Directories

Need to find file descriptor (inode), given a name

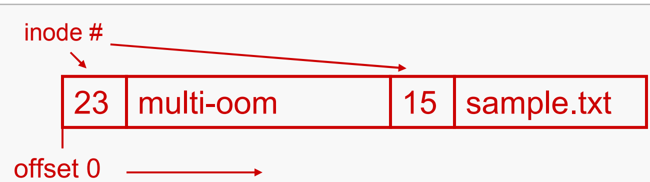
Approaches:
- Single directory (old PCs), Two-level approaches with 1 directory per user

Now exclusively hierarchical approaches:
- File system forms a tree (or DAG)

How to tell regular file from directory?
- Set a bit in the inode

Data Structures
- Linear list of (inode, name) pairs
- B-Trees that map name -> inode
- Combinations thereof

Using Linear Lists



Advantage: (relatively) simple to implement

Disadvantage: scan makes lookup (& delete!) really slow for large directories

Using B-Trees

Advantages:

- Scalable to large number of files: in growth, in lookup time
- Naturally disk-oriented

Disadvantage:

- Complex (but readily available)
- Overhead for small directories

Absolute Paths

How to resolve a path name such as "/usr/bin/ls"?

- Split into tokens using "/" separator
- Find inode corresponding to root directory
  - (how? Use fixed inode # for root)
- (*) Look up "usr" in root directory, find inode
- If not last component in path, check that inode is a directory. Go to (*), looking for next comp
- If last component in path, check inode is of desired type, return

Name Resolution

Must have a way to scan an entire directory without other processes interfering -> need a "lock" function

- But don't need to hold lock on /usr when scanning /usr/bin

Directories can only be removed if they're empty

- Requires synchronization also

Most OS cache translations in "namei" cache – maps absolute pathnames to inode

- Must keep namei cache consistent if files are deleted

Current Directory

Relative pathnames are resolved relative to current directory

- Provides default context
- Every process has one in Unix/Pintos

chdir(2) changes current directory

- cd tmp; ls; pwd vs (cd tmp; ls); pwd

lookup algorithm the same, except starts from current dir

- process should keep current directory open
- current directory inherited from parent

Hard & Soft Links

Provides aliases (different names) for a file

Hard links: (Unix: ln)

- Two independent directory entries have the same inode number, refer to same file
- Inode contains a reference count
- Disadvantage: alias only possible with same filesystem

Soft links: (Unix: ln –s)

- Special type of file (noted in inode); content of file is absolute or relative pathname – stored inside inode instead of direct block list

Windows: “junctions” & “shortcuts”

File Systems & Fault Tolerance

Failure Model

- Define acceptable failures (disk head hits dust particle, scratches disk – you will lose some data)
- Define which failure outcomes are unacceptable

Define *recovery procedure* to deal with unacceptable failures:

- Recovery moves from an incorrect state A to correct state B
- Must understand possible incorrect states A after crash!
- A is like “snapshot of the past”
- Anticipating all states A is difficult

Methods to Recover from Failure

On failure, retry entire computation

- Not a good model for persistent file systems

Use atomic changes

- Problem: how to construct larger atomic changes from the small atomic units available (i.e., single sector writes)

Use reconstruction

- Ensure that changes are so ordered that if crash occurs after every step, a recovery program can either undo change or complete it
- proactive to avoid unacceptable failures
- reactive to fix up state after acceptable failures

Sensible Invariants

In a Unix-style file system, want that:

- File & directory names are unique within parent directory
- Free list/map accounts for all free objects
  - all objects on free list are really free
- All data blocks belong to exactly one file (only one pointer to them)
- Inode’s ref count reflects exact number of directory entries pointing to it
- Don’t show old data to applications

Q.: How do we deal with possible violations of these invariants after a crash?

Crash Recovery (fsck)

After crash, fsck runs and performs the equivalent of mark-and-sweep garbage collection

Follow, from root directory, directory entries

- Count how many entries point to inode, adjust ref count

Recover unreferenced inodes:

- Scan inode array and check that all inodes marked as used are referenced by dir entry
- Move others to /lost+found

Recompute free list:

- Follow direct blocks+single+double+triple indirect blocks, mark all blocks so reached as used – free list/map is the complement

In following discussion, keep in mind what fsck could and could not fix!

Example 1: file create

On create("foo"), have to

1. Scan current working dir for entry "foo" (fail if found); else find empty slot in directory for new entry
2. Allocate an inode #in
3. Insert pointer to #in in directory: (#in, "foo")
4. Write a) inode & b) directory back

What happens if crash after 1, 2, 3, or 4a), 4b)?

Does order of inode vs directory write back matter?

Rule: never write persistent pointer to object that's not (yet) persistent

Example 2: file unlink

To unlink("foo"), must

1. Find entry "foo" in directory
2. Remove entry "foo" in directory
3. Find inode #in corresponding to it, decrement #ref count
4. If #ref count == 0, free all blocks of file
5. Write back inode & directory

Q.: what's the correct order in which to write back inode & directory?

Q.: what can happen if free blocks are reused before inode's written back?

Rule: first persistently nullify pointer to any object before freeing it (object=freed blocks & inode)

Example 3: file rename

To rename("foo", "bar"), must

1. Find entry (#in, "foo") in directory
2. Check that "bar" doesn't already exist
3. Remove entry (#in, "foo")
4. Add entry (#in, "bar")

This does not work, because?

Example 3a: file rename

To rename("foo", "bar"), conservatively

1. Find entry (#i, "foo") in directory
2. Check that "bar" doesn't already exist
3. Increment ref count of #i
4. Add entry (#i, "bar") to directory
5. Remove entry (#i, "foo") from directory
6. Decrement ref count of #i

Worst case: have old & new names to refer to file

Rule: never nullify pointer before setting a new pointer

Example 4: file growth

Suppose file_write() is called.

- First, find block at offset

Case 1: metadata already exists for block (file is not grown)

- Simply write data block

Case 2: must allocate block, must update metadata (direct block pointer, or indirect block pointer)

- Must write changed metadata (inode or index block) & data

Both writeback orders can lead to acceptable failures:

- File data first, metadata next – may lose some data on crash
- Metadata first, file data next – may see previous user's deleted data after crash (very expensive to avoid – would require writing all data synchronously)

FFS's Consistency

Berkeley FFS (Fast File System) formalized rules for file system consistency

FFS acceptable failures:

- May lose some data on crash
- May see someone else's previously deleted data
  - Applications must zero data out if they wish to avoid this + fsync
- May have to spend time to reconstruct free list
- May find unattached inodes → lost+found

Unacceptable failures:

- After crash, get active access to someone else's data
  - Either by pointing at reused inode or reused blocks

FFS uses 2 synchronous writes on each metadata operation that creates/destroy inodes or directory entries, e.g., creat(), unlink(), mkdir(), rmdir()

- Updates proceed at disk speed rather than CPU/memory speed