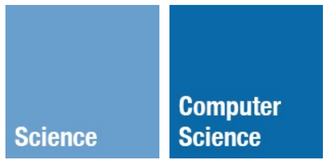
# Filesystems

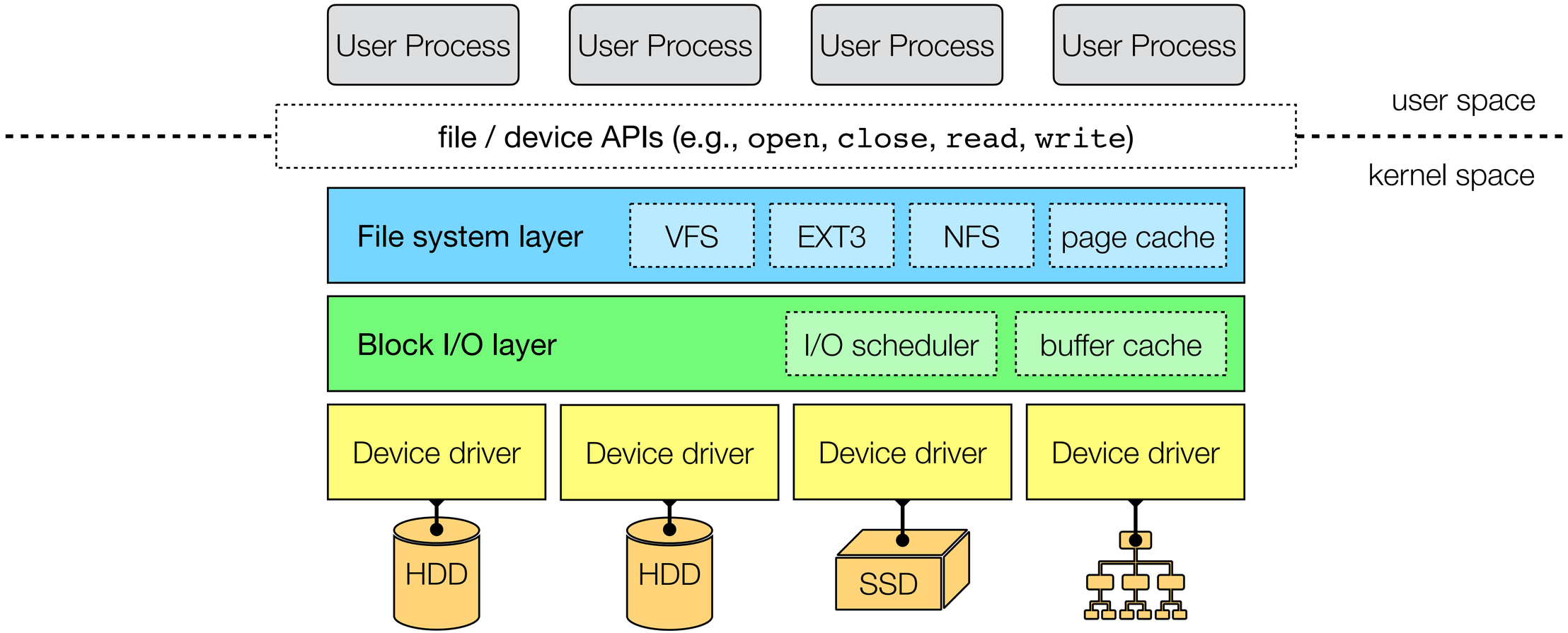



CS 450: Operating Systems
Michael Lee <lee@iit.edu>

# Agenda

- Unix file I/O API
- A simple filesystem
- Fast File System (FFS)
- FS Consistency and Journaling

# The big picture



# § Unix file I/O API

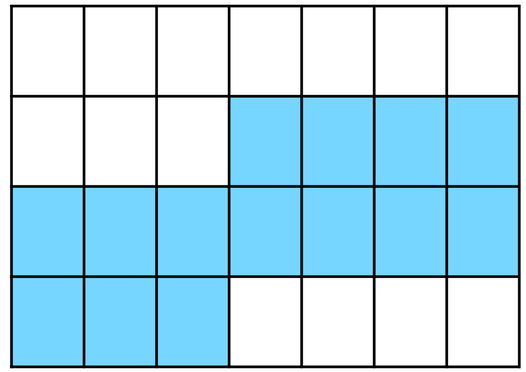
# What *is* a file?

- A named sequence of bytes
  - “Name” = some unique identifier
  - Supports reading, writing, and/or seeking
- A file does not imply any particular backing storage device!
  - But we will be focusing on disk-based files and filesystems

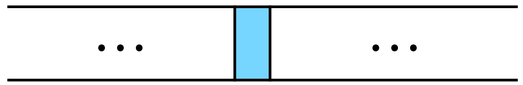
# Block vs. Stream

- *Block-oriented* files use fixed-size blocks as the unit of transfer/access
  - Typically allow blocks to be addressed individually and in arbitrary order
  - E.g., disk-based files
- *Stream-oriented* (aka character-oriented) files can be read/written a byte at a time
  - Typically doesn't support random seeks
  - E.g., network data, mouse input

*block-oriented*



*stream-oriented*



# Unix file “names”

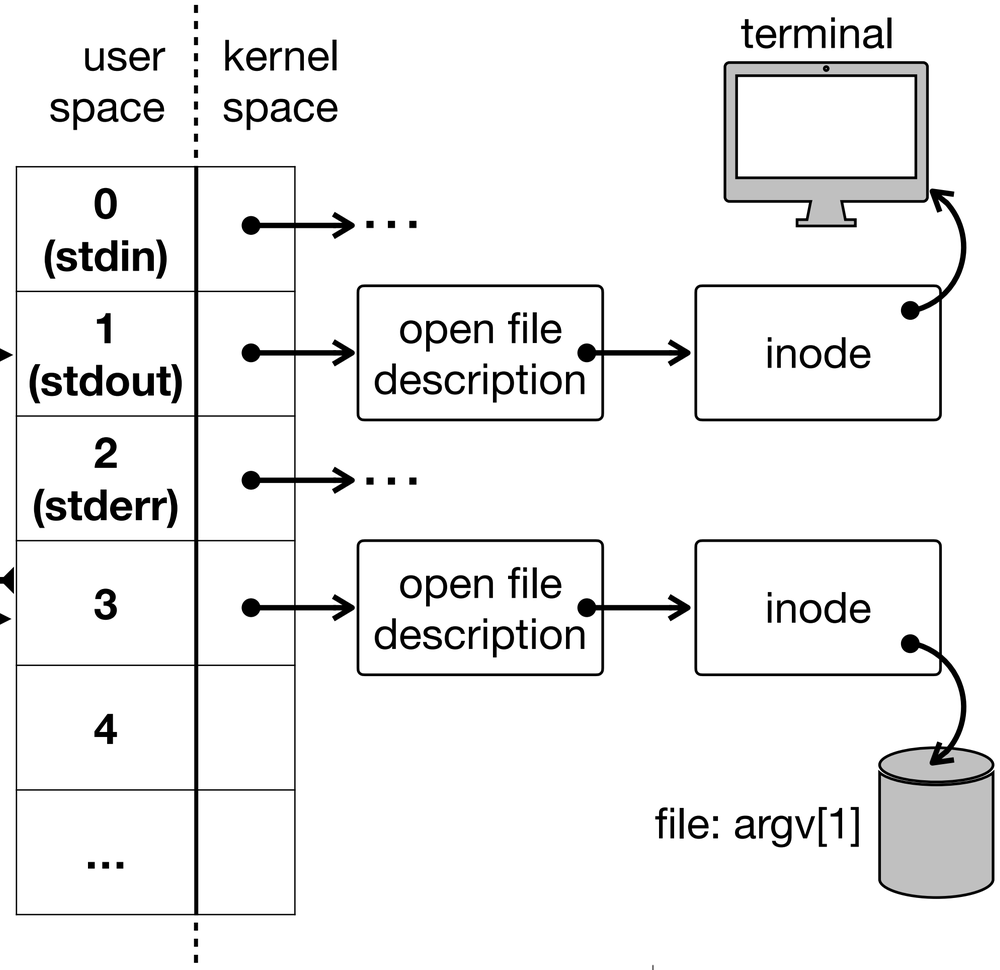
- **Inodes**: each file is assigned a unique inode (“index node”) number
- **Paths**: for user convenience, names in a hierarchical namespace are mapped to inode numbers
  - e.g., `/usr/bin/gcc` → `inode#` — represents a “link” to the file
- **File descriptors**: after opening a file, OS maintains position and access mode in an open file description table
  - Returns index as a file descriptor to user for subsequent access

# Basic file I/O API

```c
// Looks up the inode linked from `path` (creating the underlying file if
// needed) and allocates an open file description. Returns the index (FD).
int open(const char *path, int oflag, ...);

// Read up to `count` bytes from `fd` into `buf`.
ssize_t read(int fd, void *buf, size_t count);

// Write up to `count` bytes from `buf` into `fd`.
ssize_t write(int fd, const void *buf, size_t count);

// Releases `fd`. If there are no remaining references to the open file
// description indexed by `fd`, the OFD is deallocated.
int close(int fd);
```

# E.g., disk I/O

```c
// Simple `cat` utility clone
int main (int argc, char *argv[])
{
    char buf[512];
    int nread;
    int fd = open(argv[1], O_RDONLY);

    while ((nread = read(fd, buf, 512)) > 0)
    {
        write(1, buf, nread);
    }
    close(fd);
    return 0;
}
```



# § A simple filesystem

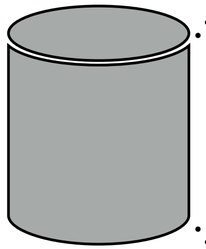
# Essential questions

- How do we keep track of disk/file metadata?
- How do we keep track of free space?
- How do we keep track of disk blocks belonging to a given file?
- How do we associate paths with files? (i.e., human legible name → inode)

# Metadata stores

- Key responsibility of the filesystem is to keep track of various metadata
- **Superblock** used to store centralized global metadata
- Simple yet efficient structure for mapping free space = **free space *bitmap***
- Each file is associated with an **inode block**, which contains metadata and pointers to blocks containing file data
- **Directories** map paths to inodes

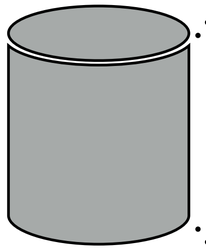
# Disk as an array of blocks



| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |
| 64 | 65 | 66 | 67 | 68 | 69 | 70 | 71 | 72 | 73 | 74 | 75 | 76 | 77 | 78 | 79 |
| 80 | 81 | 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 |
| 96 | 97 | 98 | 99 | 100 | 101 | 102 | 103 | 104 | 105 | 106 | 107 | 108 | 109 | 110 | 111 |
| 112 | 113 | 114 | 115 | 116 | 117 | 118 | 119 | 120 | 121 | 122 | 123 | 124 | 125 | 126 | 127 |

downsides?

# On-disk structures



| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| super block | free bitmap | inode 0 | inode 1 | inode 2 | inode 3 | inode 4 | inode 5 | inode 6 | inode 7 | inode 8 | inode 9 | inode 10 | inode 11 | inode 12 | inode 13 |
| inode 13 | inode 14 | inode 15 | inode 16 | inode 17 | inode 18 | inode 19 | inode 20 | inode 21 | inode 22 | inode 23 | inode 24 | inode 25 | inode 26 | inode 27 | inode 28 |
| data 0 | data 1 | data 2 | data 3 | data 4 | data 5 | data 6 | data 7 | data 8 | data 9 | data 10 | data 11 | data 12 | data 13 | data 14 | data 15 |
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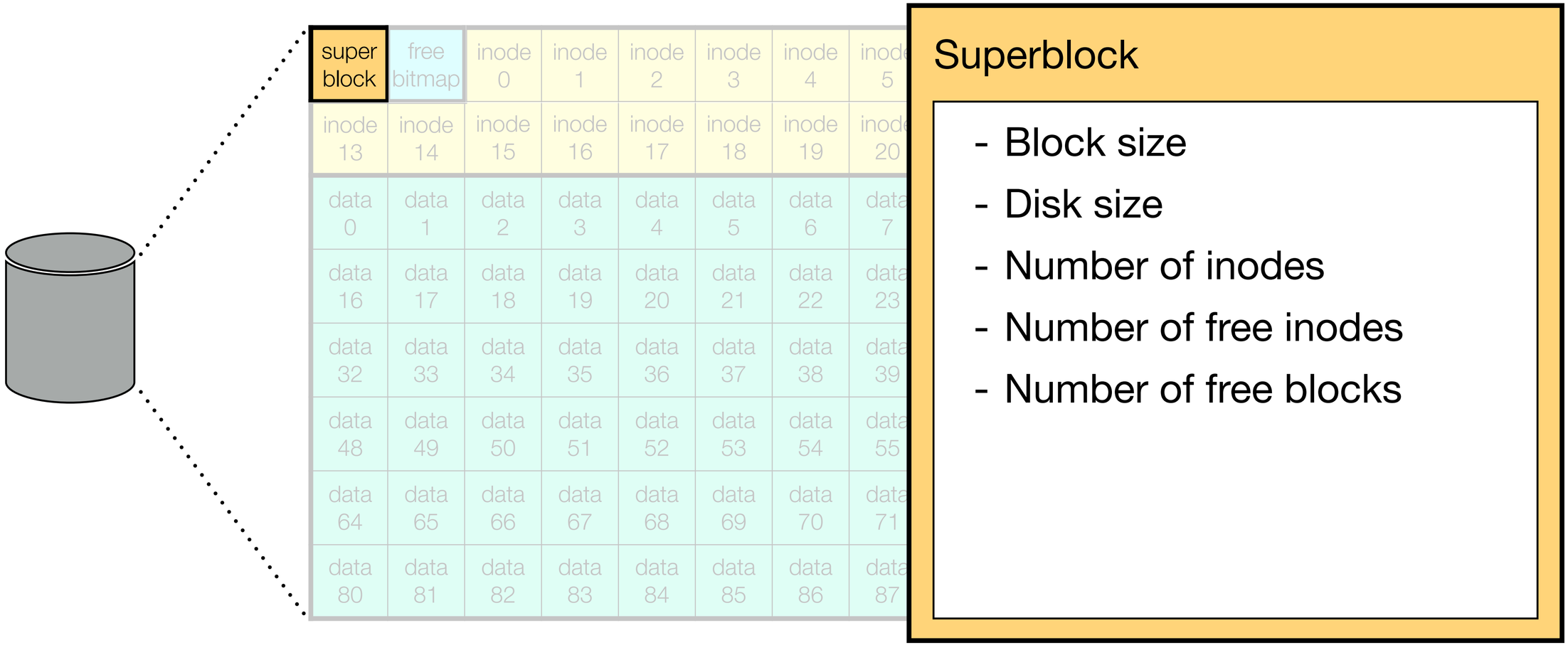
| data 32 | data 33 | data 34 | data 35 | data 36 | data 37 | data 38 | data 39 | data 40 | data 41 | data 42 | data 43 | data 44 | data 45 | data 46 | data 47 |
| data 48 | data 49 | data 50 | data 51 | data 52 | data 53 | data 54 | data 55 | data 56 | data 57 | data 58 | data 59 | data 60 | data 61 | data 62 | data 63 |
| data 64 | data 65 | data 66 | data 67 | data 68 | data 69 | data 70 | data 71 | data 72 | data 73 | data 74 | data 75 | data 76 | data 77 | data 78 | data 79 |
| data 80 | data 81 | data 82 | data 83 | data 84 | data 85 | data 86 | data 87 | data 88 | data 89 | data 90 | data 91 | data 92 | data 93 | data 94 | data 95 |

# Superblock


super block
free bitmap
inode 0
inode 1
inode 2
inode 3
inode 4
inode 5
inode 13
inode 14
inode 15
inode 16
inode 17
inode 18
inode 19
inode 20
data 0
data 1
data 2
data 3
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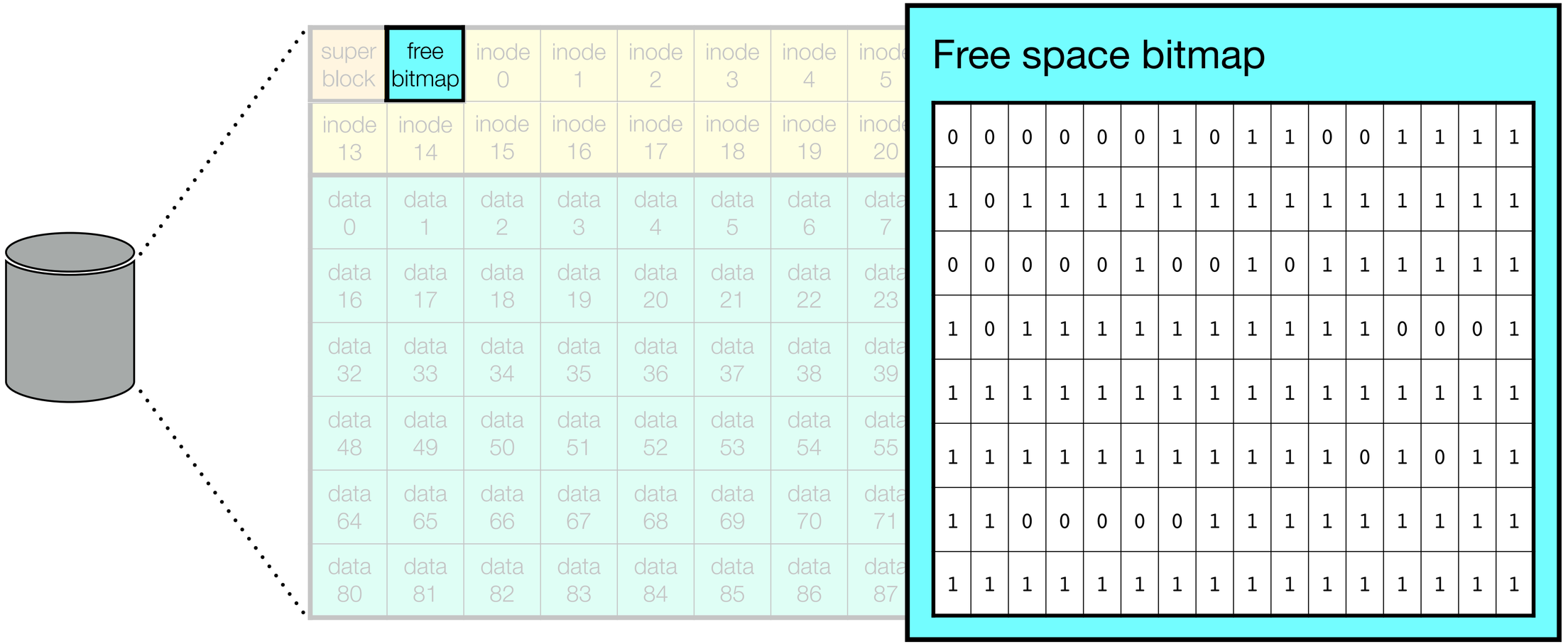
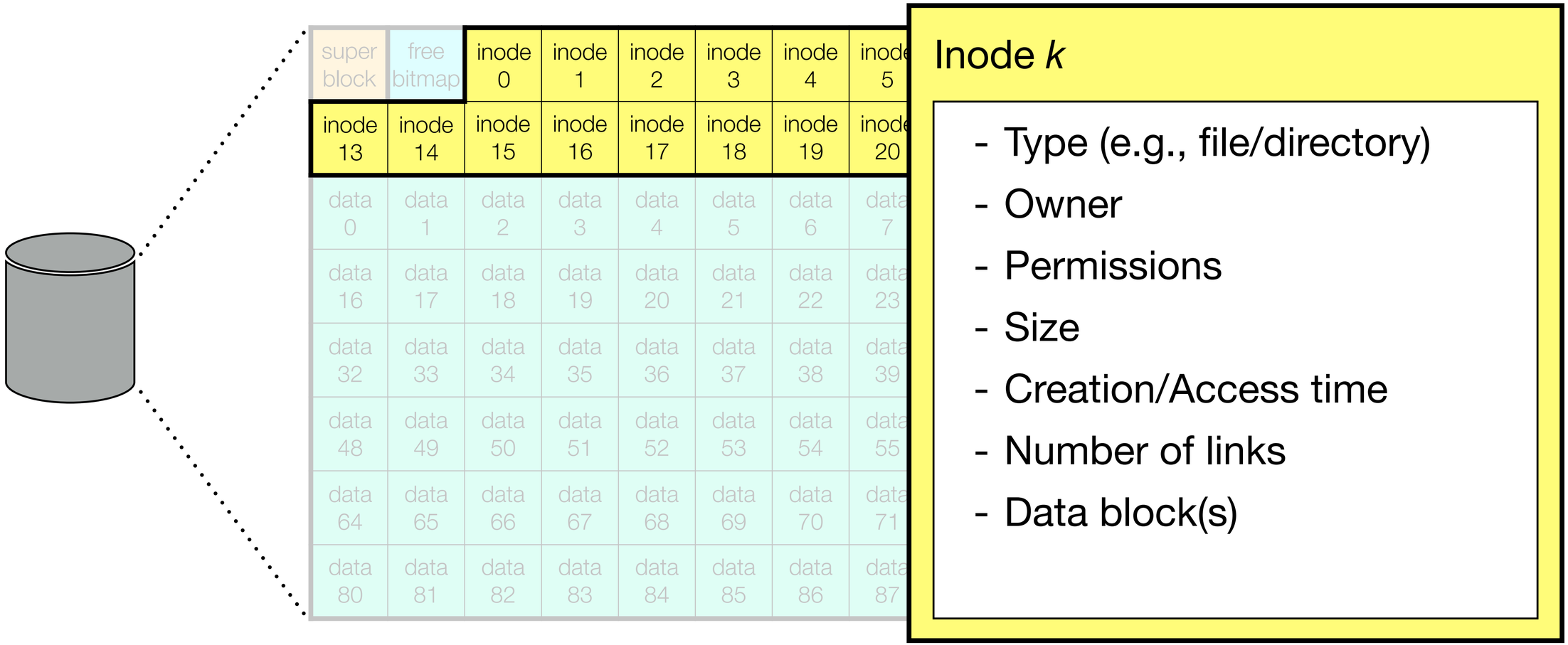
data 82
data 83
data 84
data 85
data 86
data 87
Superblock
- Block size
- Disk size
- Number of inodes
- Number of free inodes
- Number of free blocks

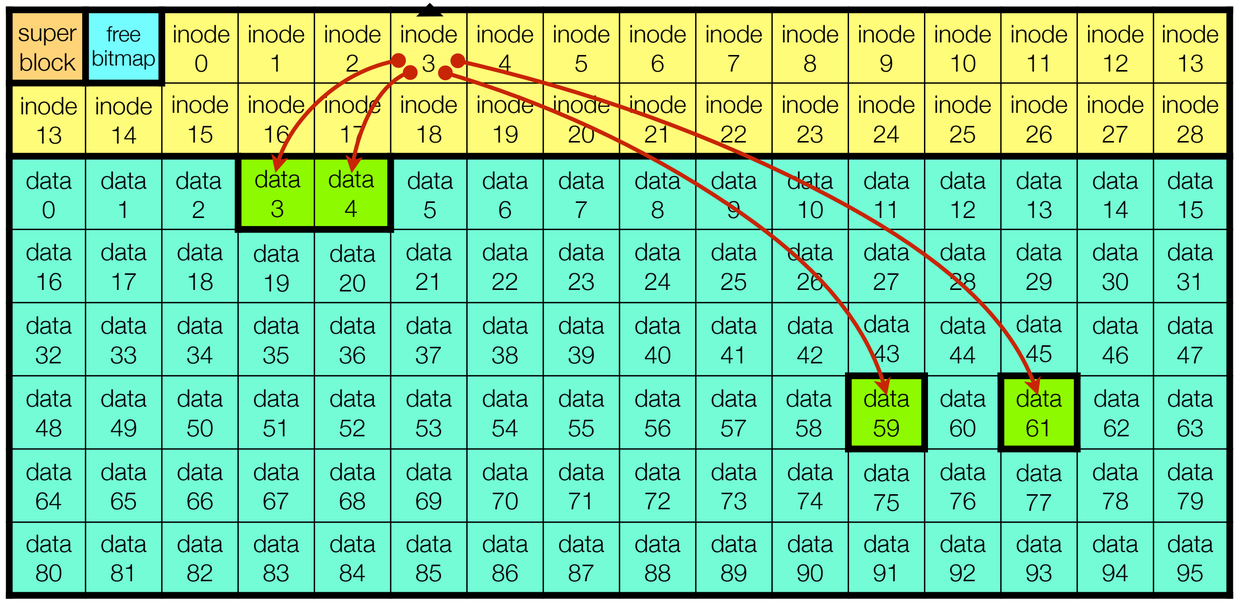
# Free space bitmap



# Inode blocks



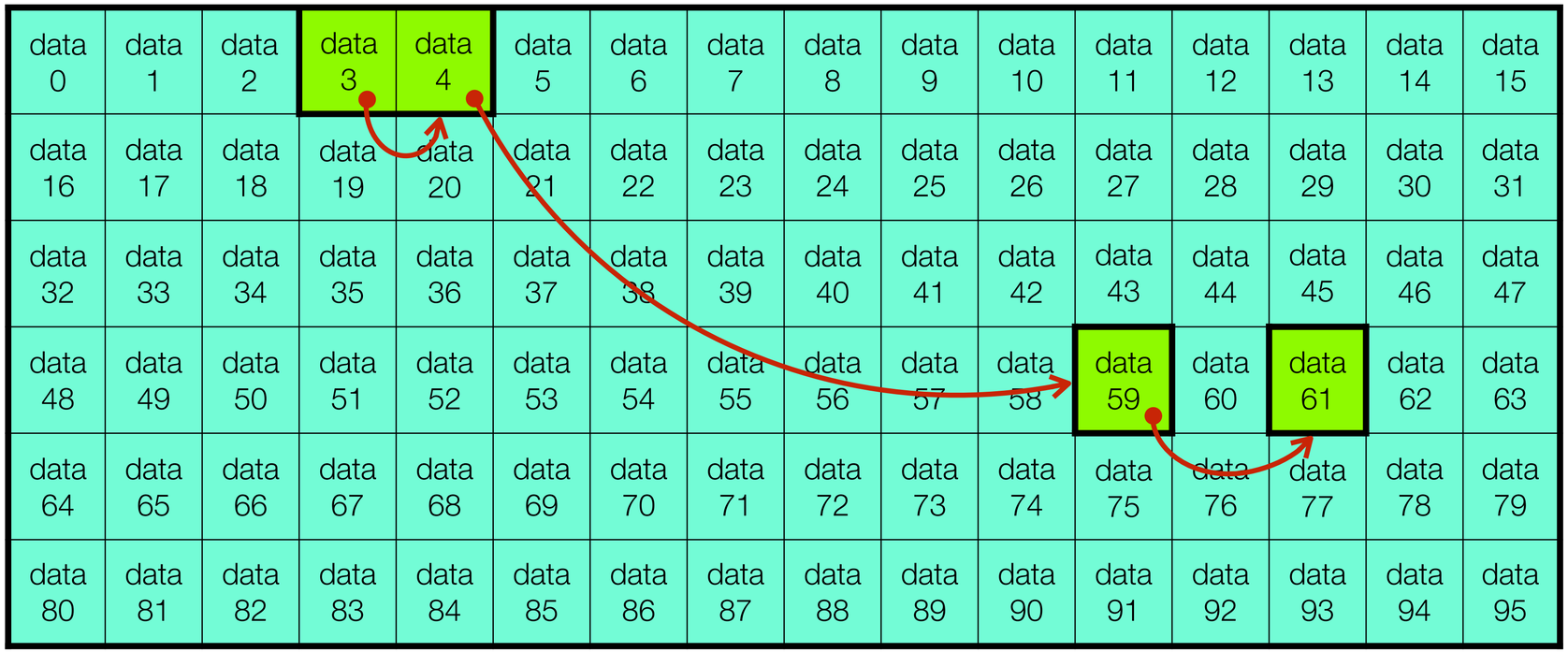
# E.g., inode block contents




## Inode 3

- Type: regular file
- Owner: michael
- RWX bits: 0644
- Size: 2 KB / 4 blocks
- Created/Accessed: [now]
- Number of links: 1 (?)
- Data blocks: 3, 4, 59, 61

# Alternative: linked allocation

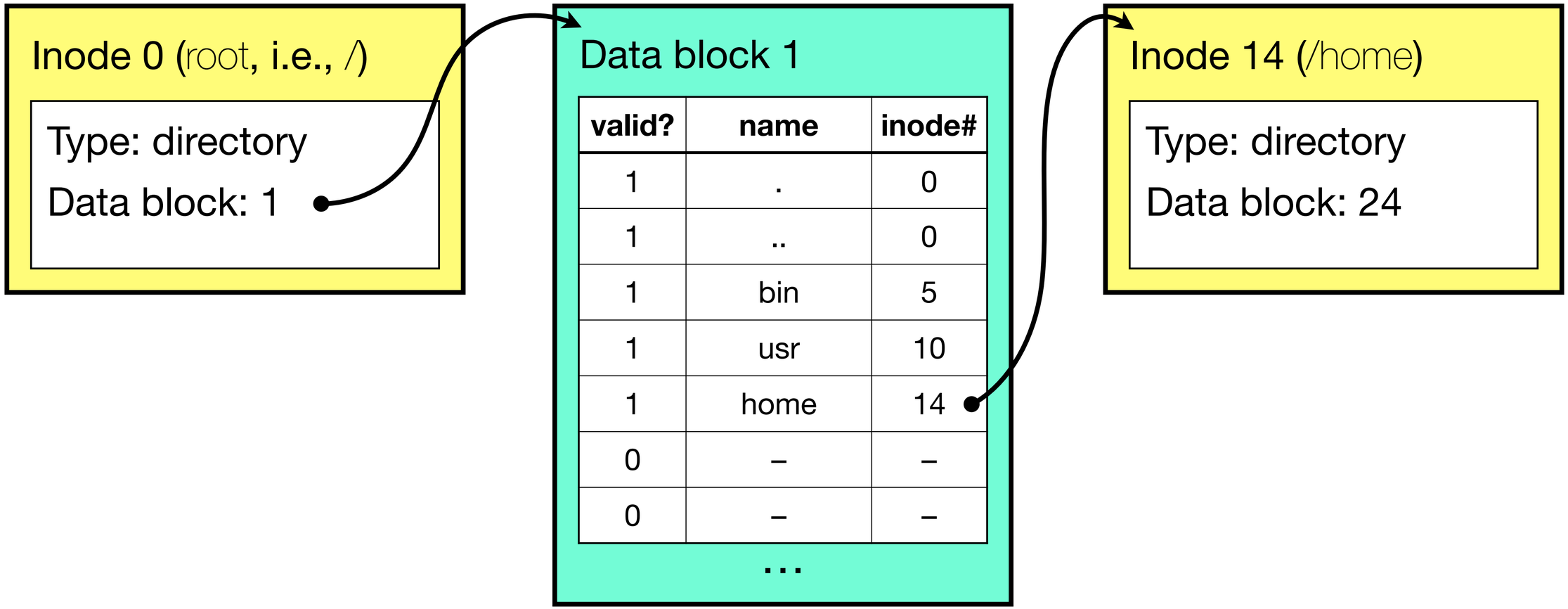



- Store only start block in inode
- Pros/Cons?

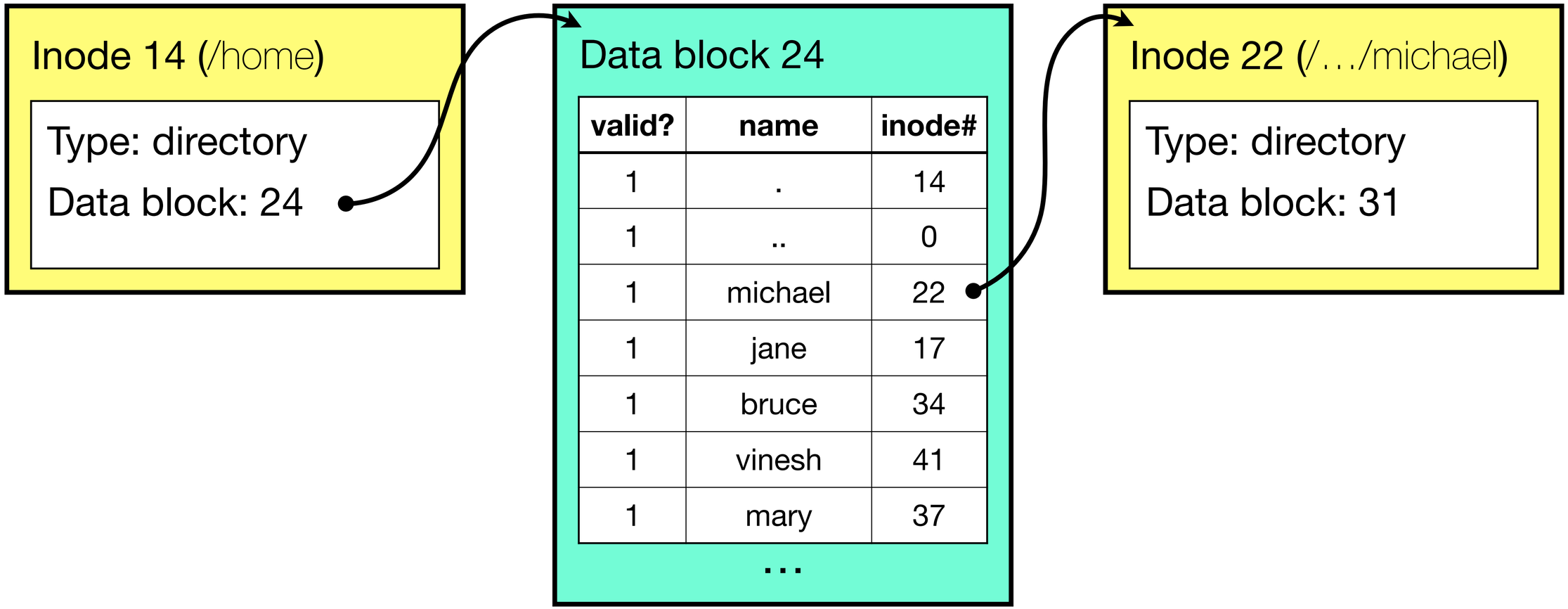
# Path lookup

- Require a path → inode number mapping mechanism
- Could use a monolithic lookup structure, but this would be expensive to maintain and search!
- Instead, each directory maintains a map of contained names to inodes
  - Mappings stored in data blocks, in a format understood by filesystem
  - Root directory inode must be at a known location

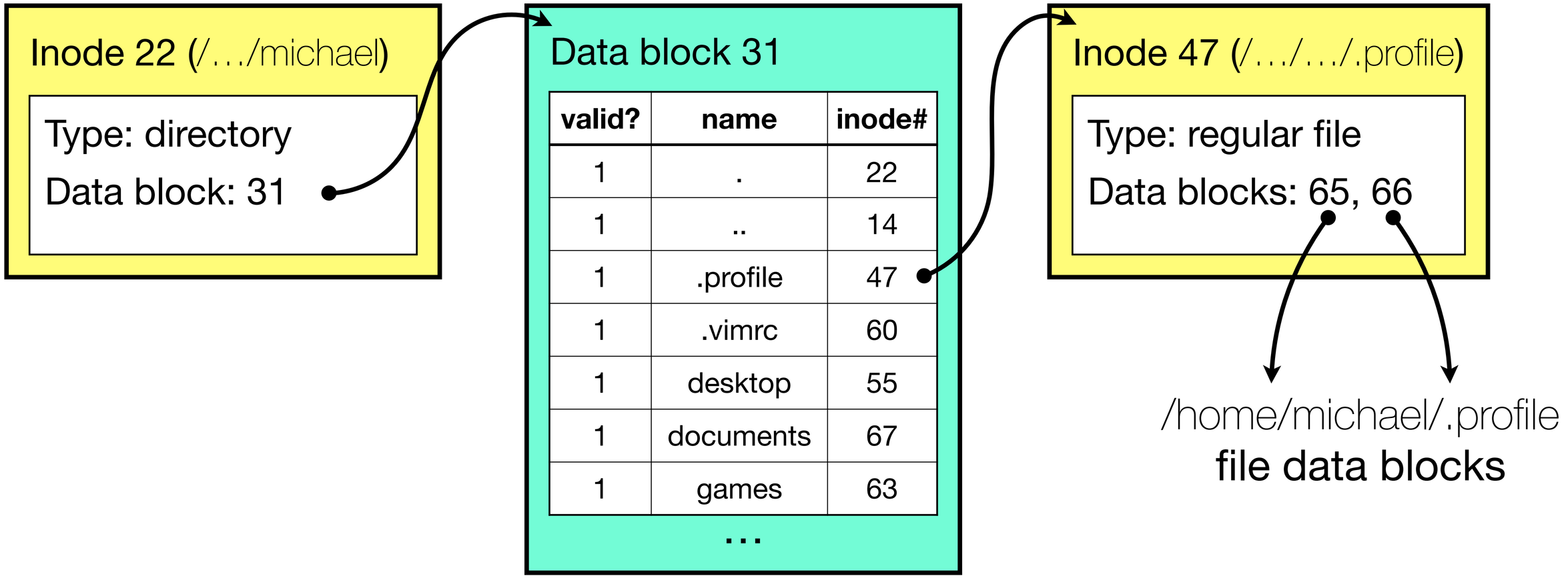
# E.g., read /home/michael/.profile



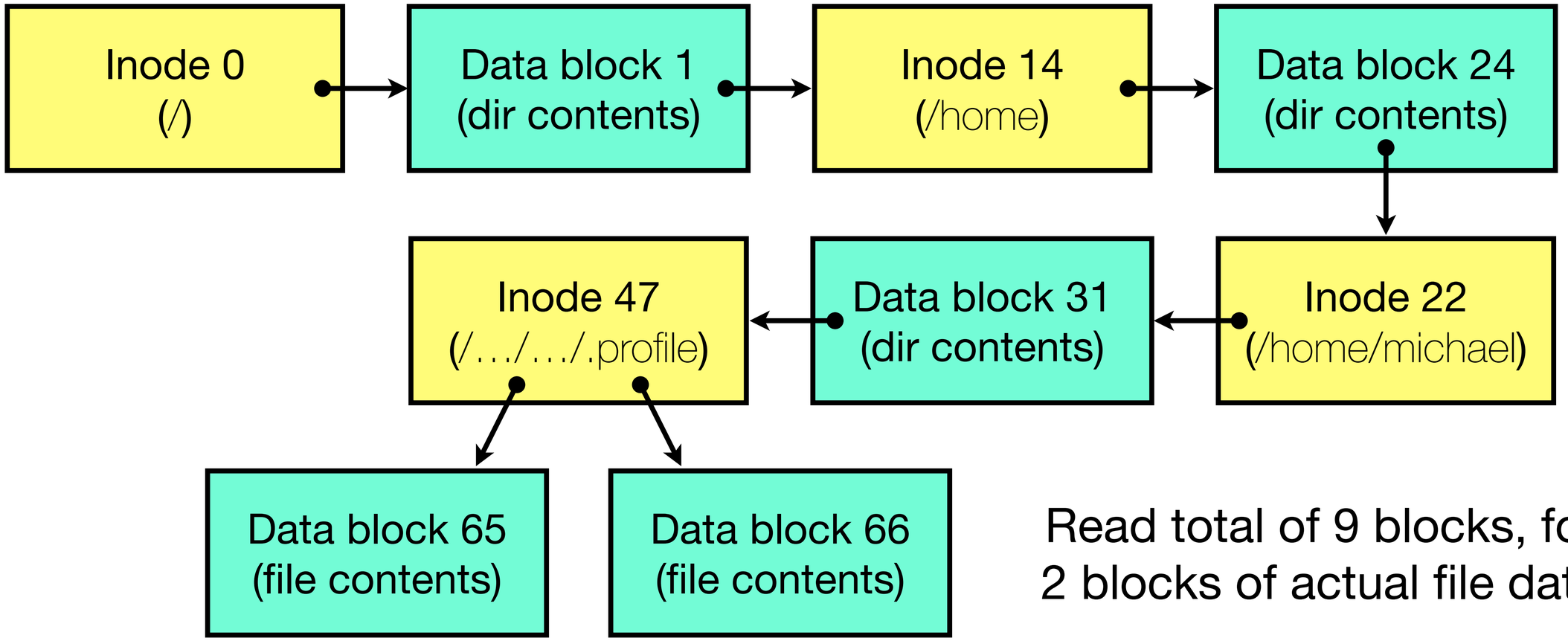
# E.g., read /home/michael/.profile



# E.g., read /home/michael/.profile



# E.g., read /home/michael/.profile

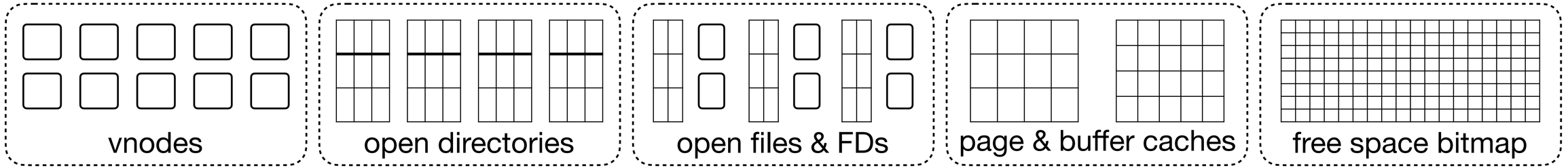


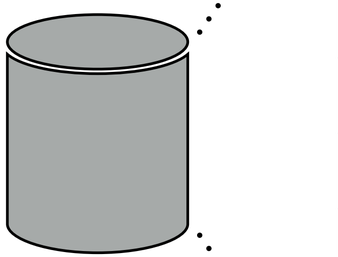

Read total of 9 blocks, for
2 blocks of actual file data

# Caches

- To avoid constant reloading of frequently used metadata/data from disk, filesystem should maintain a cache of structures
  - Vnodes = in-memory inodes
  - Directory mappings
  - Free space bitmap
  - Block-level / File-level data caches
    - aka Buffer / Page caches

# In-memory vs. On-disk structures



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# Problems with caching?

- The more data we cache, and the longer we cache it, the more *out of sync* in-memory and on-disk structures may get
  - Problem?
    - OS/FS crash before sync happens can create big problems!
      - Lost data if not written yet
      - Filesystem structure inconsistencies

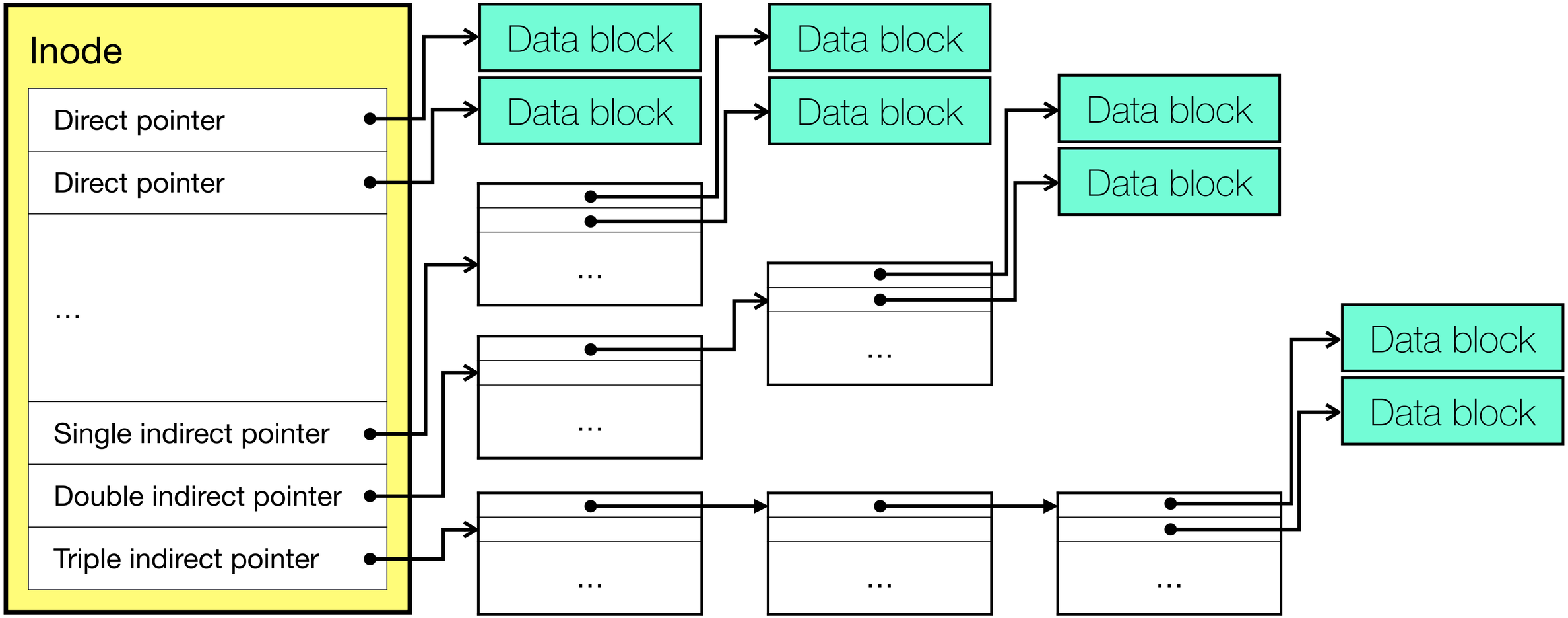
# File size limitation

- Recall, inodes reside in fixed size blocks, so can only hold a finite number of pointers to data blocks
- Typically, an inode holds 12 pointers to data blocks
  - With a block size of 512 bytes, max file size = 6 KB
- How to fix this?

# Indirect pointers

- We can store pointers to blocks that contain more pointers …
  - A single-indirect pointer references a block that contains multiple direct pointers to data blocks belonging to the file
  - A double-indirect pointer references a block that contains multiple single-indirect pointers
  - Etc.

# Indirect pointers



# E.g., computing max file size

Given a block size of 512 bytes, 32-bit block pointers, and that an inode contains 12 direct, 1 single indirect, 1 double indirect, and 1 triple indirect pointers, what is the maximum file size?

- Direct: 512 bytes × 12 = 6 KB
- Pointers per block: 512 / 4 = 128 ($2^7$)
- Single indirect: 512 bytes × 128 = $2^9 \times 2^7 = 2^{16}$ bytes (64 KB)
- Double indirect: $2^9 \times 2^7 \times 2^7 = 2^{23}$ bytes (8 MB)
- Triple indirect: $2^9 \times 2^7 \times 2^7 \times 2^7 = 2^{30}$ bytes (1 GB) **Ans: ~1.008 GB**