csci 3411: Operating Systems

File Systems

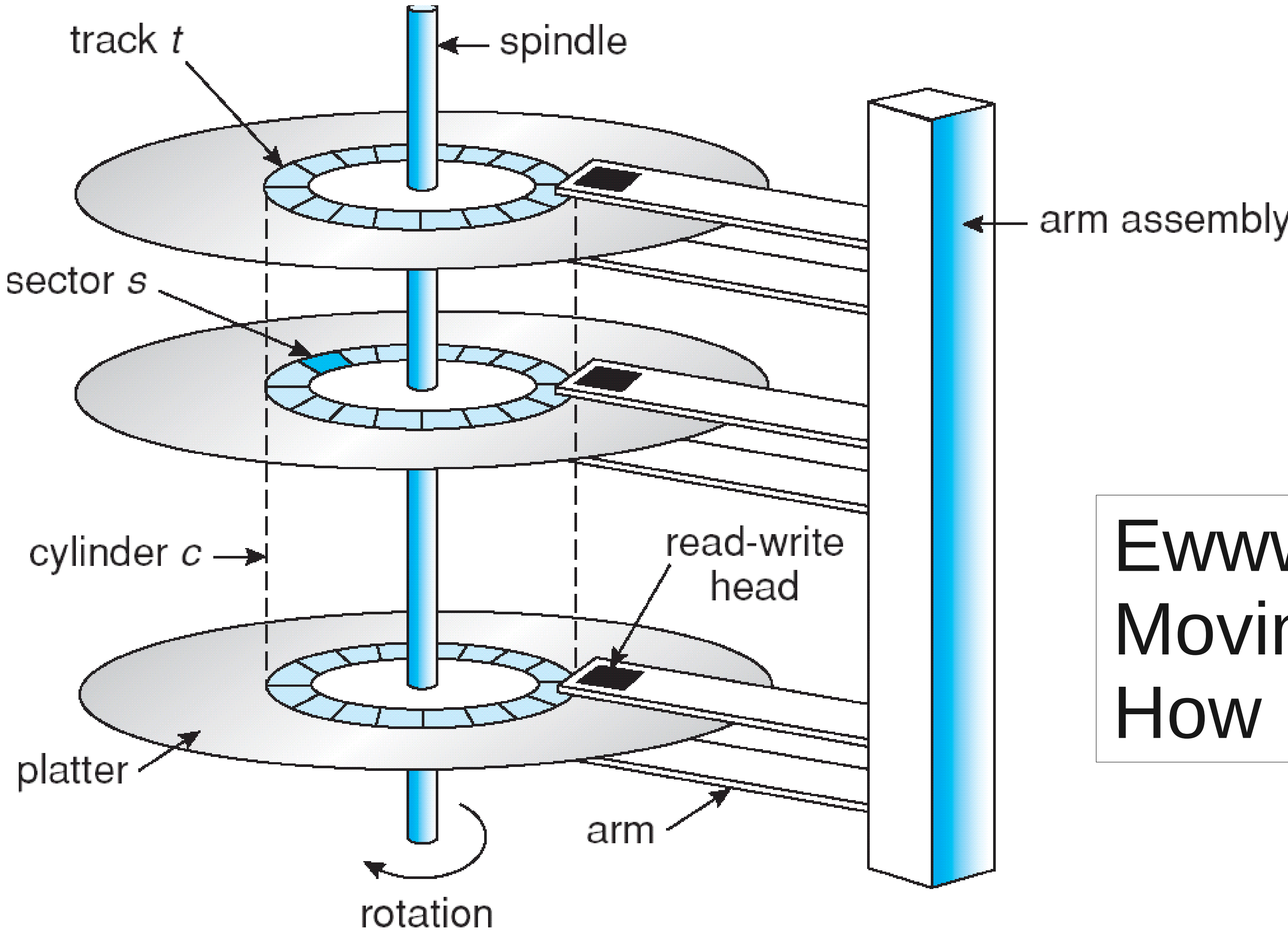
Gabriel Parmer

Slides evolved from Silberschatz

Today: File System Implementation

- We discussed
  - *abstractions* for organizing persistent storage
  - *interfaces* for programming the storage
- Today: How do we make these abstractions and interfaces efficient
  - Best utilize the capacity of the persistent storage
    - Throughput (MB/sec to/from the storage)
    - Latency to retrieve/store data
    - Space utilization: minimize fragmentation in storage

Magnetic Media (Disk)



Ewww, Yuck!
Moving Parts!
How Barbaric.

Magnetic Media II

- *Blocks* – granularity of I/O as seen by OS
  - Multiple of sector size
    - (block size = page size) is convenient (i.e. 4KB)
- Accessed by OS as 1d array of blocks
- Disks can process I/O requests in *parallel*
  - Many I/O requests for blocks can be pending at a given time

Magnetic Media III

- Disks are slow!
  - ~10ms latency to access a block[1]
    - Versus 0.0002ms to access to memory
    - Versus 0.000001ms to access to register
- Minimize frequency of disk access!

[1] http://www.anandtech.com/printarticle.aspx?i=3403

Caching!

- Paging (page cache) treats disk as extension of the storage hierarchy
  - When we didn't have enough memory, write out to disk
- *Buffer cache* holds file's data, treats memory as a cache for disk data
  - Minimize frequency of slow disk accesses, so cache file data in memory
  - When read/writes are made to files, cache the file's data
    - Further accesses to that file will check if it is in cache
    - Memory accesses instead of disk accesses

Disks: Not just slow, *Complex*

- Seeks between cylinders are *expensive*
  - Random vs. sequential access
- Sequential access[1,2] – platter rotation
  - 80MB/s bandwidth
  - 0.16ms latency
- Random access[2] – head seeks
  - 0.5MB/s bandwidth
  - 10ms latency
  - All sorts of fail

[1] http://www.anandtech.com/printarticle.aspx?i=3403
[2] http://it.anandtech.com/printarticle.aspx?i=3532

Major Filesystem Questions

- How can we track
  - Where different files are on disk
  - Where the directory structure is stored

- Where free space is on disk to satisfy allocations
  - extending/creating files/directories

- How can we do this while compensating for the physical characteristics of disks?

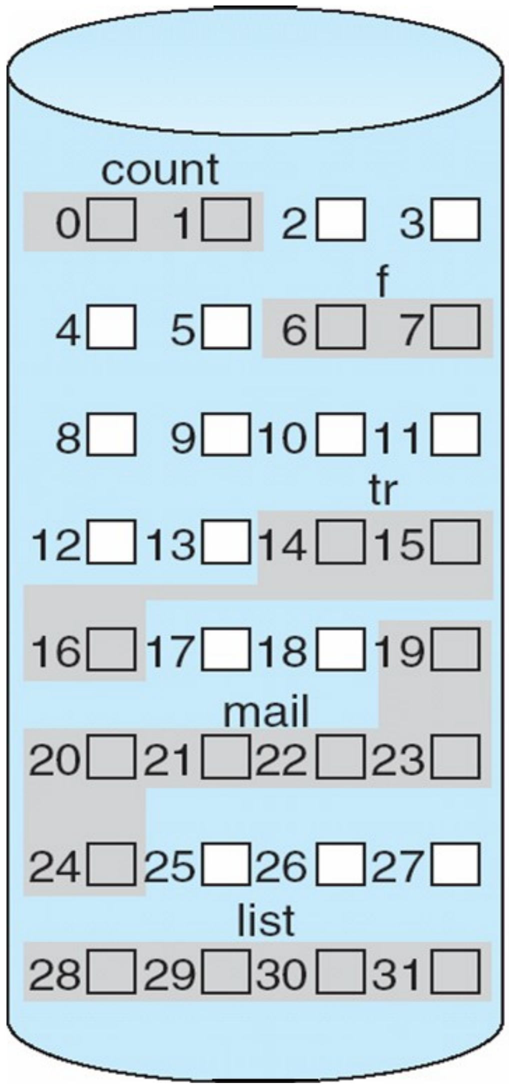
Files → Disk Blocks

- File – Logical storage unit
  - Sequence of bytes from 0 → FILE_SIZE
- Disk
  - Essentially large array of bits 0 → VERY_BIG
- Many files on disk
  - Analogy: many processes with virtual memory share single physical memory
- *How do we map from a location in a file, to a location on disk?*
  - Similar to: How do we map from an address in a virtual address space into a physical address?
  - But we have no MMU/hardware support

Contiguous Allocation

- Directory entry has
  - Each file described by a <start, length> pair
    - Where is the location of the 100th byte of a file?
    - Similar to segmentation

Contiguous Allocation II



directory

file	start	length
count	0	2
tr	14	3
mail	19	6
list	28	4
f	6	2

Contiguous Benefits/Problems?

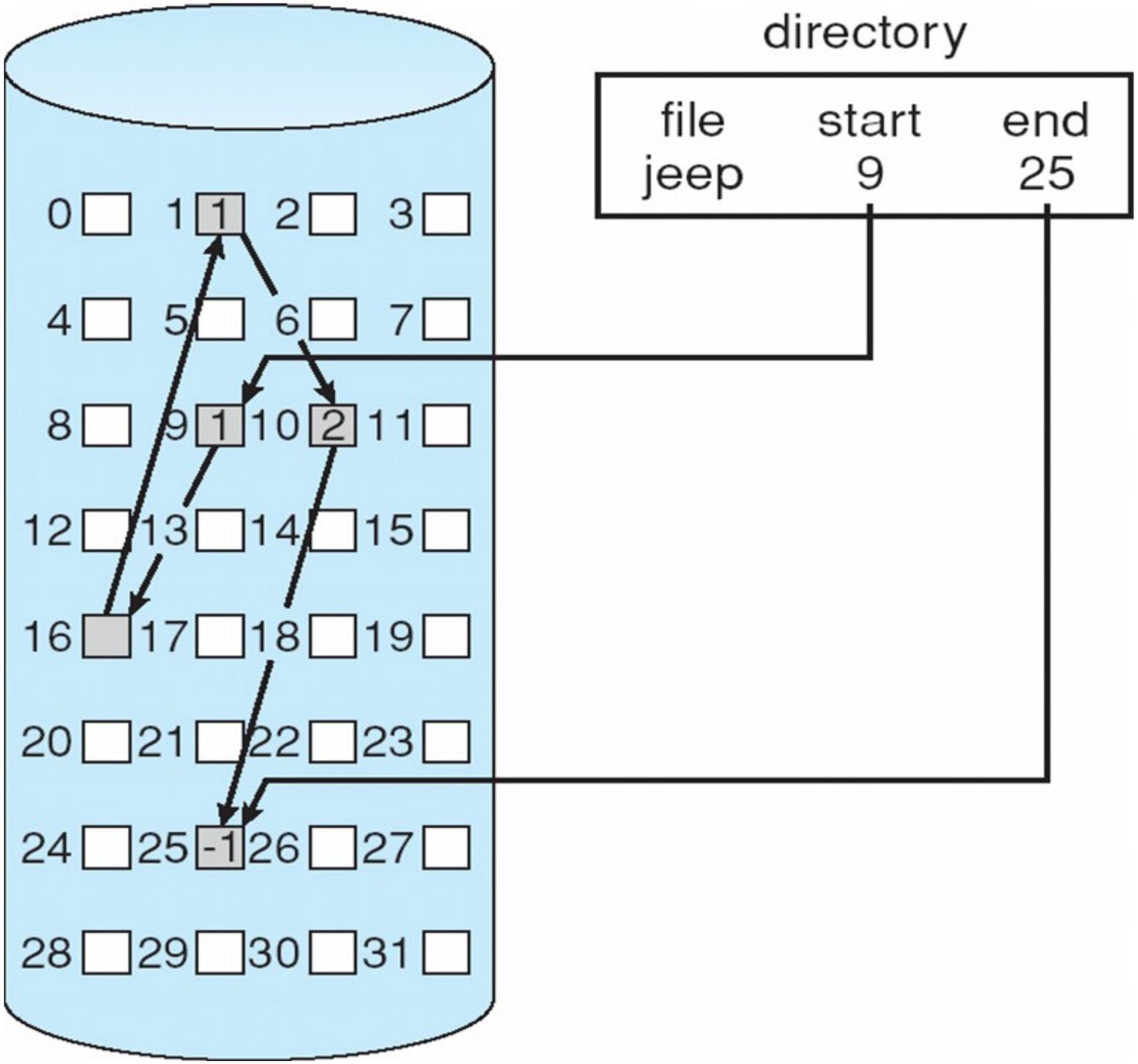
- File Access: Random/Sequential access?
- Disk Access: Seeks vs. rotation?

- Allocating files? What size?
  - First-fit, best-fit
- Growing files?
  - Didn't have this with memory mgmt!
- Fragmentation?
  - compaction/defragmentation

Linked Allocation

- File represented as a linked list of blocks
- Each block holds both
  - Data
  - Block number of next block in file
- Directory contains
  - A file's <start, end> blocks

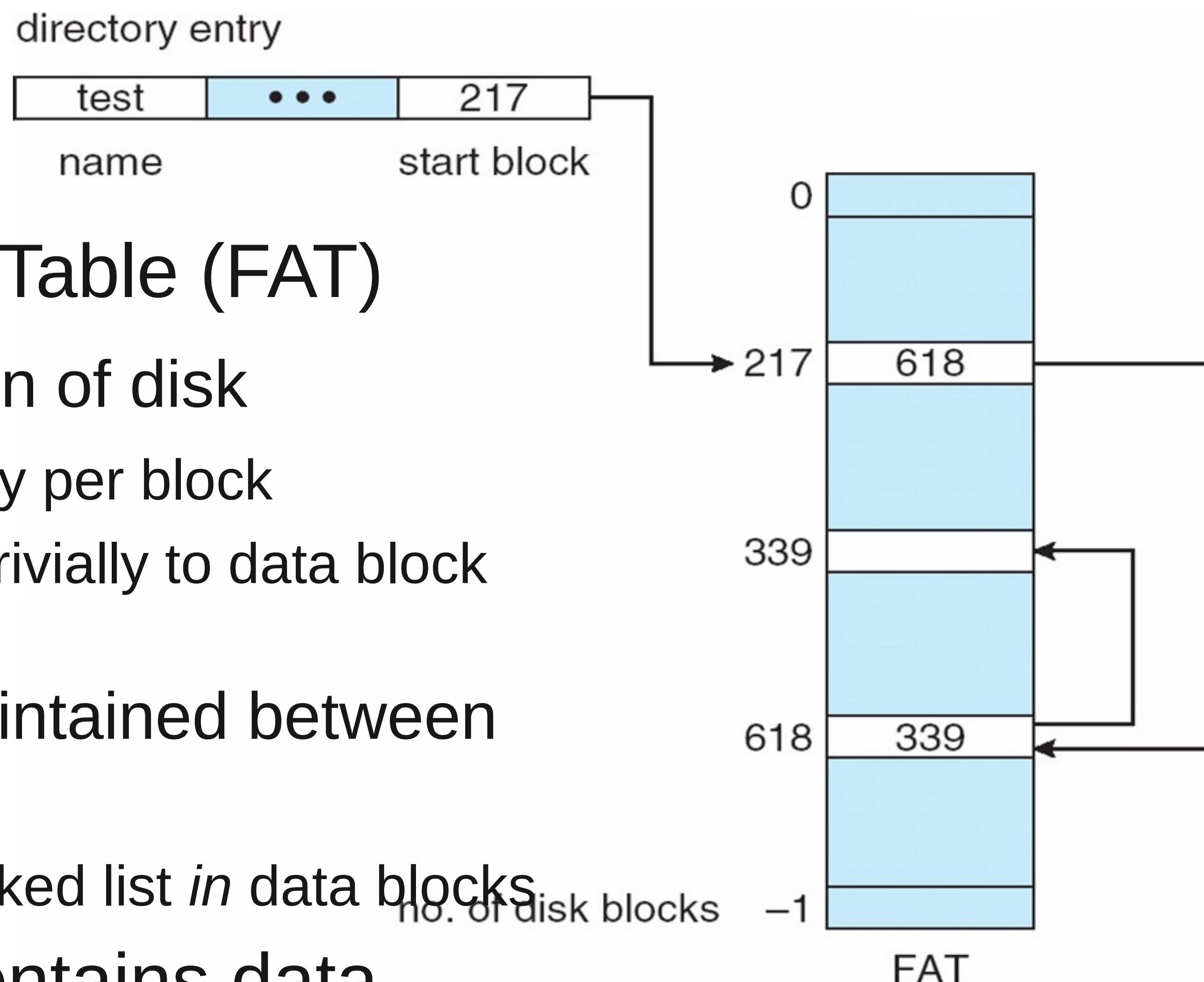
Linked Allocation II



Linked Benefits/Problems?

- Space usage for links?
- Fragmentation?
- Random/Sequential Access?
- Seeks vs. Rotation?
- Block allocation?

Not so FAT



- File Allocation Table (FAT)
  - Special section of disk
    - Has one entry per block
    - Entry maps trivially to data block on disk
  - Linked list maintained between these entries
    - Instead of linked list *in* data blocks
- Rest of disk contains data-blocks

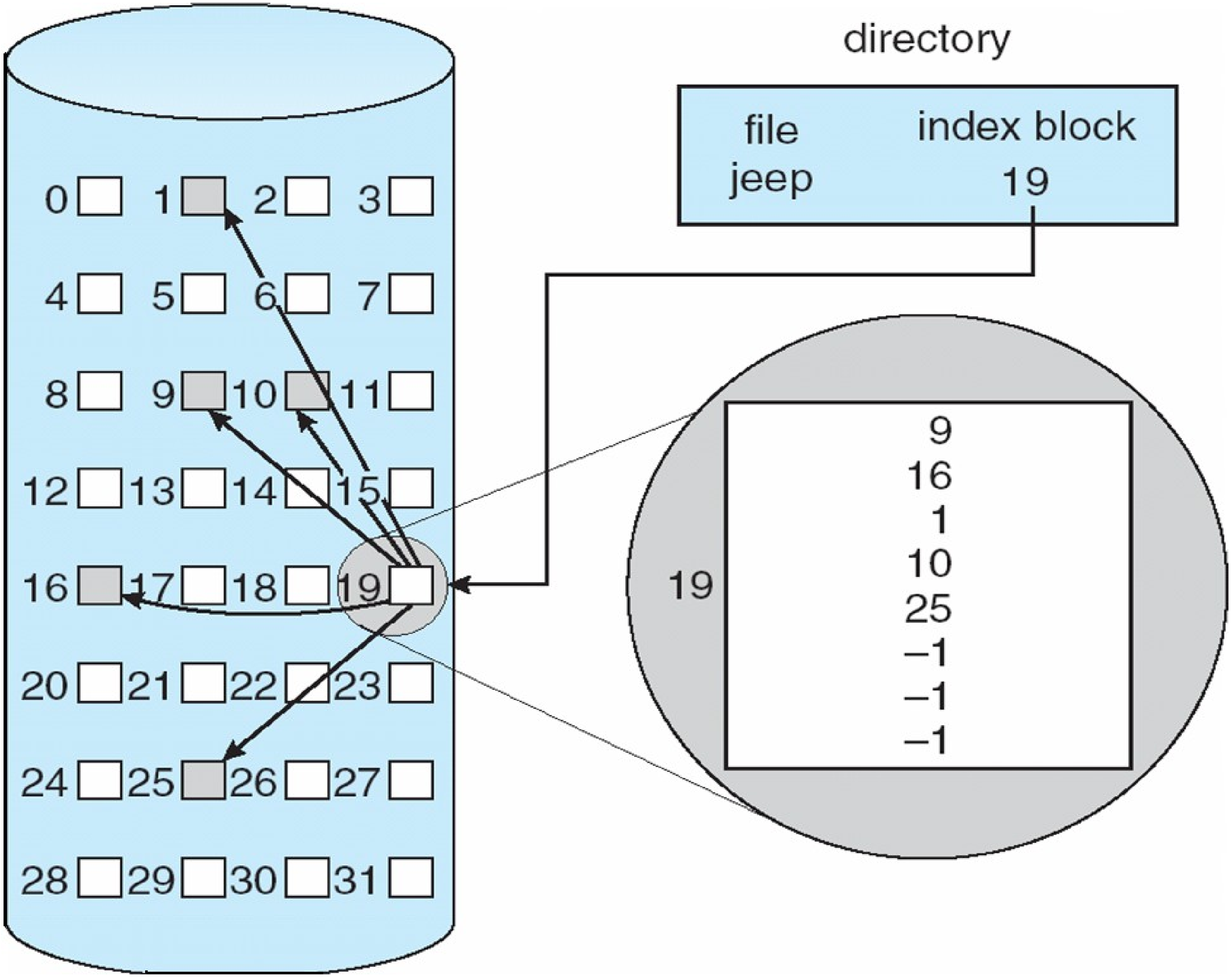
FAT Benefits/Problems?

- Space usage?
- Number of disk accesses to read
  - One data block?
  - Two data blocks?
- Sequential/Random Access?
- Seeks vs. Rotation?

Indexed Allocation

- Directory includes block location of *index*
- *Index* is an array entries containing the locations of the blocks of that file
  - Like a single-level page-table

Indexed Allocation II



Indexed Allocation III

- Block size = 100B, index holds 10 entries
  - File can be 100 * 10 = 1000B long
  - Which block contains file offset 365?

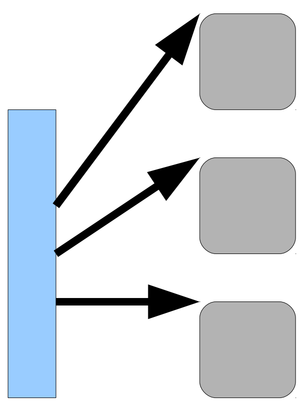
- Block size = 2^{12}B, index holds 2^{8} entries
  - File can be $2^{12} * 2^{8} = 2^{(12+8)} = 2^{20}$ bytes long
  - To find the block containing the 0xBEEF offset in the file
    - Values larger than 2^{12} = 0xB000
    - Look for entry number 0xB = 11 in the index to find the block
    - Desired data at 0x0EEF offset into block

Indexed Allocation Benefits/Probs?

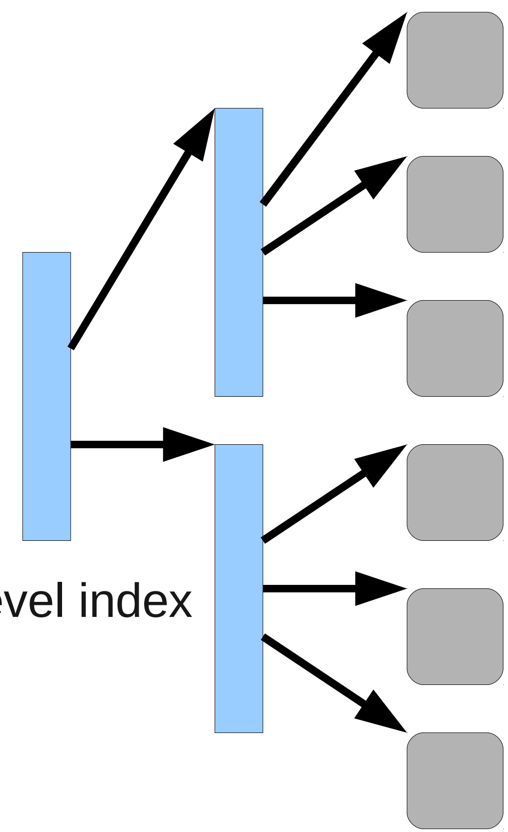
- File Size?
  - Can support larger file sizes by linking together indices
    - *linked indices*
  - One entry in an index is the location of the *next* index
- Space overhead?
  - Space used – One block index with *N* entries
    - file w/ 1 block? File with N blocks?
- How many disk accesses must we make to retrieve data blocks?
- Seeks vs. Rotation?
- Random Access within file?
- Fragmentation/Block Allocation?

Multilevel Index

- Like multilevel page-tables
- An index block contains entries of locations of
  - other index blocks which contain entries of locations of
    - File data



Single level index



Multi-level index

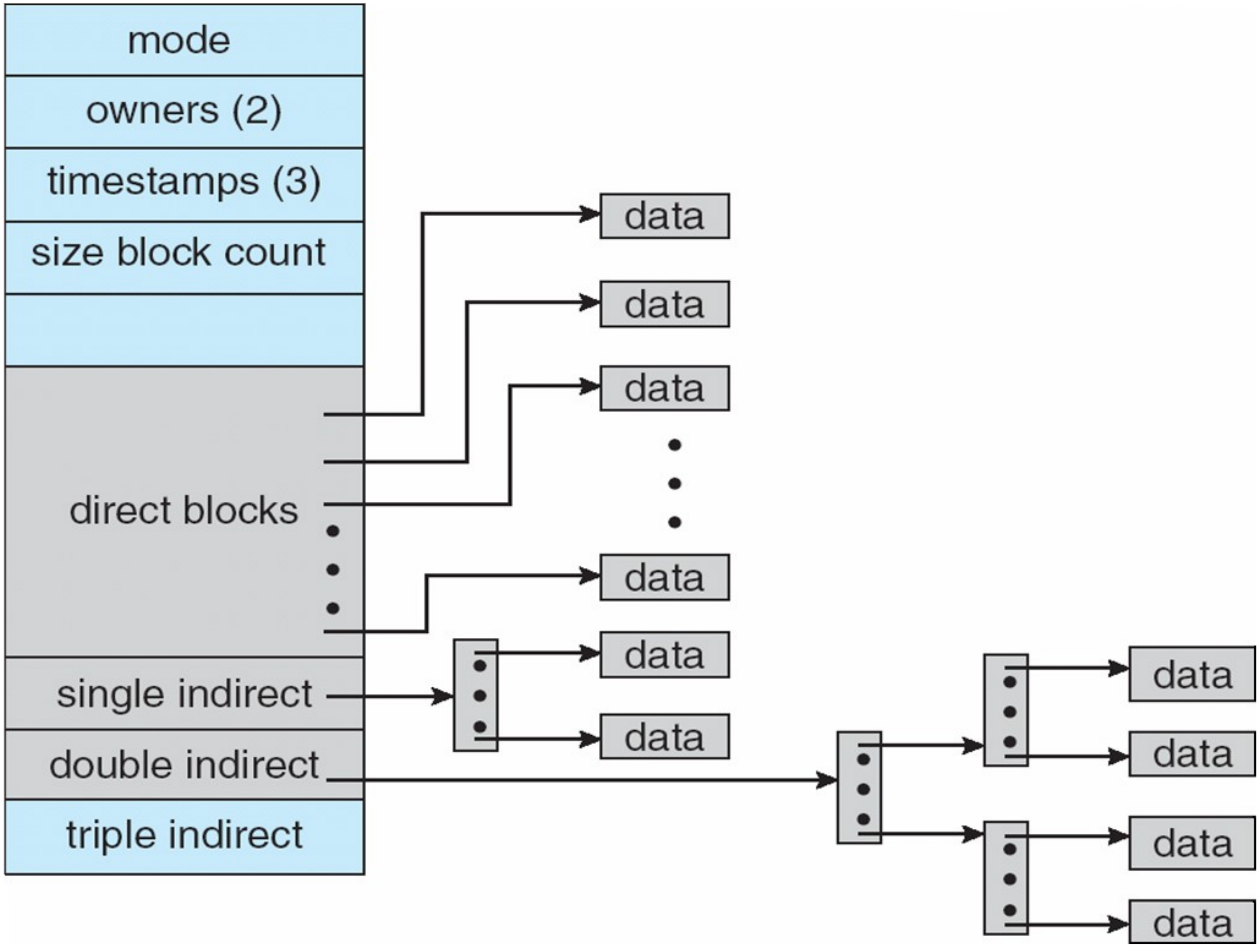
Multilevel Index Pros/Cons?

- How many disk accesses must we make to retrieve data blocks?
  - Sequential access, random access?
- File size?
  - *M* entries per index
  - *N* levels of index nodes
  - How many blocks can be addressed?

Combined Index Scheme

- Index contains
  - *N direct* references to data blocks
  - *M indirect* (or *single indirect*) references to second level indices
    - That each refer to data blocks
  - *X double indirect* references to second lvl indexes
    - That refer to third level indexes
    - That refer to data blocks
  - *Y triple indirect* references to second level indexes
    - That refer to third level indexes
    - That refer to fourth level indexes
    - That refer to data blocks

UFS/ext2/... Indices



Combined Index Pros/Cons?

- File size (blocks with *W* entries, 4K per block)?
  - *N direct* references to data blocks
  - *M single indirect* entries
  - *X double indirect* entries
  - *Y triple indirect* entries
  - *Z* entries per “multilevel” index
- Random/Sequential Access?
- Space overhead?

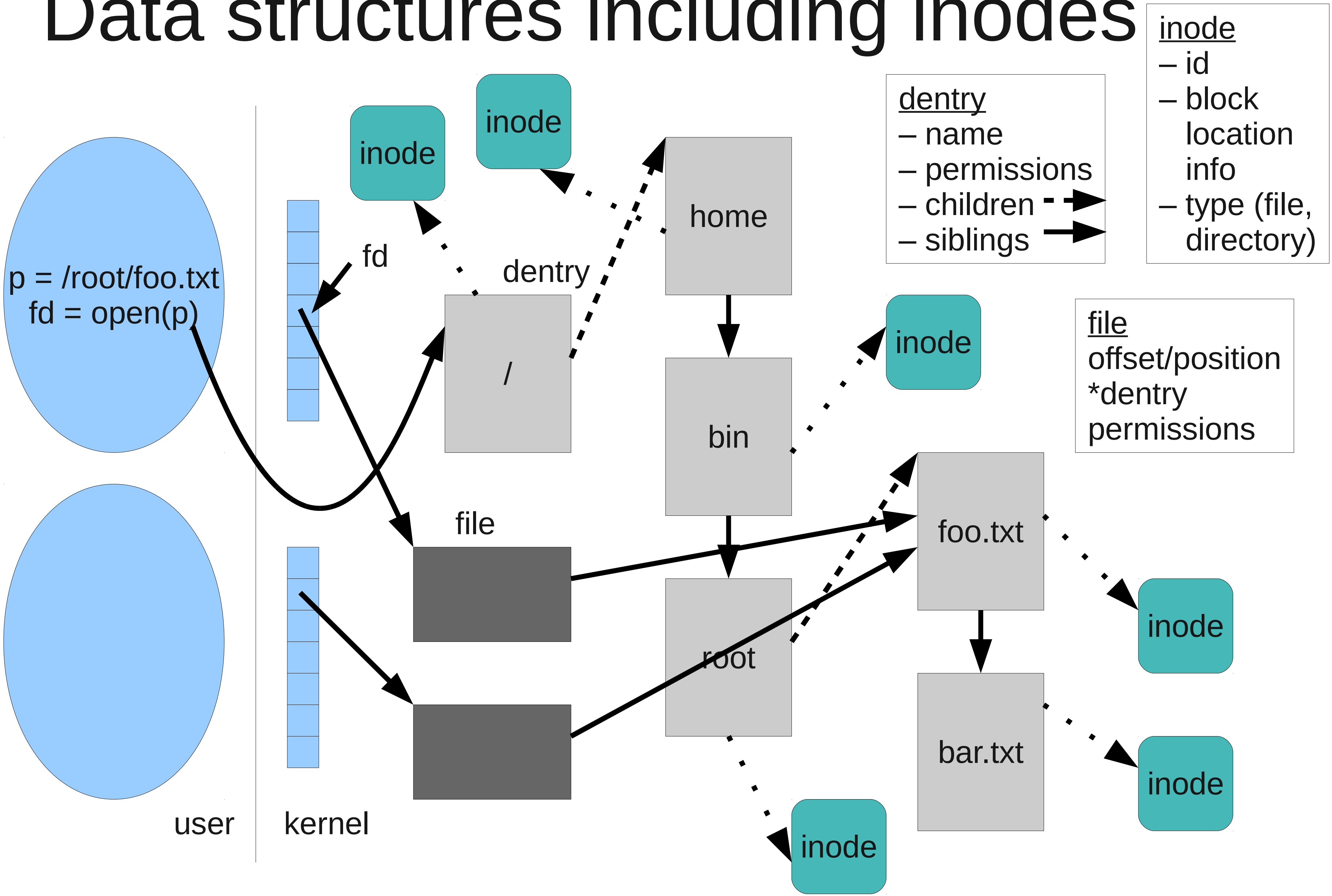
Extents

- Technique can be added to each of the preceding data-structures
- Rotation vs. seek benefit of contiguous allocation
  - None of the other methods had that benefit!!!
- Don't just refer to blocks (index or data) in index
  - Index entry: <base, length> pair
    - instead of just <base>
  - Can read *length* blocks without seeks!
- Can complicate random access
- Makes index entries larger to store *length*

inodes

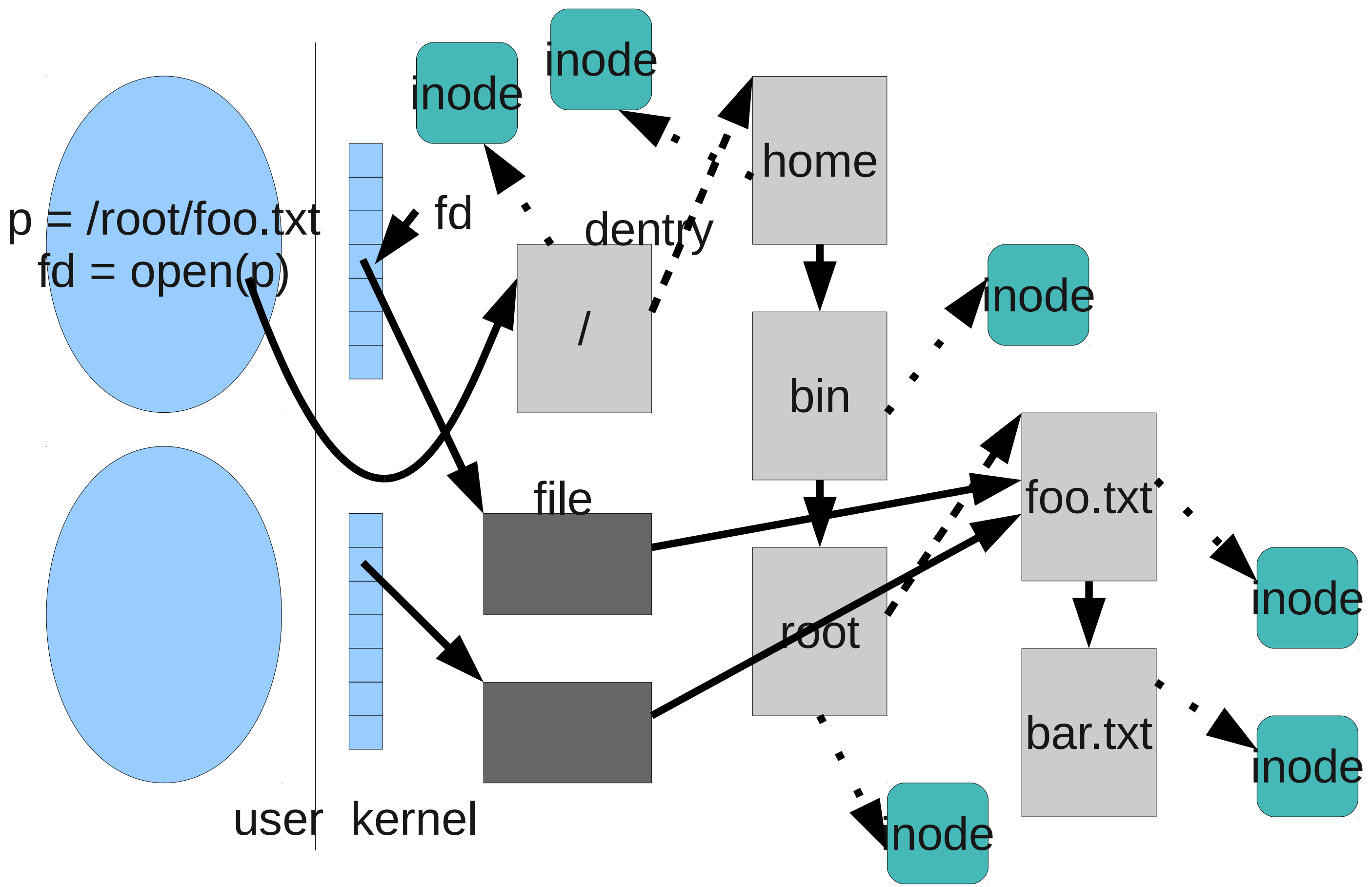
- Both file contents and directory structure are stored using these techniques
  - Directory data blocks include data about subdirectories
- UNIX/Linux in-memory data structure used for tracking the location of on-disk objects
  - Individual inodes represent either files or directories
  - Each inode has a unique identifier
    - `ls -i`
    - Often the location on disk that inode is located at
  - Includes location of that file's/directory's blocks

Data structures including inodes



Perspective

- How many disk accesses can it take to open /root/bar.txt?
- Disks satisfy about 100 serial accesses per second

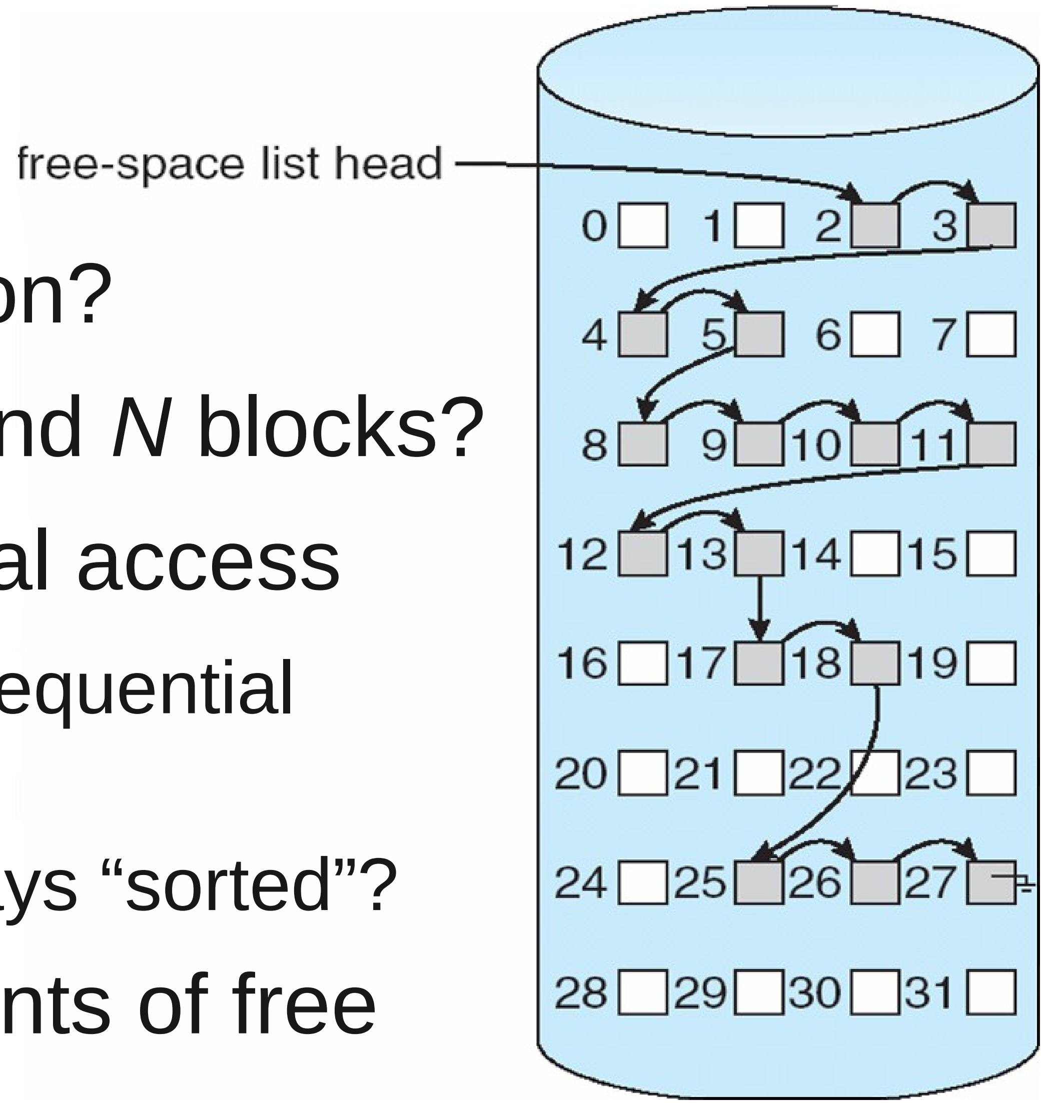


Free Space Tracking

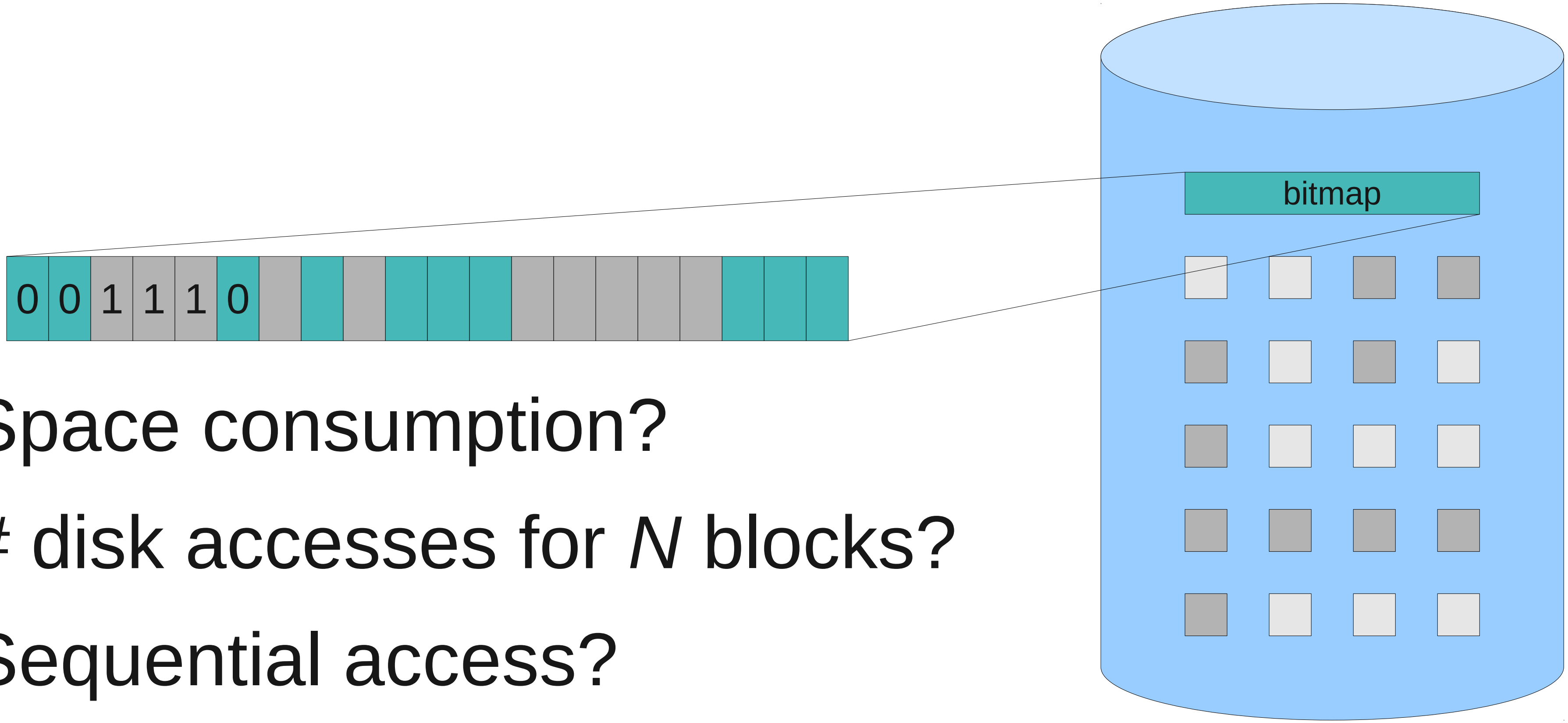
- A file/directory is created or grows when written to
- How do we find free blocks to allocate to it?

Free Space Tracking: Linked List

- Space consumption?
- # disk access to find *N* blocks?
- Promote sequential access
  - Easy to allocate sequential blocks?
  - Is the freelist always "sorted"?
- Optimization: extents of free blocks



Free Space Tracking: Bitmaps



- Space consumption?
- # disk accesses for *N* blocks?
- Sequential access?
  - Find contiguous blocks easily?