# Lecture 22: File Systems

CS 105

Spring 2025

# Review: File Systems 101

- Long-term information storage goals
  - should be able to store large amounts of information
  - information must survive processes, power failures, etc.
  - processes must be able to find information
  - needs to support concurrent accesses by multiple processes

- Solution: the File System Abstraction
  - interface that provides operations involving
    - files
    - directories (a special kind of file)

# Review: The File System Abstraction

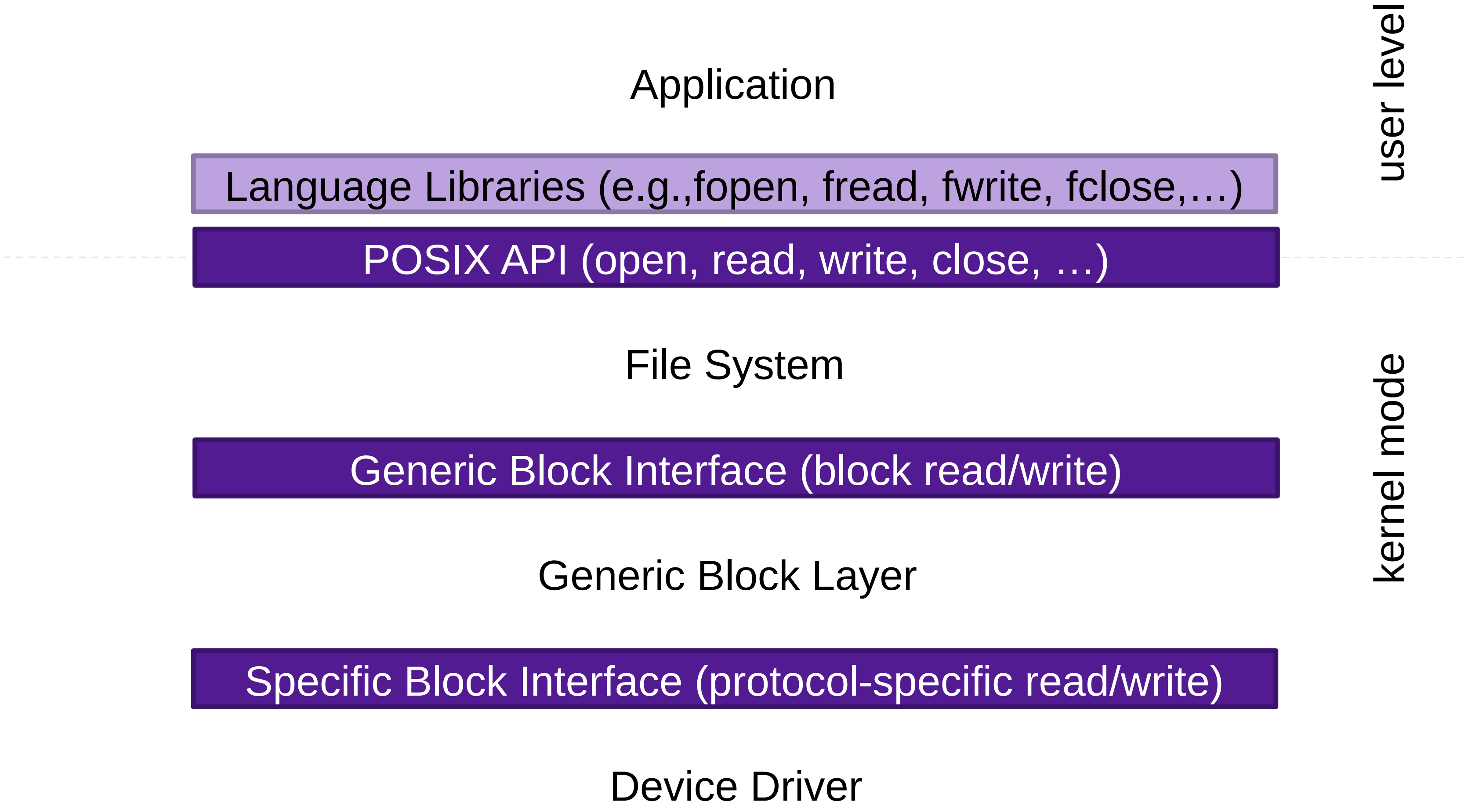
- interface that provides operations on data stored long-term on disk

- a **file** is a named sequence of stored bytes
  - name is defined on creation
  - processes use name to subsequently access that file

- a file is comprised of two parts:
  - **data**: information a user or application puts in a file
    - an array of untyped bytes
  - **metadata**: information added and managed by the OS
    - e.g., size, owner, security info, modification time

- two types of files
  - **normal files**: data is an arbitrary sequence of bytes
  - **directories**: a special type of file that provides mappings from human-readable names to low-level names (i.e., file numbers)

# Review: The File System Stack



Application

Language Libraries (e.g.,fopen, fread, fwrite, fclose,…)

POSIX API (open, read, write, close, …)

File System

Generic Block Interface (block read/write)

Generic Block Layer

Specific Block Interface (protocol-specific read/write)

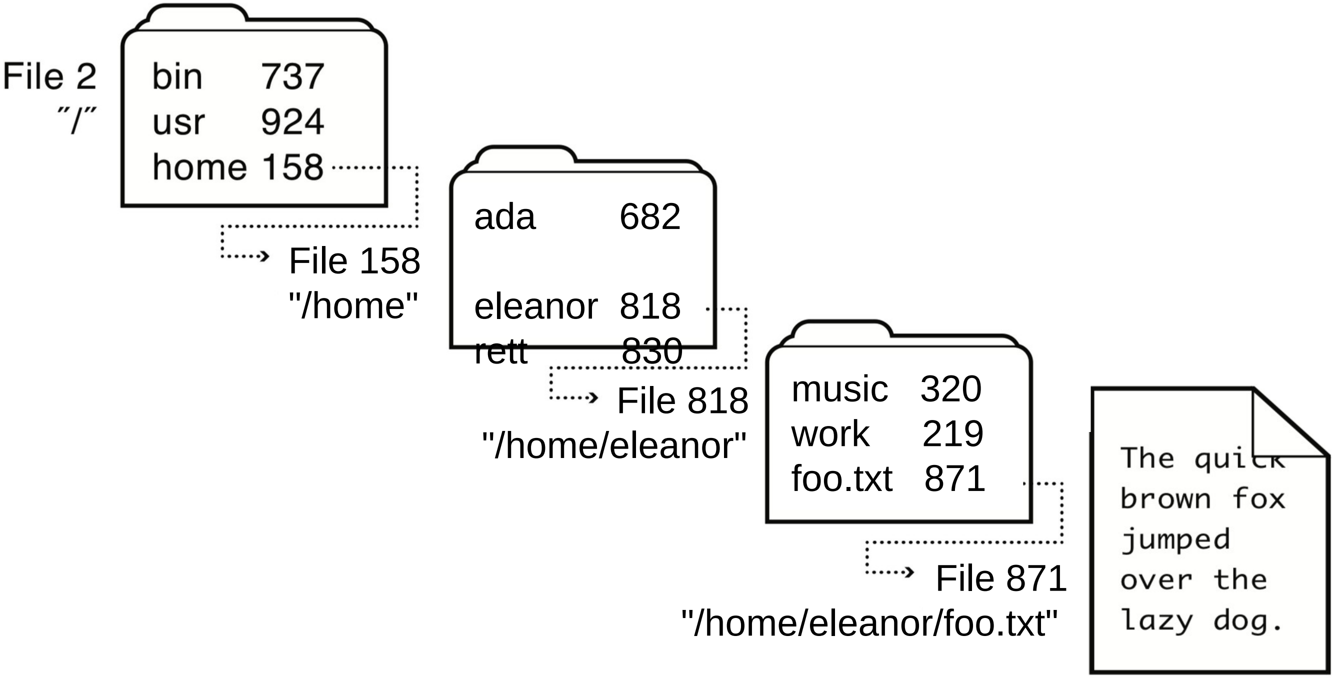
Device Driver

# Implementation Basics

- Directories: file name -> low-level names (i.e., file numbers)

# Directories

- a **directory** is a file that provides mappings from human-readable names to low-level names (i.e., file numbers):
  - a list of human-readable names
  - a mapping from each name to a specific underlying file or directory
- OS uses path name to find directories and files



# Exercise 1: Linked Allocation

- How many disk reads would be required to read (all of) a file named `/foo/bar/baz.txt`?
  - assume all files can be read will one disk read

# Multiple human-readable names

- Many file systems allow a given file to have multiple names

- Hard links are multiple file directory entries that map different path names to the same file number

- Symbolic Links or soft links are directory entries that map one name to another (effectively a redirect)

# Implementation Basics

- Directories: file name -> low-level names (i.e., file numbers)

- File system index structures: file number -> block(s)

# File System Challenges

- **Performance:** despite limitations of disks
- **Flexibility:** need to support diverse file types and workloads
- **Persistence:** store data long term
- **Reliability:** resilient to OS crashes and hardware failures

# File System Properties

- Most files are small
  - need strong support for small files (optimize the common case)
  - block size can't be too big

- Directories are typically small
  - usually 20 or fewer entries

- Some files are very large
  - must handle large files
  - large file access should be reasonably efficient

- File systems are usually about half full

# Storing Files

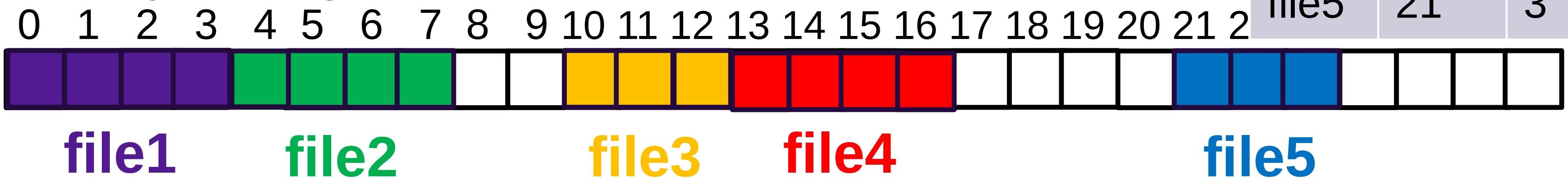
Possible ways to allocate files:

- **Continuous allocation:** all bytes together, in order
- **Linked structure:** each block points to the next block
- **Indexed structure:** index block points to many other blocks
- **Log structure:** sequence of segments, each containing updates

# Continuous Allocation

| | start | size |
|---|---|---|
| file1 | 0 | 4 |
| file2 | 4 | 4 |
| file3 | 10 | 3 |
| file4 | 13 | 4 |
| file5 | 21 | 3 |

All bytes together, in order



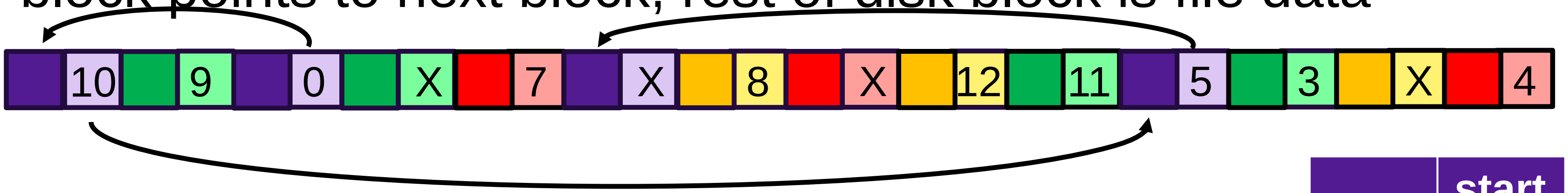
+**Simple:** state required per file = start block & size

+**Efficient:** entire file can be read with one seek

- **Fragmentation:** external is bigger problem
- **Usability:** user needs to know size of file at time of creation

# Linked Allocation

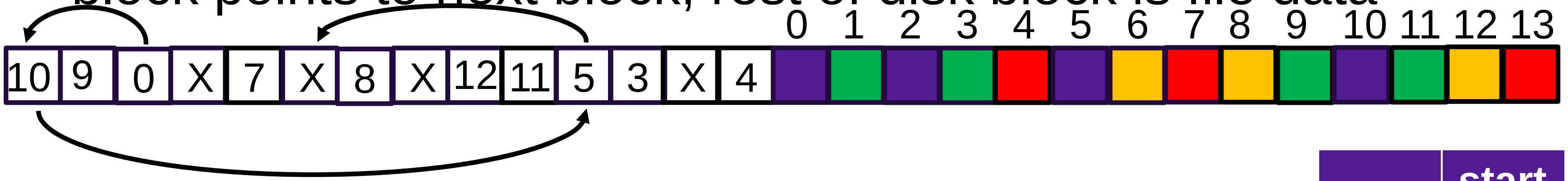
Each file is stored as linked list of blocks: One word of each block points to next block, rest of disk block is file data



| | start |
|---|---|
| file1 | 2 |
| file2 | 9 |
| file3 | 6 |
| file4 | 13 |
| file5 | 15 |

# Decoupled Linked Allocation

Each file is stored as linked list of blocks: First word of each block points to next block, rest of disk block is file data



| | start |
|---|---|
| file1 | 2 |
| file2 | 9 |
| file3 | 6 |
| file4 | 13 |
| file5 | 15 |

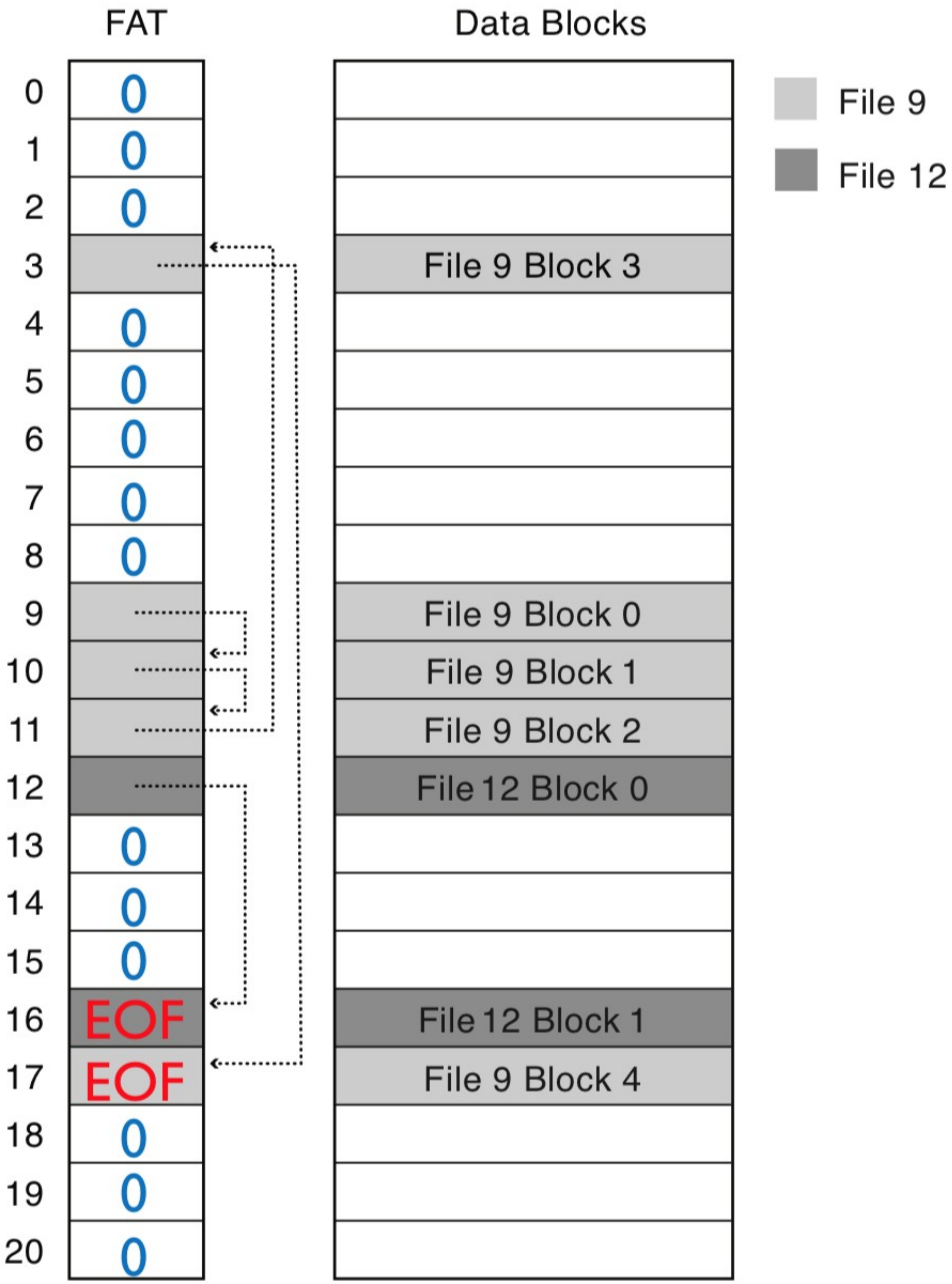
# Exercise 2: (Decoupled) Linked Allocation

- How many disk reads would be required to read (all of) a $2^{15}$ byte file named /foo/bar/baz.txt?
  - assume 4096 byte (4 KB or $2^{12}$ byte) blocks
  - assume that all directories are small enough to fit in one block

# FAT File System

- Developed by Microsoft for MS-DOS
- decoupled linked allocation
- 1 FAT entry per block ("next pointer")
  - EOF for last block
  - 0 indicates free block
- low-level file name = FAT index of first block in file

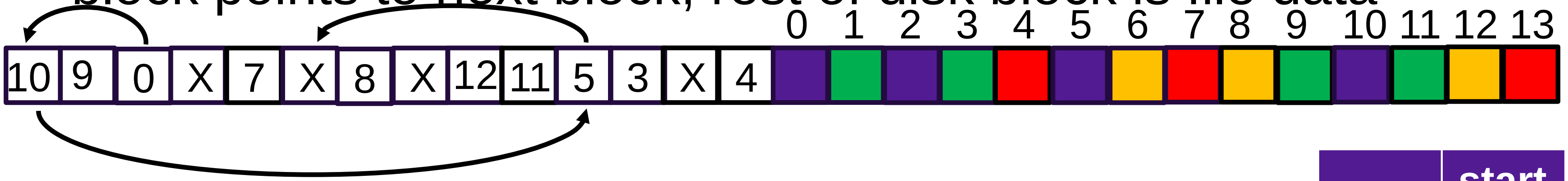
| Directory | |
|---|---|
| `cecil.txt` | 9 |
| `eleanor.txt` | 12 |



| | FAT | Data Blocks |
|---|---|---|
| 0 | 0 | |
| 1 | 0 | |
| 2 | 0 | |
| 3 | | File 9 Block 3 |
| 4 | 0 | |
| 5 | 0 | |
| 6 | 0 | |
| 7 | 0 | |
| 8 | 0 | |
| 9 | | File 9 Block 0 |
| 10 | | File 9 Block 1 |
| 11 | | File 9 Block 2 |
| 12 | | File 12 Block 0 |
| 13 | 0 | |
| 14 | 0 | |
| 15 | 0 | |
| 16 | EOF | File 12 Block 1 |
| 17 | EOF | File 9 Block 4 |
| 18 | 0 | |
| 19 | 0 | |
| 20 | 0 | |

# Linked Allocation

Each file is stored as linked list of blocks: First word of each block points to next block, rest of disk block is file data



| | start |
|---|---|
| file1 | 2 |
| file2 | 9 |
| file3 | 6 |
| file4 | 13 |
| file5 | 15 |

+**Simple:** directory only need to store 1st block of each file

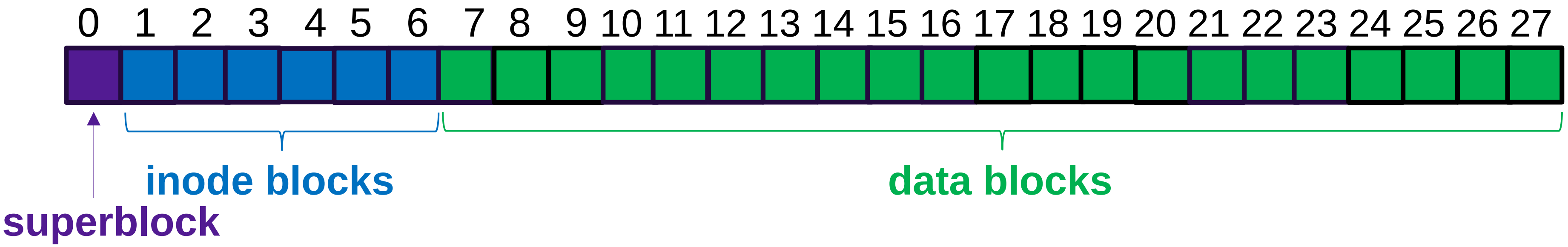
+**Space Utilization:** no space lost to external fragmentation

- **Performance:** random access is slow

~**Space Utilization:** overhead of pointers

# Indexed Allocation: Fast File System (FFS)

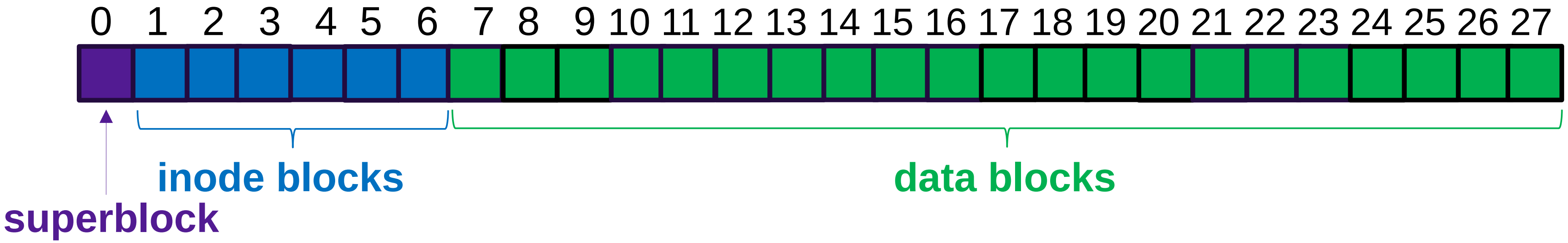
- tree-based, multi-level index



- **superblock** identifies file system's key parameters
- **inodes** store metadata and pointers
- **datablocks** store data

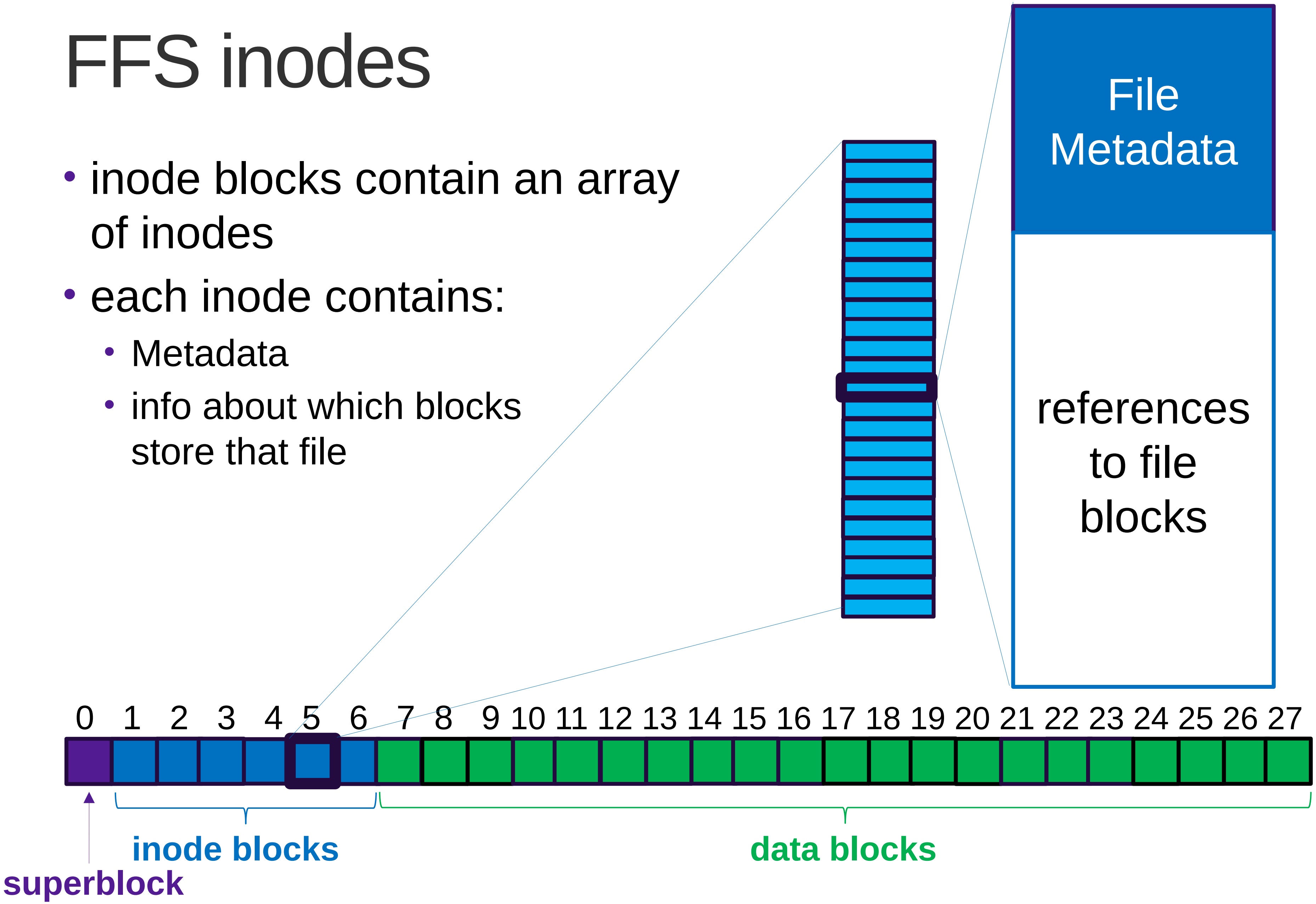
# FFS Superblock

- Identifies file system’s key parameters:
  - type
  - block size
  - inode array location and size
  - location of free list



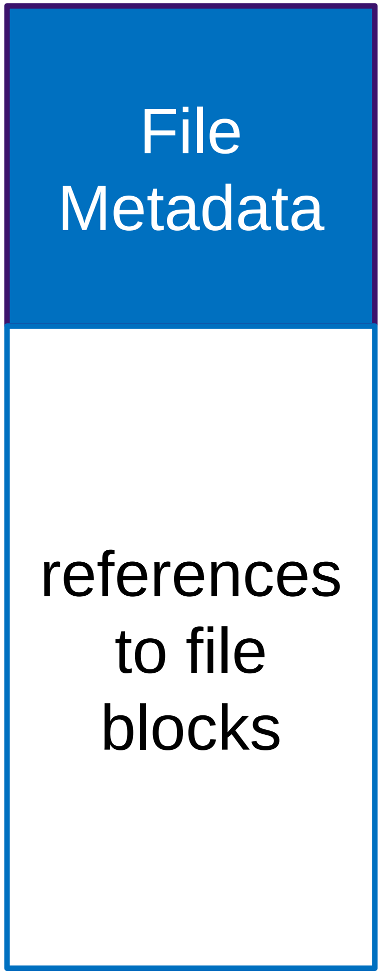
# FFS inodes

- inode blocks contain an array of inodes
- each inode contains:
  - Metadata
  - info about which blocks store that file



# inode Metadata

- Type
  - ordinary file
  - directory
  - symbolic link
  - special device
- Size of the file (in #bytes)
- # links to the i-node
- Owner (user id and group id)
- Protection bits
- Times: creation, last accessed, last modified



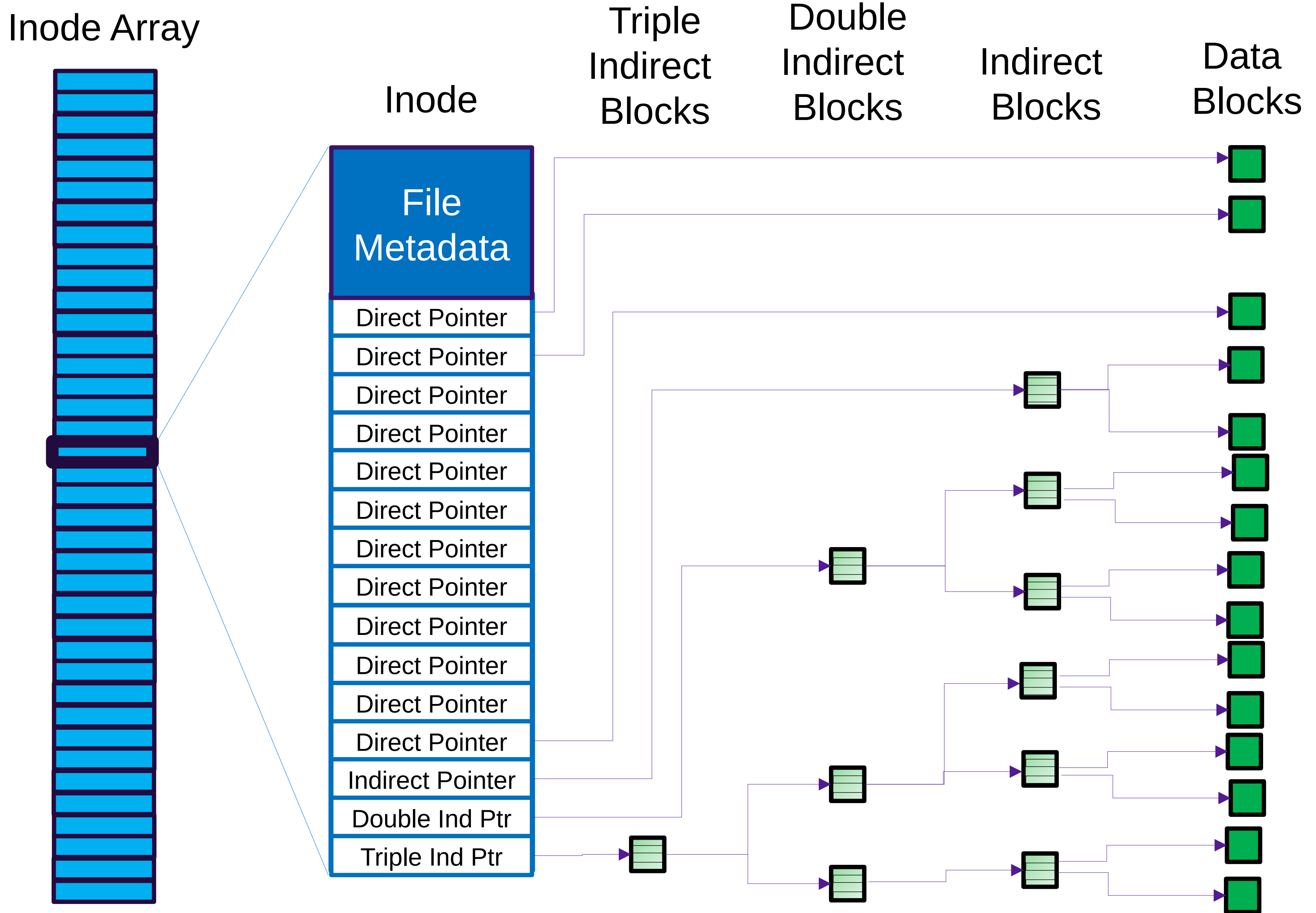
File Metadata

references to file blocks

Each "Pointer" is a block number, not a memory address

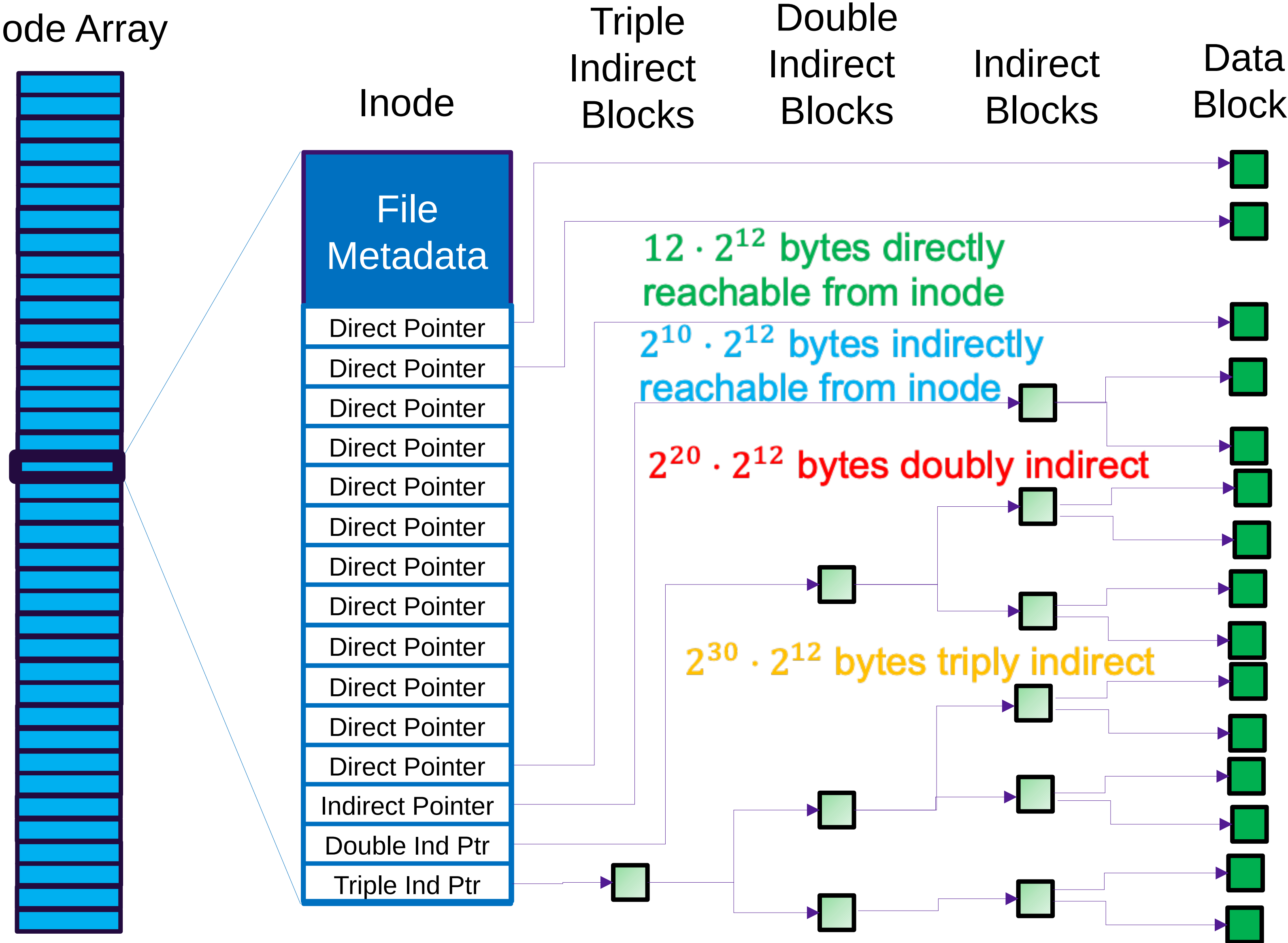
Indirect blocks contain arrays of block numbers

# FFS Index Structures



Assume: blocks are 4KB ($2^{12}$ bytes)
block numbers are 4 byte values

# Max File Size



$12 \cdot 2^{12}$ bytes directly reachable from inode

$2^{10} \cdot 2^{12}$ bytes indirectly reachable from inode

$2^{20} \cdot 2^{12}$ bytes doubly indirect

$2^{30} \cdot 2^{12}$ bytes triply indirect

# Exercise 3: Inode Structures

- Assume we are using the inode structure we just described, and assume again that each block is 4K ($2^{12}$) and that each block reference is 4 bytes.

  - Which pointers in the inode of a 32KB file would be non-null?

  - Which pointers in the inode of a 47MB file would be non-null?

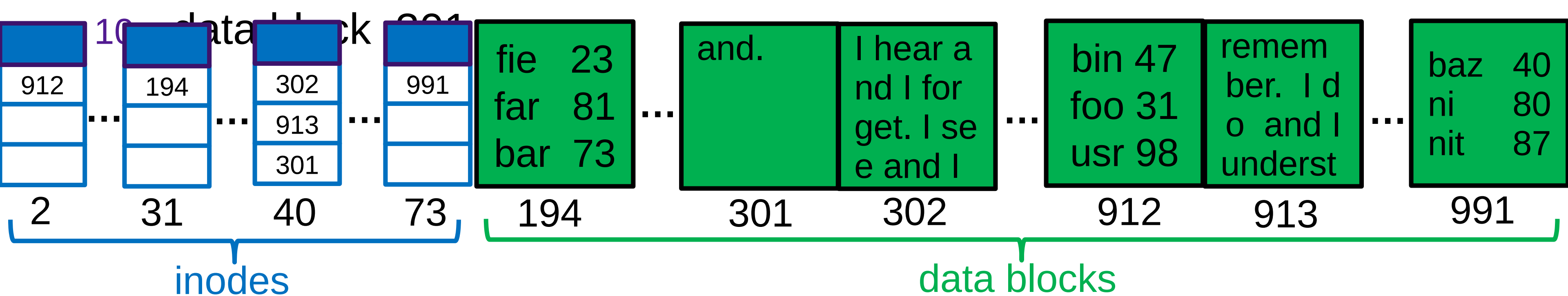
# FFS Directory Structure

- Originally: directory was array of 16 byte entries
  - 14 byte file name
  - 2 byte i-node number
- Now: implicit list. Each entry contains:
  - 4-byte inode number
  - Full record length
  - Length of filename
  - Filename
- First entry is “.”, points to self
- Second entry is “..”, points to parent inode

# Exercise 4: Indexed Allocation

How many disk reads would be required to read (all of) file /foo/bar/baz?

12)



# Key Characteristics of FFS

- Tree Structure
  - efficiently find any block of a file
- High Degree (or fan out)
  - minimizes number of seeks
  - supports sequential reads & writes
- Fixed Structure
  - implementation simplicity
- Asymmetric
  - not all data blocks are at the same level
  - supports large files
  - small files don’t pay large overheads

# Implementation Basics

- Directories: file name -> low-level names (i.e., file numbers)

- Index structures: file number -> block

- Free space maps: find a free block (ideally nearby)

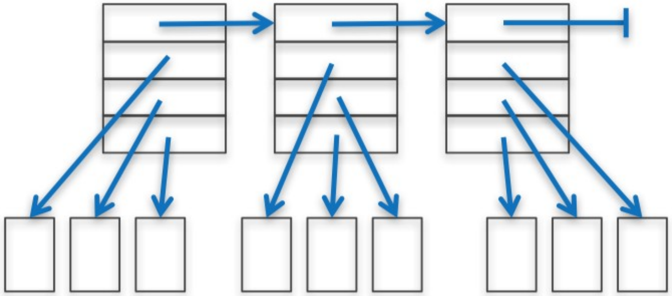
# Free List

To write files, need to keep track of which blocks are currently free

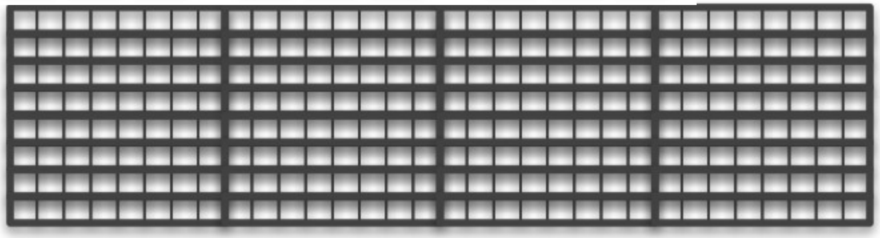
How to maintain?

- linked list of free blocks
  - inefficient (why?)

- linked list of metadata blocks that in turn point to free blocks
  - simple and efficient



- bitmap
  - actually used



# Problem: Poor Performance

- In a naïve implementation of FFS, performance starts bad and gets worse
- One early implementation delivered only 2% disk bandwidth
- The root of the problem: poor locality
  - data blocks of a file were often far from its inode
  - file system would end up highly fragmented: accessing a logically continuous file would require going back and forth across the disk

# Implementation Basics

- Directories: file name -> low-level names (i.e., file numbers)
- Index structures: file number -> block
- Free space maps: find a free block (ideally nearby)
- Performance optimizations (e.g., locality heuristics)

# Performance Optimizations

- **Grouped Allocation:** disk organized into groups that are (temporally) close, try to allocate all file blocks in same group
- **Defragmentation:** periodically rearrange files to improve locality
- **Page Cache:** to reduce costs of accessing files, cache file contents in memory (e.g., device data, memory-mapped files)
- **Copy-on-write (COW):** create new, updated copy at time of update
- **Write Buffering:** buffer writes and periodically flush to disk