Storage Systems
(part 2)

File System Interface

- UNIX file open is a Swiss Army knife:
  - Open the file, return file descriptor
  - Options:
    - if file doesn’t exist, return an error
    - If file doesn’t exist, create file and open it
    - If file does exist, return an error
    - If file does exist, open file
    - If file exists but isn’t empty, nix it then open
    - If file exists but isn’t empty, return an error
    - …

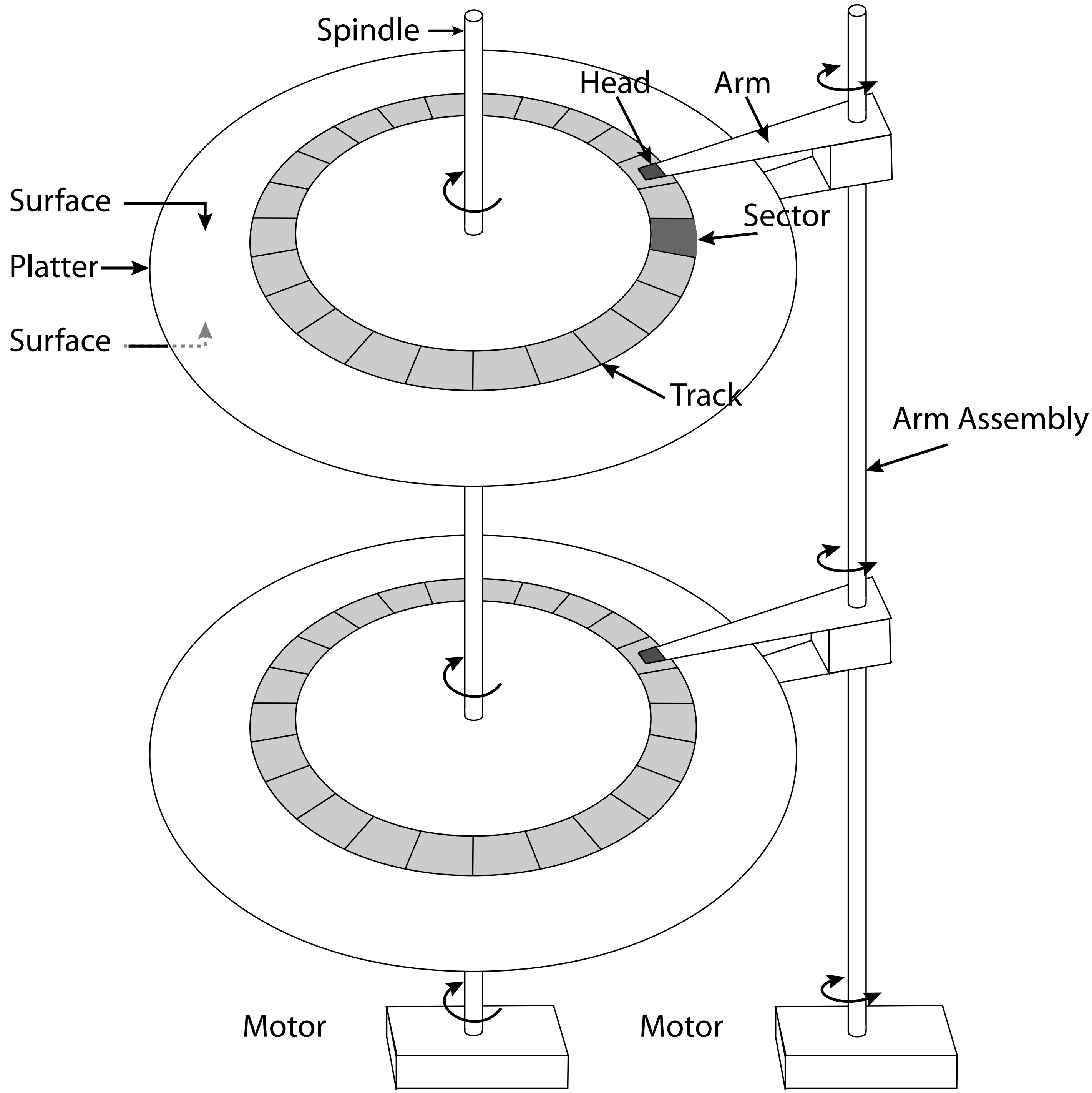
Interface Design Question

- Why not separate syscalls for open/create/exists?
  - Would be more modular!

```
if (!exists(name))
    create(name);   // can create fail?
fd = open(name);   // does the file exist?
```

Main Points

- Storage hardware
  - Disk scheduling
  - Flash memory
- File system usage patterns
- File system design



Spindle
Head
Arm
Surface
Platter
Surface
Sector
Track
Arm Assembly
Motor
Motor

Disk Performance

Disk Latency =

Seek Time + Rotation Time + Transfer Time

Toshiba Disk (2008)

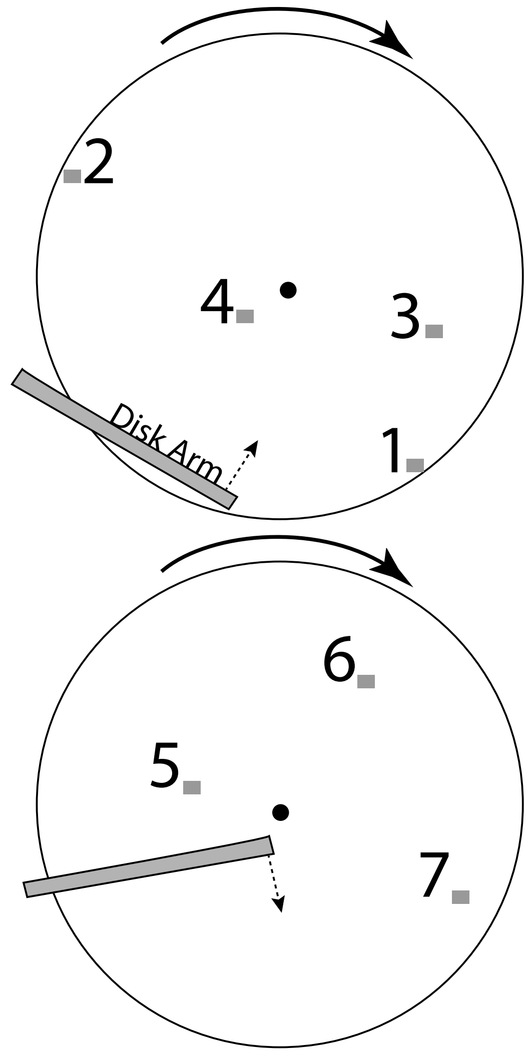
Size	
Platters/Heads	2/4
Capacity	320 GB
Performance	
Spindle speed	7200 RPM
Average seek time read/write	10.5 ms/ 12.0 ms
Maximum seek time	19 ms
Track-to-track seek time	1 ms
Transfer rate (surface to buffer)	54–128 MB/s
Transfer rate (buffer to host)	375 MB/s
Buffer memory	16 MB
Power	
Typical	16.35 W
Idle	11.68 W

Q&A

- How long to complete 500 random disk reads, in FIFO order?
  - 14 ms/read (avg seek + ½ rotation)
  - 70 random 512 byte reads/second
- How long to complete 500 sequential disk reads?
  - 16 ms/500 reads (avg seek + ½ rotation + transfer)
  - 60 random 250KB reads/second
- How large a transfer is needed to achieve 80% of the max disk transfer rate?
  - 10 MB

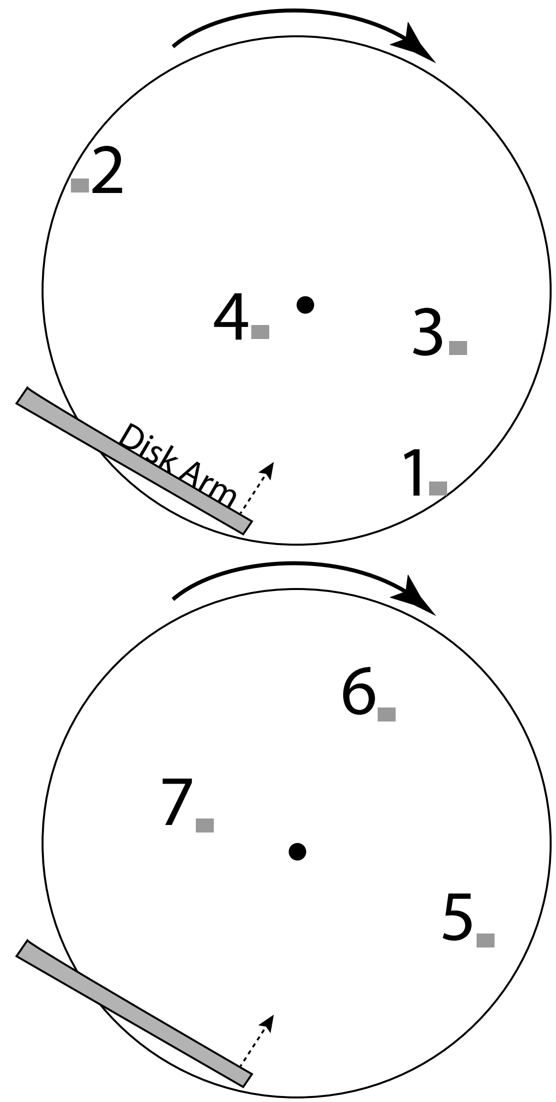
Disk Scheduling

- SCAN: move disk arm in one direction, until all requests satisfied, then reverse direction



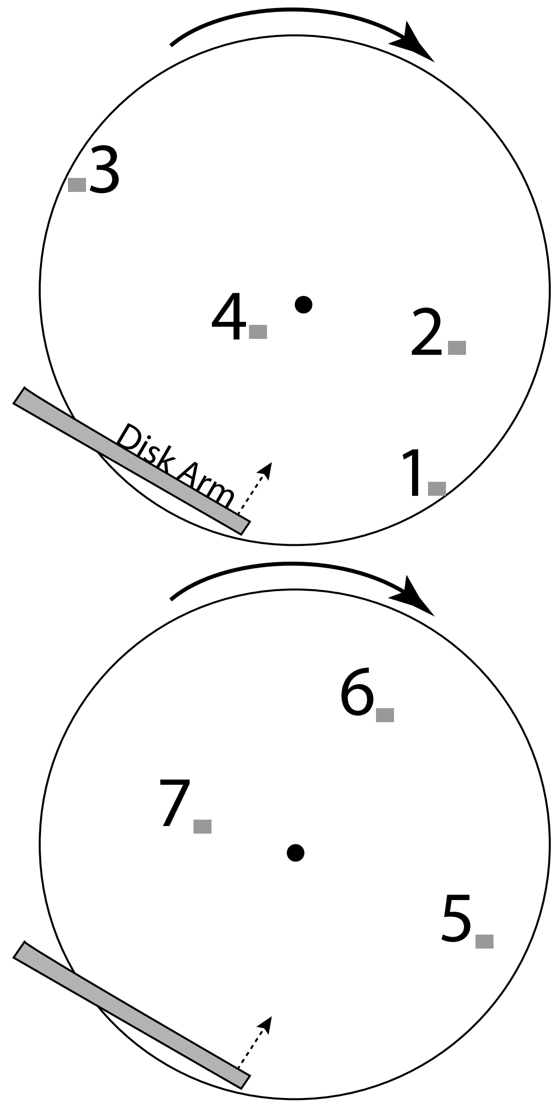
Disk Scheduling

- CSCAN: move disk arm in one direction, until all requests satisfied, then start again from farthest request



Disk Scheduling

- R-CSCAN: CSCAN but take into account that short track switch is < rotational delay



Question

- How long to complete 500 random disk reads, in any order?

Question

- How long to complete 500 random disk reads, in any order?
  - Disk seek: 1ms (most will be short)
  - Rotation: 4.15ms
  - Transfer: 5-10usec
- Total: 500 * (1 + 4.15 + 0.01) = 2.2 seconds
  - Would be a bit shorter with R-CSCAN
  - vs. 7.3 seconds if FIFO order

Question

- How long to read all of the bytes off of a disk?

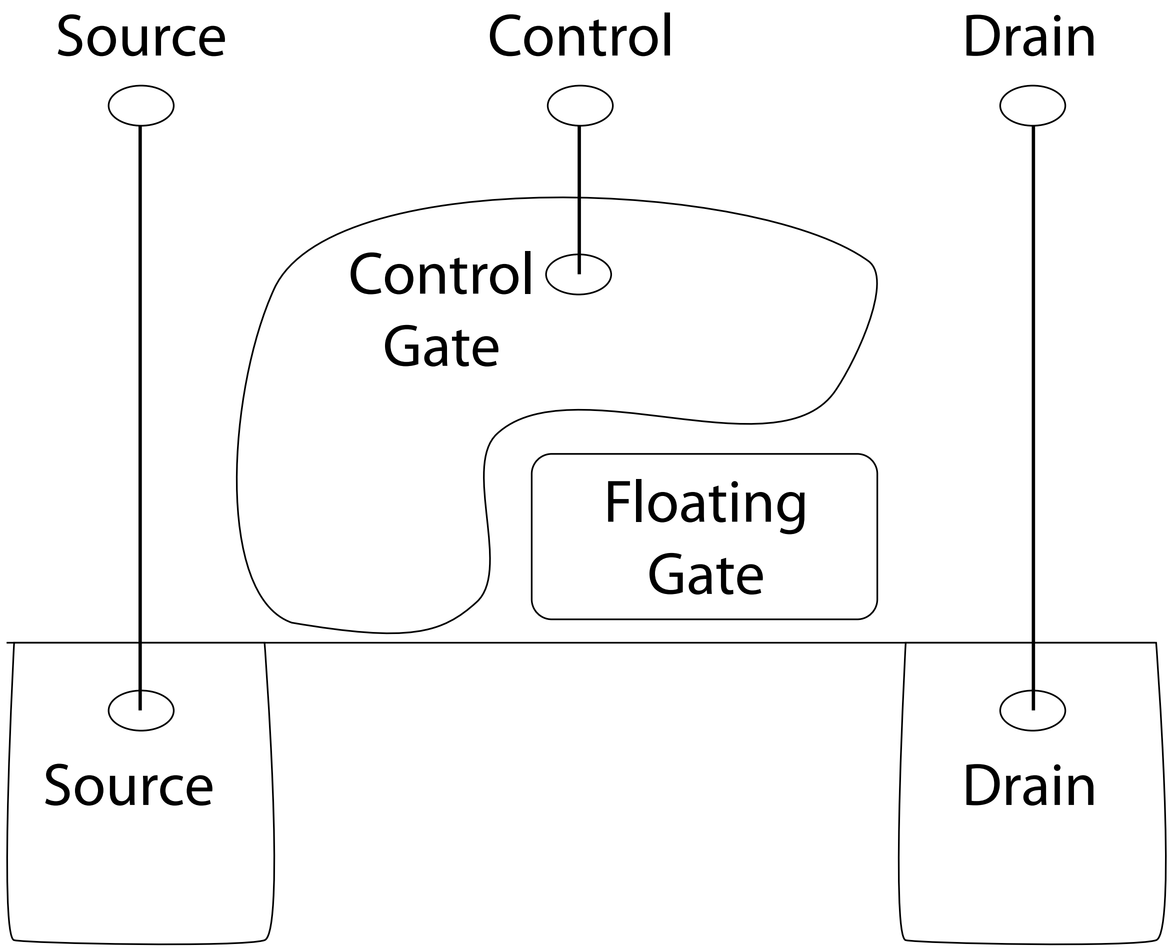
Question

- How long to read all of the bytes off of a disk?
  - Disk capacity: 320GB
  - Disk bandwidth: 54-128MB/s
- Transfer time =

  Disk capacity / average disk bandwidth

  ~ 3500 seconds (1 hour)

Flash Memory



Flash Memory

- Writes must be to “clean” cells; no update in place
  – Large block erasure required before write
  – Erasure block: 128 – 512 KB
  – Erasure time: Several milliseconds
- Write/read page (2-4KB)
  – 50-100 usec

Flash Drive (2011)

Size	
Capacity	300 GB
Page Size	4KB
Performance	
Bandwidth (Sequential Reads)	270 MB/s
Bandwidth (Sequential Writes)	210 MB/s
Read/Write Latency	75 μs
Random Reads Per Second	38,500
Random Writes Per Second	2,000 (2,400 with 20% space reserve)
Interface	SATA 3 Gb/s
Endurance	
Endurance	1.1 PB (1.5 PB with 20% space reserve)
Power	
Power Consumption Active/Idle	3.7 W / 0.7 W

Question

- Why are random writes so slow?
  - Random write: 2000/sec
  - Random read: 38500/sec

Flash Translation Layer

- Flash device firmware maps logical page # to a physical location
  - Move live pages as needed for erasure
    - Garbage collect empty erasure block by copying live pages to new location
  - Wear-levelling
    - Can only write each physical page a limited number of times
  - Avoid pages that no longer work
- Transparent to the device user

File System – Flash

- How does Flash device know which blocks are live?
  - Live blocks must be remapped to a new location during erasure
- TRIM command
  - File system tells device when pages are no longer in use

File System Workload

- File sizes
  - Are most files small or large?
  - Which accounts for more total storage: small or large files?

File System Workload

- File sizes
  - Are most files small or large?
    - SMALL
  - Which accounts for more total storage: small or large files?
    - LARGE

File System Workload

- File access
  - Are most accesses to small or large files?
  - Which accounts for more total I/O bytes: small or large files?

File System Workload

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File System Workload

- How are files used?
  - Most files are read/written sequentially
  - Some files are read/written randomly
    - Ex: database files, swap files
  - Some files have a pre-defined size at creation
  - Some files start small and grow over time
    - Ex: program stdout, system logs

File System Design

- For small files:
  - Small blocks for storage efficiency
  - Concurrent ops more efficient than sequential
  - Files used together should be stored together
- For large files:
  - Storage efficient (large blocks)
  - Contiguous allocation for sequential access
  - Efficient lookup for random access
- May not know at file creation
  - Whether file will become small or large
  - Whether file is persistent or temporary
  - Whether file will be used sequentially or randomly

File System Design

- Data structures
  - Directories: file name -> file metadata
    - Store directories as files
  - File metadata: how to find file data blocks
  - Free map: list of free disk blocks
- How do we organize these data structures?
  - Device has non-uniform performance

Design Challenges

- Index structure
  - How do we locate the blocks of a file?
- Index granularity
  - What block size do we use?
- Free space
  - How do we find unused blocks on disk?
- Locality
  - How do we preserve spatial locality?
- Reliability
  - What if machine crashes in middle of a file system op?

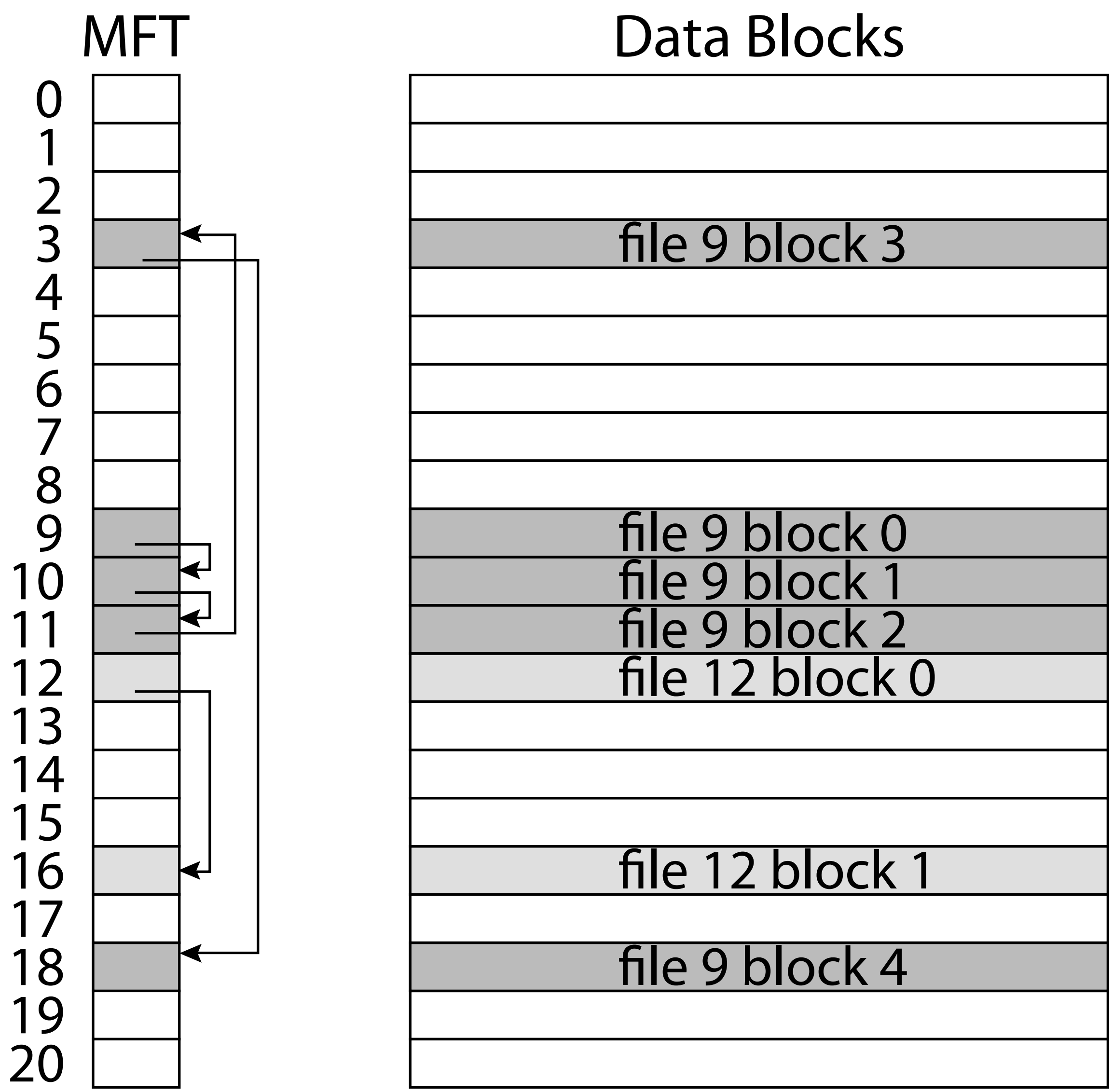
File System Design Options

	FAT	FFS	NTFS
Index structure	Linked list	Tree (fixed, assym)	Tree (dynamic)
granularity	block	block	extent
free space allocation	FAT array	Bitmap (fixed location)	Bitmap (file)
Locality	defragmentation	Block groups + reserve space	Extents Best fit defrag

Microsoft File Allocation Table (FAT)

- Linked list index structure
  - Simple, easy to implement
  - Still widely used (e.g., thumb drives)
- File table:
  - Linear map of all blocks on disk
  - Each file a linked list of blocks

FAT


MFT
Data Blocks
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
file 9 block 3
file 9 block 0
file 9 block 1
file 9 block 2
file 12 block 0
file 12 block 1
file 9 block 4

FAT

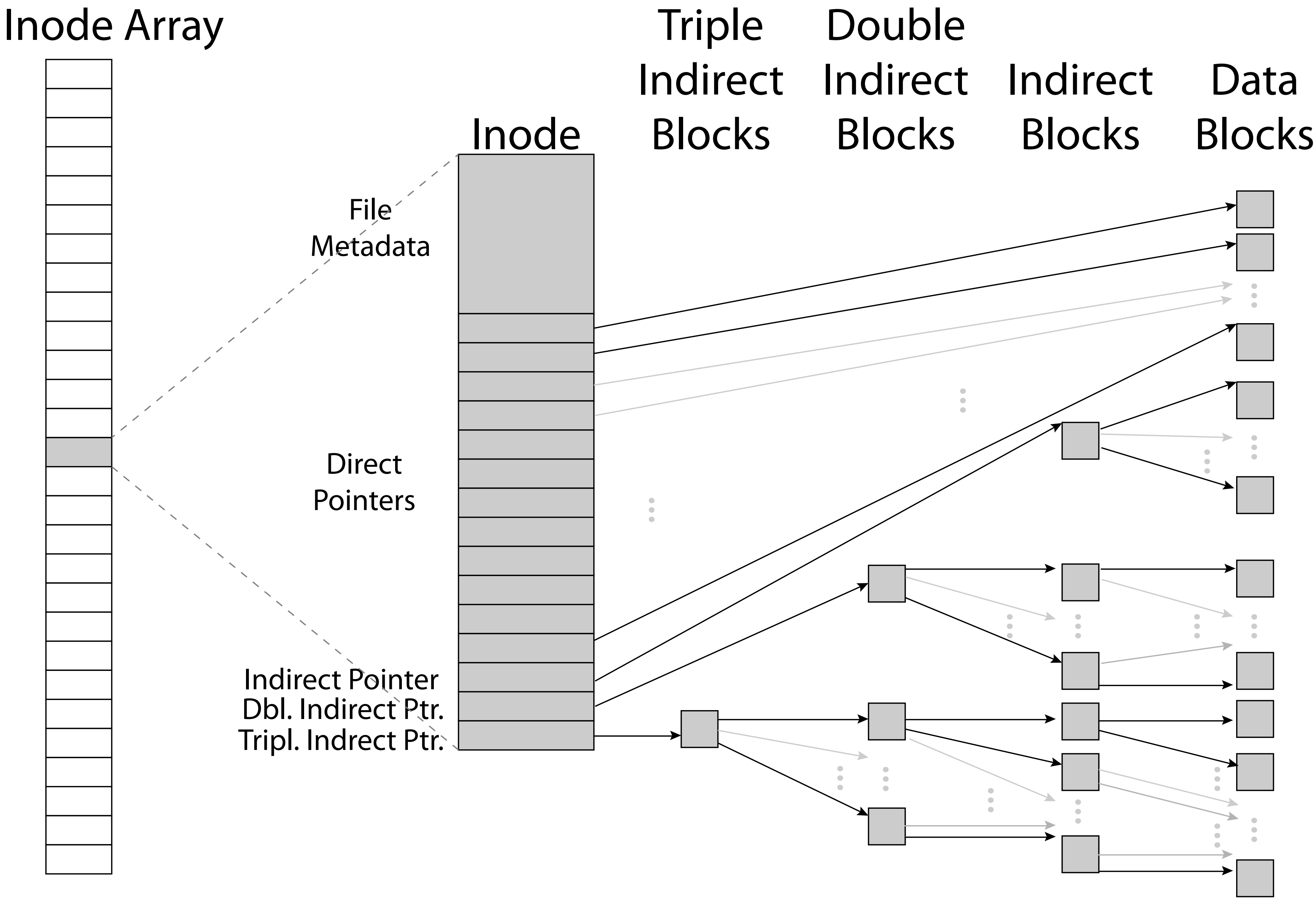
- Pros:
  - Easy to find free block
  - Easy to append to a file
  - Easy to delete a file
- Cons:
  - Random access is very slow
  - Fragmentation
    - File blocks for a given file may be scattered
    - Files in the same directory may be scattered
    - Problem becomes worse as disk fills

Berkeley FFS (Fast File System)

- File metadata: inode table
  - similar to FAT table, except only for metadata
- File data: Assymetric tree
  - Small files: shallow tree
  - Large files: deep tree
  - Efficient storage for small files
  - Efficient lookup for random access in large files

FFS inode

- Metadata
  - File owner, access permissions, access times, …
- Set of 12 data pointers
  - With 4KB blocks => max size of 48KB files
- Indirect block pointer
  - pointer to disk block of data pointers
  - 4KB block size => 1K data blocks => 4MB file
- Doubly indirect block pointer
  - 4GB file
- …



Inode Array
Inode
Triple Indirect Blocks
Double Indirect Blocks
Indirect Blocks
Data Blocks
File Metadata
Direct Pointers
Indirect Pointer
Dbl. Indirect Ptr.
Tripl. Indrect Ptr.

FFS Locality

- File metadata spread throughout disk
  - Locate file metadata near file blocks
- First fit allocation
  - Small files fragmented, large files contiguous
- Block group allocation
  - Files in same directory located in nearby tracks