Operating Systems Design
13. File System Implementation

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Terms

- Disk
  - Non-volatile block-addressable storage.
- Block = sector
  - Smallest chunk of I/O on a disk
  - Most disks have 512-byte blocks
- Partition
  - Subset of all blocks on a disk. A disk has ≥ 1 partitions
- Volume
  - Disk, disks, or partition that contains a file system
  - A volume may span disks

More terms

- Superblock
  - Area on the volume that contains key file system information
- Metadata
  - Attributes of a file, not the file contents (data)
  - E.g., modification time, length, permissions, owner
- inode
  - A structure that stores a file's metadata and location of its data

Files

- Contents (Data)
  - Unstructured (byte stream) or structured (records)
  - Stored in data blocks
  - Find a way of allocating and tracking the blocks that a file uses
- Metadata
  - Usually stored in an inode … sometimes in a directory entry
  - Except for the name, which is stored in a directory

Directories

- A directory is just a file containing names & references
  - Name → (metadata, data) *Unix (UFS) approach*
  - (Name, metadata) → data *MS-DOS (FAT) approach*
- Linear list
  - Search can be slow for large directories.
  - Cache frequently-used entries
- Hash table
  - Linear list but with hash structure
  - Hash(name)
- More exotic structures: B-Tree, HTree

Block allocation: Contiguous

- Each file occupies a set of adjacent blocks
- You just need to know the starting block & file length
- We’d love to have contiguous storage for files!
  - Minimize disk seeks when accessing a file

Problems with contiguous allocation

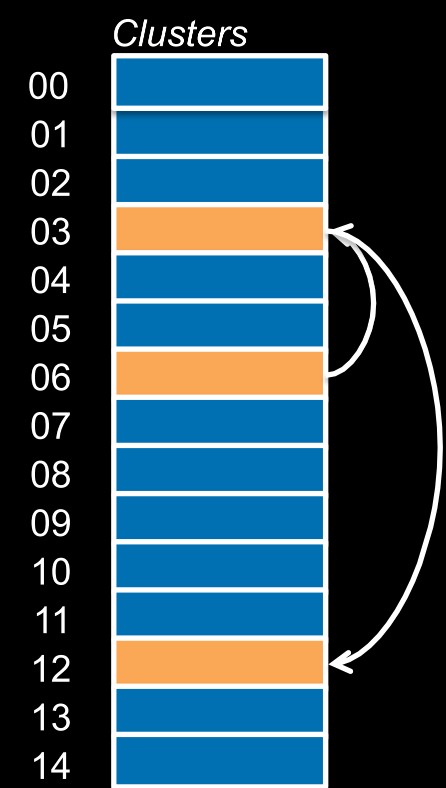
- Storage allocation is a pain (remember main memory?)
  - External fragmentation: free blocks of space scattered throughout
  - vs. Internal fragmentation: unused space within a block (allocation unit)
  - Periodic defragmentation: move files (yuck!)
- Concurrent file creation: how much space do you need?
- Compromise solution: extents
  - Allocate a contiguous chunk of space
  - If the file needs more space, allocate another chunk (extent)
  - Need to keep track of all extents
  - Not all extents will be the same size: it depends how much contiguous space you can allocate

Block allocation: Linked Allocation

- A file's data is a linked list of disk blocks
  - Directory contains a pointer to the first block of the file
  - Each block contains a pointer to the next block
- Problems
  - Only good for sequential access
  - Each block uses space for the pointer to the next block
- Clusters
  - Multiples of blocks: reduce overhead for block pointer & improve throughput
  - *A cluster is the smallest amount of disk space that can be allocated to a file*
  - Penalty: increased internal fragmentation

File Allocation Table (DOS/Windows FAT)

- Variation of Linked Allocation
- Section of disk at beginning of the volume contains a file allocation table
- The table has one entry per block. Contents contain the next logical block (cluster) in the file.



Directory entry:

myfile.txt	metadata	06

FAT table: one per file system

0	0	0	12	0	0	03	0	0	0	0	0	-1	0

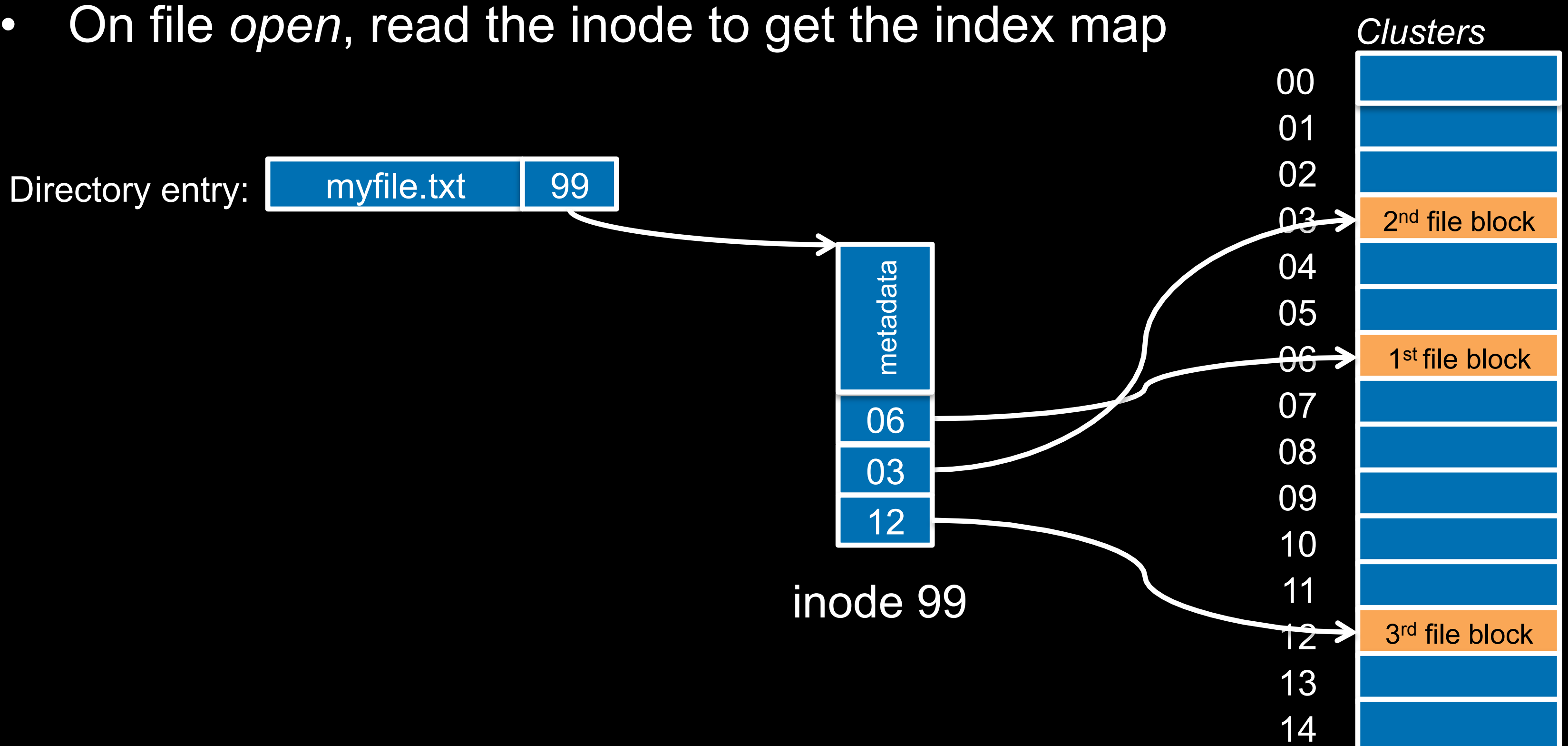
- FAT-16: 16-bit block pointers
  - 16-bit cluster numbers; up to 64 sectors/cluster
  - Max file system size = 2 GB (with 512 byte sectors)
- FAT-32: 32-bit block pointers
  - 32-bit cluster numbers; up to 64 sectors/cluster
  - Max file system size = 8 TB (with 512 byte sectors)
  - Max file size = 4 GB

Indexed Allocation (Block map)

- Linked allocation is not efficient for random access
- FAT requires storing the *entire* table in memory for efficient access
- Indexed allocation:
  - Store the entire list of block pointers for a file in one place: the index block (inode)
  - One inode per file
  - We can read this into memory when we open the file

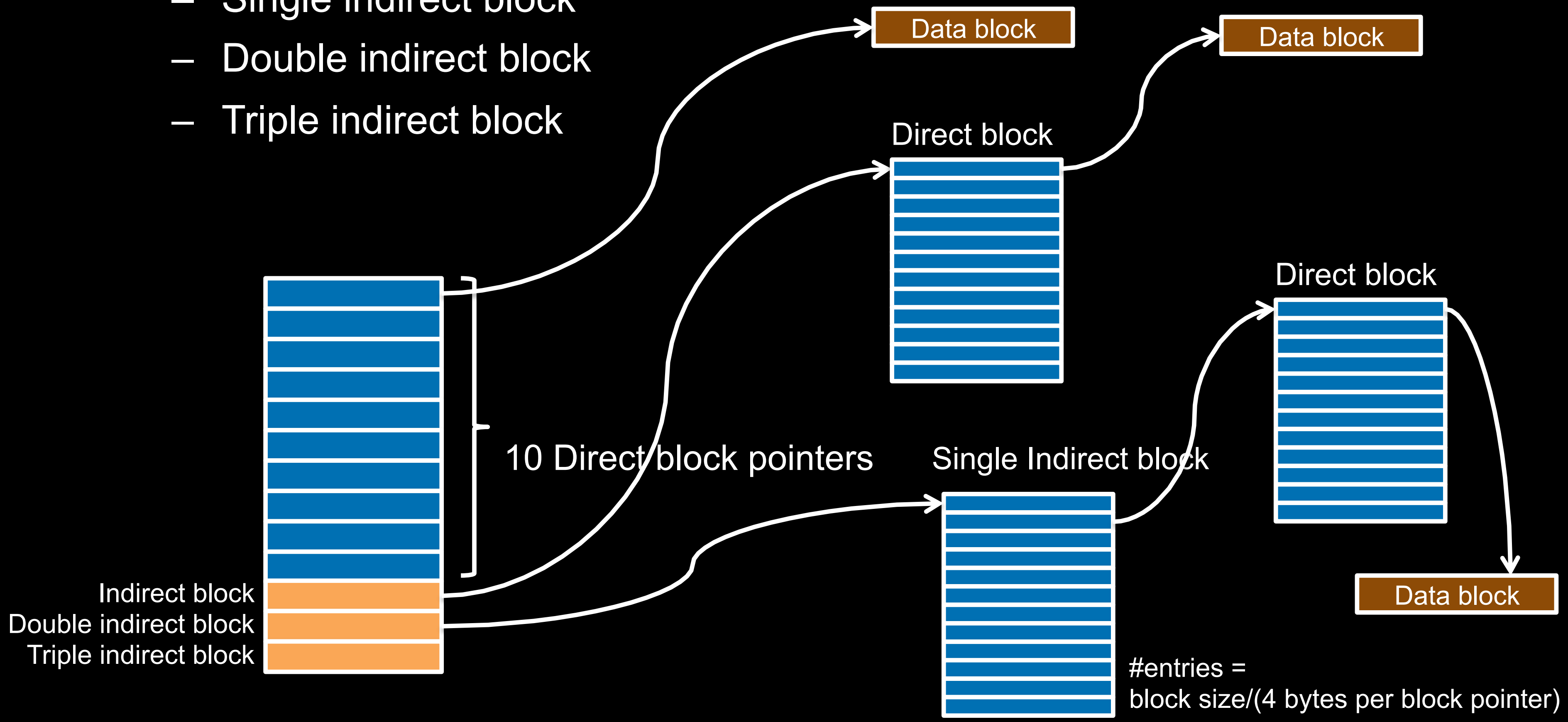
Indexed Allocation (block/cluster map)

- Directory entry contains name and inode number
- inode contains file metadata (length, timestamps, owner, etc.) *and* a block map
- On file *open*, read the inode to get the index map



Combined indexing (Unix File System)

- We want inodes to be a fixed size
- Large files get
  - Single indirect block
  - Double indirect block
  - Triple indirect block



Combined Indexing: inside the inode

- Direct block numbers
  - These contain block numbers that contain the file's data
- Indirect block number
  - This is a block number of a block that contains a list of direct block numbers. Each block number is the number of a block that contains the file's data
- Double indirect block number
  - This refers to a block that contains a list of indirect block numbers. Each indirect block number is the number of a block that contains a list of direct block numbers
- Triple indirect block number
  - This refers to a block that contains a list of double indirect block numbers. Each double indirect block number is the number of a block that contains a list of indirect direct block numbers. Each of these contains a list of direct block numbers

Example

- Unix File System
  - 1024-byte blocks, 32-bit block pointers
  - inode contains
    - 10 direct blocks, 1 indirect, 1 double-indirect, 1 triple indirect
- Capacity
  - Direct blocks will address: 1K × 10 blocks = 10,240 bytes
  - 1 level of indirect blocks: additional (1K/4)×1K = 256K bytes
  - 1 Double indirect blocks: additional (1K/4) × (1K/4) × 1K = 64M bytes
  - Maximum file size = 10,240 + 256K + 64M = 65,792K bytes

Extent lists

- Extents: Instead of listing block addresses
  - Each address represents a range of blocks
  - Contiguous set of blocks
  - E.g., 48-bit block # + 2-byte length (total = 64 bits)

- Why are they attractive?
  - Less block numbers to store if we have lots of contiguous allocation

- Problem: file seek operations
  - Locating a specific location requires traversing a list
  - Extra painful with indirect blocks

Directories

- A directory is just a file
  - Name → (metadata, data)
  - or (Name, metadata) → data
- Linear list
  - Search can be slow for large directories
  - Cache frequently-used entries
- Hash table
  - Linear list but with hash structure
  - Hash(name)
- B-Tree
  - Balanced tree (constant depth) with high fan-out
  - Variations include B+ Tree and HTree

Implementing File Operations

Initialization

- Low-level formatting (file system independent)
  - Define blocks (sectors) on a track
  - Create spare sectors
  - Identify and remap bad blocks
- High-level formatting (file system specific)
  - Define the file system structure
  - Initialize the free block map
  - Initialize sizes of inode and journal areas
  - Create a top-level (root) directory

Opening files

Two-step process

1. Pathname Lookup (*namei* function in kernel)
   - Traverse directory structure based on the pathname to find file
   - Return the associated inode
   - (cache frequently-used directory entries)

2. Verify access permissions
   - If OK, allocate in-memory structure to maintain state about access (e.g., that file is open read-only)

Writing files

A *write* either overwrites data in a file or adds data to the file, causing it to grow

- Allocate disk blocks to hold data
- Add the blocks to the list of blocks owned by the file
  - Update free block bitmap, the inode, and possibly indirect blocks
  - Write the file data
  - Modify inode metadata (file length)
  - Change current file offset in kernel

Deleting files

- Remove name from the directory
  - Prevent future access
- If there are no more links to the inode (disk references)
  - mark the file for deletion
- … and if there are no more programs with open handles to the file (in-memory references)
  - Release the resources used by the file
    - Return data blocks to the free block map
    - Return inode to the free inode list
- Example:
  - Open temp file, delete it, continue to access it
  - OS cleans up the data when the process exits

Additional file system operations

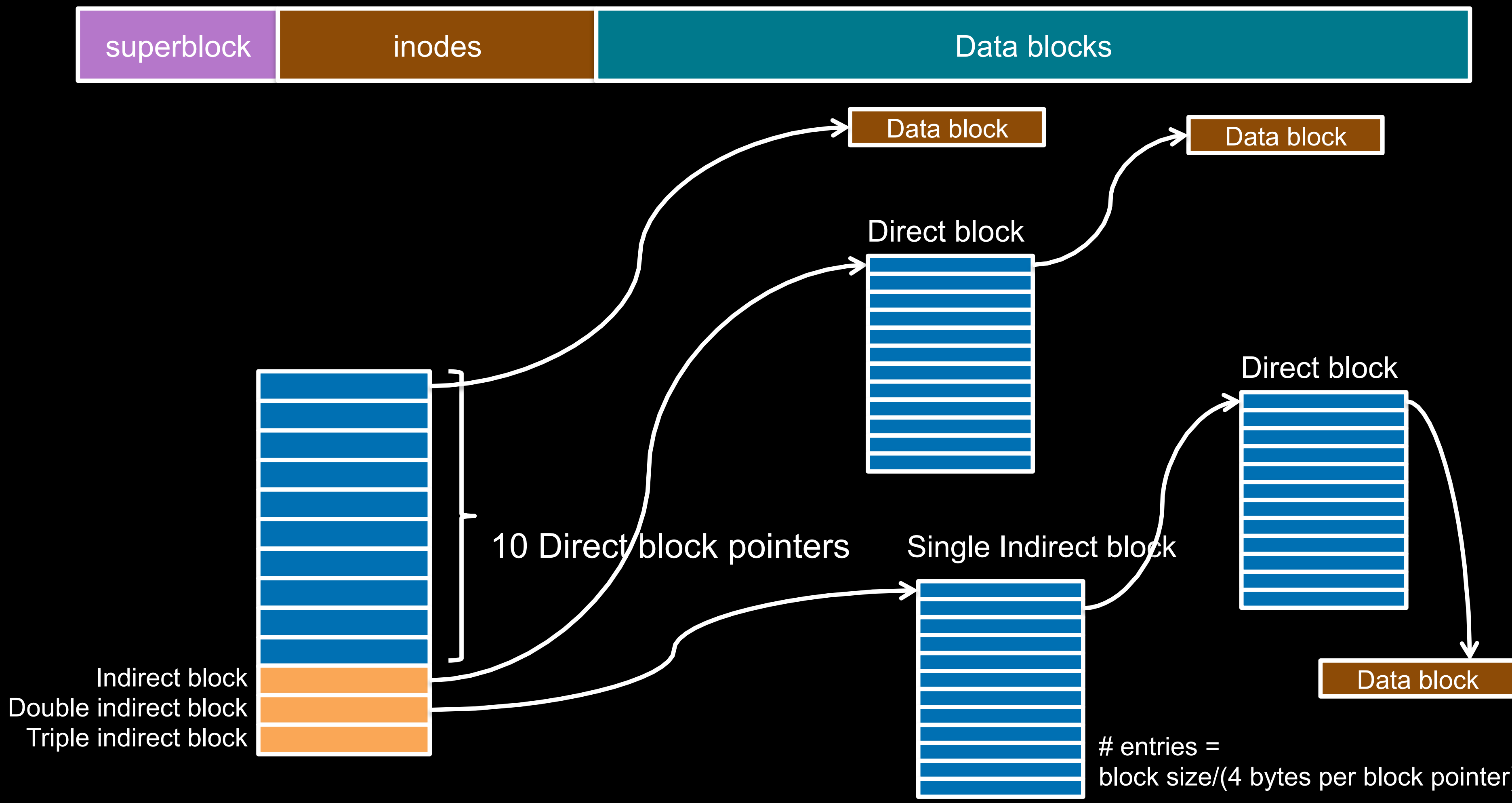
- Hard links (aliases)
  - Multiple directory entries (file names) that refer to the same inode
  - inode contains reference count to handle deletion
- Symbolic links
  - File data contains a path name
  - Underlying file can disappear or change
- Access control lists (ACLs)
  - Classic UNIX approach: user, group, world permissions
  - ACL: enumerated list of users and permissions
    - Variable size

Additional file system operations

- Extended attributes (NTFS, HFS+, XFS, etc.)
  - E.g., store URL from downloaded web/ftp content, app creator, icons
- Indexing
  - Create a database for fast file searches
- Journaling
  - Batch groups of changes. Commit them at once to a transaction log

Unix File System (UFS)

inodes with direct, indirect, double-indirect, and triple-indirect blocks



Unix File System (UFS)

Superblock contains:

- Size of file system
- # of free blocks
- list of free blocks (+ pointer to free block lists)
- index of the next free block in the free block list
- Size of the inode list
- Number of free inodes in the file system
- Index of the next free inode in the free inode list
- Modified flag (clean/dirty)

Unix File System (UFS)

- Free space managed as a linked list of blocks
  - Eventually this list becomes random
  - Every disk block access will require a seek!
- Fragmentation is a big problem
- Typical performance was often:

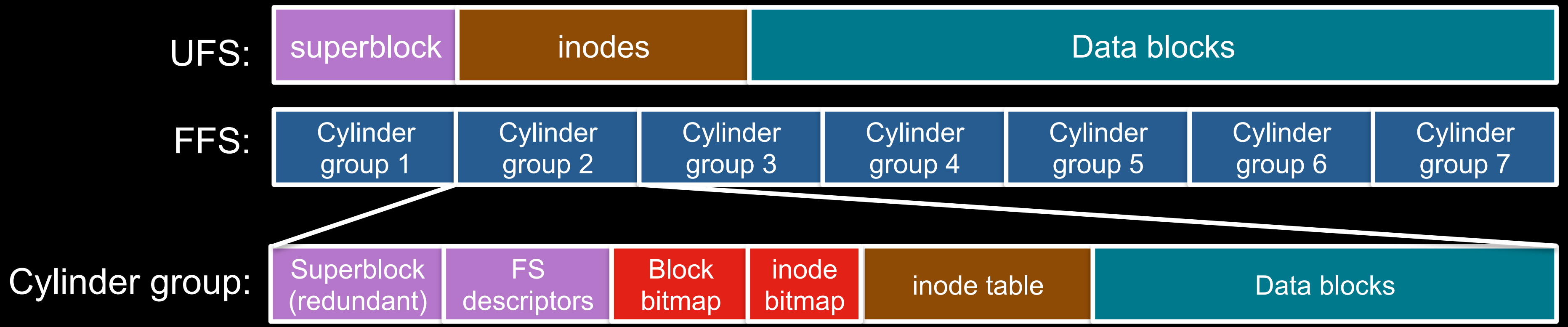
  2–4% of raw disk bandwidth!

BSD Fast File System (FFS)

- Try to improve UFS
- Improvement #1: Use larger blocks
  - ≥ 4096 bytes instead of UFS's 512-byte or 1024-byte blocks
    - Block size is recorded in the superblock
  - Just doubling the block size resulted in > 2x performance!
  - 4 KB blocks let you have 4 GB files with only two levels of indirection
  - Problem: increased internal fragmentation
    - Lots of files were small
  - Solution: Manage fragments within a block (down to 512 bytes)
    - A file is 0 or more full blocks and possibly one fragmented block
    - Free space bitmap stores fragment data
    - As a file grows, fragments are copied to larger fragments and then to a full block
    - Allow user programs to find the optimal block size
      - Standard I/O library and others use this
  - Also, avoid extra writes by caching in the system buffer cache

BSD Fast File System (FFS)

- Improvement #2: Minimize head movement (reduce seek time)
  - Seek latency is usually much higher than rotational latency
  - Keep file data close to its inode to minimize seek time to fetch data
  - Keep related files & directories together
  - Cylinder: collection of all blocks on the same track on all heads of a disk
  - Cylinder group: Collection of blocks on one or more consecutive cylinders



How do you find inodes?

- UFS was easy:
  - inodes_per_block = sizeof(block)/sizeof(inode)
  - inode_block = inode / inodes_per_block
  - block_offset = (inode % inodes_per_block) * sizeof(inode)
- FFS
  - We need to know how big each chunk of inodes in a cylinder group is: keep a table

BSD Fast File System (FFS)

- Optimize for sequential access

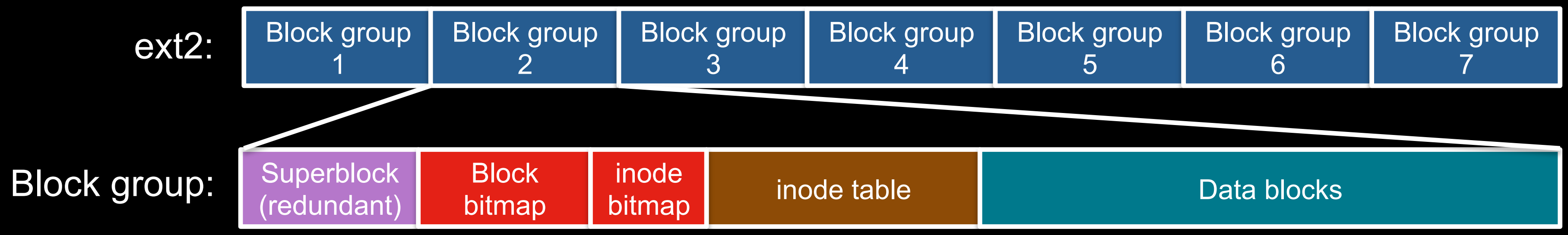
- Allocate data close together
  - Pre-allocate up to 8 adjacent blocks when allocating a block
    - Achieves good performance under heavy loads
    - Speeds sequential reads
- Prefetch
  - If 2 or more logically sequential blocks are read
    - Assume sequential read and request one large I/O on the entire range of sequential blocks
  - Otherwise, schedule a read-ahead

BSD Fast File System (FFS)

- Improve fault tolerance
  - Strict ordering of writes of file system metadata
  - *fsck* still requires up to five passes to repair
  - <u>All metadata writes are synchronous </u>(not buffered)
  - This limits the max # of I/O operations
- Directories
  - Max filename length = 256 bytes (vs. 12 bytes of UFS)
- Symbolic links introduced
  - Hard links could not point to directories and worked only within the FS
- Performance:
  - 14-47% of raw disk bandwidth
  - Better than the 2-5% of UFS

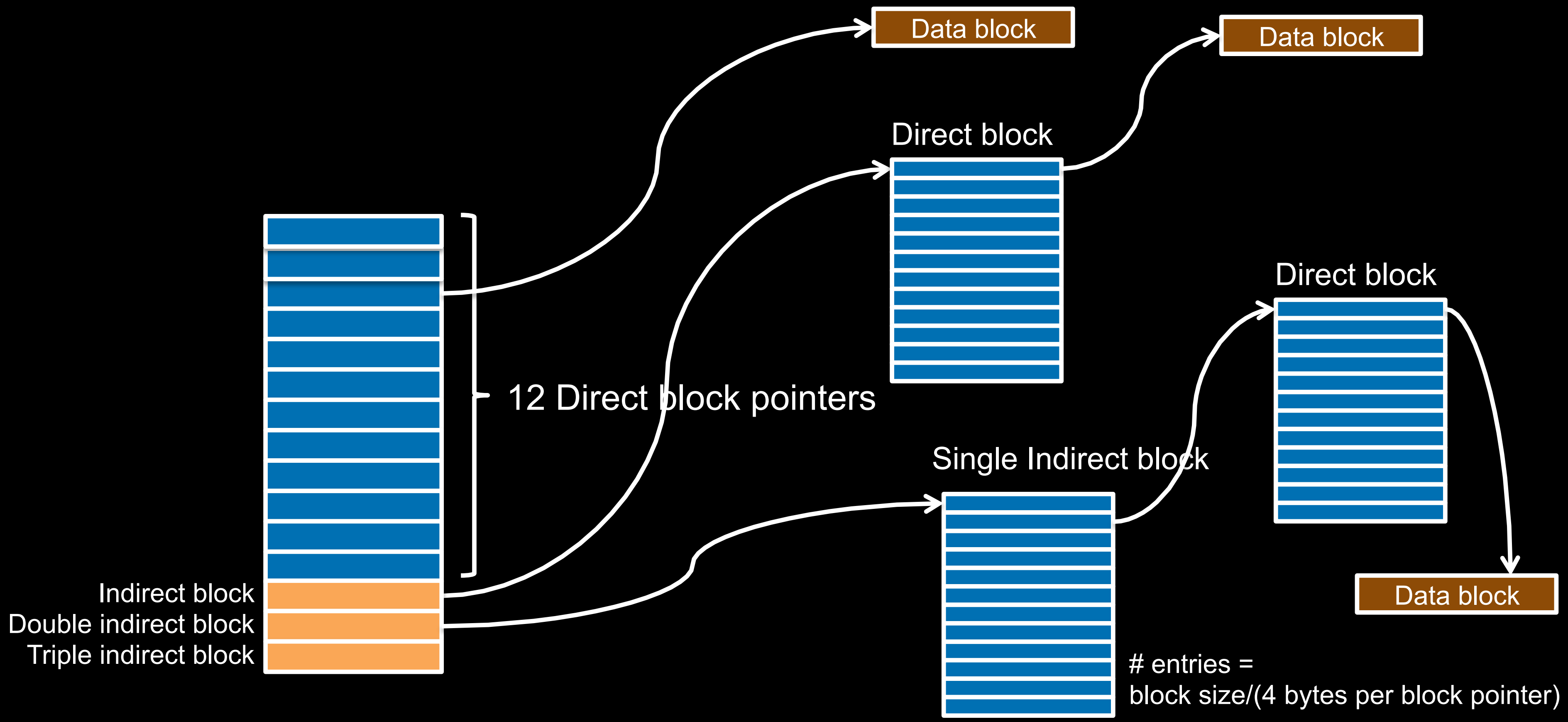
Linux ext2

- Similar to BSD FFS
- No fragments
- No cylinder groups (not useful in modern disks) – block groups
- Divides disk into fixed-size block groups
  - Like FFS, somewhat fault tolerant: recover chunks of disk even if some parts are not accessible



Linux ext2

inodes with direct, indirect, double-indirect, and triple-indirect blocks



Linux ext2

- Improve performance via aggressive caching
  - Reduce fault tolerance because of no synchronous writes
  - Almost all operations are done in memory until the buffer cache gets flushed
- Unlike FFS:
  - No guarantees about the consistency of the file system
    - Don't know the order of operations to the disk: risky if they don't all complete
  - No guarantee on whether a write was written to the disk when a system call completes
- In most cases, ext2 is *much* faster than FFS

Journaling

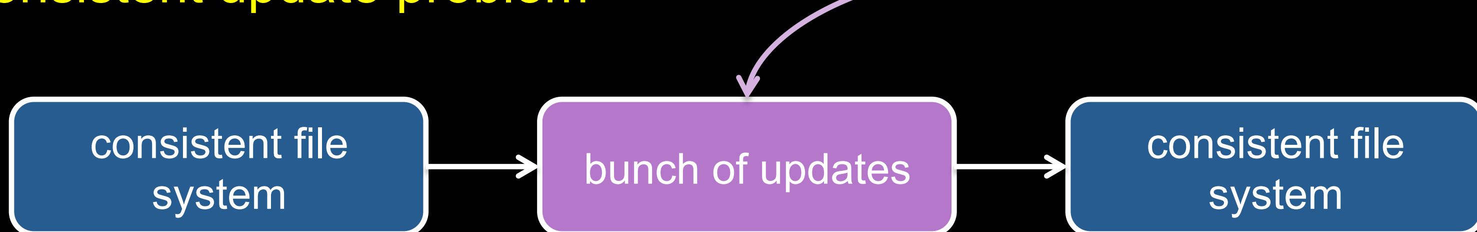
File system inconsistencies

Example:

- Writing a block to a file may require:
  - inode is
    - updated with a new block pointer
    - Updated with a new file size
  - Data free block bitmap is updated
  - Data block contents written to disk

- If *all* of these are not written, we have a file system inconsistency
- Consistent update problem

Don't crash here!



Journaling

- Journaling = write-ahead logging
- Keep a transaction-oriented journal of changes
  - Record what you are about to do (*along with the data*)

```
Transaction-begin
  New inode 779
  New block bitmap, group 4
  New data block 24120
Transaction-end
```

  - Once this has committed to the disk then overwrite the real data
  - If all goes well, we don’t need this transaction entry
  - If a crash happens any time after the log was committed
    - Replay the log on reboot (redo logging)
- This is called *full data journaling*

Writing the journal

- Writing the journal all at once would be great but is risky
  - We don’t know what order the disk will schedule the block writes
  - Don’t want to risk having a “transaction-end” written while the contents of the transaction have not been written yet
  - Write all blocks *except* transaction-end
  - Then write transaction-end
- If the log is replayed and a transaction-end is missing, ignore the log entry

Cost of journaling

- We're writing everything twice

  …and constantly seeking to the journal area of the disk

- Optimization
  - Do not write user data to the journal
  - Metadata journaling (also called ordered journaling)

```
Transaction-begin
  New inode 779
  New block bitmap, group 4
Transaction-end
```

- What about the data?
  - Write it to the disk first (not in the journal)
  - Then mark the end of the transaction
  - This prevents pointing to garbage after a crash and journal replay

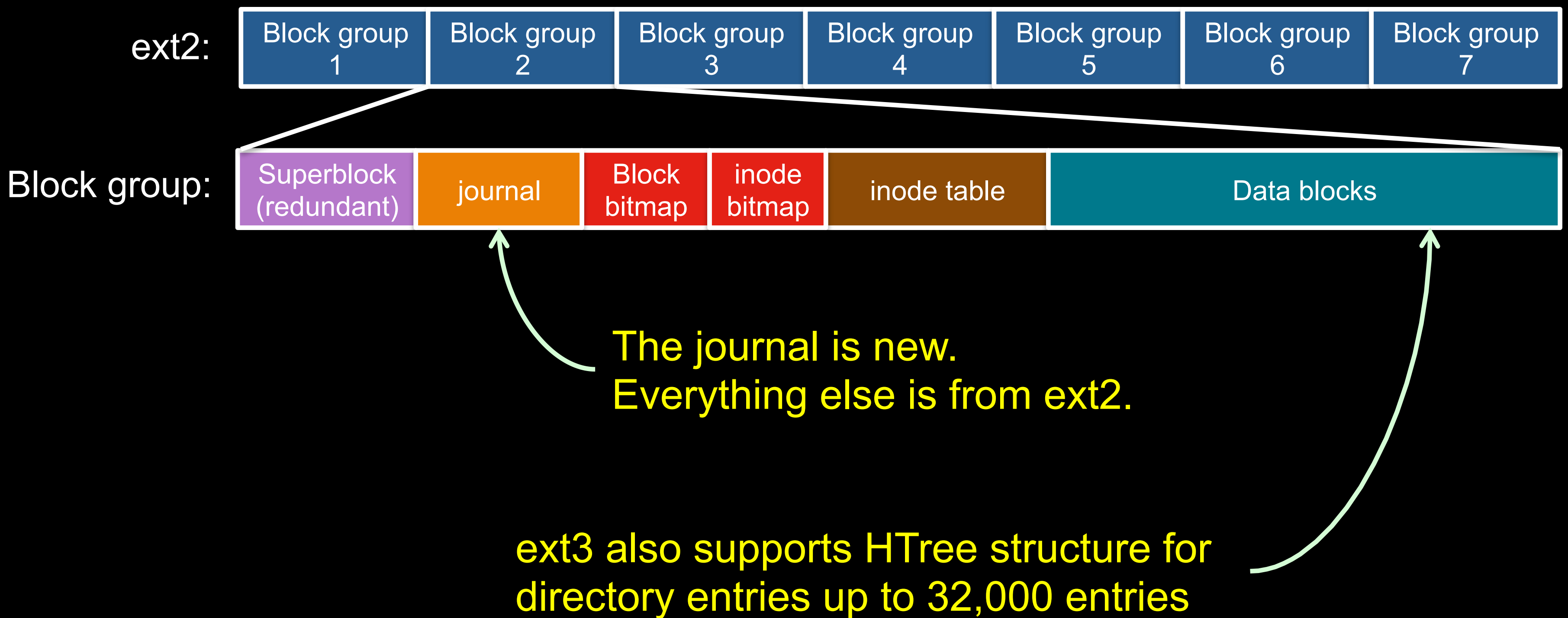
Linux ext3

- ext3 = ext2 + journaling (mostly)
- Goal: improved fault recovery
  - Reduce the time spent in checking file system consistency & repairing the file system

ext3 journaling options

- journal
  - full data + metadata journaling
  - [slowest]
- ordered
  - Data blocks written first, then metadata journaling
  - Write a transaction-end only when the other writes have completed
- writeback
  - Metadata journaling with no ordering of data blocks
  - Recent files can get corrupted after a crash
  - [fastest]

ext3 layout



ext2:
Block group 1
Block group 2
Block group 3
Block group 4
Block group 5
Block group 6
Block group 7
Block group:
Superblock (redundant)
journal
Block bitmap
inode bitmap
inode table
Data blocks
The journal is new.
Everything else is from ext2.
ext3 also supports HTree structure for directory entries up to 32,000 entries

Linux ext4: extensions to ext3

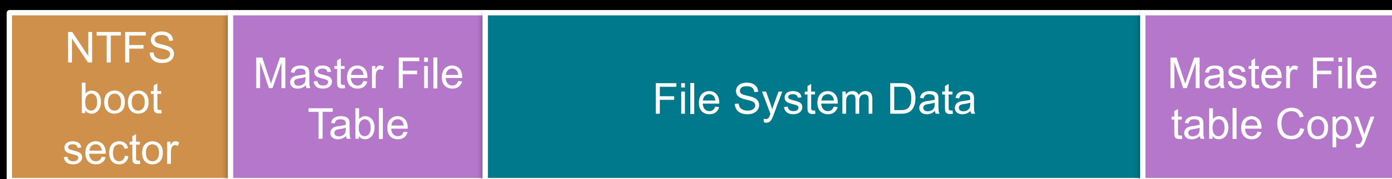
- Large file system support
  - 1 exabyte (10^{18} bytes); file sizes to 16 TB
- Extents used instead of block maps
  - Range of contiguous blocks
  - 1 extent can map up to 12 MB of space (4 KB block size)
  - 4 extents per inode. Additional ones are stored in an HTree (constant-depth tree similar to a B-tree)
- Ability to pre-allocate space for files
  - Increase chance that it will be contiguous
- Delayed allocation
  - Allocate on flush – only when data is written to disk
  - Improve block allocation decisions because we know the size

Linux ext4: extensions to ext3

- Over 64,000 directory entries (vs. 32,000 in ext3)
  - HTree structure
- Journal checksums
  - Monitor journal corruption
- Faster file system checking
  - Ignore unallocated block groups
- Interface for multiple-block allocations
  - Increase contiguous storage
- Timestamps in nanoseconds

Microsoft NTFS

- Standard file system for Windows; successor to FAT-32
- 64-bit volume sizes, journaling, and data compression
- Cluster-based (file compression not supported on clusters > 4 KB)



Boot Sector: info about layout of the volume & FS structures; Windows bootloader

MFT: contains information about all files in the file system

File system data: all the data that is not in the MFT

MFT Copy: copy of critical part of MFT for recovery (first 4 records)

NTFS Master File Table

- The MFT is itself a file (starting at a well-known place)
- It contains file records (inode) for all files, including itself
  - B-Tree structure
- MFT Special files:

MFT record 0	$Mft	Master file table
MFT record 1	$MftMirr	Duplicate of 1st 4 records of MFT
MFT record 2	$LogFile	Metadata journal for recovery
MFT record 3	$Volume	Info about the file system volume
MFT record 4	$AttrDef	Attribute definitions
MFT record 5		Root folder
MFT record 6	$Bitmap	Cluster bitmap (free/used clusters)

And a few more less interesting ones…

- Because the Bitmap is just a file, the volume bitmap is a file, the size of a volume can be easily expanded

NTFS MFT & Attributes

- MFT can grow just like any other file
  - To minimize fragmentation, 12.5% of the volume is reserved for use by the MFT ("MFT Zone")
- Each file record is 1, 2, or 4 KB (determined at FS initialization)
- File record info: set of typed attributes
  - Some attributes may have multiple instances (e.g., name & MS-DOS name)
  - Resident attributes: attributes that fit in the MFT record
  - If the attributes take up too much space, additional clusters are allocated
    - an "Attribute List" attribute is added
    - Describes location of all other file records
    - Attributes stored outside of the MFT record are Nonresident attributes

NTFS File Data

- File data is an attribute
  - NTFS supports multiple data attributes per file
  - One main, unnamed stream associated with a data file; other named streams are possible
  - Manage related data as a single unit
- Small folders and small data files can fit entirely within the MFT.
  - Large folders are B-tree structures and point to external clusters
- Block allocation: via extents

Microsoft NTFS

- Directories
  - Stored as B+ trees in alphabetic order
  - Name, MFT location, size of file, last access & modification times
  - Size & times are duplicated in the file record & directory entry
    - Designed top optimize some directory listings
- Write-ahead logging
  - Writes planned changes to the log, then writes the blocks
- Transparent data compression of files
  - Method 1: compress long ranges of zero-filled data by not allocating them to blocks (sparse files)
  - Method 2: break file into 16-block chunks
    - Compress each chunk
    - If at least one block is not saved then do not compress the chunk

The next generation: ReFS for Windows 8

- ReFS = Resilient File System
- Goals
  - Verify & auto-correct data; checksums for metadata
  - Optimize for extreme scale
  - Never take the file system offline – even in case of corruption
  - Allocate-on-write transactional model
  - Shared storage pools for fault tolerance & load balancing
  - Data striping for performance; redundancy for fault tolerance
- General approach
  - Use B+ trees to represent all information on the disk
    - "Table" interface for enumerable sets of key-value pairs
  - Provide a generic key-value interface to implement files, directories, and all other structures

Log Structured File Systems

NAND flash memory

- Memory arranged in "pages" – similar to disk sectors
  - Unit of allocation and programming
  - Individual bytes cannot be written
- Conventional file systems
  - Modify the same blocks over and over
  - At odds with NAND flash performance
  - Also, optimizations for seek time are useless
- Limited erase-write cycles
  - 100,000 to 1,000,000 cycles
  - Employ wear leveling to distribute writes among all (most) blocks
  - Bad block "retirement"
- Options:
  - Managed NAND = NAND flash + integrated controller
    - Handles block mapping
    - Can use conventional file systems
  - OS file system software optimized for Flash

Dynamic wear leveling

- Dynamic wear leveling
  - Monitors high- and low-use areas of the memory
    - At a certain point it will swap high-use blocks with low-use ones
  - Map logical block addresses to flash memory block addresses
  - When a block of data is written to flash memory, it is written to a new location and the map is updated
  - Blocks that are never modified will not get reused

- Static wear leveling
  - Static data is moved periodically to give all blocks a chance to wear evenly

File systems designed for wear leveling

- YAFFS2 and JFFS2
  - YAFFS is favored for disks > 64 MB
    - File system of choice for Android
  - JFFS is favored for smaller disks
    - Typically used in embedded systems
  - Only address dynamic wear leveling

YAFFS

- Unit of allocation = “chunk”
- Several (32 – 128+) chunks = 1 block
  - Unit of erasure for YAFFS
- Log structure: all updates written sequentially
  - Each log entry is 1 chunk in size:
    - *Data chunk*
    - or *Object header* (describes directory, file, link, etc.)
  - Sequence numbers are used to organize a log chronologically
  - Each chunk contains:
    - Object ID: object the chunk belongs to
    - Chunk ID: where the chunk belongs in the file
    - Byte count: # bytes of valid data in the chunk

YAFFS

Create a file

Chunk	ObjectId	ChunkID		
0	500	0	Live	Object header for file (length=0)
1				
2				
3				

Block 1

Adapted from http://www.yaffs.net/files/yaffs.net/HowYaffsWorks.pdf

YAFFS

Write some data to the file

Chunk	ObjectId	ChunkID		
0	500	0	Live	Object header for file (length=0)
1	500	1	Live	First chunk of data
2	500	2	Live	Second chunk of data
3	500	3	Live	Third chunk of data

Block 1

Adapted from http://www.yaffs.net/files/yaffs.net/HowYaffsWorks.pdf

YAFFS

Close the file: write new header

Chunk	ObjectId	ChunkID		
0	500	0	Deleted	Object header for file (length=0)
1	500	1	Live	First chunk of data
2	500	2	Live	Second chunk of data
3	500	3	Live	Third chunk of data

Block 1

0	500	0	Live	Object header for file (length=*n*)

Block 2

Adapted from http://www.yaffs.net/files/yaffs.net/HowYaffsWorks.pdf

YAFFS

Open file; modify first chunk; close file

Chunk	ObjectId	ChunkID			
0	500	0	Deleted	Object header for file (length=0)	Block 1
1	500	1	Deleted	First chunk of data	
2	500	2	Live	Second chunk of data	
3	500	3	Live	Third chunk of data	

0	500	0	Deleted	Object header for file (length=*n*)	Block 2
1	500	1	Live	New first chunk of data	
2	500	0	Live	New object header for file (length=*n*)	

Adapted from http://www.yaffs.net/files/yaffs.net/HowYaffsWorks.pdf

YAFFS Garbage Collection

- If all chunks in a block are deleted, the block can be erased & reused
- If blocks have some free chunks
  - We need to do garbage collection
  - Copy active chunks onto other blocks so we can free a block
    - Passive collection: pick blocks with few used chunks
    - Aggressive collection: try harder to consolidate chunks

YAFFS in-memory structures

- Construct file system state in memory
  - Map of in-use chunks
  - In-memory object state for each object
  - File tree/directory structure to locate objects
  - Scan the log backwards chronologically
    highest→lowest sequence number
  - Checkpointing: save the state of these structures at unmount time to speed up the next mount

YAFFS error detection/correction

- ECC used for error recovery
  - Correct 1 bad bit per 256 bytes
  - Detect 2 bad bits per 256 bytes
  - Bad blocks:
    if read or write fails, ask driver to mark the block as bad

JFFS1

- Log-structured file system
  - Nodes containing data & metadata are stored sequentially, progressing through the storage space: circular log
  - Node contains inode number, all metadata, and variable data
  - Each new node contains a version higher than a previous one
  - inode numbers are 32-bits; never reused
  - Old nodes (for data that is covered in later nodes) are "dirty space"
- On mount, the entire file system is scanned to rebuild the directory hierarchy
- Garbage collection: go through dirty space – find unneeded nodes and data blocks that are overwritten

JFFS2

- Keep linked lists representing individual erase blocks
  - Most of erase blocks will be on the *clean list* or *dirty list*
- Roughly 99/100 of the time, pick a block from the dirty list. Otherwise, pick a block from the clean list.
  - Optimize garbage collection to rese blocks which are partially obsolete
  - Move data sufficiently so that no one erase block will wear out before the others
- Node types
  - inode: inode metadata and possibly a range of data. Data may be compressed
  - Directory entry: inode number, name, and version
  - Clear marker: newly-erased block may be safely used for storage

JFFS2 mounting

- Physical medium is scanned & checked for validity
  - Raw node references are allocated, inode cache structures allocated
- First pass through physical nodes
  - Build full map of data for each inode (and detect obsolete nodes)
- Second pass
  - Find inodes that have no remaining links on the file system and delete them
- Third pass
  - Free temporary info that was cached for each node

The End