POSIX File Systems

COS 316 Lecture 6

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Figure 1: PDP-11/40 [3]

UNIX History: How did UNIX become a de-facto standard?

- 1970, “Unics” began as a rewrite of “Multics” (Multiplexed Information and Computer Services)
  - “Uniplexed Information and Computing Service”, a pun because original UNIX was single-tasking
  - Name credit: Brian Kerninghan!
- Developed at first by Bell Labs, first release was “Research Unix” to UIUC
- Mostly used in research until the late 1980’s
- 1990s: Linux and BSD offshoots (after copyright dispute settled in 1994)
  - Linux serves a primary role for server based web applications in the 90’s dot-com boom
- 2000: Apple uses BSD as basis for Darwin, core of OS X and iOS
- BSD (Berkeley Software Distribution) and System V UNIX co-developed over years

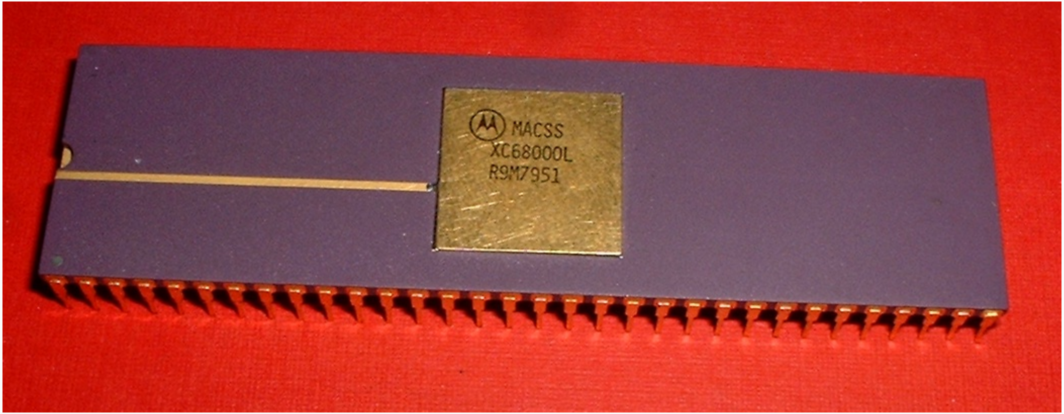

Figure 2: Motorola 68000 [2]

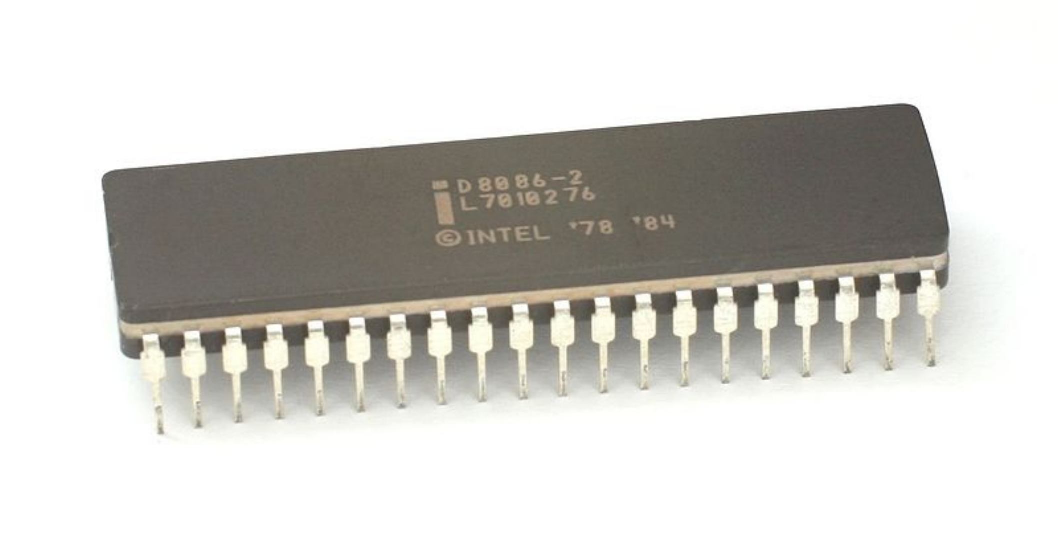

Figure 3: Intel 8086 [1]

Why File Systems?

- Common themes in UNIX systems:
  - User oriented
  - Multiple applications
  - Time sharing
- Need a way to store and organize persistent data
  - Other ways we might organize persistent data?

Key Abstraction

- Data is organized into “files”
  - A linear array of bytes of arbitrary length
  - Meta data about the bytes (modification and creation time, owner, permissions)
- Files organized into “directories”
  - A list of other files or sub-directories
- Common root directory
  - Contrast with drive letters in Windows

UNIX File System Layers

Block layer	organizes disk into fix-sized blocks
File layer	organizes blocks into arbitrary-length files
Inode number layer	names files as uniquely numbered inodes
Directory layer	human-readable names for files in a directory
Absolute path name layer	a global root directory

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Absolute path name layer	a global root directory

- For each of these we'll look at:
    - Names
    - Values
    - Allocation algorithm
    - Translation algorithm

Block layer

- In practice:
  - Tape has contiguous magnetic stripe
  - Disk has plates and arms
  - NAND flash (SSDs) even more complex to deal with wear leveling, data striping...
- ***Names***: integer block numbers
- ***Values***: fix-sized “blocks” of contiguous persistent memory

Block layer

```
typedef block uint8_t[4096]

# There is some hardware-specific translation from
# blocks to, e.g., plate number and offset
struct device {
  block blocks[N]
}
```

Block layer: Allocation

Super Block: a special block number to keep a bitmap of occupied blocks

```
struct super_block {
  int32_t total_size
  int32_t free_block_map_block_num
}

def (device *device) allocate_new_block() returns block_number:
  superblock = (device[SUPERBLOCK_INDEX] as super_block
  for i, b in device[superblock.fre_block_map_block_num]:
    if b != 0xffff:
      empty_block_bit = b.lowest_zero_bit()
      b |= 1 << empty_block_bit
      return i * 8 + empty_block_bit
```

Block layer: Translation

```
struct device {
  block blocks[N]
}

def (device *device) block_number_to_block(int32_t block_num) returns block:
    return device.blocks[block_num + 1]
```

File layer

A *file* is a linear array of bytes of arbitrary length:

- May span multiple blocks
- May grow or shrink over time

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Reuse block allocation for inode allocation

File layer

```
struct inode {
  int32_t block_numbers[N];
  int32_t filesize
}
```

File layer

```
struct inode {
  int32_t block_numbers[N];
  int32_t filesize
}

def (inode *inode) offset_to_block(int offset) returns block:
  block_idx = offset / BLOCKSIZE
  block_num = inode.block_numbers[block_idx]
  return device.block_number_to_block[block_num]
```

```
struct inode {
  int32_t block_numbers[N];
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def (inode *inode) offset_to_block(int offset) returns block:
  block_idx = offset / BLOCKSIZE
  block_num = inode.block_numbers[block_idx]
  return device.block_number_to_block[block_num]
```

Block size: 4096

int32_t → 4 bytes

what is N?

4B bytes ≈ 4GB

What's the maximum file size this scheme can support?

N * Blocksize = max file size

4096 → 4092 / 4 ≈ 1023 · 4096 ≈ 4M

File layer

```
struct inode {
  int32_t block_numbers[N];
  int32_t filesize
}

def (inode *inode) offset_to_block(int offset) returns block:
  block_idx = offset / BLOCKSIZE
  block_num = inode.block_numbers[block_idx]
  return device.block_number_to_block[block_num]
```

What’s the maximum file size this scheme can support?

$(4096-4)/4 * 4k \approx 4MB$

What's a scheme that would allow larger files?

1. Spn more block per inode: 1→32

2. Change the struct

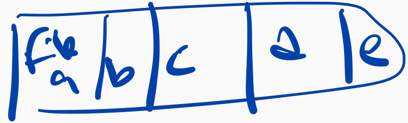
↳ Linked list of 'inodes'

hash table?

tree

inode {
int32 direct[N-M]
int32 indirect[M]

3 ↳



Inode number layer

- Names: Inode *numbers*
- Values: Inode structs

Inode number layer

- Names: Inode *numbers*
- Values: Inode structs
- Allocation
  - Can re-use block allocation and block numbers
  - File systems often use special inode allocation to avoid slow seeks on disk for common operations
- Translation
  - If re-using block allocation: $inode\_number\_to\_inode \equiv block\_number\_to\_block$

Recap so far

- Name files by inode number (e.g. 43982), translate to inode structs
- Inodes translate to a list of ordered block numbers that store the file's data
- Block numbers translate to blocks—the actual file data

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Remaining issues:

1. Numbers are convenient names for machines, but not so much for humans
2. How do we *discover* files?

Directory layer

Structure files into collections called “directories”. Each file in a directory gets a human readable name—i.e. an (almost) arbitrary ASCII string

- ***Names***: Human readable names within a “directory”
    - `resume.docx`, `a.out`, `profile.jpg`…
- ***Values***: Inode numbers

Directories can contain files as well as other *sub-directories*

Directory layer: Allocation

```
struct dirent {
  string filename
  int    inode_number
}

struct inode {
  int32_t filesize
  bool directory
  union {
    int32_t block_numbers[N]
    dirent  files[M]
  }
}
```

Directory Layer: Translation

```
typedef directory inode when inode.directory

def (dir *directory) lookup(string filename) returns inode_number:
  for block_num in dir.block_numbers:
    block = block_number_to_block(block_num) as files[]
    if file_inode = files.find(filename):
      return file_inode
  return -1
```

Directory Layer: Translation

Paths name files by concatenating directory and file names with /: `path/to/a/file.txt`

```
def (dir *directory) lookup(string path) returns inode_number:
  let (next_path, rest) = path.split_first('/')
  for block_num in dir.block_numbers:
    block = block_number_to_block(block_num) as files[]
    if inode = files.find(next_path):
      if rest.empty():
        return inode
      else
        next_dir = block_number_to_block(inode) as directory
        return next_dir.lookup(rest)
  return -1
```

Absolute path name layer

- Each running UNIX program has a “working directory” (`wd`)
- File lookups are relative to the `wd`
- What if we want to name files outside of our `wd`’s directory hierarchy?
    - E.g. share files between users
- What if we want globally meaningful paths?

Absolute path name layer

Solution:

- Special name /, hardcoded to a specific inode number
- All directories are part of a global file system tree rooted at /
  - the "root" directory

Names: One name, /

Values: Hardcoded inode number, e.g., 1

Allocation: nil

Translation: $\lambda\_ \rightarrow 1$

Naming in UNIX File System: Recap

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5. Inode structs translate to an ordered list of block numbers

Naming in UNIX File System: Recap

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2. Paths translate to recursive lookup for human-readable names in each directory
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4. Inode numbers translate to inode structs
5. Inode structs translate to an ordered list of block numbers
6. Block numbers translate to blocks—the actual file data

Up Next

- Problems with location-addressed naming (e.g. UNIX file system)
  - Transactions
  - Versioning
  - Data corruption
- We'll look at Git's content addressable store
- Please read chapter 10 of the Git book: Git Internals

Problem set 1 due Thursday

Assignment 2 due next Tuesday

References

[1] *Intel 8086*. Wikimedia Commons.

[2] *Motorola 68000 microprocessor, pre-release version XC68000L with R9M mask*. Wikimedia Commons.

[3] *PDP11/40 as exhibited in Vienna Technical Museum*. Wikimedia Commons.