

Case study: ext2 FS

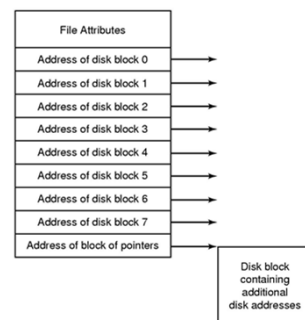
The ext2 file system

- 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

- 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 -li' on Unix (Linux)
- Directories map file names to inode numbers
 - Map human-oriented to system-oriented names

Recap: i-nodes



Ext2 i-nodes

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

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

Inode Contents

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

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

mode
uid
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atime
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mtime
size
block count
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single indirect
double indirect
triple indirect

Inode Contents - Size

- 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

- What does 'size of a file' really mean?
 - The space consumed on disk?
 - With or without the metadata?
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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 + overheads

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Inode Contents

- 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

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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.

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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: 32
- double indirect
- triple indirect

•Single Indirect Block
–Block number of a block containing block numbers

28	0			10				7
29	3	8		4				11
38	SI							
46	0	9	17	5		15		
61								
43	56	1				16	6	63

Disk

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
 $12 * 1K + 1K/4 * 1K = 268 \text{ KiB}$
- 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

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- ctime
- mtime
- size
- block count
- reference count
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40,58,26,8,12,
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•Double Indirect Block
–Block number of a block containing block numbers of blocks containing block numbers

Inode Contents

- mode
- uid
- gid
- atime
- ctime
- mtime
- size
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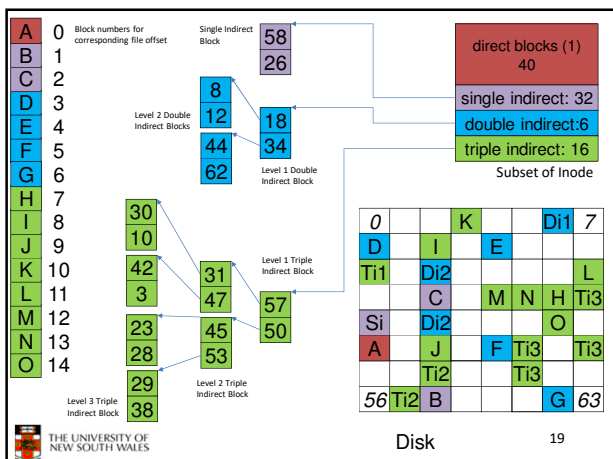
•Double Indirect Block
–Block number of a block containing block numbers of blocks containing block numbers

•Triple Indirect
–Block number of a block containing block numbers of blocks containing block numbers of blocks containing block numbers ☺

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



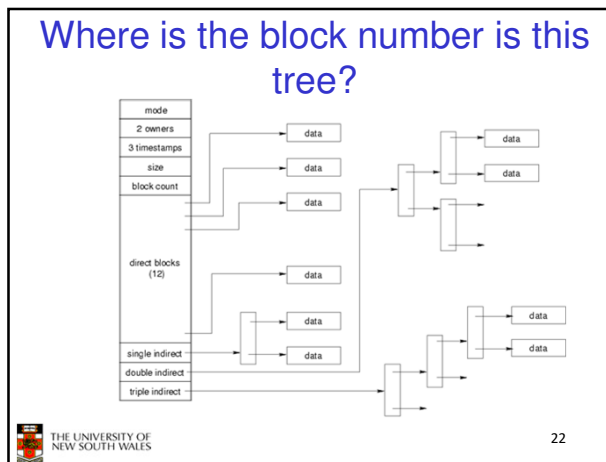
Max File Size

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

$$12 + 256 + 65536 + 16777216 = 16843020 \text{ blocks} \approx 16 \text{ GB}$$

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)`



Solution?

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

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)

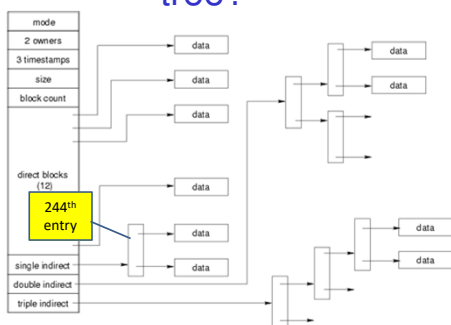
Solution

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 in this tree?

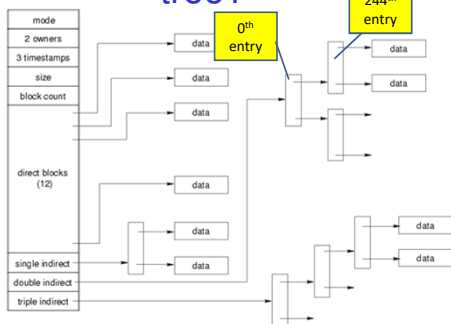


Solution

Address = 5242880 ==>
 Block number = 5242880/4096 = 1280
 Double indirect offset (20-bit) = 1280 - 1036 = 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
1049612 --- ????	Triple-indirect blocks

Where is the block number in this tree?



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
- 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)

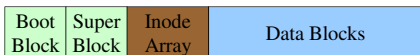
Worst Case Access Patterns with Unallocated Indirect Blocks

- 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



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



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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



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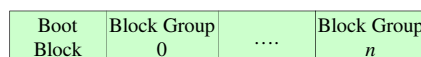
Berkeley Fast Filesystem (FFS)

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



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Layout of an Ext2 FS

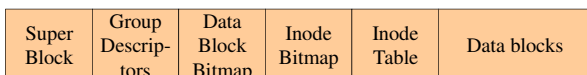


- Partition:
 - Reserved boot block,
 - Collection of equally sized *block groups*
 - All block groups have the same structure



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Layout of a Block Group



1 blk n blks 1 blk 1 blk m blks k blks

- Replicated** super block
 - For e2fsck
- 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)



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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**



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Group Descriptors

- Location of the bitmaps
- Counter for free blocks and inodes in this group
- Number of directories in the group

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
 - Add to length of previous entry

Ext2fs Directories

- "f1" = inode 7
- "file2" = inode 43
- "f3" = inode 85

Inode No	Rec Length	Name Length	Name
7	12	2	'f' '1' '0' '0'
43	16	5	'f' 'i' 'l' 'e' '2'
85	12	2	'f' '3' '0' '0'
		0	

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

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

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Hard links

(a) Situation prior to linking
 (b) After the link is created
 (c) After the original owner removes the file

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Symbolic links

- 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

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Ext2fs Directories

- Deleting a filename
–rm file2

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

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Ext2fs Directories

- Deleting a filename
–rm file2
- Adjust the record length to skip to next valid entry

Inode No
Rec Length
Name Length
Name
7
32
2
'f' '1' '0' '0'
7
12
2
'f' '3' '0' '0'
0

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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)
 - Use the sync command to force a FS flush
- FS operations are non-atomic
 - Incomplete transaction can leave the FS in an inconsistent state

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FS reliability

dir entries

i-nodes

data blocks

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

FS reliability

dir entries

i-nodes

data blocks

- 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

dir entries

i-nodes

data blocks

- 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

dir entries

i-nodes

data blocks

- 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