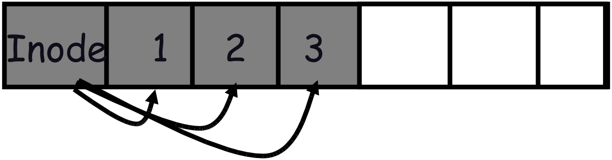
  - Key: can access any block in a cylinder without performing a seek. Next fastest place is adjacent cylinder.
  - Tries to put everything related in same cylinder group
  - Tries to put everything not related in different group (?!)

Clustering in FFS

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



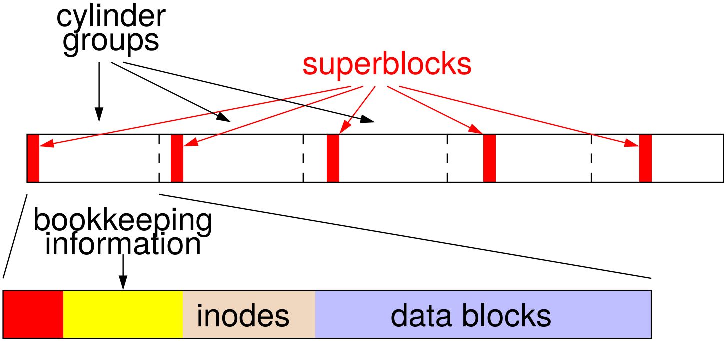
- Tries to keep inode in same cylinder as file data:
  - (If you look at inode, most likely will look at data too)



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

What does disk layout look like?

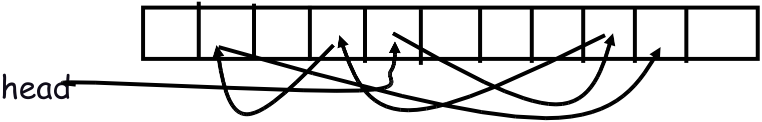
- Each cylinder group basically a mini-Unix file system:



- 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
  - Time to find free block increases if fewer free blocks

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` can get to 110% full)
  - Only root can allocate blocks once FS 100% 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
  - Could have named contiguous blocks with single pointer and length (Linux ext2fs, XFS)
- Writes of metadata done synchronously
  - Really hurts small file performance
  - Make asynchronous with write-ordering ("soft updates") or logging/journaling… more next lecture
  - 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 ~3% more overhead
  - 1 sector: 5ms + 4ms + 5μs ($\approx 512\,\mathrm{B}/(100\,\mathrm{MB/s})$) $\approx$ 9ms
  - 50 sectors: 5ms + 4ms + .25ms = 9.25ms
  - How to use?
- Fact: if transfer huge, seek + rotation negligible
  - LFS: Hoard data, write out MB at a time
- Next lecture:
  - FFS in more detail
  - More advanced, modern file systems