# Case study: ext2 FS

# The ext2 file system

it didn't deal with file system crashes very well. it has to run the file system checker if it wasn't cleanly shut down

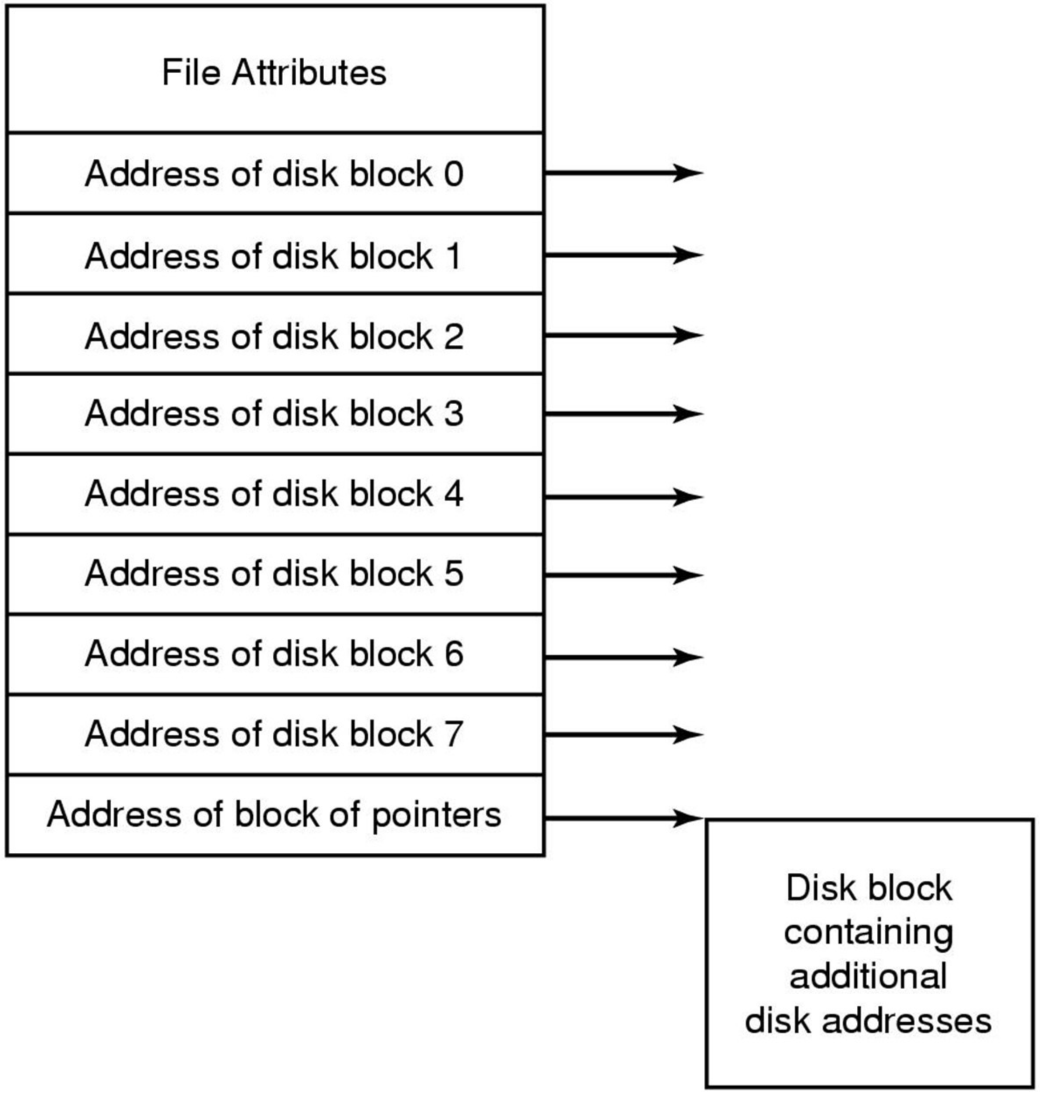
- Second Extended Filesystem
  - The main Linux FS before ext3
  - Evolved from Minix filesystem (via "Extended Filesystem")
- Features
  - Block size (1024, 2048, and 4096) configured at FS creation
  - inode-based FS
  - Performance optimisations to improve locality (from BSD FFS)
- Main Problem: unclean unmount →**`e2fsck`**
  - Ext3fs keeps a journal of (meta-data) updates
  - Journal is a file where updates are logged
  - Compatible with ext2fs

# Recap: i-nodes

access right, counting info,

- Each file is represented by an inode on disk
- Inode contains the fundamental file metadata
  - Access rights, owner, accounting info
  - (partial) block index table of a file
- Each inode has a unique number
  - System oriented name
  - Try ‘ls –i’ on Unix (Linux)
- Directories map file names to inode numbers
  - Map human-oriented to system-oriented names

# Recap: i-nodes



| |
|---|
| mode |
| uid |
| gid |
| atime |
| ctime |
| mtime |
| size |
| block count |
| reference count |
| direct blocks (12) |
| single indirect |
| double indirect |
| triple indirect |

# Ext2 i-nodes

- Mode
  - Type
    - Regular file or directory
  - Access mode
    - rwxrwxrwx
- Uid
  - User ID
- Gid
  - Group ID

| |
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# Inode Contents

- atime
  - Time of last access
- ctime
  - Time when file was created
- mtime
  - Time when file was last modified

# Inode Contents - Size

| |
|---|
| mode |
| uid |
| gid |
| atime |
| ctime |
| mtime |
| size |
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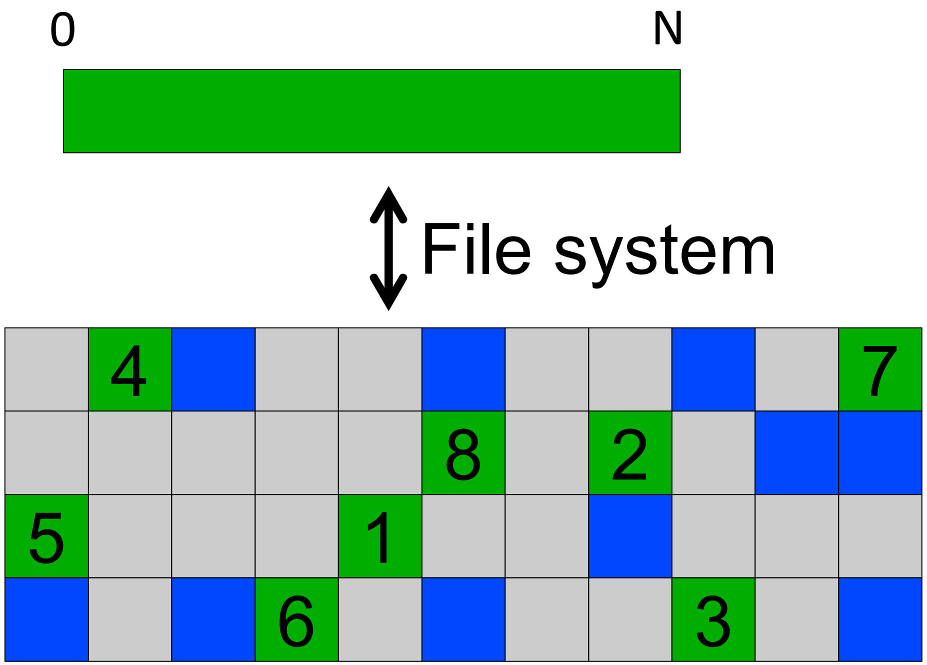
- What does ‘size of a file’ really mean?
  - The space consumed on disk?
    - With or without the metadata?
  - The number of bytes written to the file?
  - The highest byte written to the file?

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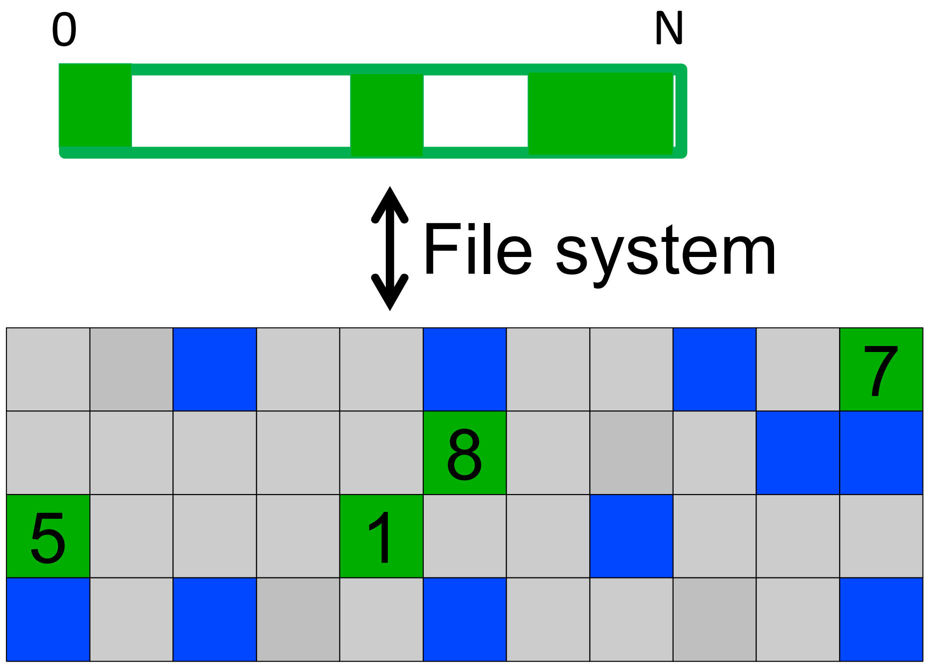

# Inode Contents - Size

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| gid |
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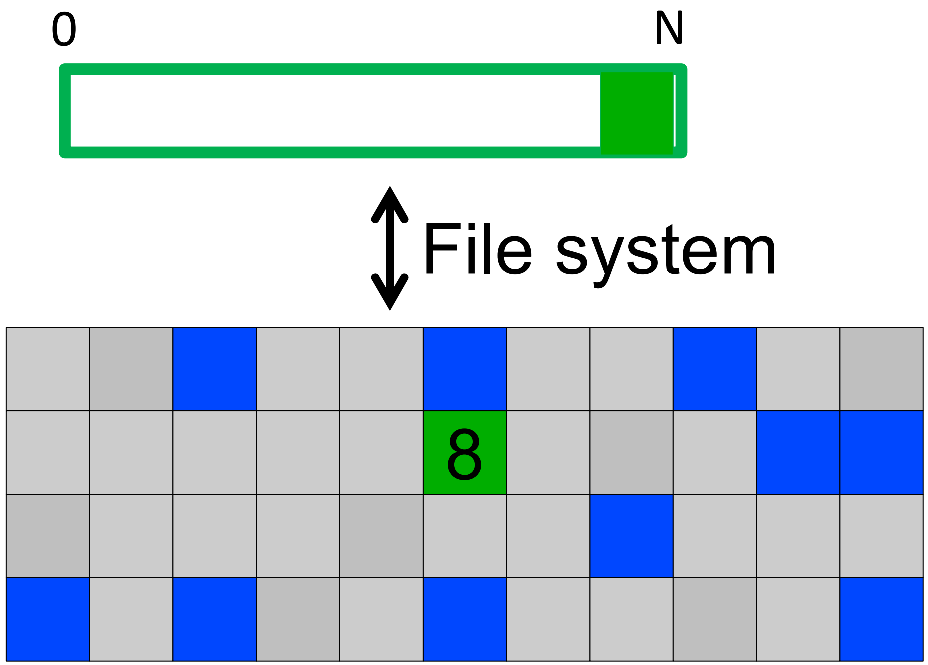


| | |
|---|---|
| | mode |
| | uid |
| | gid |
| access | atime |
| create | ctime |
| modify | mtime |
| | size |
| | block count |
| | reference count |
| | direct blocks (12) |
| | single indirect |
| | double indirect |
| | triple indirect |

# Inode Contents

- Size
  - Offset of the highest byte written
- Block count
  - Number of disk blocks used by the file.
  - Note that number of blocks can be much less than expected given the file size
- Files can be sparsely populated
  - E.g. write(f,“hello”); lseek(f, 1000000); write(f, “world”);
  - Only needs to store the start and end of file, not all the empty blocks in between.
  - Size = 1000005
  - Blocks = 2 + any indirect blocks

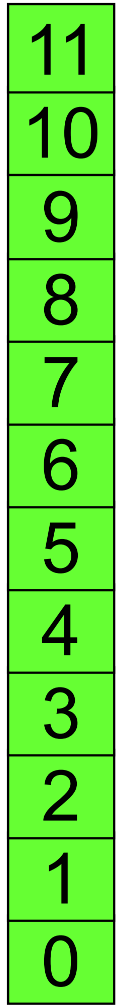
overheads, inode file meta data

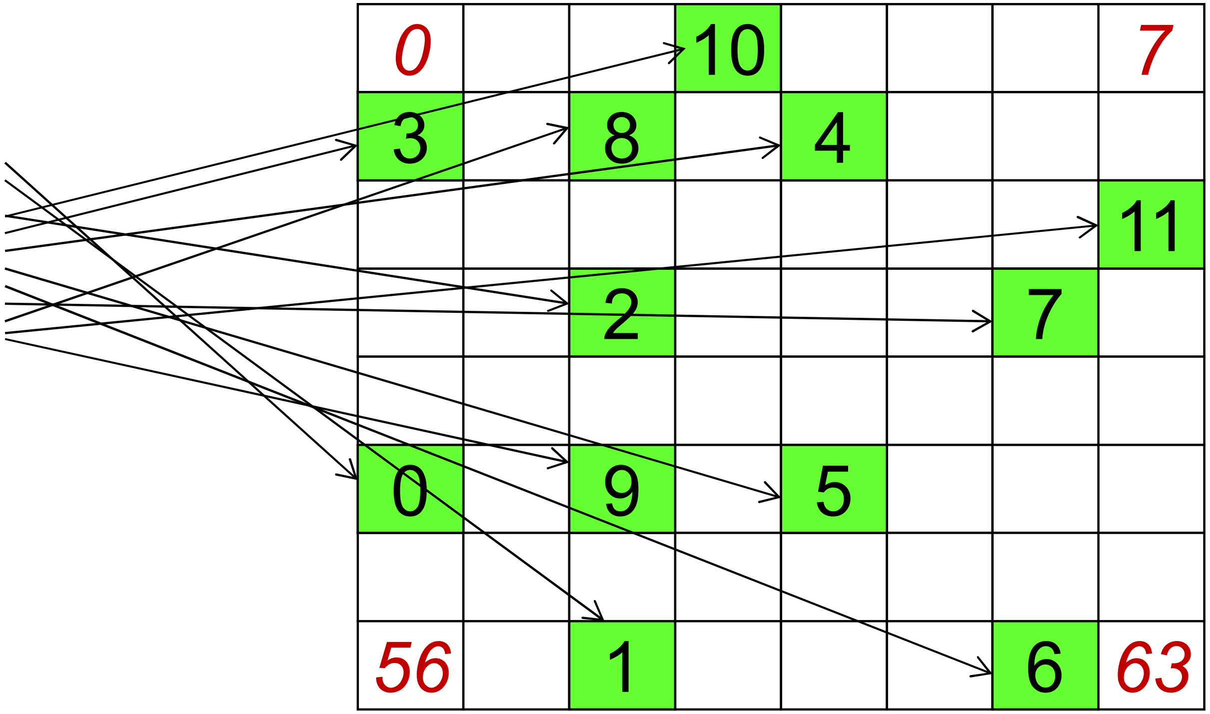
# Inode Contents

| |
|---|
| mode |
| uid |
| gid |
| atime |
| ctime |
| mtime |
| size |
| block count |
| reference count |
| direct blocks (12) 40,58,26,8,12, 44,62,30,10,42,3,21 |
| single indirect |
| double indirect |
| triple indirect |

- Direct Blocks
  - Block numbers of first 12 blocks in the file
  - Most files are small
    - We can find blocks of file *directly* from the inode

File




Disk

# Problem

- How do we store files with data at offsets greater than 12 blocks?
  - Adding significantly more direct entries in the inode results in many unused entries most of the time.

# Inode Contents

| |
|---|
| mode |
| uid |
| gid |
| atime |
| ctime |
| mtime |
| size |
| block count |
| reference count |
| direct blocks (12)<br>40,58,26,8,12,<br>44,62,30,10,42,3,21 |
| single indirect: 32 |
| double indirect |
| triple indirect |

- Single Indirect Block
  - Block number of a block containing block numbers

| |
|---|
| 28 |
| 29 |
| 38 |
| 46 |
| 61 |
| *43* |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *0* | | | 10 | | | | *7* |
| 3 | | 8 | | 4 | | | |
| | | | | | | | 11 |
| | | 2 | | 12 | 13 | 7 | |
| SI | | | | | 14 | | |
| 0 | | 9 | 17 | 5 | | 15 | |
| | | | | | | | |
| *56* | | 1 | | | 16 | 6 | *63* |

Disk

| |
|---|
| 17 |
| 16 |
| 15 |
| 14 |
| 13 |
| 12 |
| 11 |
| 10 |
| 9 |
| 8 |
| 7 |
| 6 |
| 5 |
| 4 |
| 3 |
| 2 |
| 1 |
| 0 |

# Single Indirection

- Requires two disk access to read
  - One for the indirect block; one for the target block
- Max File Size
  - Assume 1Kbyte block size, 4 byte block numbers

    12 * 1K + 1K/4 * 1K = 268 KiB
- For large majority of files (< 268 KiB), given the inode, only one or two further accesses required to read any block in file.

# Inode Contents

| |
|---|
| mode |
| uid |
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- Double Indirect Block
  - Block number of a block containing block numbers of blocks containing block numbers

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# Inode Contents

- Double Indirect Block
  - Block number of a block containing block numbers of blocks containing block numbers
- Triple Indirect
  - Block number of a block containing block numbers of blocks containing block numbers of blocks containing block numbers ☺

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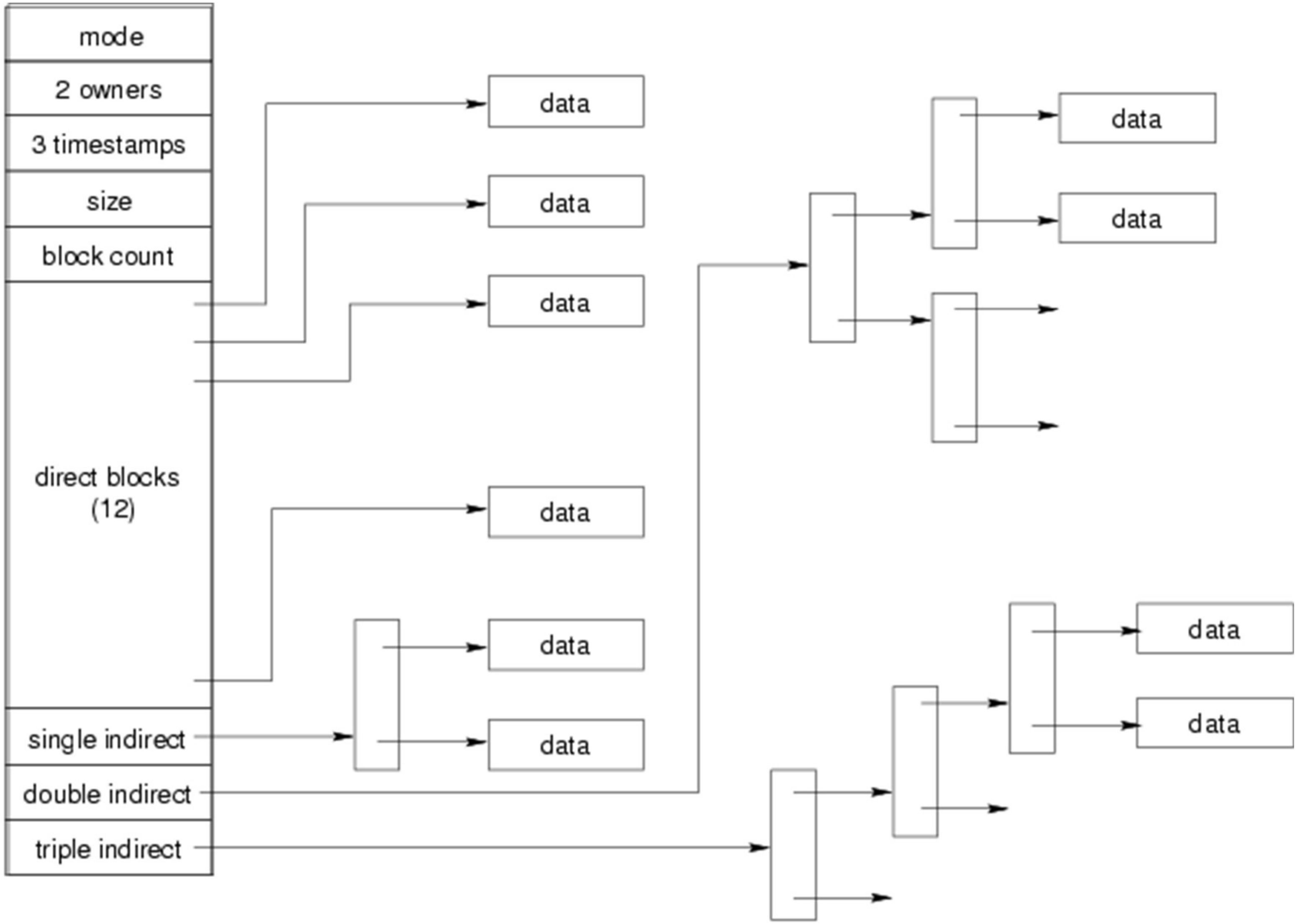
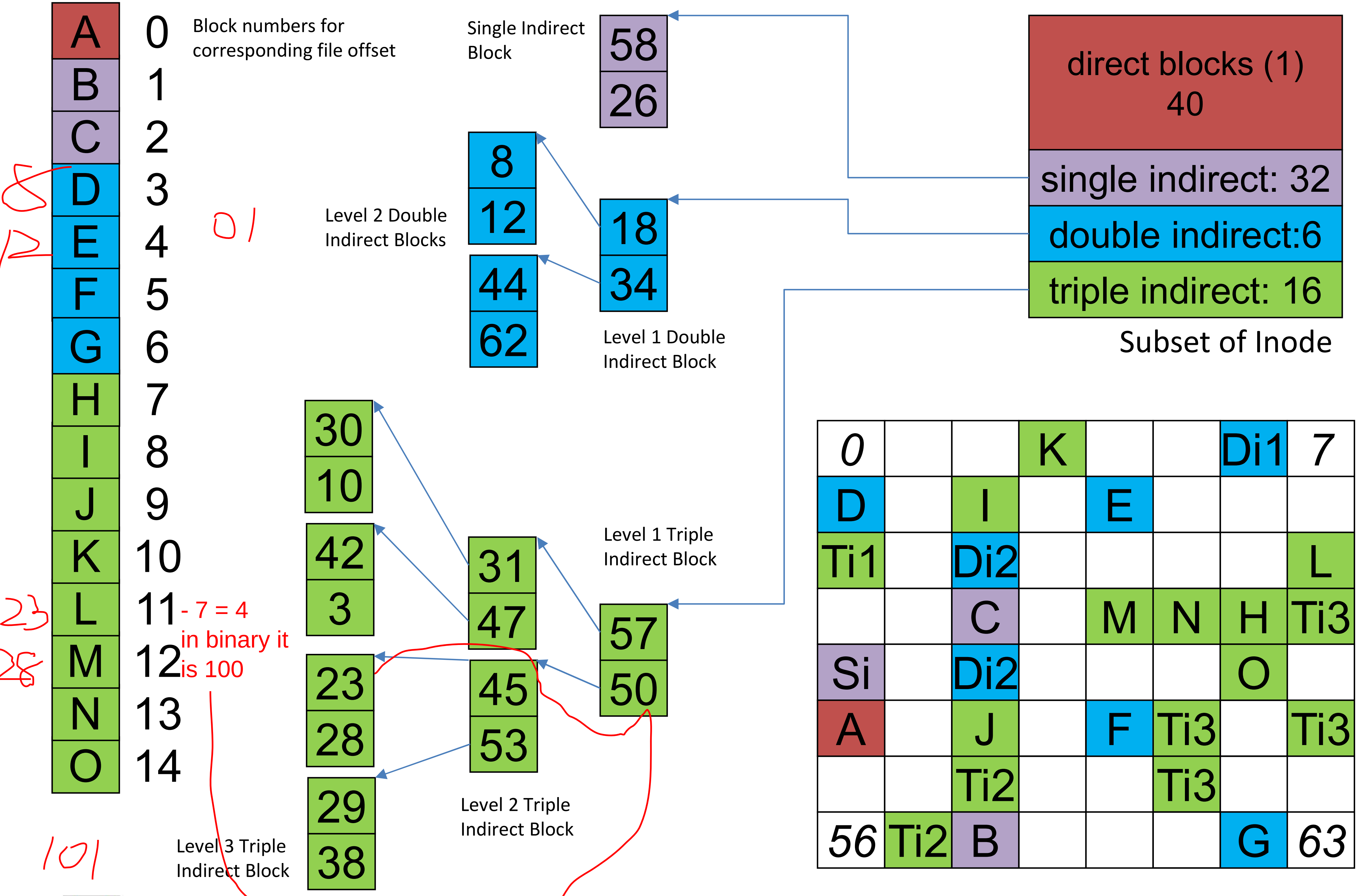
# UNIX Inode Block Addressing Scheme



# UNIX Inode Block Addressing Scheme

- Assume 8 byte blocks, containing 4 byte block numbers
- => each block can contain 2 block numbers (1-bit index)
- Assume a single direct block number in inode


A B C D E F G H I J K L M N O
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Block numbers for corresponding file offset
Single Indirect Block
58
26
direct blocks (1) 40
single indirect: 32
double indirect:6
triple indirect: 16
Subset of Inode
Level 2 Double Indirect Blocks
8
12
44
62
18
34
Level 1 Double Indirect Block
30
10
42
3
23
28
29
38
31
47
45
53
57
50
Level 1 Triple Indirect Block
Level 2 Triple Indirect Block
Level 3 Triple Indirect Block
0
K
Di1
7
D
I
E
Ti1
Di2
L
C
M
N
H
Ti3
Si
Di2
O
A
J
F
Ti3
Ti3
Ti2
Ti3
56
Ti2
B
G
63
- 7 = 4
in binary it is 100
01
101

Disk

# Max File Size

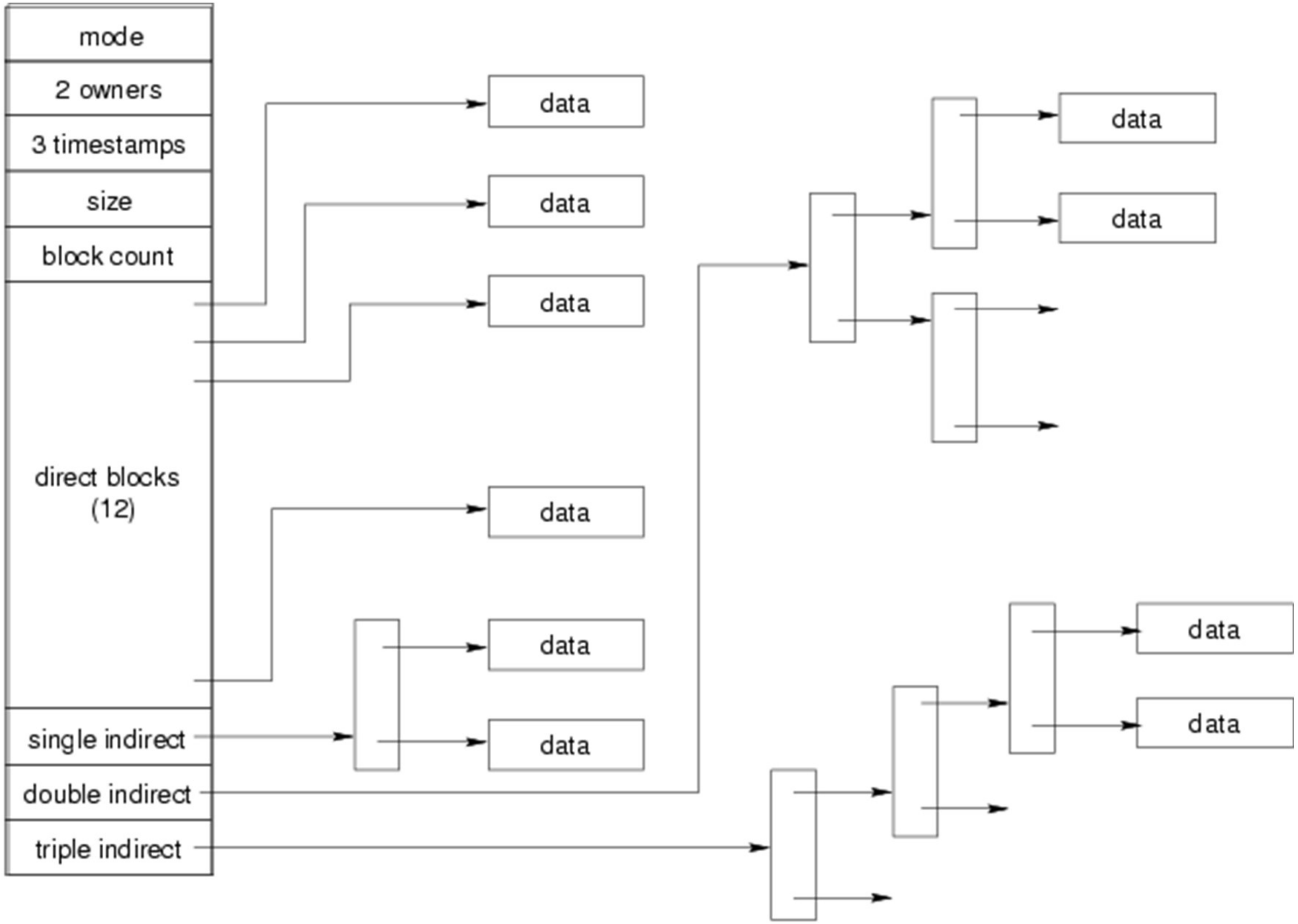
- Assume 4 bytes block numbers and 1K blocks
- The number of addressable blocks
  - Direct Blocks = 12
  - Single Indirect Blocks = 256 1k / 4 = 256
  - Double Indirect Blocks = 256 * 256 = 65536
  - Triple Indirect Blocks = 256 * 256 * 256 = 16777216
- Max File Size

  12 + 256 + 65536 + 16777216 = 16843020 blocks ≈ 16 GB

# Where is the data block number stored?

- Assume 4K blocks, 4 byte block numbers, 12 direct blocks
- A 1 byte file produced by
  - lseek(fd, 1048576, SEEK_SET) /* 1 megabyte */
  - write(fd, "x", 1)
- What if we add
  - lseek(fd, 5242880, SEEK_SET) /* 5 megabytes */
  - write(fd, "x", 1)

# Where is the block number is this tree?



# Solution?

4K blocks, 4 byte block numbers => 1024 block numbers in indirect blocks (10 bit index)

$1024 = 2^{10}$ ?

| Block # range | location |
|---|---|
| 0 ---11 | Direct blocks |
| 12 --- 1035 (11 + 1024) | Single-indirect blocks |
| 1036 --- 1049611 (1035 + 1024 * 1024) | Double-indirect blocks |
| 1049612 --- ???? | Triple-indirect blocks |

File (not to scale)

0 N

# Solution

1 Mega

Address = 1048576 ==>

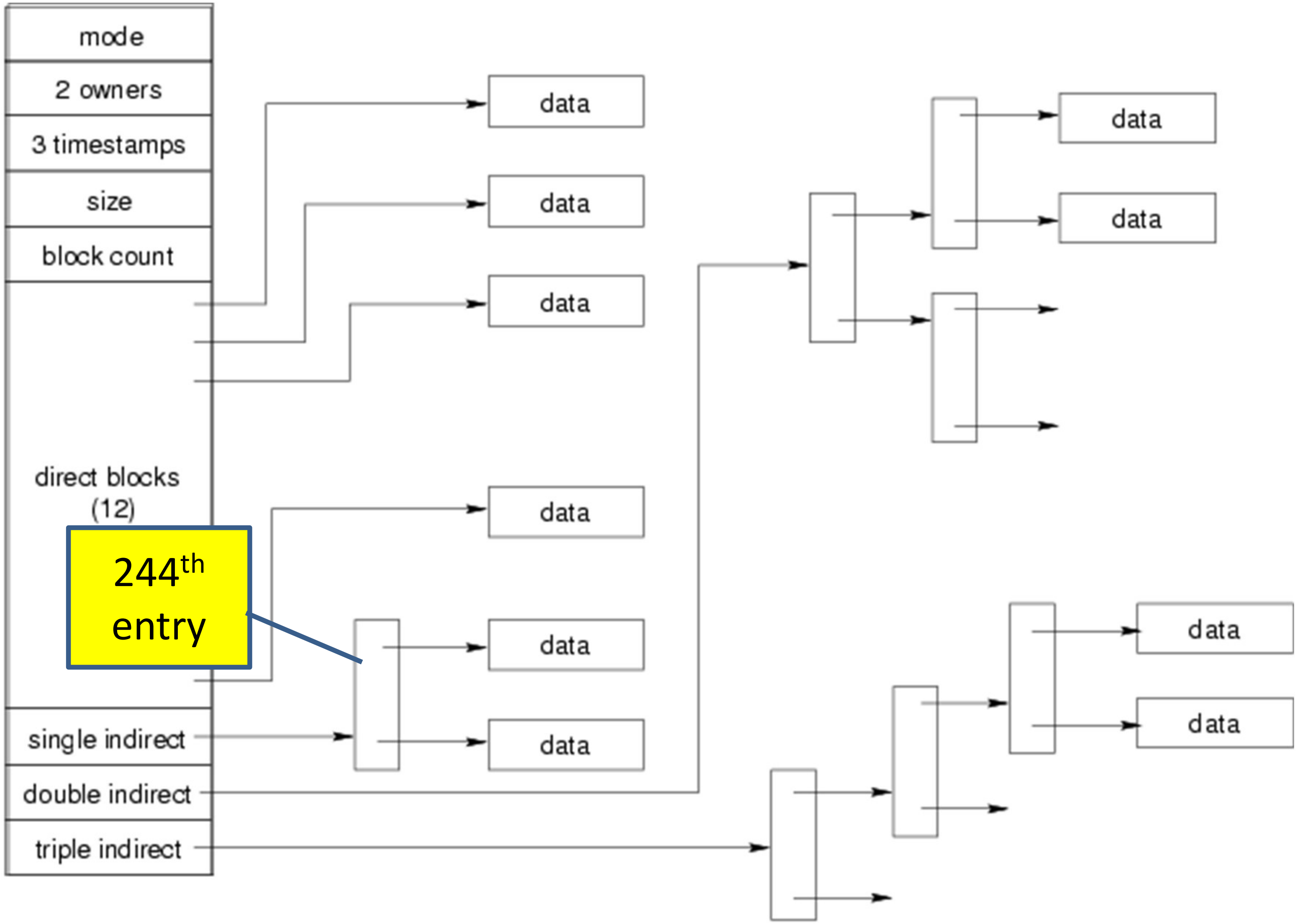
block number=1048576/4096=256

Single indirect offset = 256 – 12

= 244

| Block # range | location |
|---|---|
| 0 ---11 | Direct blocks |
| 12 --- 1035 ✓ | Single-indirect blocks |
| 1036 --- 1049611 ✓ | Double-indirect blocks |
| 1049612 --- ???? | Triple-indirect blocks |

# Where is the block number is this tree?



# Solution

Address = 5242880 ==>

Block number = 5242880/4096
=1280

Double indirect offset (20-bit)

= 1280 – 1036 base ?

= 244

Top 10 bits = 0

Lower 10 bits = 244

| Block # range | location |
|---|---|
| 0 ---11 | Direct blocks |
| 12 --- 1035 | Single-indirect blocks |
| 1036 --- 1049611 | Double-indirect blocks |
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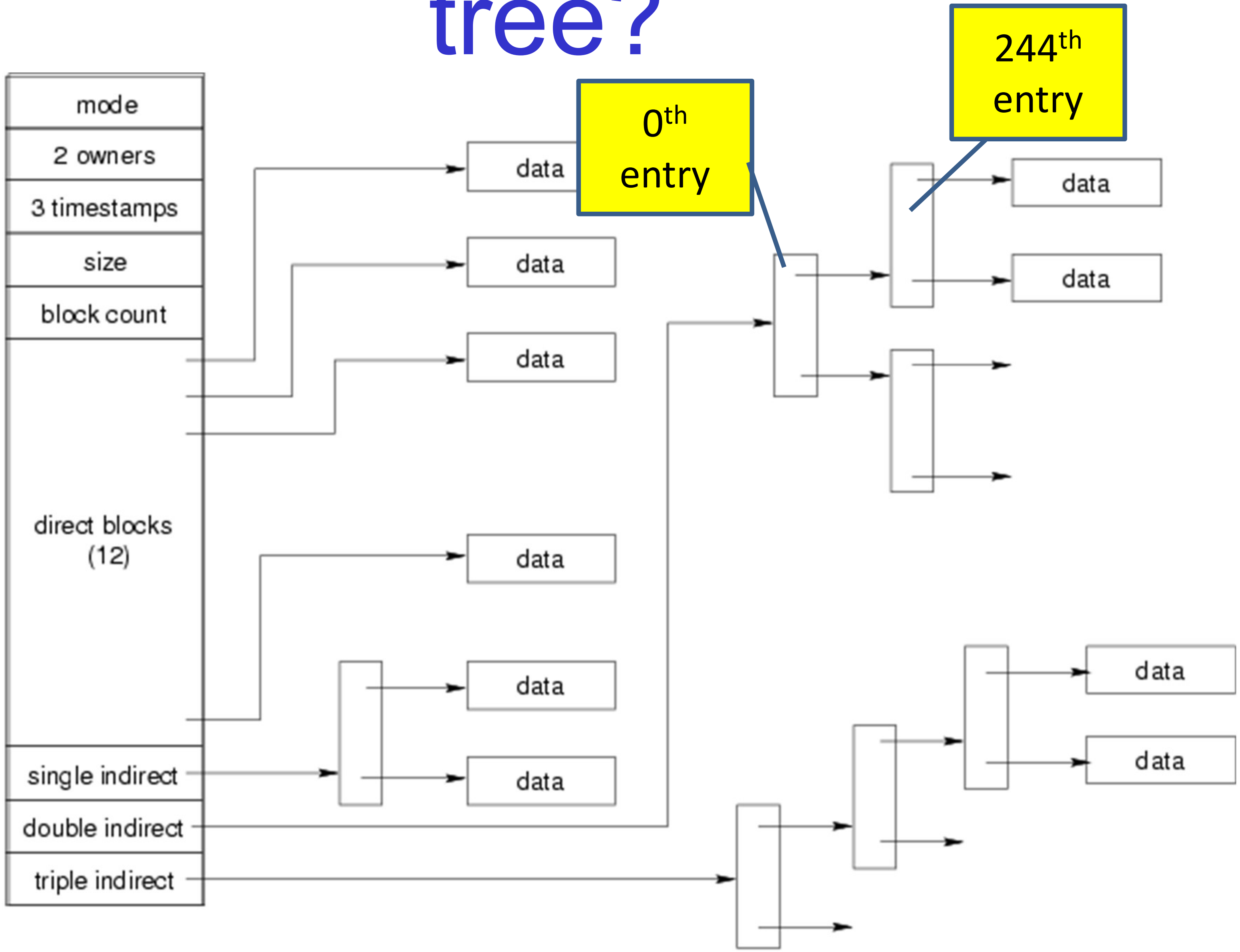
# Where is the block number is this tree?

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# Some Best and Worst Case Access Patterns

Assume Inode already in memory

- To read 1 byte
  - Best:
    - 1 access via direct block
  - Worst:
    - 4 accesses via the triple indirect block

the difference between read and write is that if a single block already has contents in it, we need to read it first, change it and write it back to disk.

- To write 1 byte
  - Best:
    - 1 write via direct block (with no previous content)
  - Worst:
    - 4 reads (to get previous contents of block via triple indirect) + 1 write (to write modified block back)

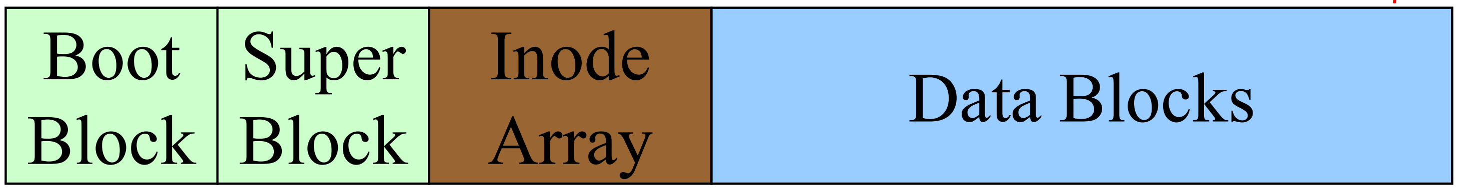
# Worst Case Access Patterns with Unallocated Indirect Blocks

- Worst to write 1 byte
  - 4 writes (3 indirect blocks; 1 data)
  - 1 read, 4 writes (read-write 1 indirect, write 2; write 1 data)
  - 2 reads, 3 writes (read 1 indirect, read-write 1 indirect, write 1; write 1 data)
  - 3 reads, 2 writes (read 2, read-write 1; write 1 data)
- Worst to read 1 byte
  - If reading writes a zero-filled block on disk
  - Worst case is same as write 1 byte
  - If not, worst-case depends on how deep is the current indirect block tree.

# Inode Summary

- The inode (and indirect blocks) contains the on-disk metadata associated with a file
  - Contains mode, owner, and other bookkeeping
  - Efficient random and sequential access via *indexed allocation*
  - Small files (the majority of files) require only a single access
  - Larger files require progressively more disk accesses for random access
    - Sequential access is still efficient
  - Can support really large files via increasing levels of indirection

# Where/How are Inodes Stored




if I put inode and data blocks they are far apart, the pointer has to move back and forth

- System V Disk Layout (s5fs)
  - Boot Block
    - contain code to bootstrap the OS
  - Super Block

    when you format the disk, you can format inode, size of blocks (formatter)
    - Contains attributes of the file system itself
    - e.g. size, number of inodes, start block of inode array, start of data block area, free inode list, free data block list
  - Inode Array
  - Data blocks

# Some problems with s5fs

- Inodes at start of disk; data blocks end
  - Long seek times
    - Must read inode before reading data blocks
- Only one superblock
  - Corrupt the superblock and entire file system is lost
- Block allocation was suboptimal
  - Consecutive free block list created at FS format time
    - Allocation and de-allocation eventually randomises the list resulting in random allocation
- Inode free list also randomised over time
  - Directory listing resulted in random inode access patterns

# Berkeley Fast Filesystem (FFS)

- Historically followed s5fs
  - Addressed many limitations with s5fs
  - ext2fs mostly similar

# Layout of an Ext2 FS

| Boot Block | Block Group 0 | …. | Block Group *n* |
|---|---|---|---|

- Partition:
  - –Reserved boot block,
  - –Collection of equally sized *block groups*
  - –All block groups have the same structure

# Layout of a Block Group

| Super Block | Group Descrip-tors | Data Block Bitmap | Inode Bitmap | Inode Table | Data blocks |
|---|---|---|---|---|---|
| 1 blk | *n* blks | 1 blk | 1 blk | *m* blks | *k* blks |

- *Replicated* super block
  - For e2fsck
- *Replicated* Group descriptors
- Bitmaps identify used inodes/blocks
- All block groups have the same number of data blocks
- Advantages of this structure:
  - Replication simplifies recovery
  - Proximity of inode tables and data blocks (reduces seek time)

# Superblocks

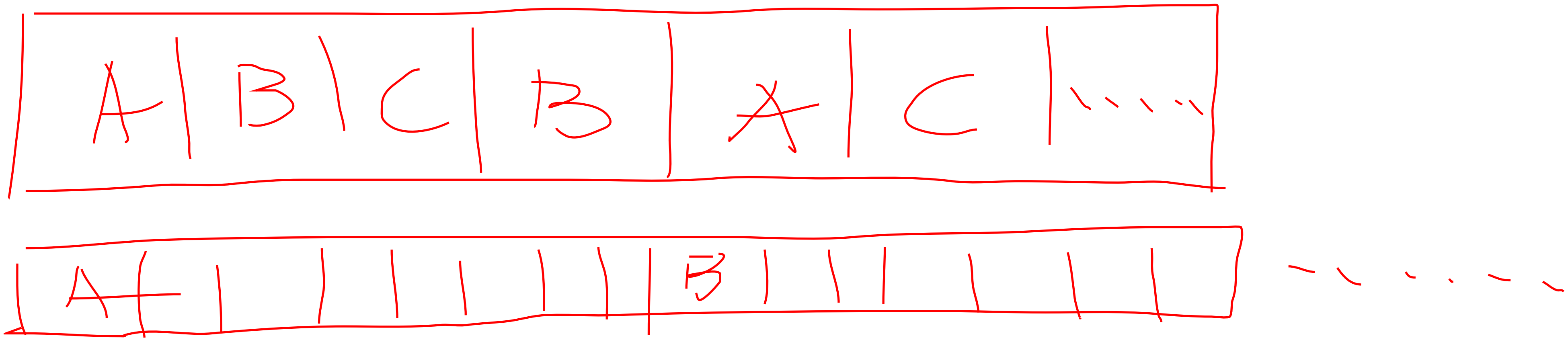
- Size of the file system, block size and similar parameters
- Overall free inode and block counters
- Data indicating whether file system check is needed:
  - Uncleanly unmounted
  - Inconsistency
  - Certain number of mounts since last check
  - Certain time expired since last check
- Replicated to provide redundancy to aid recoverability

# Group Descriptors

- Location of the bitmaps
- Counter for free blocks and inodes in this group
- Number of directories in the group
- Replicated to provide redundancy to aid recoverability

# Performance considerations

- EXT2 optimisations
  - Block groups cluster related inodes and data blocks
- –Pre-allocation of blocks on write (up to 8 blocks)
- •8 bits in bit tables
- •Better contiguity when there are concurrent writes
- –Aim to store files within a directory in the same group



# Thus far…

- Inodes representing files laid out on disk.
- Inodes are referred to by number!!!
  – How do users name files? By number?

# Ext2fs Directories

| inode | rec_len | name_len | type | name… |
|---|---|---|---|---|

- Directories are files of a special type
    - Consider it a file of special format, managed by the kernel, that uses most of the same machinery to implement it
        - Inodes, etc…
- Directories translate names to inode numbers
- Directory entries are of variable length
- Entries can be deleted in place
    - inode = 0 empty entry within the directory
    - Add to length of previous entry

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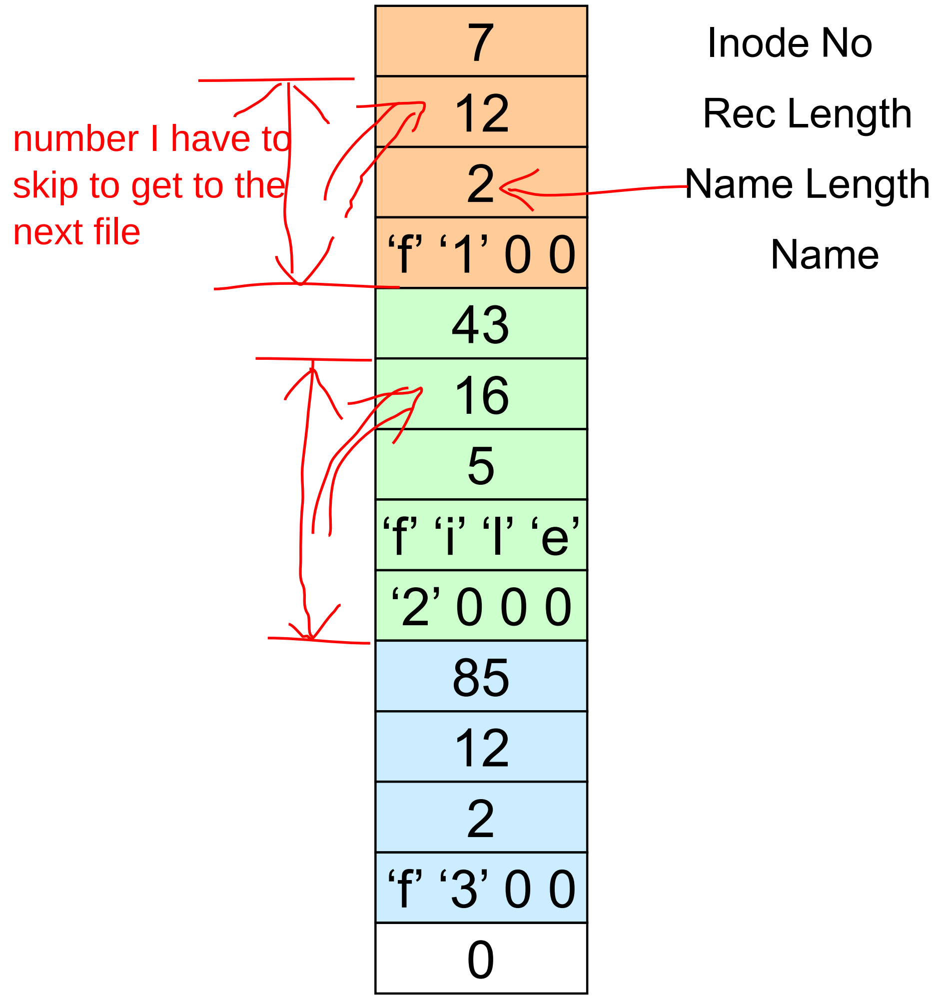
# Ext2fs Directories

- “f1” = inode 7
- “file2” = inode 43
- “f3” = inode 85



# Hard links

- Note that inodes can have more than one name
  - Called a *Hard Link*
  - Inode (file) 7 has three names
    - "f1" = inode 7
    - "file2" = inode 7
    - "f3" = inode 7

| | |
|---|---|
| 7 | Inode No |
| 12 | Rec Length |
| 2 | Name Length |
| 'f' '1' 0 0 | Name |
| 7 | |
| 16 | |
| 5 | |
| 'f' 'i' 'l' 'e' | |
| '2' 0 0 0 | |
| 7 | |
| 12 | |
| 2 | |
| 'f' '3' 0 0 | |
| 0 | |

| |
|---|
| mode |
| uid |
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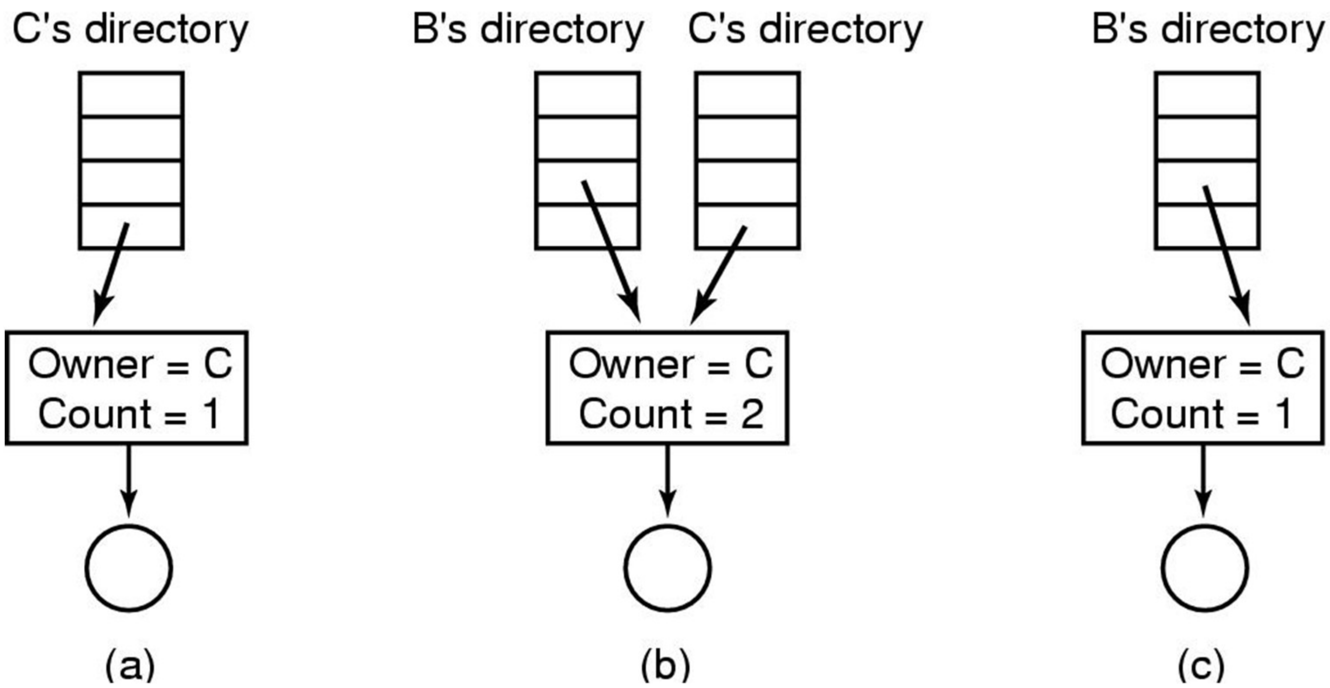
# Inode Contents

- We can have many names for the same inode.
- When we delete a file by name, i.e. remove the directory entry (link), how does the file system know when to delete the underlying inode?
  - Keep a *reference count* in the inode
    - Adding a name (directory entry) increments the count
    - Removing a name decrements the count
    - If the reference count == 0, then we have no names for the inode (it is unreachable), we can delete the inode (underlying file or directory)

# Hard links




(a) Situation prior to linking

(b) After the link is created

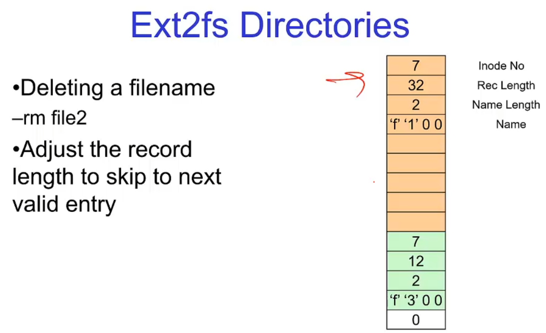
(c)After the original owner removes the file

you can only hard link when you are the root

# Symbolic links

/home/username is a symbolic link to the cse network file system

- A symbolic link is a file that contains a reference to another file or directory
  - Has its own inode and data block, which contains a path to the target file
  - Marked by a special file attribute
  - Transparent for some operations
  - Can point across FS boundaries




hard link refers to inode in the same file system, so it cannot across file system boundaries, for example, I can't create a hard link from local file to nfs partition

delete: adjust the record length to skip to next valid entry

# FS reliability

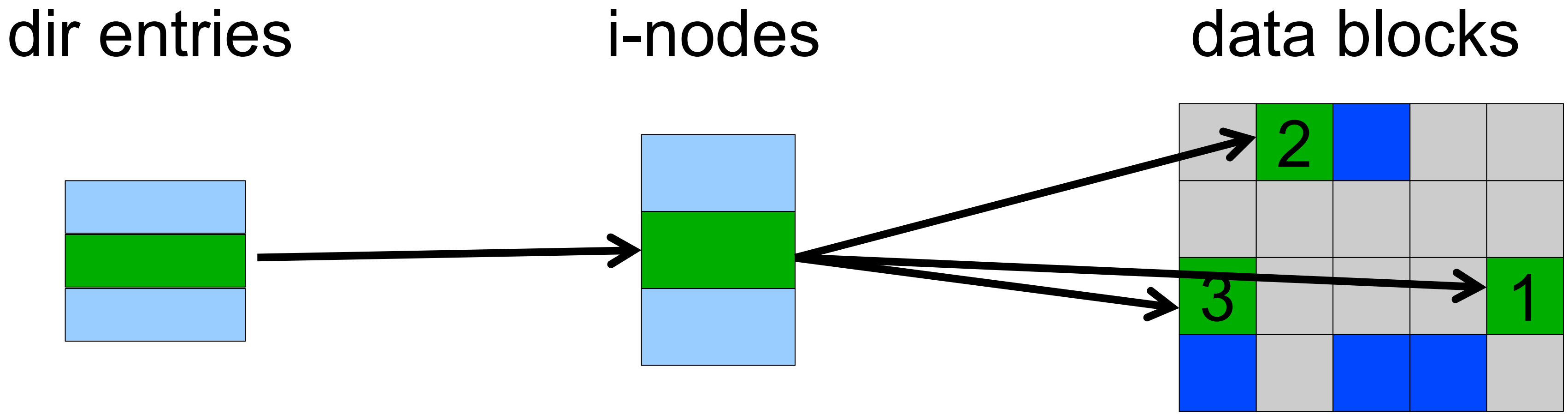
- Disk writes are buffered in RAM
  - OS crash or power outage ==> lost data
  - Commit writes to disk periodically (e.g., every 30 sec)

    strong consistency: database, usb write etc
  - Use the `sync` command to force a FS flush

    however, file system itself can be in a inconsistent state
- FS operations are non-atomic
  - Incomplete transaction can leave the FS in an inconsistent state

# FS reliability

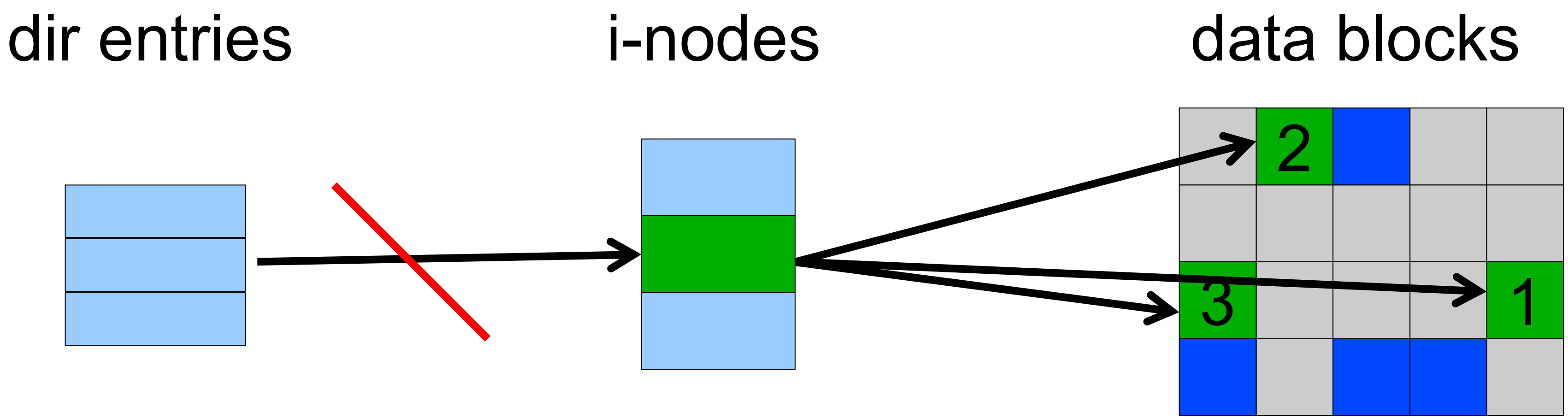
example of inconsistency




- Example: deleting a file
  1. Remove the directory entry
  2. Mark the i-node as free
  3. Mark disk blocks as free

if power outage at first step, we essentially lost access to our file because we don't have the directory entry anymore, but files and data blocks are still on our disk.
if we do the second step first, then files will be overwritten
if we do the third step first, it is still problematic, some other files may write over the data blocks owned by another file

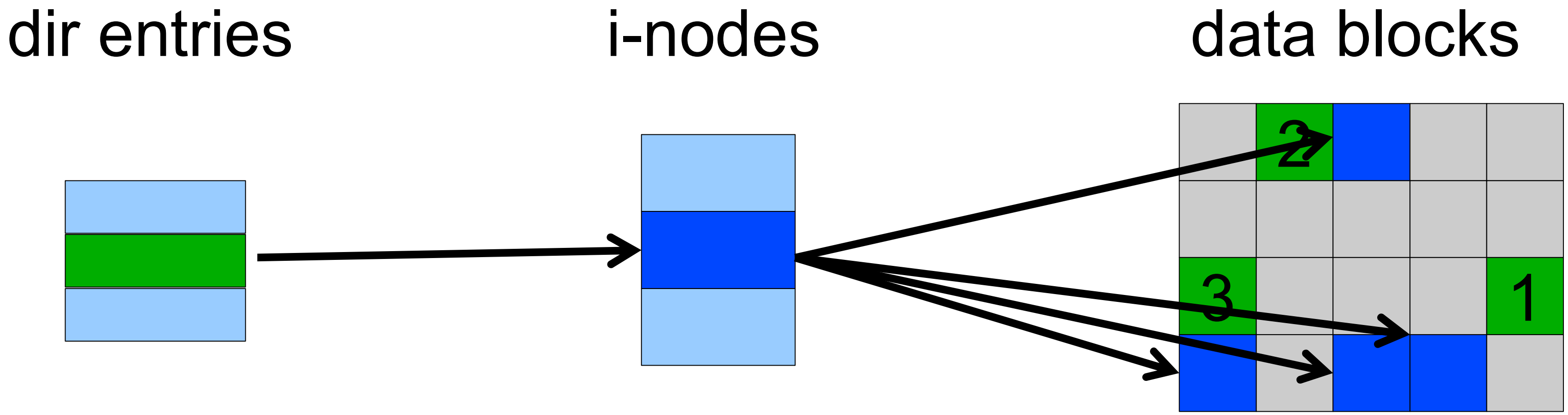
# FS reliability




- Example: deleting a file
  1. Remove the directory entry--> crash
  2. Mark the i-node as free
  3. Mark disk blocks as free

The i-node and data blocks are lost

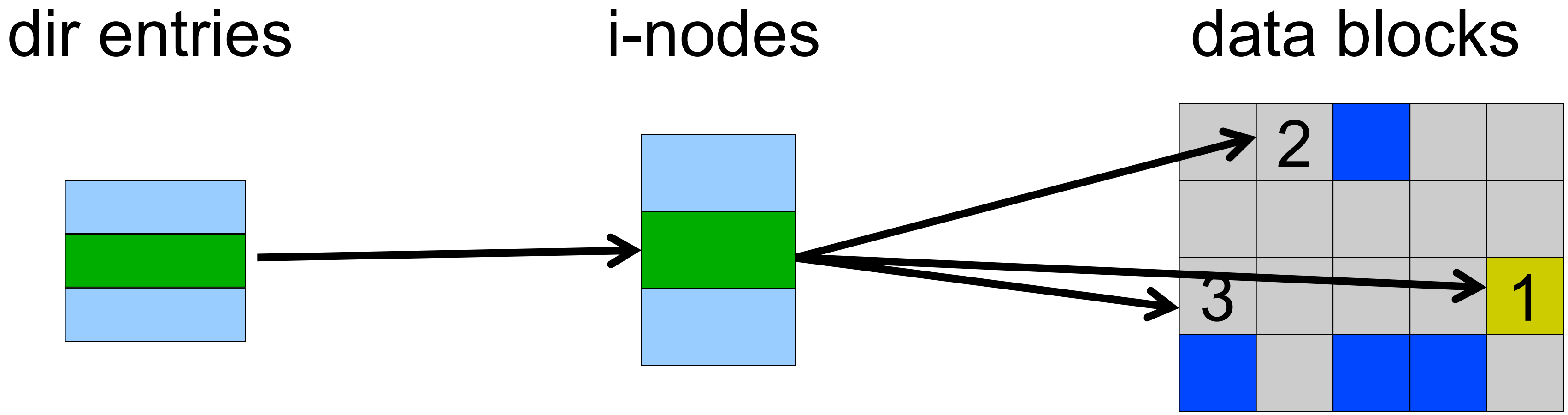
# FS reliability




- Example: deleting a file
  1. Mark the i-node as free --> crash
  2. Remove the directory entry
  3. Mark disk blocks as free

The dir entry points to the wrong file

# FS reliability




- Example: deleting a file
  1. Mark disk blocks as free --> crash
  2. Remove the directory entry
  3. Mark the i-node as free

The file randomly shares disk blocks with other files

# FS reliability

- e2fsck
  - Scans the disk after an unclean shutdown and attempts to restore FS invariants
- Journaling file systems
  - Keep a journal of FS updates
  - Before performing an atomic update sequence,
  - write it to the journal
  - Replay the last journal entries upon an unclean shutdown
  - Example: ext3fs