Operating Systems

14. File System Implementation

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Spring 2015

File System Implementation

File System Design Challenge

How do we organize a hierarchical file system on an array of blocks?

... and make it space efficient & fast?

Directory organization

- 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 complex structures: B-Tree, Htree
  - Balanced tree, constant depth
  - Great for huge directories

Block allocation: Contiguous

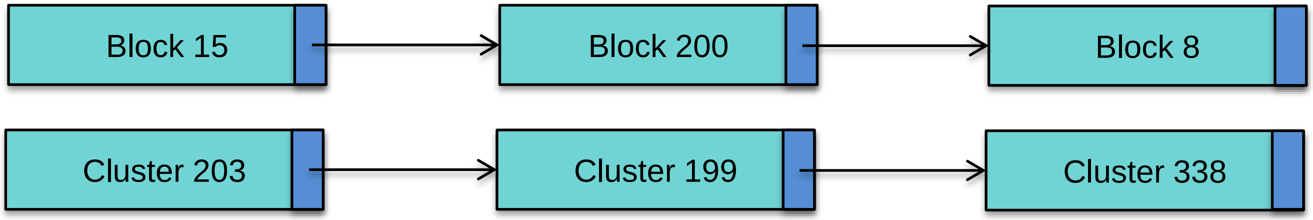
- Each file occupies a set of adjacent blocks
- You just need to know the starting block & file length
- We'd love to have contiguous storage for files!
  – Minimizes disk seeks when accessing a file

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 entire 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

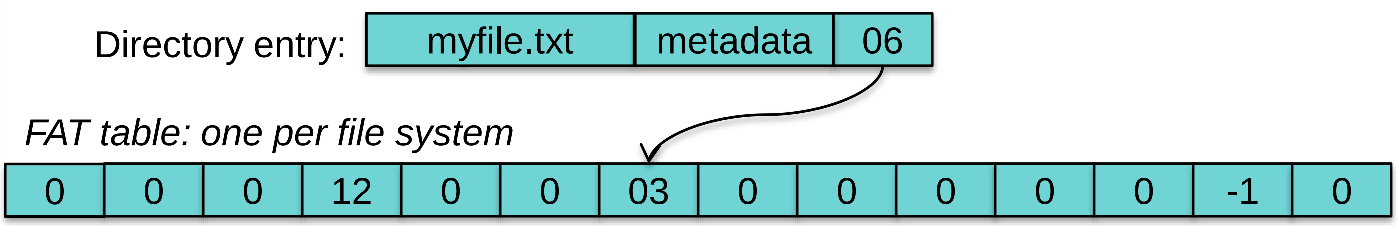
Block allocation: Linked Allocation

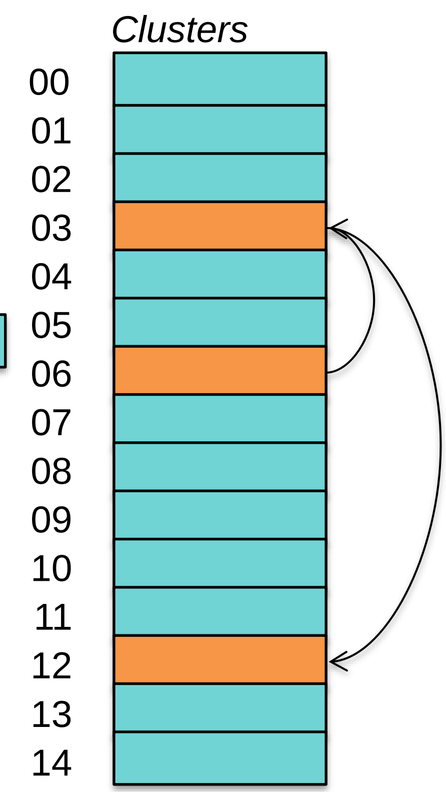
- A file's data is a linked list of disk blocks
  - Directory contains a pointer to the first block of the file
  - Each block contains a pointer to the next block
- Problems
  - Only good for sequential access
  - Each block uses space for the pointer to the next block
- Clusters
  - Multiples of blocks: 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.





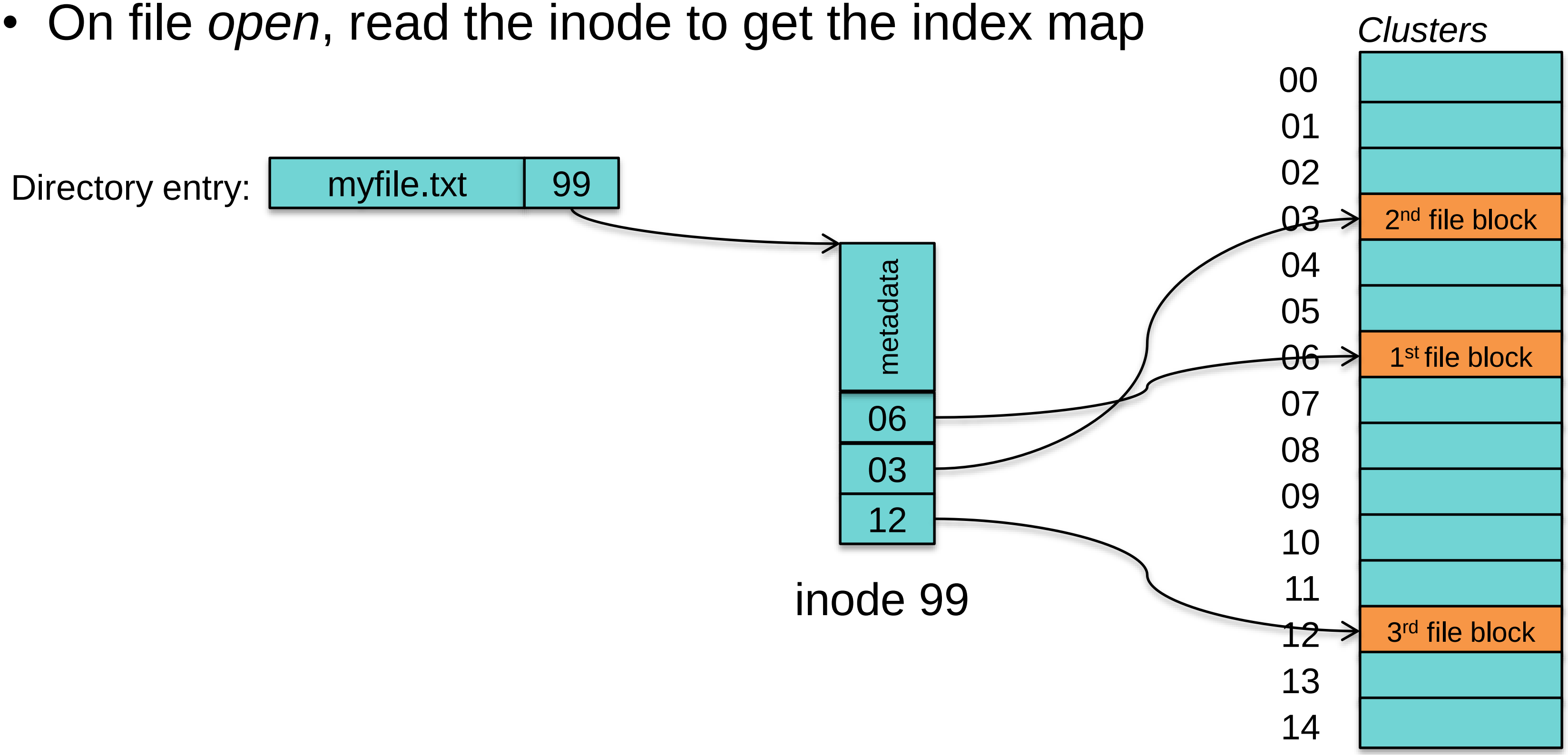
- FAT-16: 16-bit block pointers
  - 16-bit cluster numbers; up to 64 sectors/cluster
  - Max file system size = 2 GB (with 512 byte sectors)
- FAT-32: 32-bit block pointers
  - 32-bit cluster numbers; up to 64 sectors/cluster
  - Max file system size = 8 TB (with 512 byte sectors)
  - Max file size =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

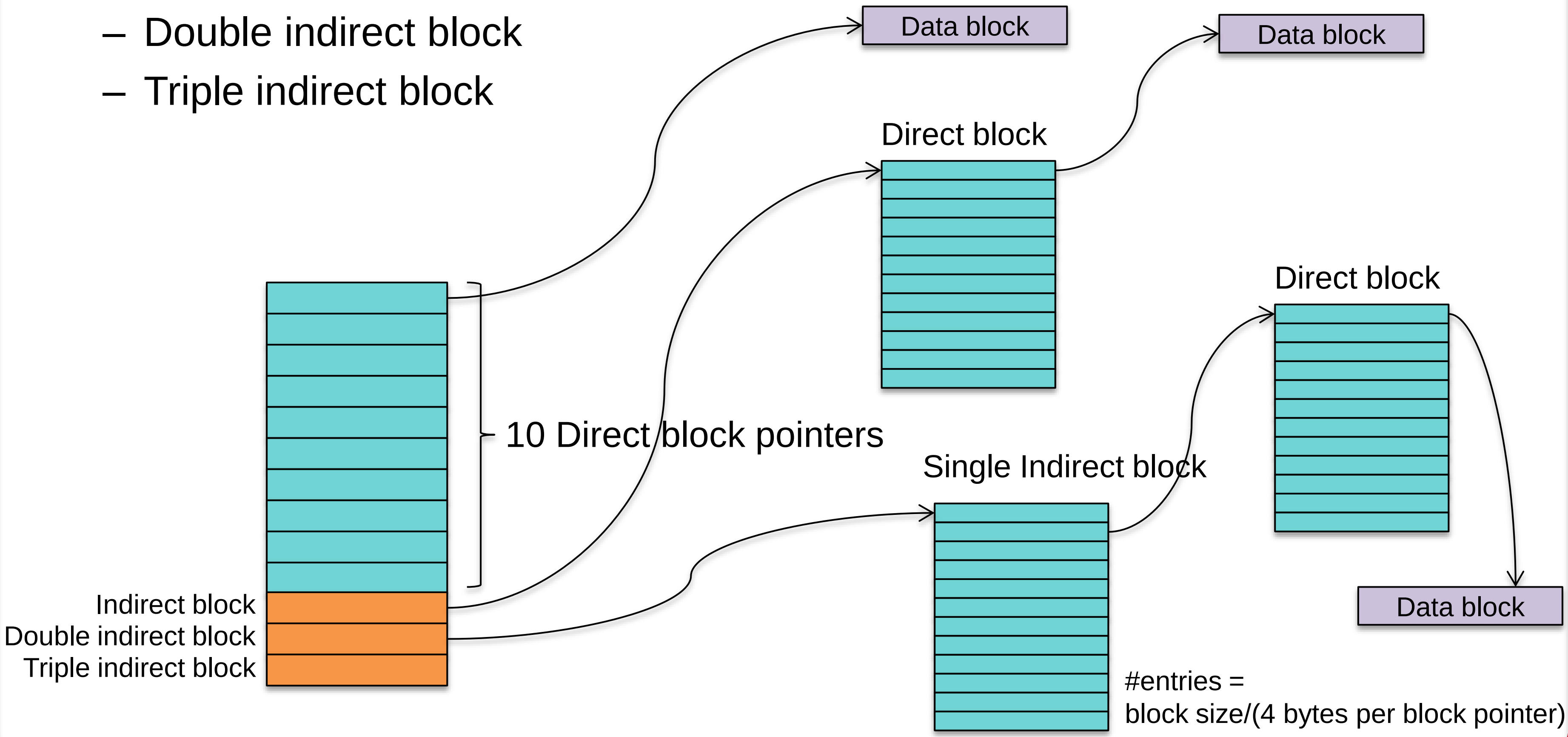
Indexed Allocation (block/cluster map)

- 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. Having these gives us direct access to 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

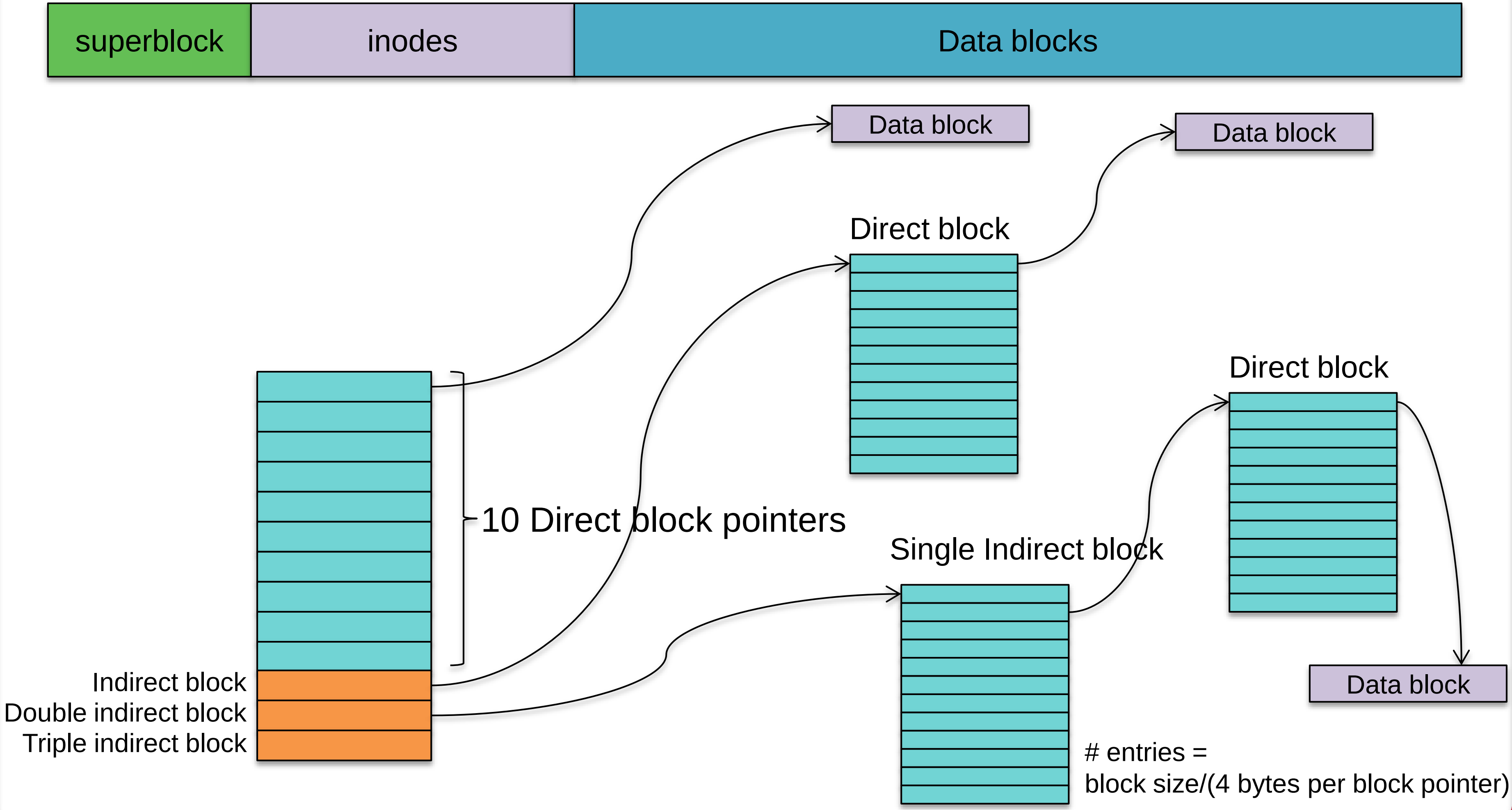
- Unix File System
  - 1024-byte blocks, 32-bit block pointers
  - inode contains
    - 10 direct blocks, 1 indirect, 1 double-indirect, 1 triple indirect
- Capacity
  - Direct blocks will address: 1K × 10 blocks = 10,240 bytes
  - 1 Indirect block: additional (1K/4)×1K = 256K bytes
  - 1 Double indirect block: additional (1K/4) × (1K/4) × 1K = 64M bytes
  - 1 Triple indirect block: additional (1K/4) × (1K/4) × (1K/4) × 1K = 16G bytes
  - Maximum file size = 10,240 + 256K + 64M + 16G =
    = 17247250432 bytes ≈ **16G 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?
  - Fewer 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

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:

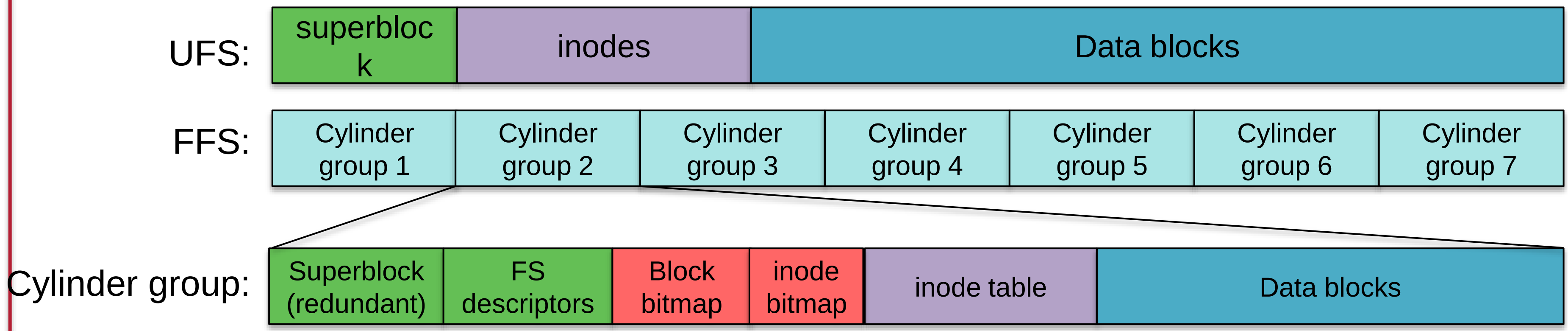
  2–4% of raw disk bandwidth!

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 – to get block # for and inode:

  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

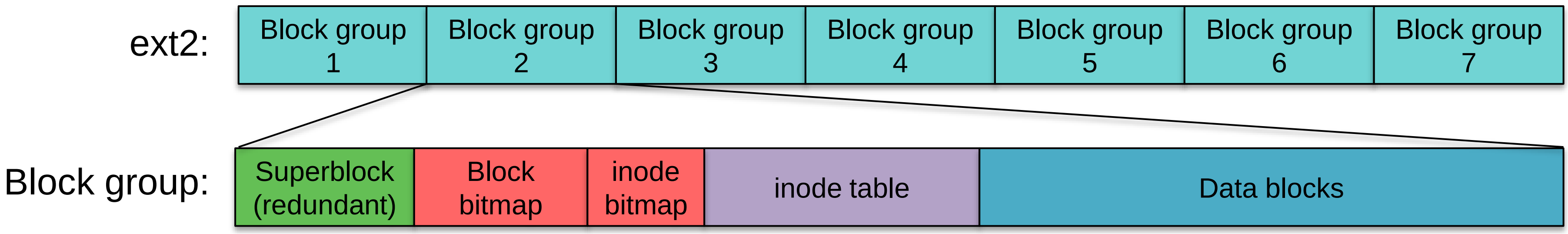
- Allocate data blocks that are close together
  - Pre-allocate up to 8 adjacent blocks when allocating a block
    - Achieves good performance under heavy loads
    - Speeds sequential reads
- Prefetch
  - If 2 or more logically sequential blocks are read
    - Assume sequential read and request one 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
  - All metadata writes are synchronous (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

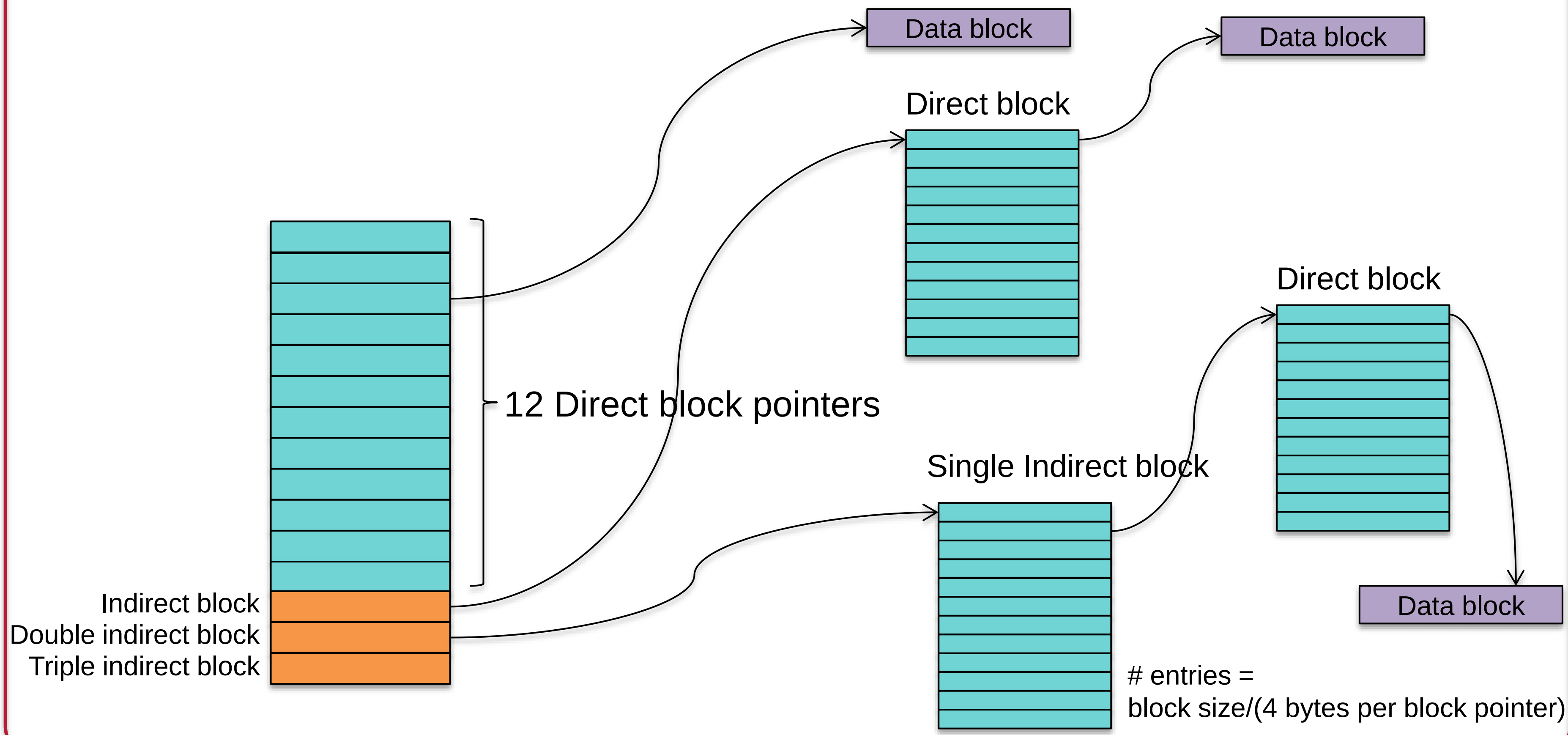
Linux ext2

- 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

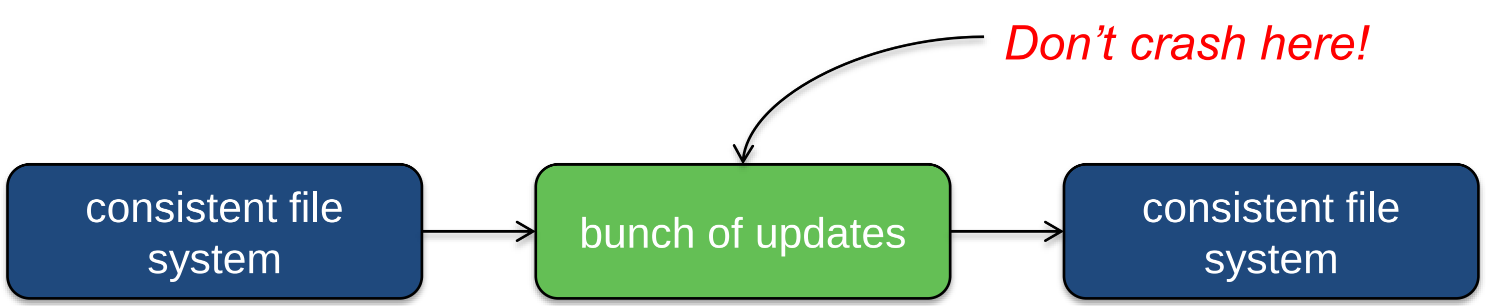
Journaling

Consistent Update Problem

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 *<u>all</u>* of these are not written, we have a file system inconsistency



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
  - Wait for the *writes* to complete
  - Then write transaction-end
- If the log is replayed and a transaction-end is missing, ignore the log entry

wait for writes to complete

```
jwrite("Transaction-begin")
jwrite("New inode 779")
jwrite("New block bitmap, group 4")
jwrite("New data block 24120")
```

```
jwrite("Transaction-end")
```

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

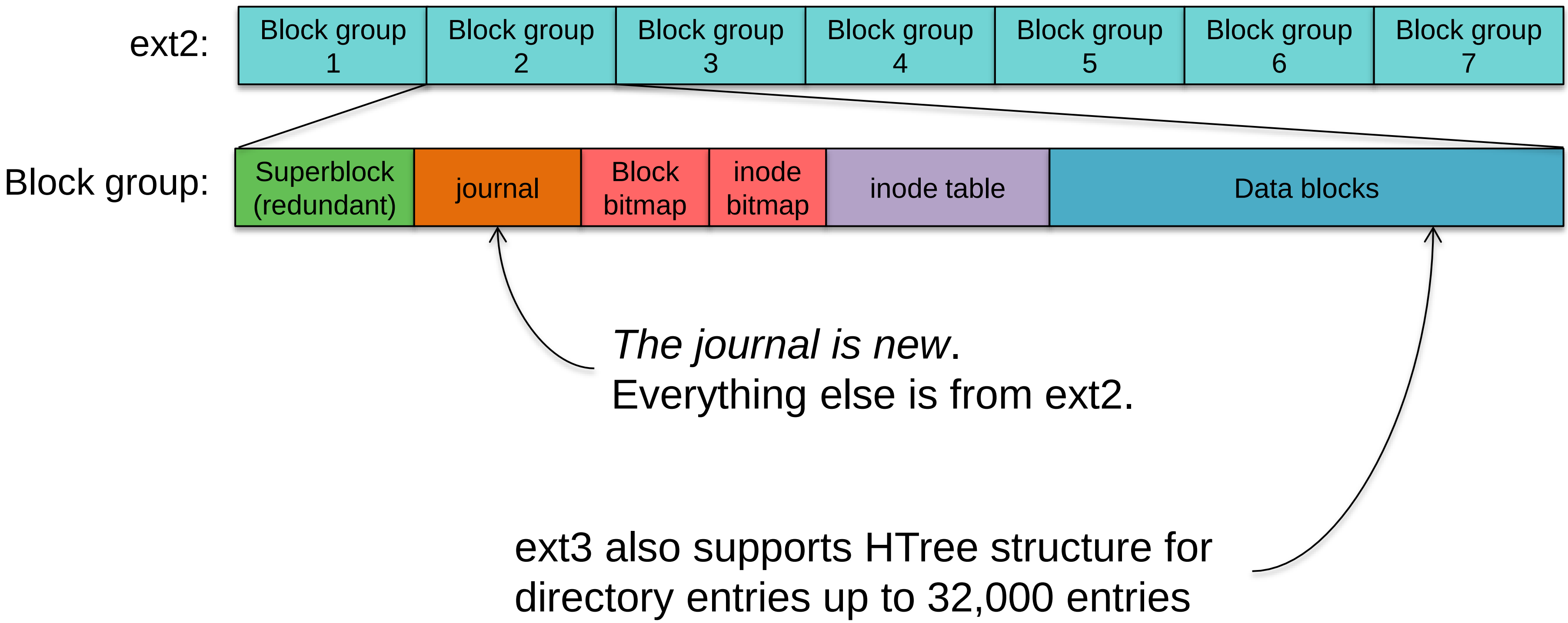
Linux ext3

- 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: less need for indirect blocks
  - 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

Latest MS file system: ReFS

- ReFS = Resilient File System for Windows Server 2012
- 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

The End