Outline

1. FFS in more detail
2. Crash recoverability
3. Soft updates
4. Journaling

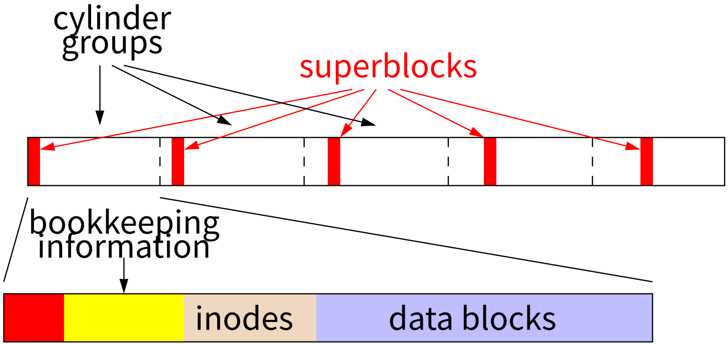
Review: FFS background

- **1980s improvement to original Unix FS, which had:**
  - 512-byte blocks
  - Free blocks in linked list
  - All inodes at beginning of disk
  - Low throughput: 512 bytes per average seek time
- **Unix FS performance problems:**
  - Transfers only 512 bytes per disk access
  - Eventually random allocation $\rightarrow$ 512 bytes / disk seek
  - Inodes far from directory and file data
  - Within directory, inodes far from each other
- **Also had some usability problems:**
  - 14-character file names a pain
  - Can't atomically update file in crash-proof way

Review: FFS [McKusic] basics

- **Change block size to at least 4K**
  - To avoid wasting space, use “fragments” for ends of files
- **Cylinder groups spread inodes around disk**
- **Bitmaps replace free list**
- **FS reserves space to improve allocation**
  - Tunable parameter, default 10%
  - Only superuser can use space when over 90% full
- **Usability improvements:**
  - File names up to 255 characters
  - Atomic *rename* system call
  - Symbolic links assign one file name to another

Review: FFS disk layout



- **Each cylinder group has its own:**
  - Superblock
  - Bookkeeping information
  - Set of inodes
  - Data/directory blocks

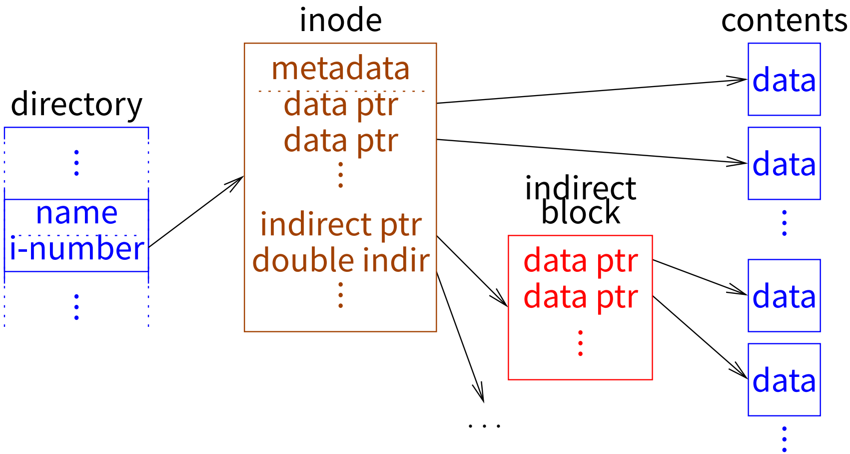
Superblock

- **Contains file system parameters**
  - Disk characteristics, block size, CG info
  - Information necessary to locate inode given i-number
- **Replicated once per cylinder group**
  - At shifting offsets, so as to span multiple platters
  - Contains magic number `0x011954` to find replicas if 1st superblock dies (Kirk McKusick's birthday?)
- **Contains non-replicated "summary information"**
  - # blocks, fragments, inodes, directories in FS
  - Flag stating if FS was cleanly unmounted

Bookkeeping information

- **Block map**
  - Bit map of available fragments
  - Used for allocating new blocks/fragments
- **Summary info within CG**
  - # free inodes, blocks/frags, files, directories
  - Used when picking cylinder group from which to allocate
- **# free blocks by rotational position (8 positions)**
  - Was reasonable in 1980s when disks weren't commonly zoned
  - Back then OS could do stuff to minimize rotational delay

Inodes and data blocks



- **Each CG has fixed # of inodes (default one per 2K data)**
- **Each inode maps offset → disk block for one file**
- **An inode also contains metadata for its file**
  - permissions, access/modification/change times, link count, . . .

Inode allocation

- **Each file or directory created requires a new inode**
- **New file? Put inode in same CG as directory if possible**
- **New directory? Use different CG from parent**
  - Consider CGs with greater than average # free inodes
  - Chose CG with smallest # directories
- **Within CG, inodes allocated randomly (next free)**
  - Would like related inodes as close as possible
  - OK, because one CG doesn't have that many inodes
  - All inodes in CG can be read and cached with small # of reads

Fragment allocation

- **Allocate space when user writes beyond end of file**
- **Want last block to be a fragment if not full-size**
  - If already a fragment, may contain space for write – done
  - Else, must deallocate any existing fragment, allocate new
- **If no appropriate free fragments, break full block**
- **Problem: Slow for many small writes**
  - May have to keep moving end of file around
- **(Partial) soution: new `stat` struct field `st_blksize`**
  - Tells applications file system block size
  - stdio library can buffer this much data

Block allocation

- **Try to optimize for sequential access**
  - If available, use rotationally close block in same cylinder (obsolete)
  - Otherwise, use block in same CG
  - If CG totally full, find other CG with quadratic hashing
    i.e., if CG #*n* is full, try $n + 1^2, n + 2^2, n + 3^2, \ldots \pmod{\#CGs}$
  - Otherwise, search all CGs for some free space
- **Problem: Don't want one file filling up whole CG**
  - Otherwise other inodes will have data far away
- **Solution: Break big files over many CGs**
  - But large extents in each CGs, so sequential access doesn't require many seeks
  - How big should extents be?

Block allocation

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  - How big should extents be?
  - Extent transfer time should be much greater than seek time

Directories

- **Directories have normal inodes with different type bits**
- **Contents considered as 512-byte *chunks***
- **Each chunk has `direct` structure(s) with:**
  - 32-bit inumber
  - 16-bit size of directory entry
  - 8-bit file type (added later)
  - 8-bit length of file name
- **Coalesce when deleting**
  - If first `direct` in chunk deleted, set inumber = 0
- **Periodically compact directory chunks**
  - But can never move directory entries across chunks
  - Recall only 512-byte sector writes atomic w. power failure

Updating FFS for the 90s

- **No longer wanted to assume rotational delay**
  - With disk caches, want data contiguously allocated
- **Solution: Cluster writes**
  - FS delays writing a block back to get more blocks
  - Accumulates blocks into 64KiB *clusters*, written at once
- **Allocation of clusters similar to fragments/blocks**
  - Summary info
  - Cluster map has one bit for each 64K if all free
- **Also read in 64K chunks when doing read ahead**

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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 containing 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, file names must be unique
  - All directories must be reachable

Crash recovery permeates FS code

- Have to ensure fsck can recover file system
- **Example: Suppose all data written asynchronously**
  - Any subset of data structures may be updated before a crash
- **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!

Sidenote: kernel-internal disk write routines

- **BSD has three ways of writing a block to disk**

1. `bdwrite` – **delayed write**
   - Marks cached copy of block as dirty, does not write it
   - Will get written back in background within 30 seconds
   - Used if block likely to be modified again soon
2. `bawrite` – **asynchronous write**
   - Start write but return immediately before it completes
   - E.g., use when appending to file and block is full
3. `bwrite` – **synchronous write**
   - Start write, sleep and do not return until safely on disk

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** (`bwrite`)
  - 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
  - Makes `bawrite` as slow as `bwrite` for many updates to same block

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 slowing normal case does not make recovery fast**
  - If fsck takes one minute, then disks get $10\times$ bigger, then $100\times$ …
- **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

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First attempt: Ordered updates

- **Want to avoid crashing after "bad" subset of writes**
- **Must follow 3 rules in ordering updates [Ganger]:**
  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

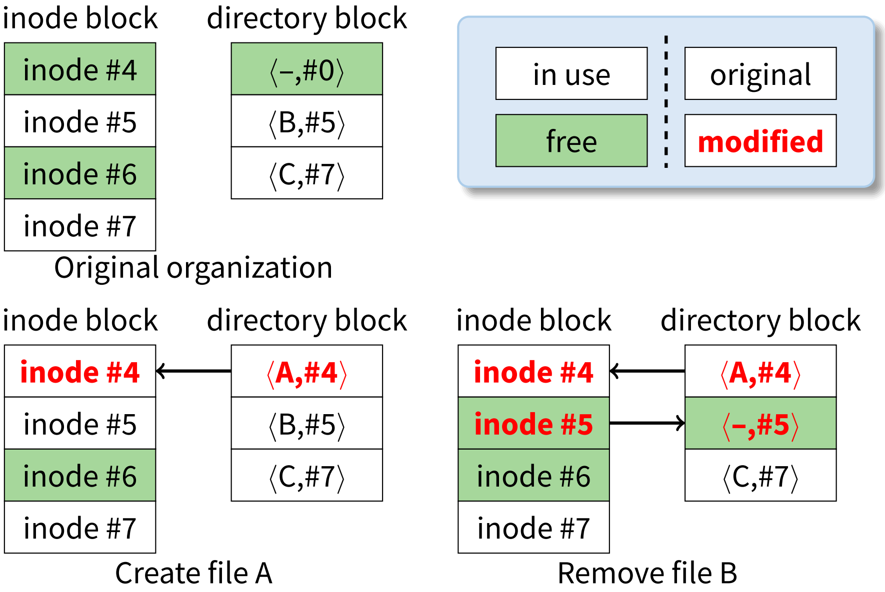
Ordered updates (continued)

- **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
  - By rule #1, must write X before writing Y
- **We say $Y \to X$, pronounced "Y *depends on* X"**
  - Means Y cannot be written before X is written
  - X is called the dependee, Y the *depender*
- **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*, but delay writes**
  - Both files in same directory block & inode block
- **Can't write directory until *A*'s inode initialized (rule #1)**
  - 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 *B*'s directory entry cleared (rule #2)**
  - 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 slow**
  - Check every directory entry and every inode link count

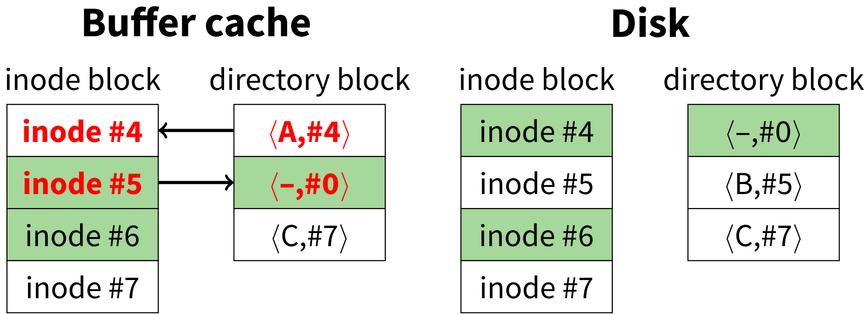
Cyclic dependencies illustrated



More problems

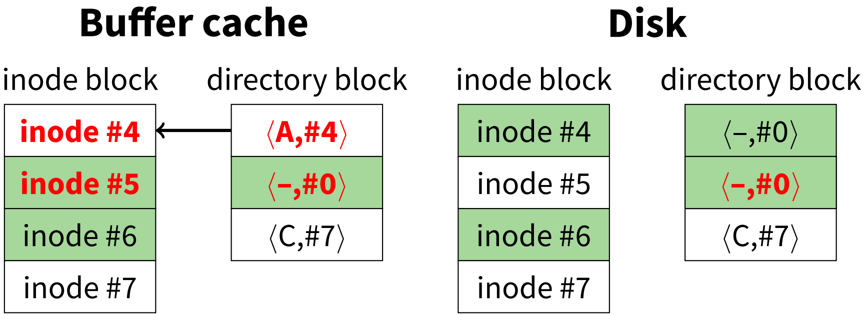
- **Crash might occur between ordered but related writes**
  - E.g., summary information wrong after block freed
- **Block aging**
  - Block that always has dependency will never get written back
- **Solution: *Soft updates* [Ganger]**
  - Write blocks in any order
  - But keep track of dependencies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

Breaking dependencies with rollback



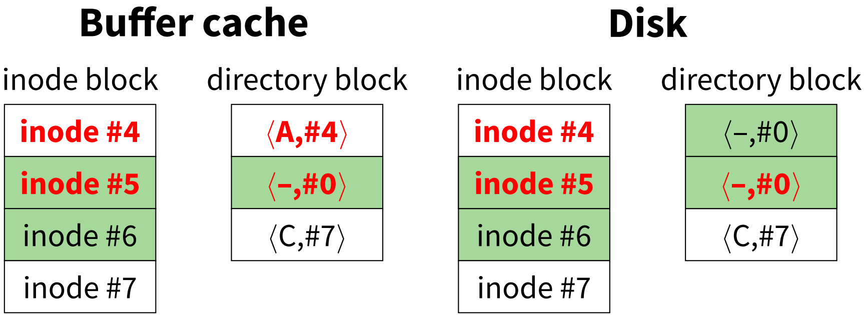
- **Deleted Created file A and deleted file B**
- **Now say we decide to write directory block. . .**
- **Can’t write file name *A* to disk—has dependee**

Breaking dependencies with rollback



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

Breaking dependencies with rollback



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

Breaking dependencies with rollback

Buffer cache

inode block	directory block
inode #4	**⟨A,#4⟩**
inode #5	**⟨–,#0⟩**
inode #6	⟨C,#7⟩
inode #7	

Disk

inode block	directory block
inode #4	**⟨A,#4⟩**
inode #5	**⟨–,#0⟩**
inode #6	⟨C,#7⟩
inode #7	

- **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)

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An alternative: Journaling

- **Biggest crash-recovery challenge is inconsistency**
  - Have one logical operation (e.g., create or delete file)
  - Requires multiple separate disk writes
  - If only some of them happen, end up with big problems
- **Most of these problematic writes are to metadata**
- **Idea: Use a *write-ahead* log to *journal* metadata**
  - Reserve a portion of disk for a 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

Journaling (continued)

- **Group multiple operations into one log entry**
  - E.g., clear directory entry, clear inode, update free map—either all three will happen after recovery, or none
- **Performance advantage:**
  - Log is consecutive portion of disk
  - Multiple operations can be logged at disk b/w
  - Safe to 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)

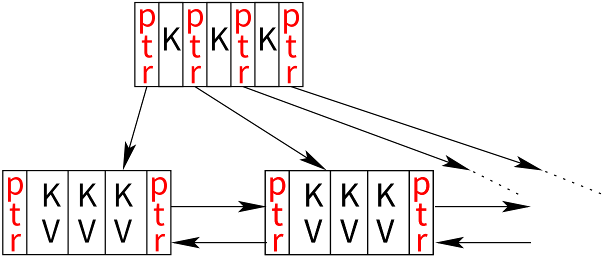
Journaling details

- **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

Case study: XFS [Sweeney]

- **Main idea: Think big**
  - Big disks, files, large # of files, 64-bit everything
  - Yet maintain very good performance
- **Break disk up into *Allocation Groups* (AGs)**
  - 0.5 – 4 GB regions of disk
  - New directories go in new AGs
  - Within directory, inodes of files go in same AG
  - Unlike cylinder groups, AGs too large to minimize seek times
  - Unlike cylinder groups, no fixed # of inodes per AG
- **Advantages of AGs:**
  - Parallelize allocation of blocks/inodes on multiprocessor (independent locking of different free space structures)
  - Can use 32-bit block pointers within AGs (keeps data structures smaller)

B+-trees



- **XFS makes extensive use of B+-trees**
  - Indexed data structure stores ordered Keys & Values
  - Keys must have an ordering defined on them
  - Stored data in blocks for efficient disk access
- **For B+-tree with n items, all operations $O(\log n)$:**
  - Retrieve closest $\langle$key, value$\rangle$ to target key k
  - Insert a new $\langle$key, value$\rangle$ pair
  - Delete $\langle$key, value$\rangle$ pair

B+-trees continued

- **See any algorithms book for details (e.g., [Cormen])**
- **Some operations on B-tree are complex:**
  - E.g., insert item into completely full B+-tree
  - May require "splitting" nodes, adding new level to tree
  - Would be bad to crash & leave B+tree in inconsistent state
- **Journal enables atomic complex operations**
  - First write all changes to the log
  - If crash while writing log, incomplete log record will be discarded, and no change made
  - Otherwise, if crash while updating B+-tree, will replay entire log record and write everything

B+-trees in XFS

- **B+-trees are complex to implement**
  - But once you've done it, might as well use everywhere
- **Use B+-trees for directories (keyed on filename hash)**
  - Makes large directories efficient
- **Use B+-trees for inodes**
  - No more FFS-style fixed block pointers
  - Instead, B+-tree maps: file offset $\rightarrow$ $\langle$start block, # blocks$\rangle$
  - Ideally file is one or small number of contiguous extents
  - Allows small inodes & no indirect blocks even for huge files
- **Use to find inode based on inumber**
  - High bits of inumber specify AG
  - B+-tree in AG maps: starting i# $\rightarrow$ $\langle$block #, free-map$\rangle$
  - So free inodes tracked right in leaf of B+-tree

More B+-trees in XFS

- **Free extents tracked by *two* B+-trees**
  1. start block # $\to$ # free blocks
  2. # free blocks $\to$ start block #
- **Use journal to update both atomically & consistently**
- **#1 allows you to coalesce adjacent free regions**
- **#1 allows you to allocate near some target**
  - E.g., when extending file, put next block near previous one
  - When first writing to file, put data near inode
- **#2 allows you to do best fit allocation**
  - Leave large free extents for large files

Contiguous allocation

- **Ideally want each file contiguous on disk**
  - Sequential file I/O should be as fast as sequential disk I/O
- **But how do you know how large a file will be?**
- **Idea: delayed allocation**
  - *write* syscall only affects the buffer cache
  - Allow write into buffers before deciding where to place on disk
  - Assign disk space only when buffers are flushed
- **Other advantages:**
  - Short-lived files never need disk space allocated
  - *mmap*ed files often written in random order in memory, but will be written to disk mostly contiguously
  - Write clustering: find other nearby stuff to write to disk

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 add B-trees like 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 with soft updates)
  - Possible contention for end of log on multi-processor
  - *fsync* must sync other operations' metadata to log, too