slides kindly provided by:

Tam Vu, Ph.D
Professor of Computer Science
Director, Mobile & Networked Systems Lab
Department of Computer Science
University of Colorado Boulder

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Christopher Godley
PhD Student
Department of Computer Science
University of Colorado Boulder

File System

What is a File?

- Logical unit of data
- Sequence of bytes mapped into storage
- Abstract Object with a defined API
- Applications must interpret the meaning of the actual data – not the file system.

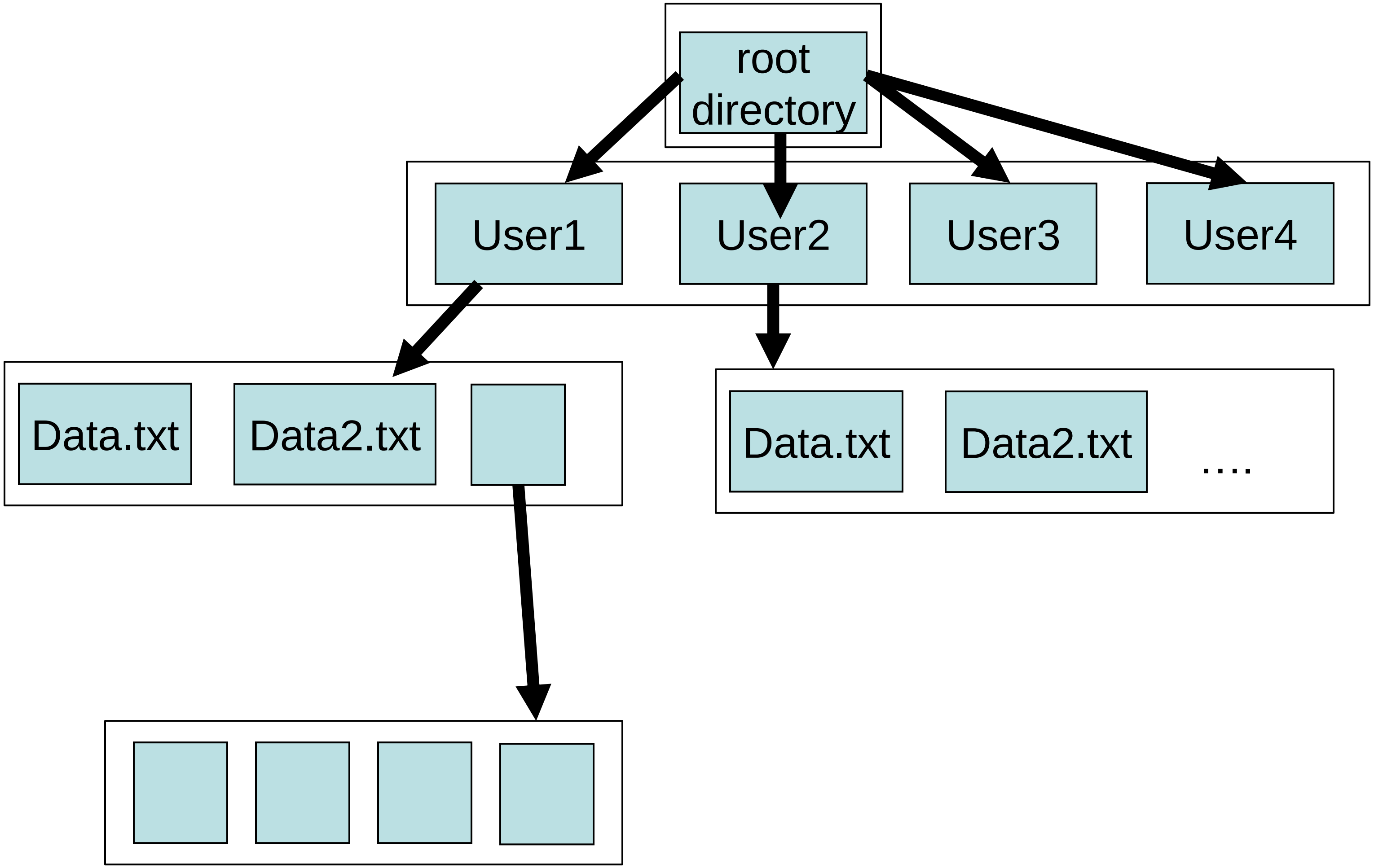
What is a File System?

- Contains set of files
- Provides additional attributes per file
  - Name
  - Unique system ID
  - Size
  - Access Rights
  - Timing information
  - Type
  - Creator
  - ….and more…
- Provides access to the files via API
  - Create
  - Delete
  - Copy
  - Move
  - Rename

  - Sequential
  - Direct/Random

  - Open
  - Read
  - Write
  - Seek
  - Append
  - Truncate

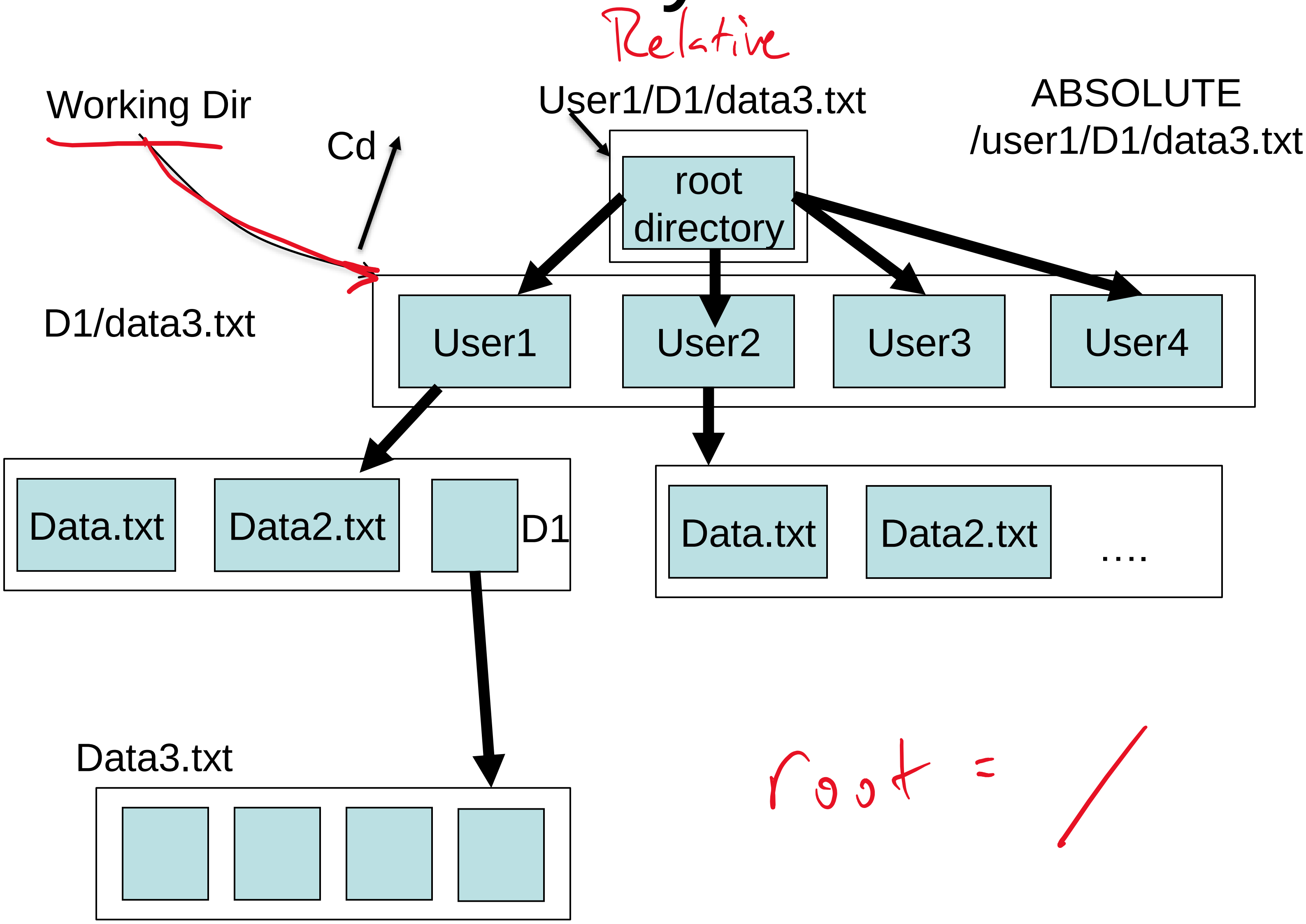
Organization of Files



Directory Structure

- File system stores information about all files and directories in a *directory structure* that is also stored on disk/flash
- Directory structures:
  1. Single Level (flat) Directory
  2. Two Level Directory
  3. Tree-structured Directories

Directory Structure



Relative

User1/D1/data3.txt

ABSOLUTE

/user1/D1/data3.txt

Working Dir

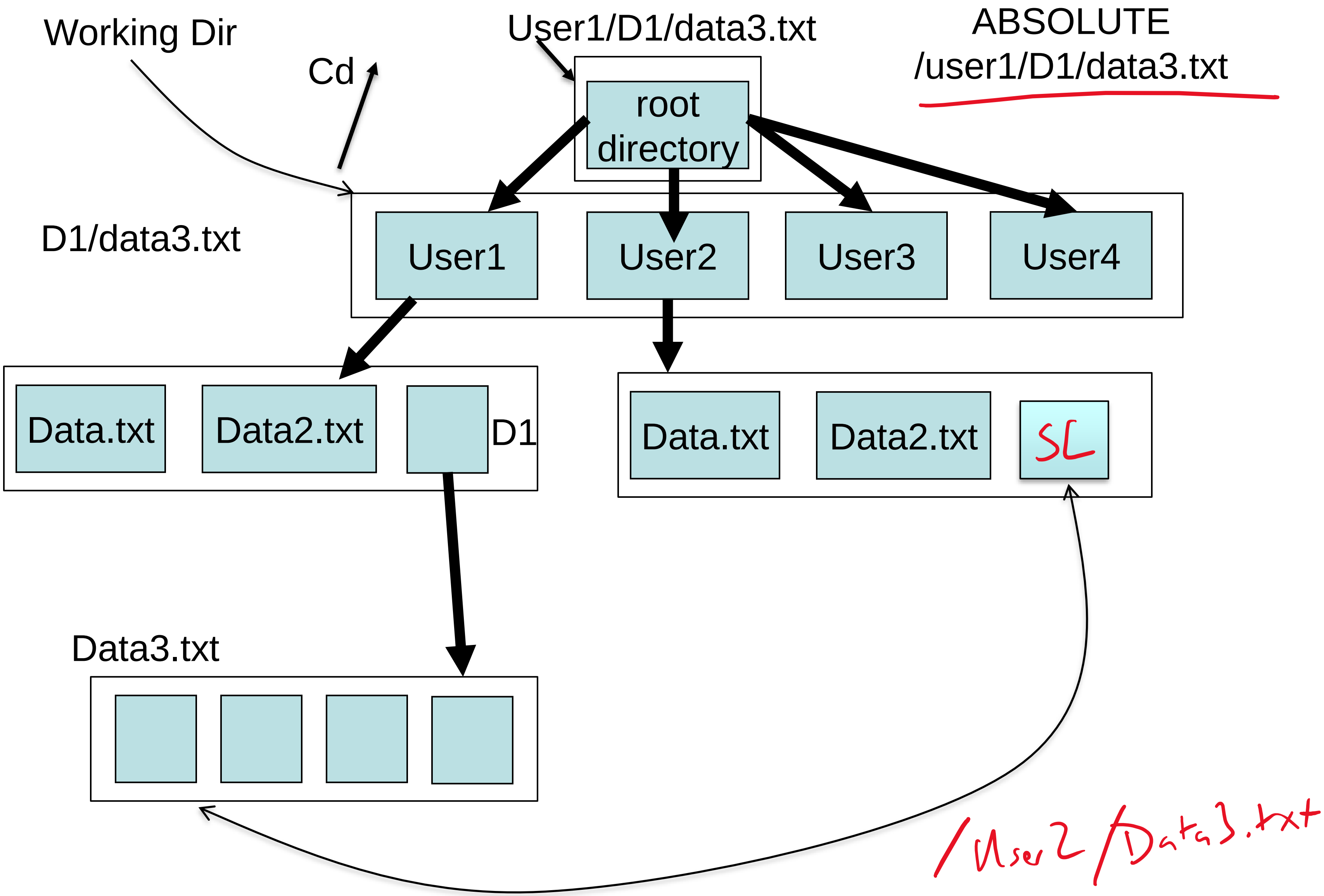
Cd

D1/data3.txt

Data3.txt

root = /

Sharing Files



Sharing File - Symbolic Links

- a symbolic link is not a file
  - it is a pointer to a file
  - so operations on a link behave differently than operations on a file

- when searching for a file through the directory tree, the OS needs to avoid cycles, because otherwise it will search endlessly
  - One policy is to avoid traversing any symbolic links. This policy avoid cycles
  - or the OS could keep a record of all visited directories to avoid revisiting the same directory – expensive!

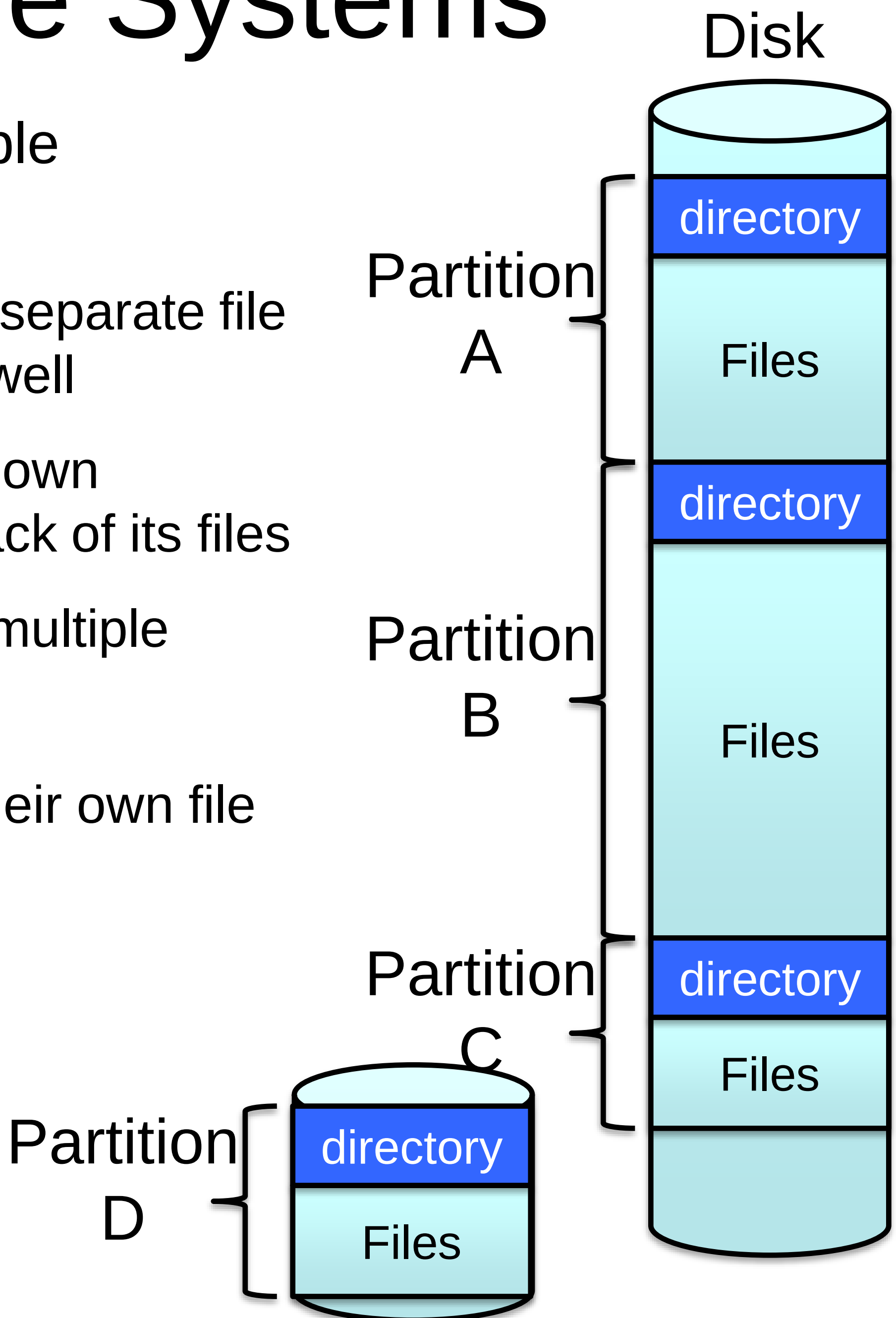
- When deleting a link, the file pointed to is not deleted

- When deleting a file
  - Can leave symbolic links dangling, and leave it to the user to clean up dangling links- this is the policy of Windows, UNIX

Virtual File System

Multiple File Systems

- A typical disk may have multiple partitions
  - Each partition may contain a separate file system, and possibly OS as well
  - Each file system will have its own directory structure to keep track of its files
  - A file system may also span multiple disks (e.g. RAID, not shown)
- Other I/O devices may contain their own file systems
  - e.g. a USB flash drive
- Want to share these files on a **single computer's file system**



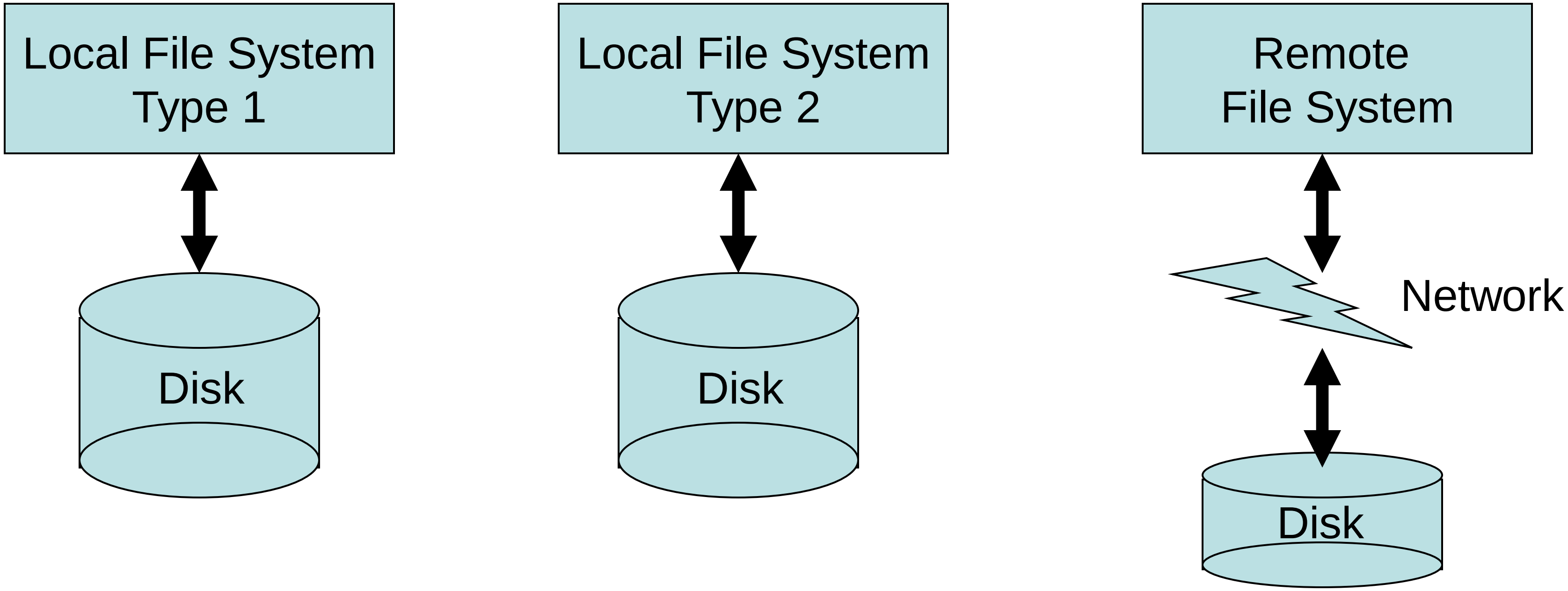
Virtual File Systems

- Create
- Delete
- Rename
- Move
- Copy

Local File System Interface

- Open
- Read
- Write
- Seek
- Append
- Truncate

- Sequential
- Direct/Random



Local File System Type 1

Local File System Type 2

Remote File System

Network

Disk

Disk

Disk

Virtual File Systems

- Create
- Delete
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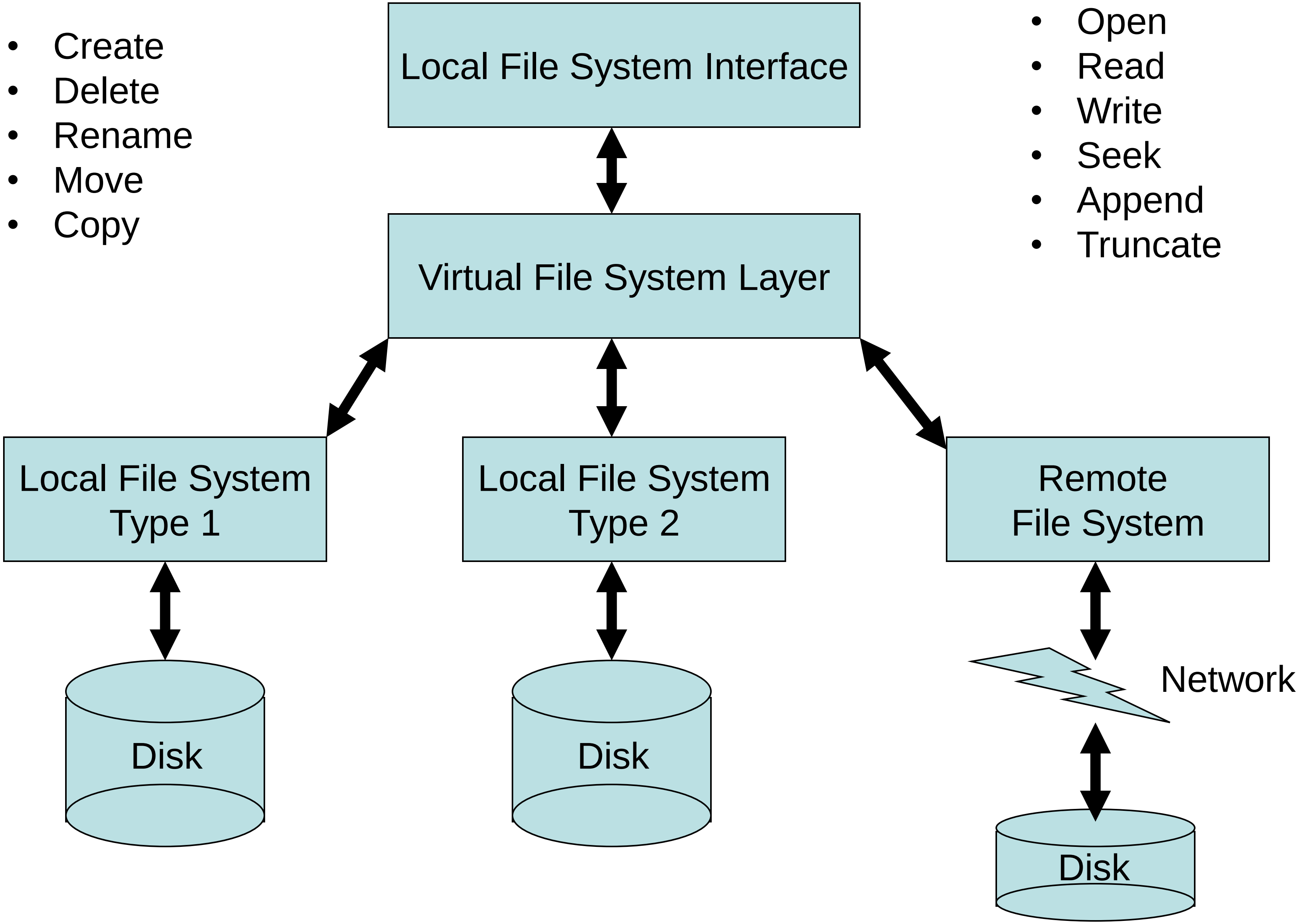


Local File System Interface

Virtual File System Layer

Local File System Type 1

Local File System Type 2

Remote File System

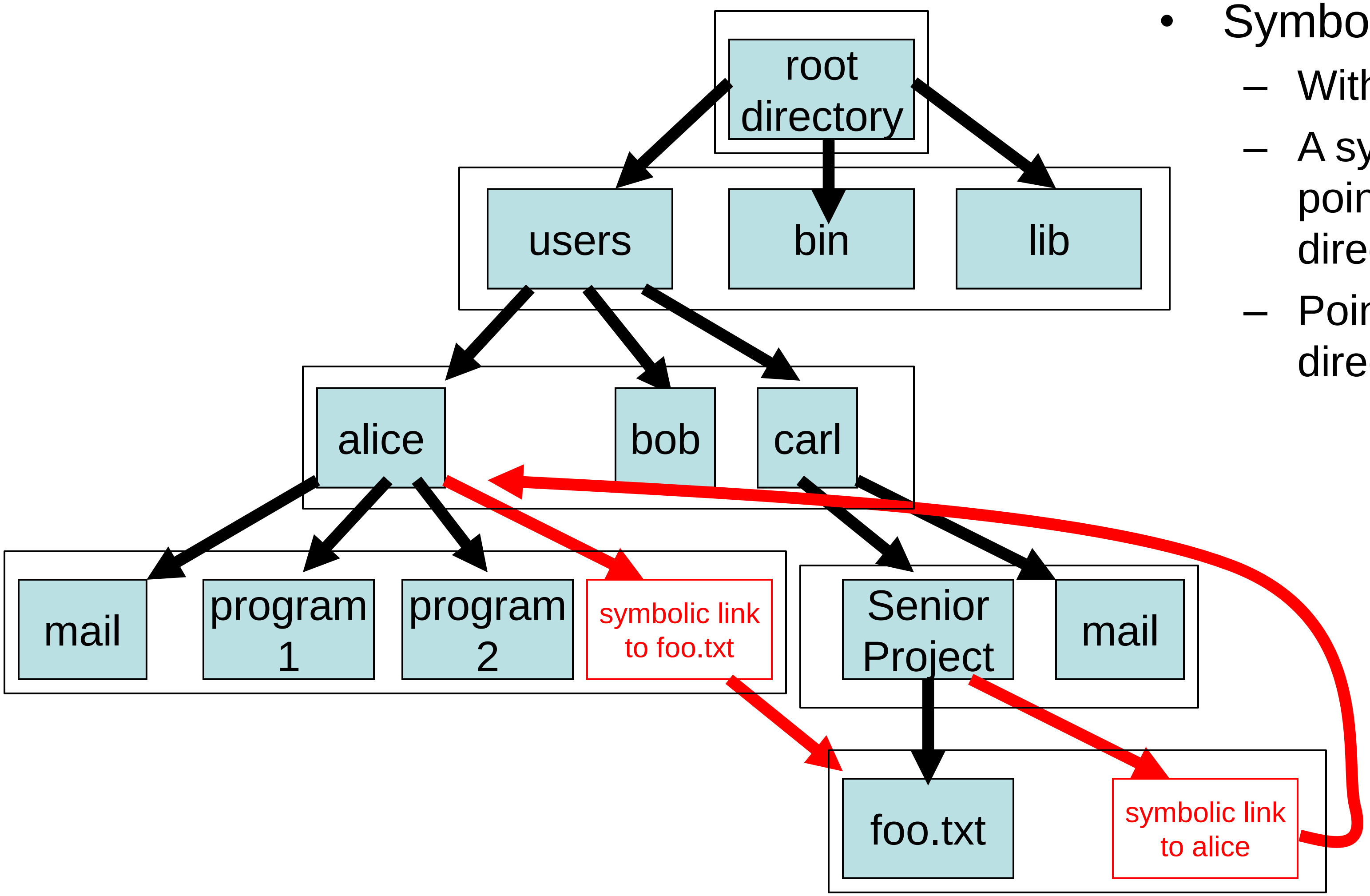
Disk

Disk

Network

Disk

Symbolic Links



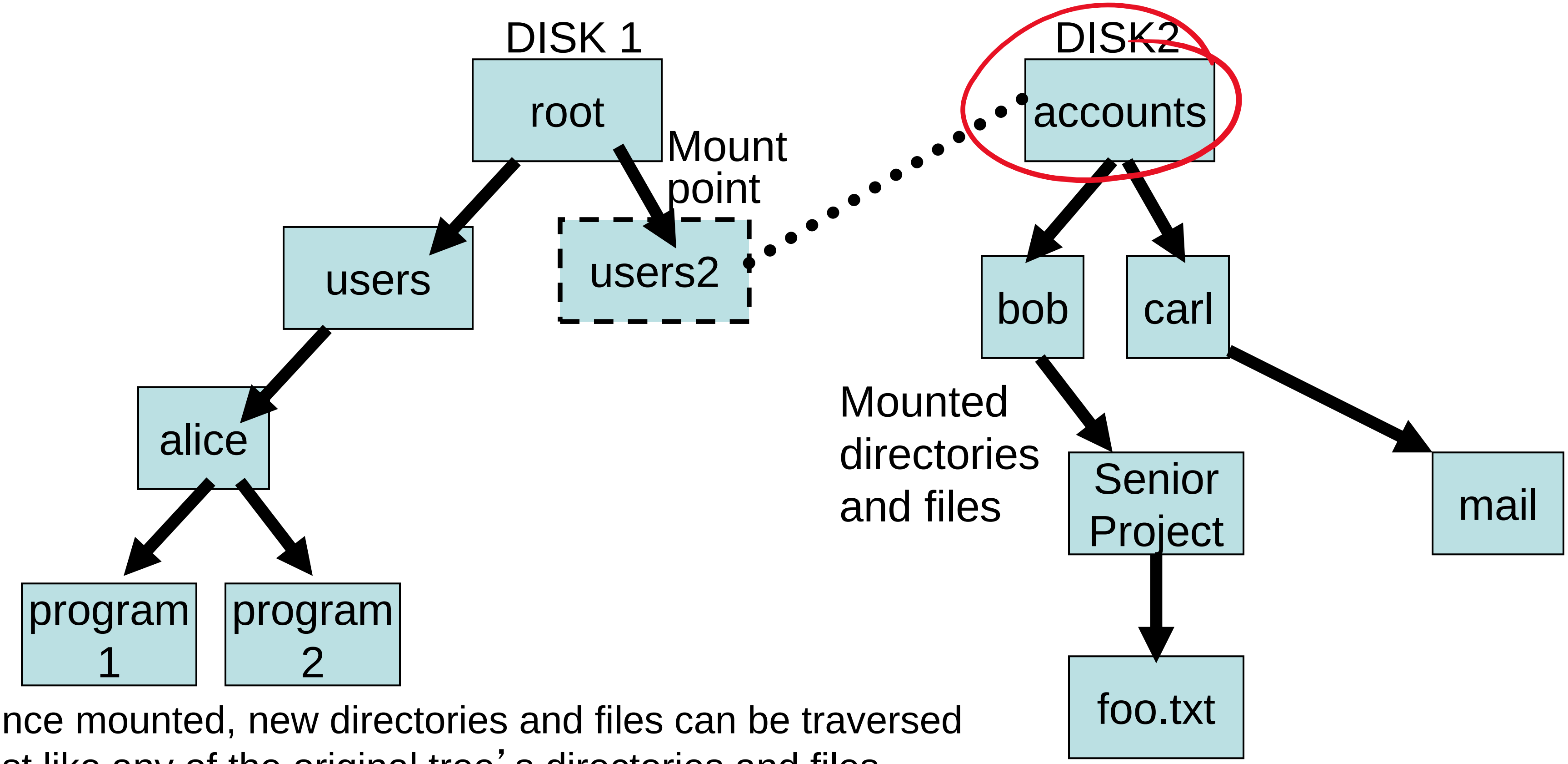
- Symbolic links
  - Within a file system
  - A symbolic link is a pointer to a directory entry
  - Points to a file or directory

Sharing Directories and Files

- Symbolic links
  - Within a file system
  - A symbolic link is a pointer to a directory entry
  - Points to a file or directory
- Files may be stored on different disks
  - Or different partitions within a disk
  - Or on removable media
  - Need access to the share files
  - Should be within the same directory structure

Mounting File Systems

- Want to share files within the same directory structure though some files may be stored on different disks, or different partitions within a disk
  - *Mount* these new file systems so they appear within your current directory structure

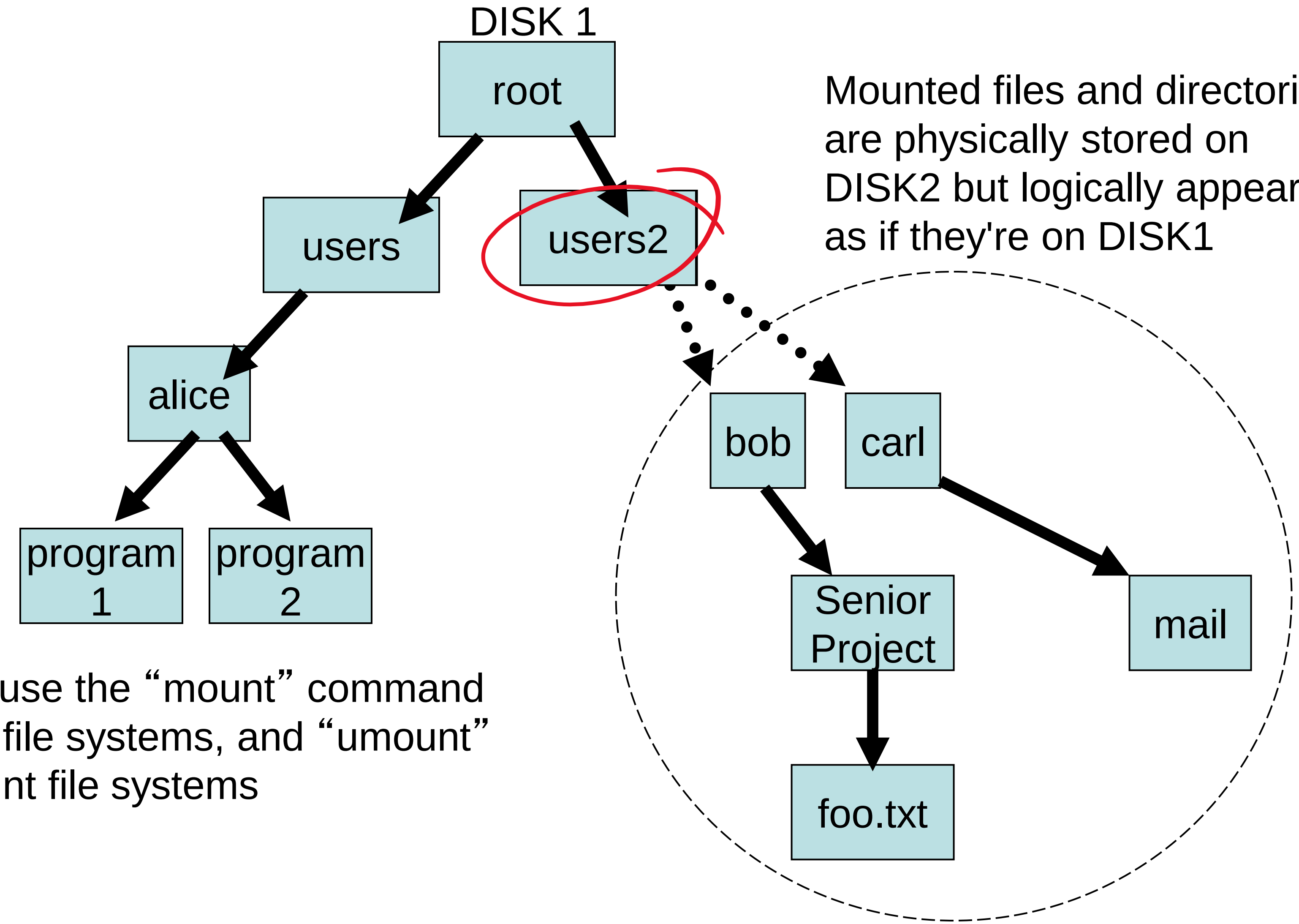


Mounted directories and files

Once mounted, new directories and files can be traversed just like any of the original tree’s directories and files

Mounting File Systems

Final result of file mounting



Mounted files and directories are physically stored on DISK2 but logically appear as if they're on DISK1

In Linux, use the “mount” command to mount file systems, and “umount” to unmount file systems

Mounting File Systems

- Example: to mount a remote directory,
  - say the /xfs filesystem at home.colorado.EDU,
    - as a local directory /xfs,
  - type:

```
mkdir  /xfs

/bin/mount home.colorado.edu:/vol/xfs  /xfs
```

- When a file system is no longer needed
  - unmount the file system

→ /etc/fstab

Mounting File Systems

- Ideally, you can mount the new file system (e.g. USB Stick) anywhere within the current directory tree
  - Unix follows this flexible approach
    - The Unix file manager keeps track of what file systems are mounted in which directory by setting a flag in the in-memory copy of the inode for that directory. **The flag indicates that the directory is a mount point.**
    - A field then points to an entry in the mount table, indicating which device is mounted there.
    - The mount table entry contains a pointer to the disk location of the mounted file system.

Mounting File Systems

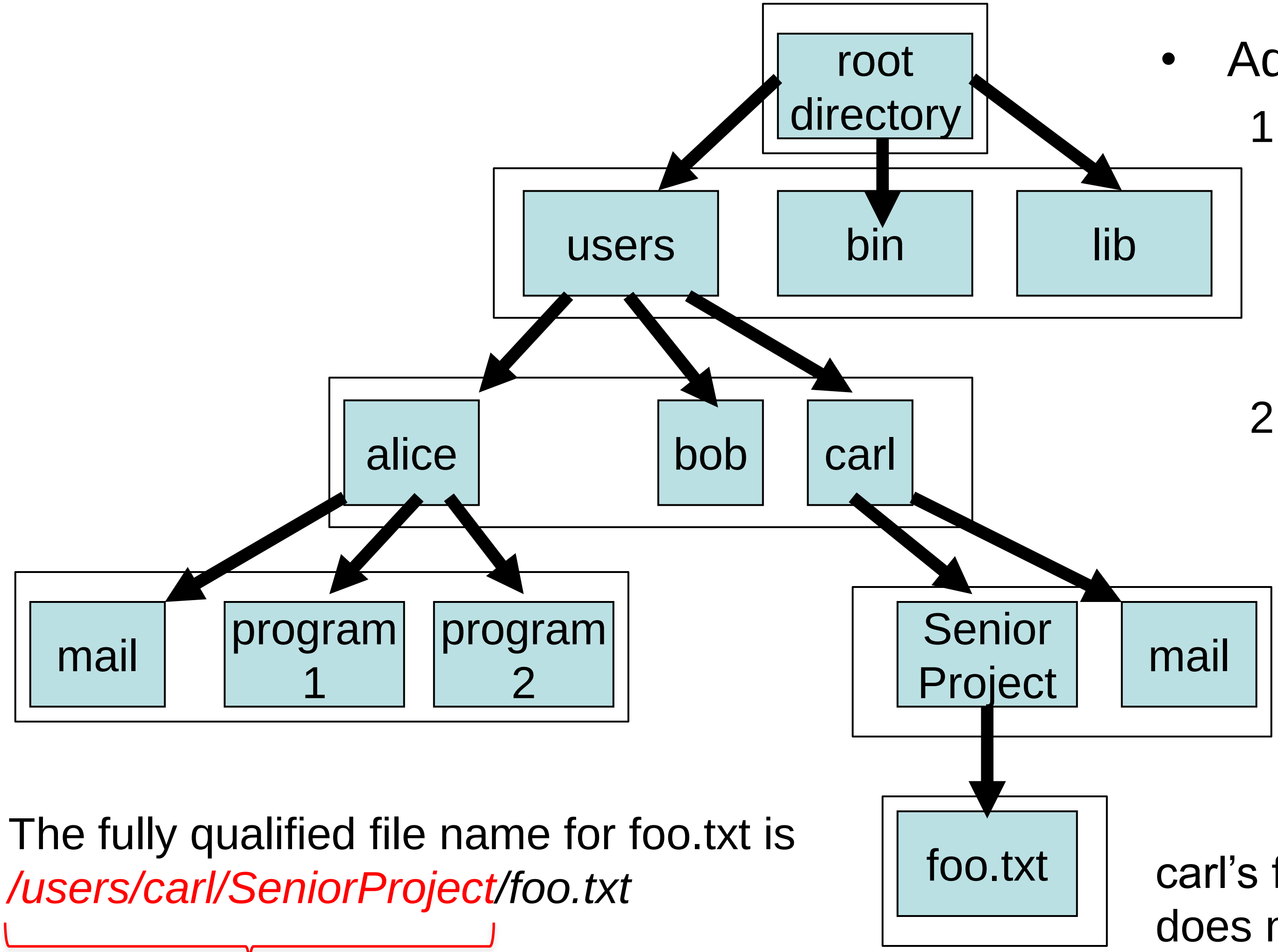
- Ideally, you can mount the new file system anywhere within the current directory tree (cont.)
  - Windows mounts a new device containing a file system
    - At the top level, e.g. D:\ or F:\
    - Later versions also allow mounting anywhere
  - Mac OS mounts a new device with a file system at the root level
    - adds a folder icon on the screen

Virtual File Systems

- Mounted file system could be of a different type than the current OS file system
- How does the OS manage this heterogeneity?
  - Implement a Virtual File System (VFS) layer that abstracts file representation and manipulation
  - VFS layer specifies an abstract model of a file and directory and abstract operations on files and directories
- The VFS translates abstract operations to/from the specific language of the mounted file system.
- Note, the mounted file system need not to be local
  - Distributed file systems allow file systems to be across networks

File System Implementation

Tree-structured Directory



- Advantages:
  1. hierarchical & customized organization of files by each user
  2. Unique naming
     - no name conflicts
  3. users can share & access files in other directories

The fully qualified file name for foo.txt is */users/carl/SeniorProject/foo.txt*

$\underbrace{\textit{/users/carl/SeniorProject}}_{\text{“path” or directory name}}$

carl’s file name “mail” does not conflict with alice’s file name “mail”

File System Implementation

- File system elements are stored on *both*:
  - Disk/flash – persistent storage
  - Main memory/RAM – volatile storage
- On *disk/flash*, **the entire file system is stored**, including 5 main elements:
  1. its entire directory tree structure
  2. each file’s attributes are in a File Control Block
  3. each file’s data
  4. a *boot block*, typically the first block of a volume, that contains info needed to boot an operating system from this volume. Empty if no OS to boot.
  5. a *volume control block* that contains volume or partition details,
     e.g. tracks free blocks on disk,
     the number of blocks in a partition,
     size of a block, etc.

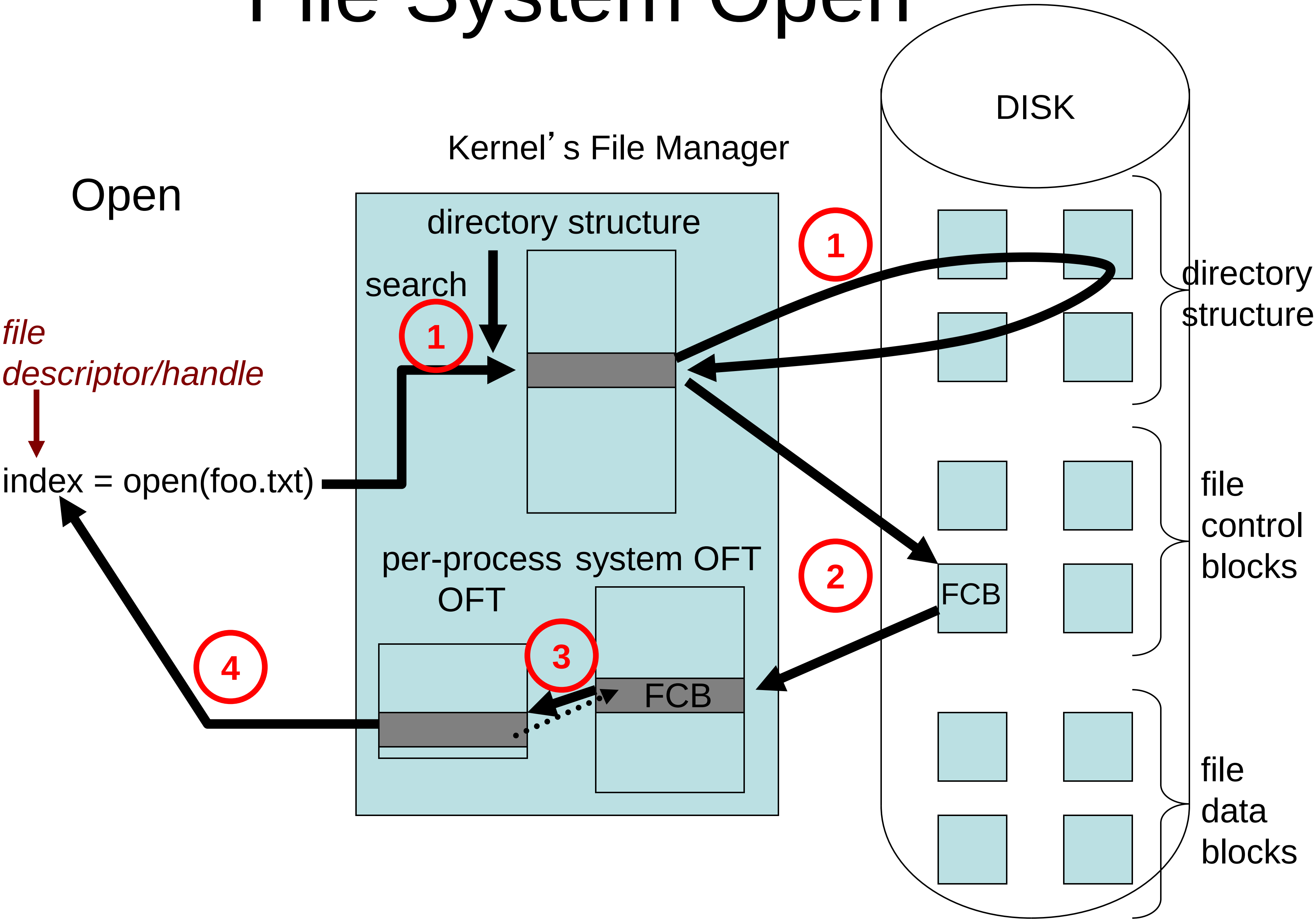
example FCB

name
unique ID
file permissions
dates (created,...)
size
location on disk

The four main file system components in ***memory*** are:

1. **Recently accessed parts of the directory structure tree** are stored in memory – for faster look up
2. OS also maintains a ***system-wide open file table*** **(OFT)** that tracks process-independent info of open files
   - the file header containing attributes about the open file is stored here
   - an open count of the number of processes that have files open is stored here
3. OS also maintains a ***per-process OFT*** - tracks all files that have been opened by a particular process, may store access rights, etc.
   - Also keeps a *current-file-position pointer*, i.e. where in the file the process is currently reading/writing
4. OS keeps a ***mount table of devices with file systems*** that have been mounted as volumes

File System Open



File System Open (steps)

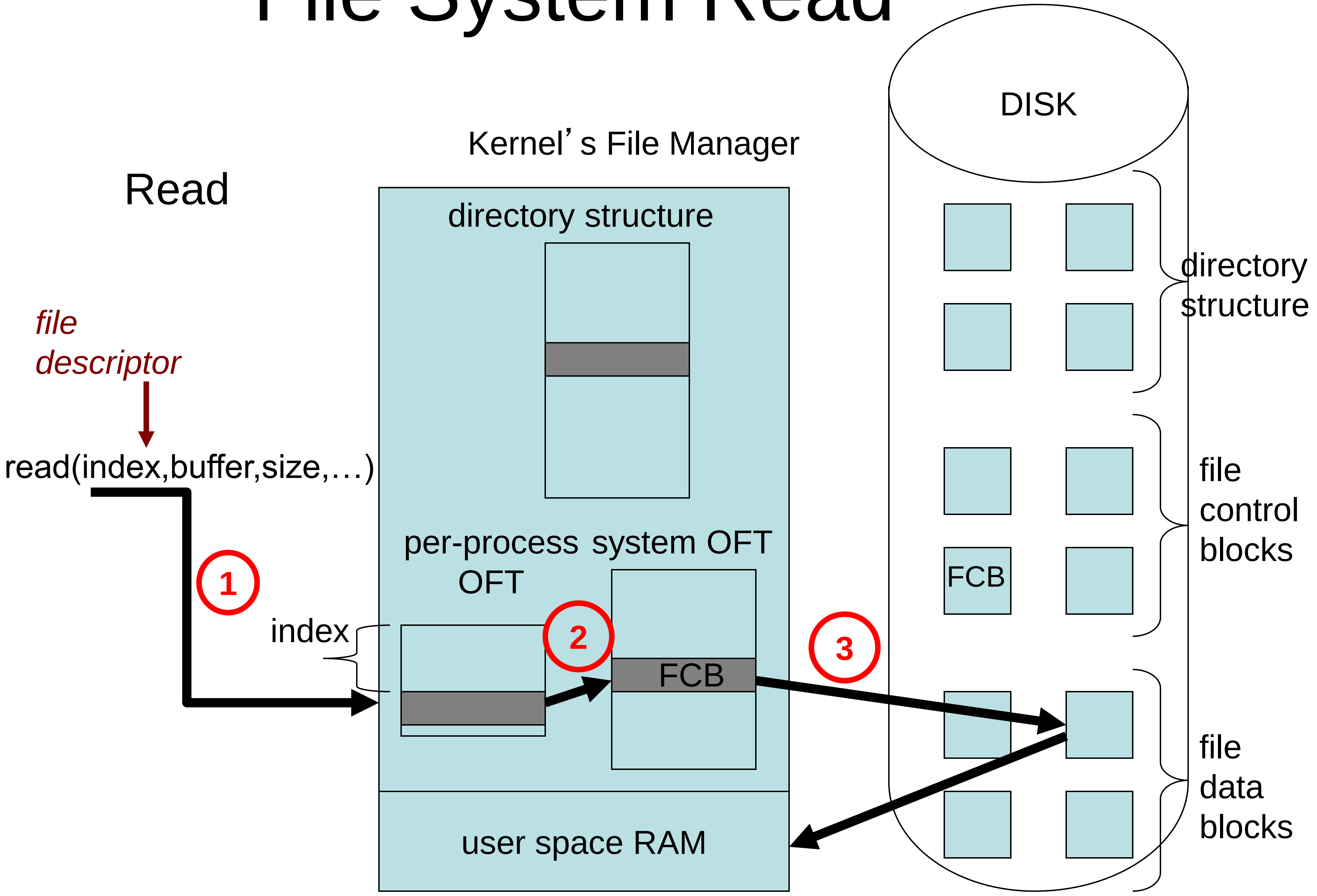
- When a process calls open(foo.txt) to set up access to a file, the following procedural steps are followed:

1. the directory structure is searched for the file name foo.txt
    - if the directory entries are in memory, then the search is fast
    - otherwise, directories and directory entries have to be retrieved from disk and cached for later accesses
2. once the file name is found, the directory entry contains a pointer to the FCB on disk
    - retrieve the FCB from disk
    - copy the FCB into the system OFT. This acts as a cache for future file opens.
    - Increment the open file counter for this file in the system OFT
3. add an entry to the per-process OFT that points to the file's FCB in the system OFT
4. return a file descriptor or handle to the process that called open()

File System Open

- Some OS’s employ a mandatory lock on an open file
  - Only one process at a time can use an open file
  - Windows policy
- Other OS’s allow optional or advisory locks
  - UNIX policy
  - It’ s up to users to synchronize access to files

File System Read



Read

file descriptor

read(index,buffer,size,…)

1

index

Kernel’s File Manager

directory structure

per-process OFT

system OFT

2

FCB

user space RAM

3

DISK

directory structure

file control blocks

FCB

file data blocks

File System Close

- on a close(),
  1. remove the entry from the per-process OFT
  2. decrement the open file counter for this file in the system OFT
  3. if counter = 0, then write back to disk any metadata changes to the FCB, e.g. its modification date
     - Note: there may be a temporary inconsistency between the FCB stored in memory and the FCB on disk – designers of file systems need to be aware of this. A similar inconsistency occurred for modified memory-mapped file data in RAM that had not yet been written to disk.

File Allocation

File Allocation

Approaches:

1. Contiguous file allocation
   - a file is laid out contiguously, i.e. if a file is n blocks long, then a starting address b is selected and the file is allocated blocks b, b+1, b+2, ..., b+n-1

2. Linked Allocation
   - each file is a linked list of disk blocks

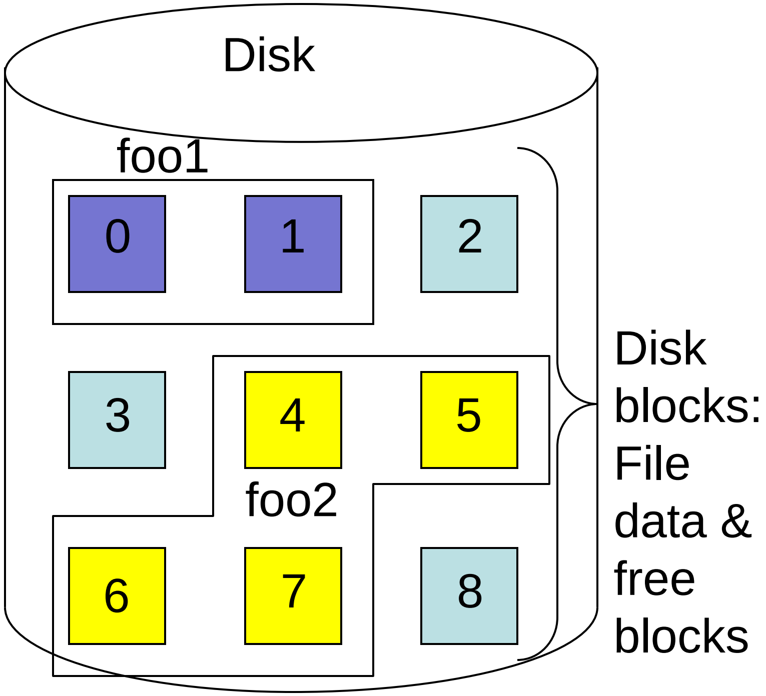
3. File Allocation Table (FAT) is an important variation of linked lists
   - Don’t embed the pointers of the linked list with the file data blocks themselves
   - Instead, separate the pointers out and put them in a special table – the file allocation table (FAT)
   - The FAT is located at a section of disk at the beginning of a volume

4. Indexed Allocation
   - collect all pointers into a list or table called an *index block*
   - the index j into the list or index block retrieves a pointer to the j’th block on disk

Approach #1: Contiguous File Allocation

File headers

file	start	length
foo1	0	2
foo2	4	4



- Advantage: fast performance (low seek times because the blocks are all allocated near each other on disk)

Approach #1: Contiguous File Allocation

- Disadvantages:
  - Problem 1: external fragmentation (same problem as trying to contiguously fit processes into RAM)
    - same solutions apply: first fit, best fit, etc.
    - also compact memory/defragment disk
    - can be performed in the background late at night, etc.
  - Problem 2: May not know size of file in advance
    - allocate a larger size than estimated
    - if file exceeds allocation, have to copy file to a larger free “hole” between allocated files
  - Problem 3: Over-allocation of a “slow growth” file
    - A file may eventually need 1 million bytes of space
    - But initially, the file doesn’t need much, and it may be growing at a very slow rate, e.g. 1 byte/sec
    - So for much of the lifetime of the file, allocating 1 MB wastes allocation

General File Allocation

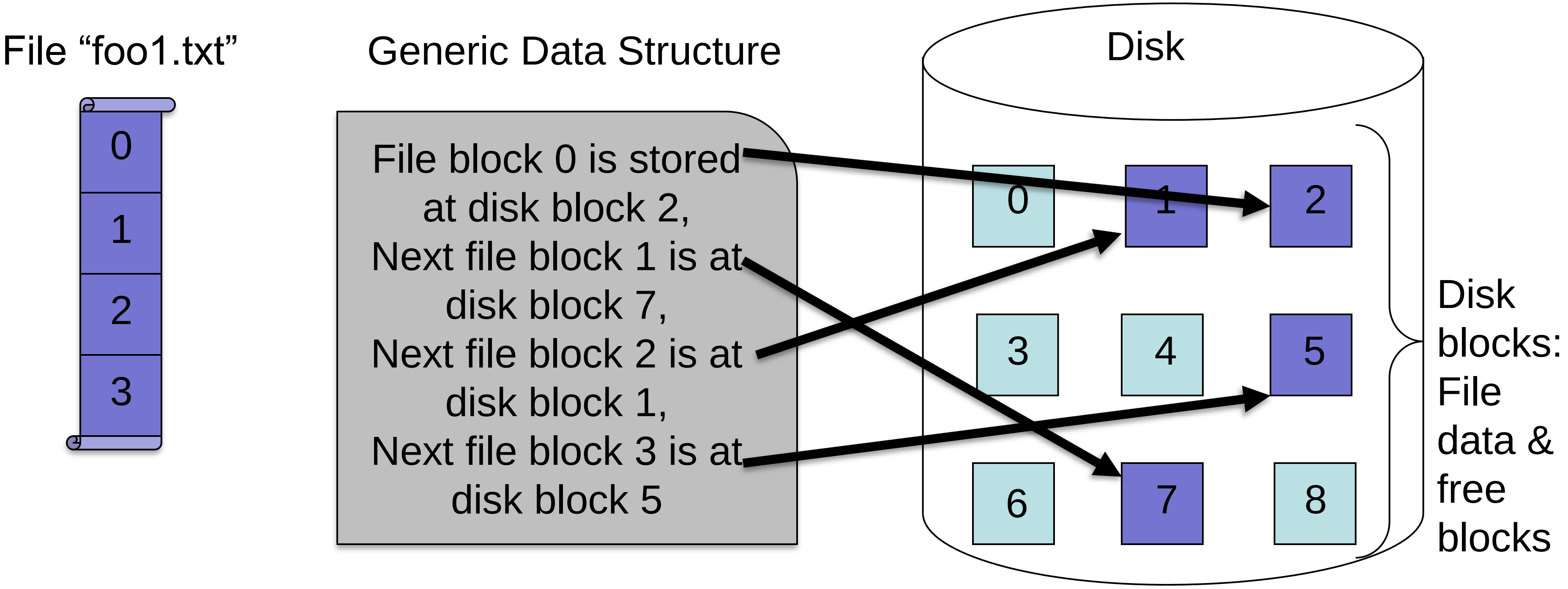
- Page table solved external fragmentation problem for process allocation

- Apply a similar concept to file allocation
  - Divide disk into fixed-sized blocks, just as main memory was divided into fixed-sized physical frames

  - Allow a file's data blocks to be spread across any collection of disk blocks, not necessarily contiguous

  - *Need a data structure to keep track of what block of a file is stored on which block in disk*

General File Allocation



File "foo1.txt"

Generic Data Structure

File block 0 is stored at disk block 2,
Next file block 1 is at disk block 7,
Next file block 2 is at disk block 1,
Next file block 3 is at disk block 5

Disk

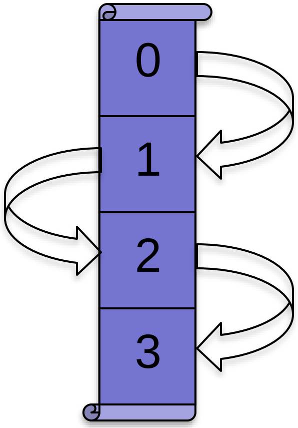
Disk blocks: File data & free blocks

- Generic data structure can be:
  - A Linked list and variants
  - Indexed allocation (somewhat resembles a page table) and variants

Approach #2: Linked File Allocation

- Linked Allocation
  - each file is a linked list of disk blocks
  - to add to a file, just modify the linked list either in the middle or at the tail, depending on where you wish to add a block
  - to read from a file, traverse linked list until reaching the desired data block

File “foo1.txt”



Linked File Allocation

- Linked Allocation
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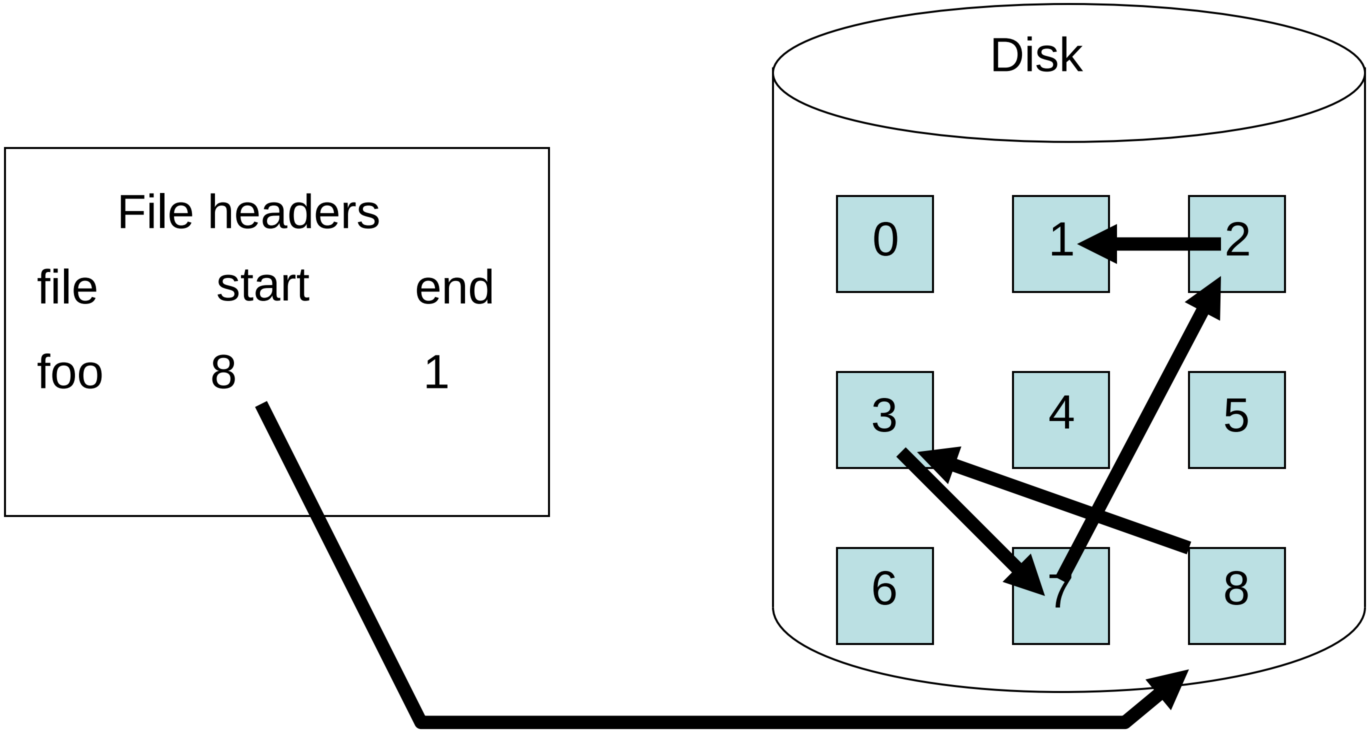

File headers

file	start	end
foo	8	1

Linked File Allocation

- Advantages:
  - – solves problems of contiguous allocation
    - no external fragmentation
    - don’t need to know size of a file a priori
  - – Minimal bookkeeping overhead in file header – just a pointer to start of file on disk
    - (-) Compromise is that all the pointer overhead is stored in each disk block
  - – Good for sequential read/write data access
  - – Easy to insert data into middle of linked list

Linked File Allocation

- Disadvantages:
  - performance of random (direct) data access is extremely slow for reads/writes
    - because you have to traverse the linked list until indexing into the correct disk block
  - Space is required for pointers on disk in every disk block
  - reliability is fragile
    - if one pointer is in error or corrupted, then lose the rest of the file after that pointer

File Allocation

Approaches:

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4. Indexed Allocation
   - collect all pointers into a list or table called an *index block*
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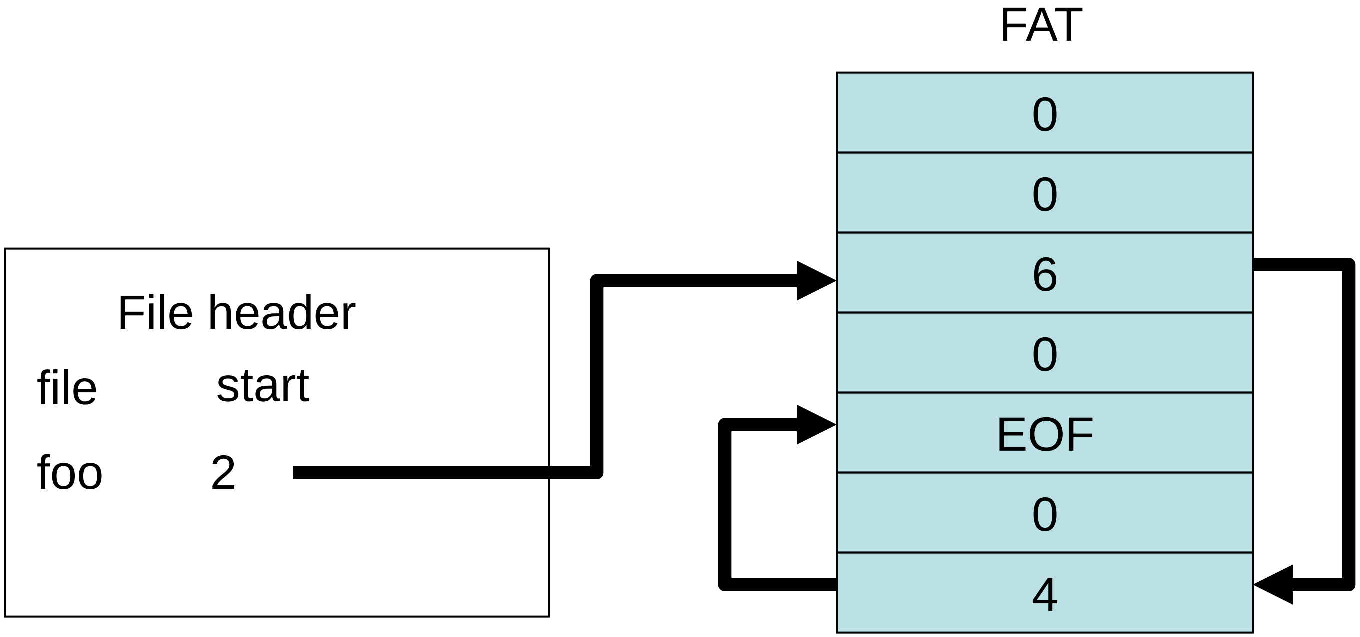
Approach #3: File Allocation Table (FAT)

- the File Allocation Table (FAT) is an important variation of linked lists
  - Don’t embed the pointers of the linked list within the file data blocks themselves
  - Instead, separate the pointers out and put them in a special table – the file allocation table (FAT)
  - The FAT is located at a section of disk at the beginning of a volume

File Allocation Table

- entries in the FAT point to other entries in the FAT as a linked list, but their values are interpreted as the disk block number
- unused blocks in FAT initialized to 0



File Allocation Table

- FAT file systems used in MS-DOS and Win95/98
  - Bill Gates designed/coded original FAT file system
  - replaced by NTFS (basis of Windows file systems from WinNT through Windows Vista/7)
  - Variants include FAT16, FAT32, etc. FAT16 and FAT32 refer to the size of the address used in the FAT.

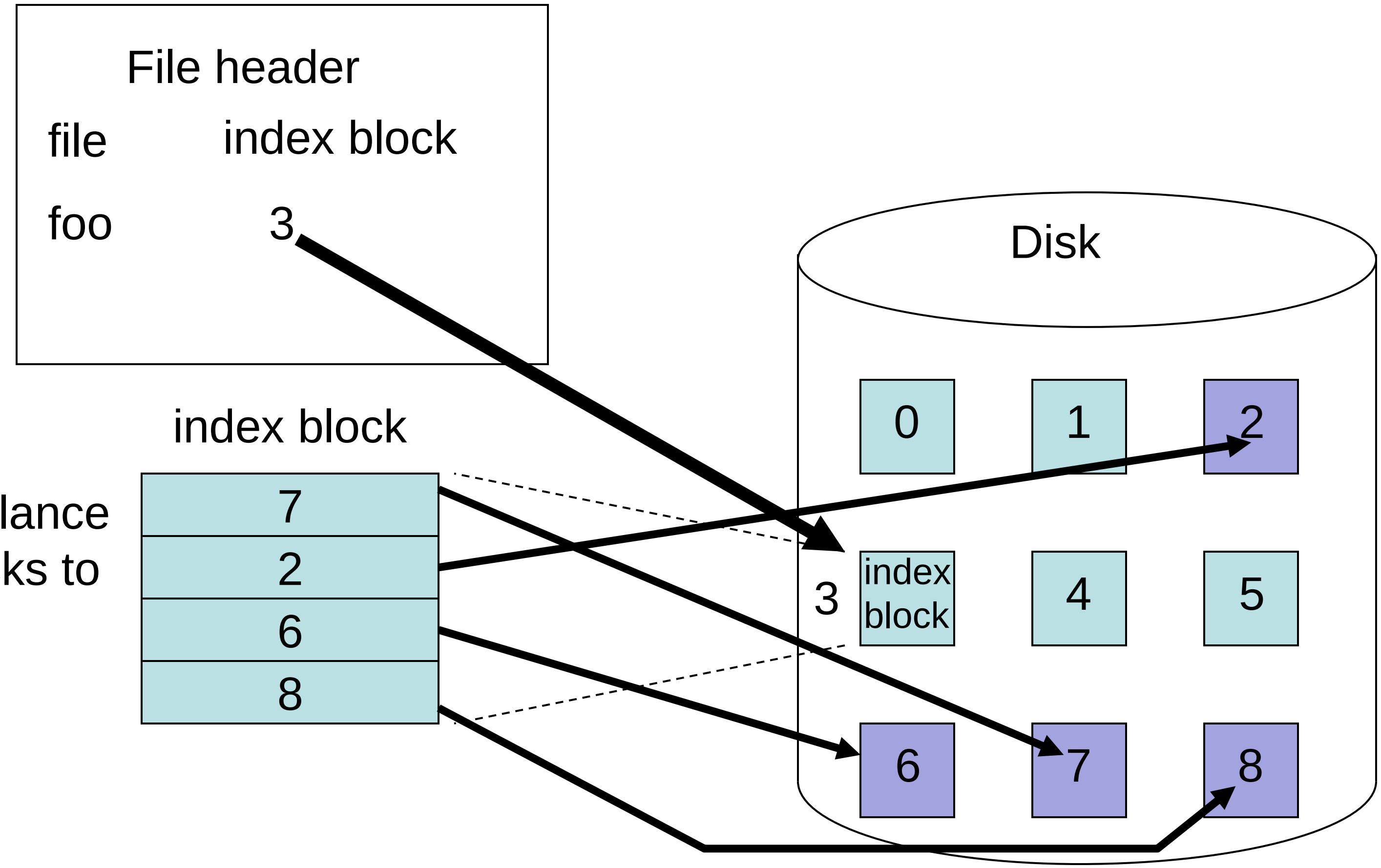
File Allocation Table

- Linked list for a file is terminated by a special end-of-file EOF value
- (+) Allocating a new block is simple - find the first 0-valued block
- (+) Random Reads/Writes faster than pure linked list
  - the pointers are all located in the FAT near each other at the beginning of disk volume - low disk seek time
- (-) still have to traverse the linked list though to find location of data – this is still a slow operation

Approach #4: Indexed Allocation

- Conceptually, collect all pointers into a list or table called an *index block*
  - the index j into the list or index block retrieves a pointer to the j'th block on disk
  - Looks kind of like a page table, except it's extensible
- Unlike the FAT, the index block can be stored in any block on disk, not just in a special section at the beginning of disk
- Unlike the FAT, the index is just a linear list of pointers

Indexed Allocation



File header

file	index block
foo	3

index block

7
2
6
8

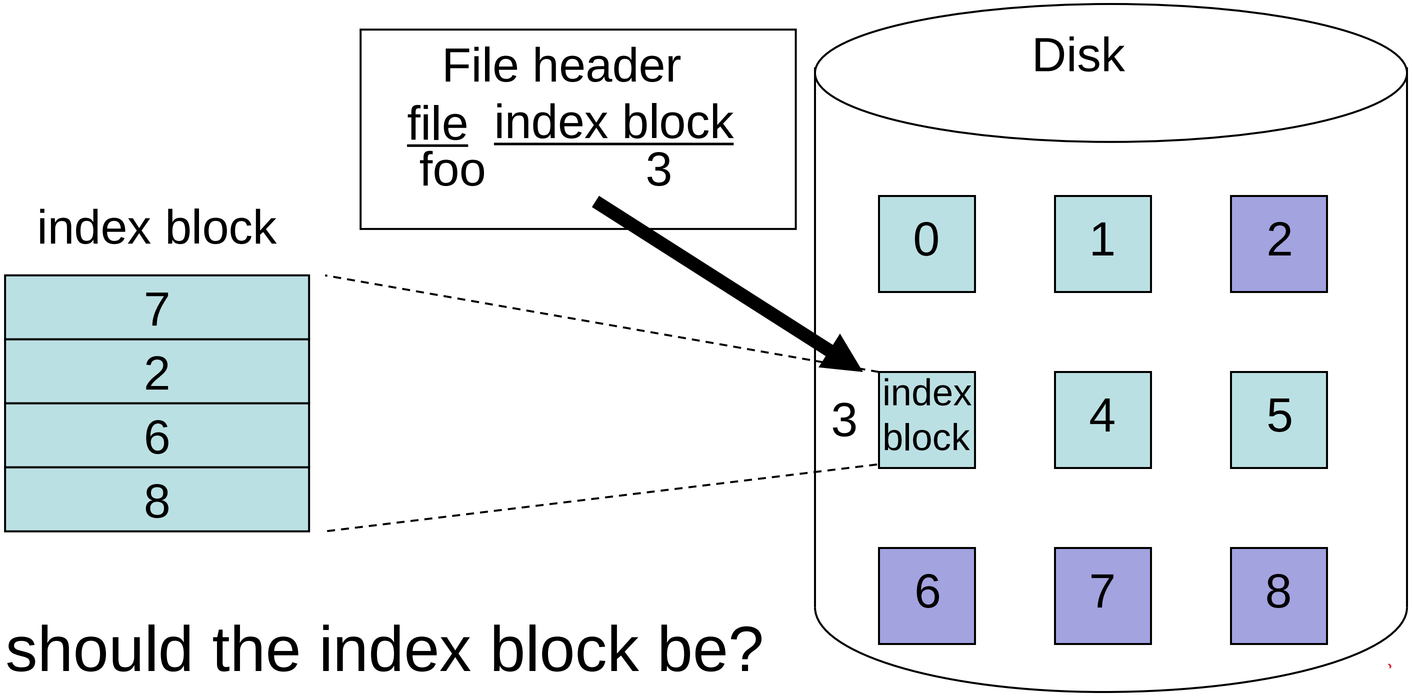
note resemblance of index blocks to page tables!

Indexed Allocation

- Solves many problems of contiguous and linked list allocation:
  - no external fragmentation
  - size of file not required a priori
  - don’t have to traverse linked list for random/direct reads/writes
    - just index quickly into the index block

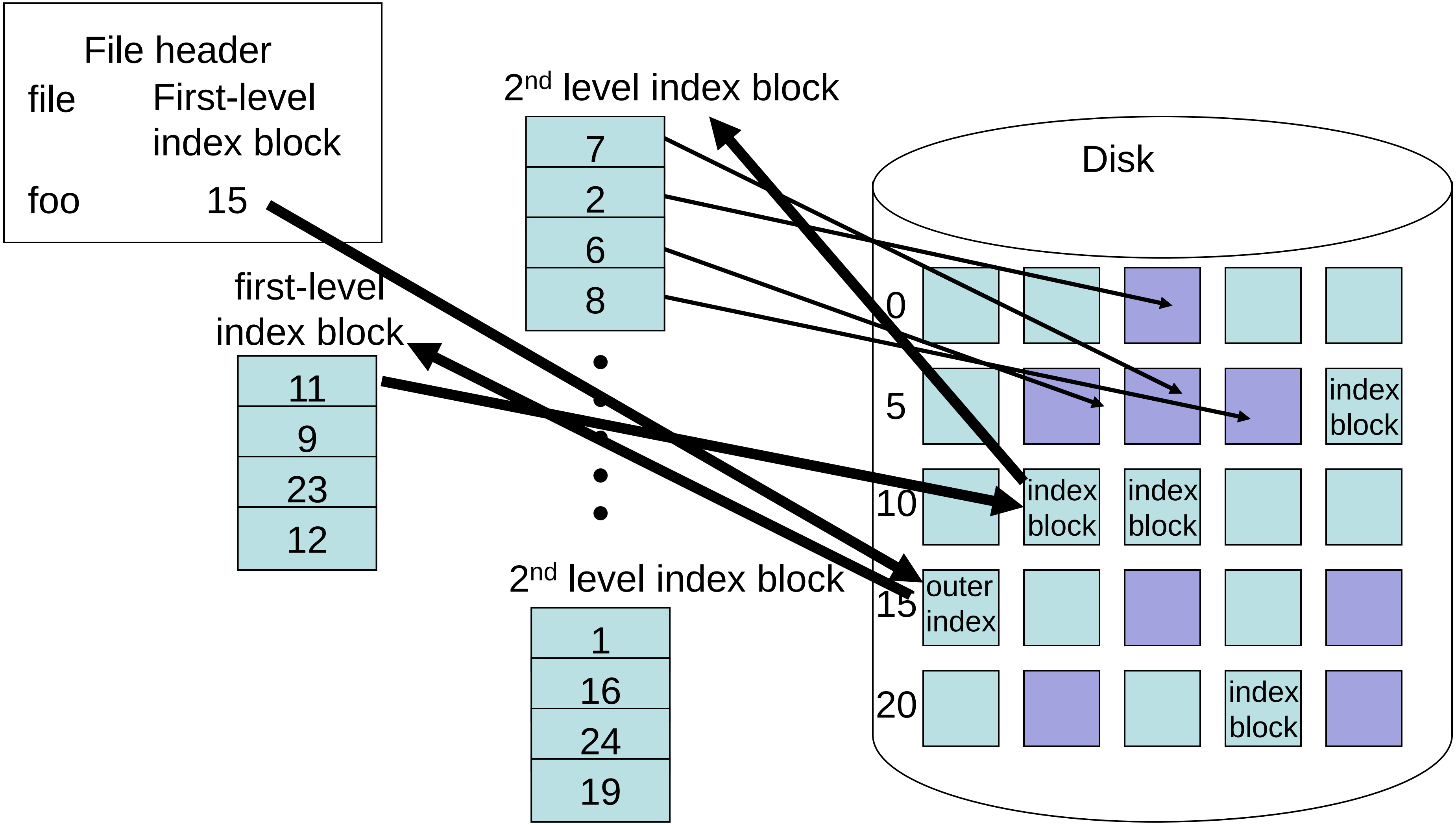
Indexed Allocation

- Solutions:
  1. link together index blocks –
     - each index block has link to next index block
  2. *multilevel index* (like hierarchical page tables!)
     - First level is list of all index blocks for file
     - Second level is list of all data blocks in that section of the file



How big should the index block be?

Approach #5: Multilevel Indexed Allocation



File header

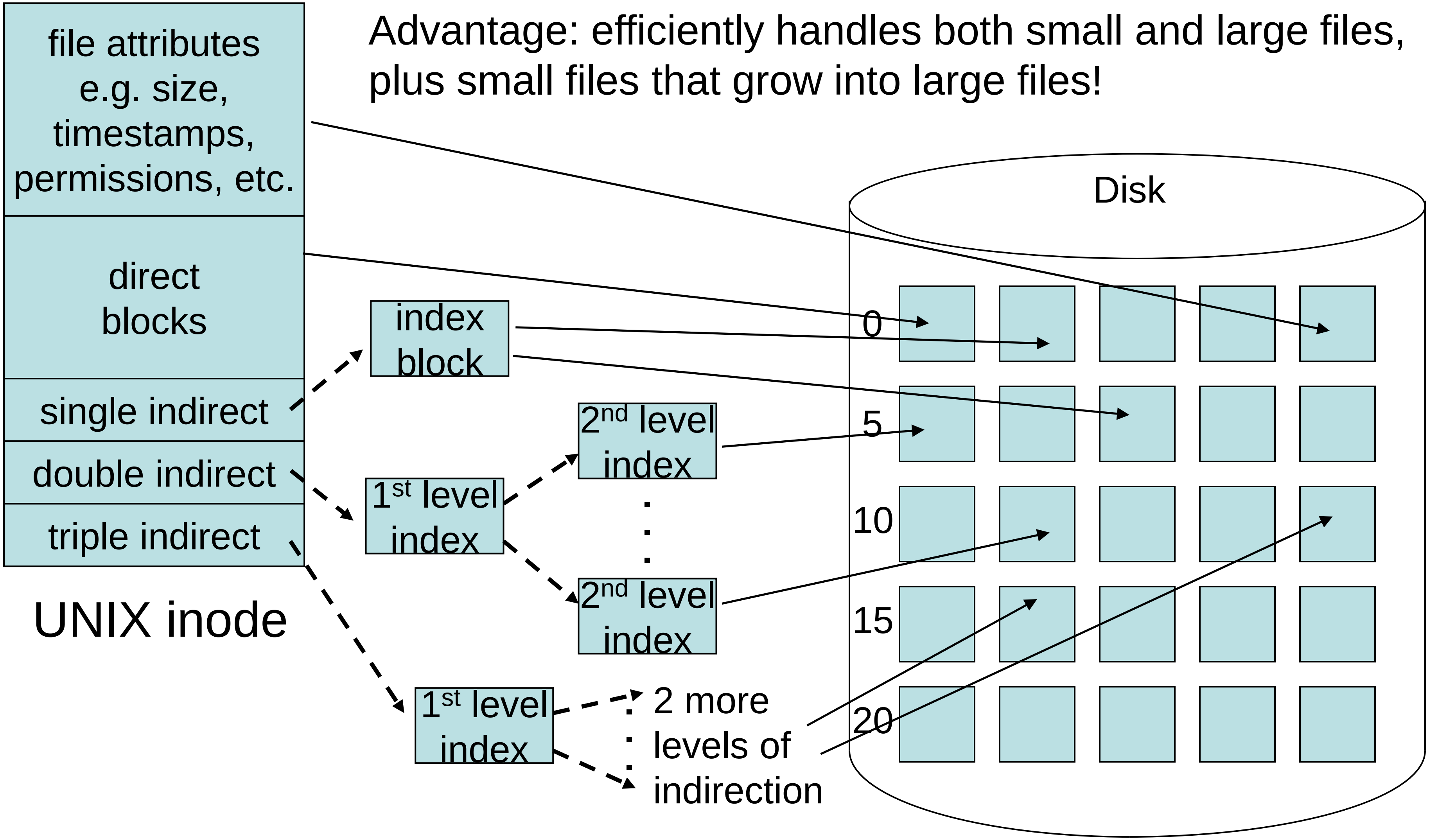
file	First-level index block
foo	15

Multilevel Indexed Allocation

- Problem with multi-level indexing:
  - accessing small files might take just as long as large files
  - have to go through the same # of levels of indexing, hence same # of disk operations
  - accessing the data of a 100 byte file requires at leas 4 block reads

UNIX Multilevel Indexed Allocation

Advantage: efficiently handles both small and large files, plus small files that grow into large files!



UNIX Multilevel Indexed Allocation

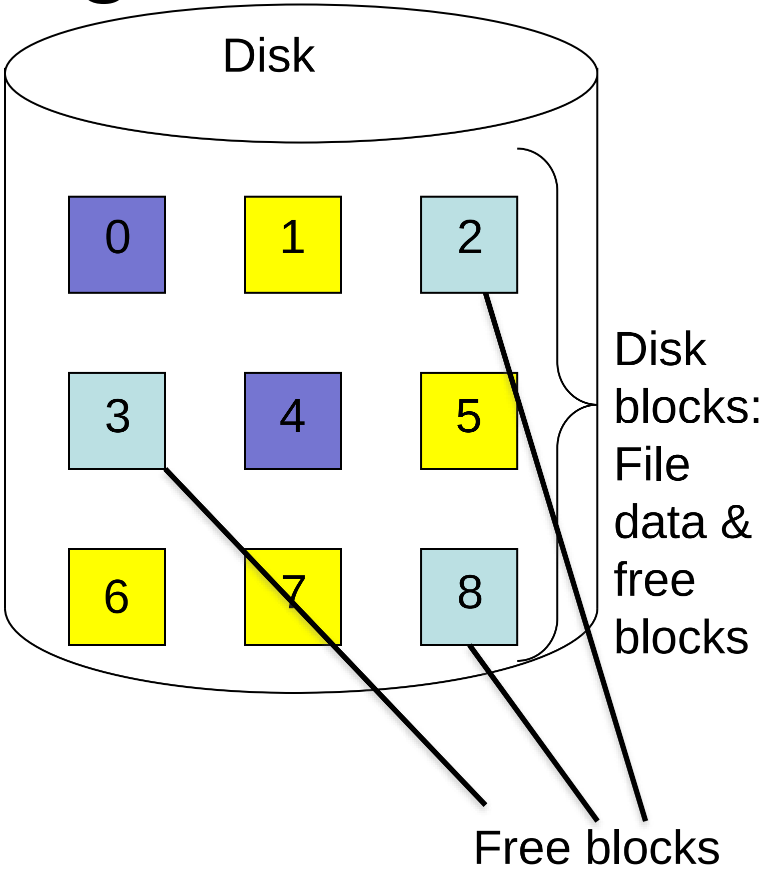
- for small files
  - only uses a small index block of 15 entries, so there is very little wasted memory
- for large files
  - the indirect pointers allow expansion of the index block to span a large number of disk blocks

Comparing File Allocation with Process Allocation

- In both cases, mapping an entity to storage
  - Process address space allocated frames in RAM via page tables
  - File data is allocated to disk/flash
- Differences:
  - Address spaces are fixed in size and known in advance,
  - Files grow/contract over time – files need a mapping/allocation system that is more flexible than page tables, which can’t grow
  - Address spaces can be sparse and mostly unused, while file data is all “used”

Free Space Management

- Another aspect of managing a file system is managing free space
  - the file system needs to keep track of what blocks of disk are free/unallocated
  - keeps a free-space “list”
  - In this example, need to keep track that disk blocks 2, 3 and 8 are free/unallocated



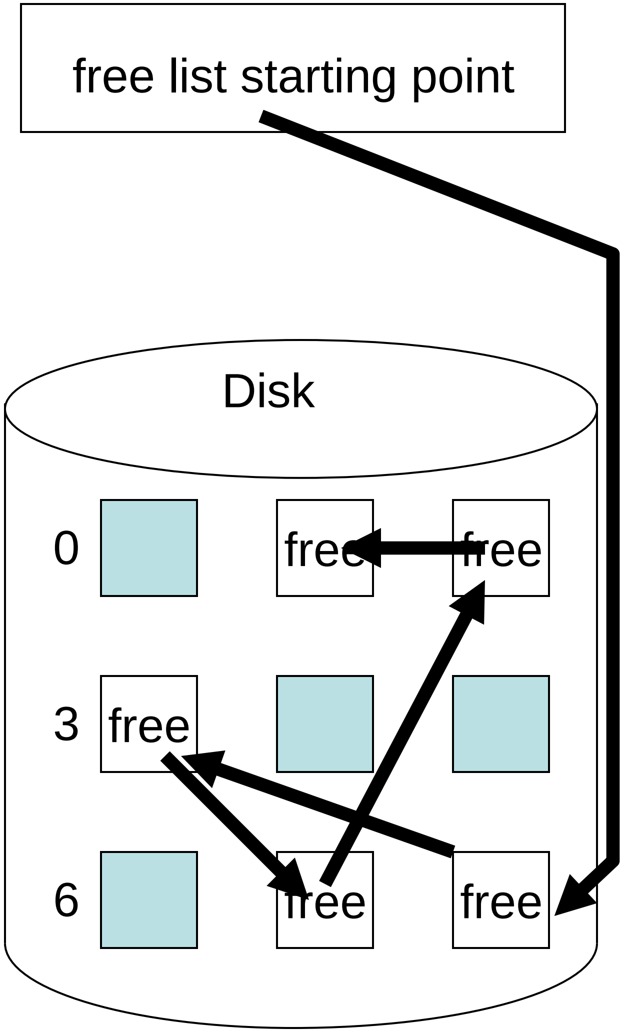
Free Space Management Approaches

1. Bit Vector or Bit Map

- each block is represented by a bit.
- Concatenate all such bits into an array of bits, namely a bit vector.
  - The j’th bit indicates whether the j’th block has been allocated.
  - if bit = 1, then a block is free, else if bit = 0, then block is allocated

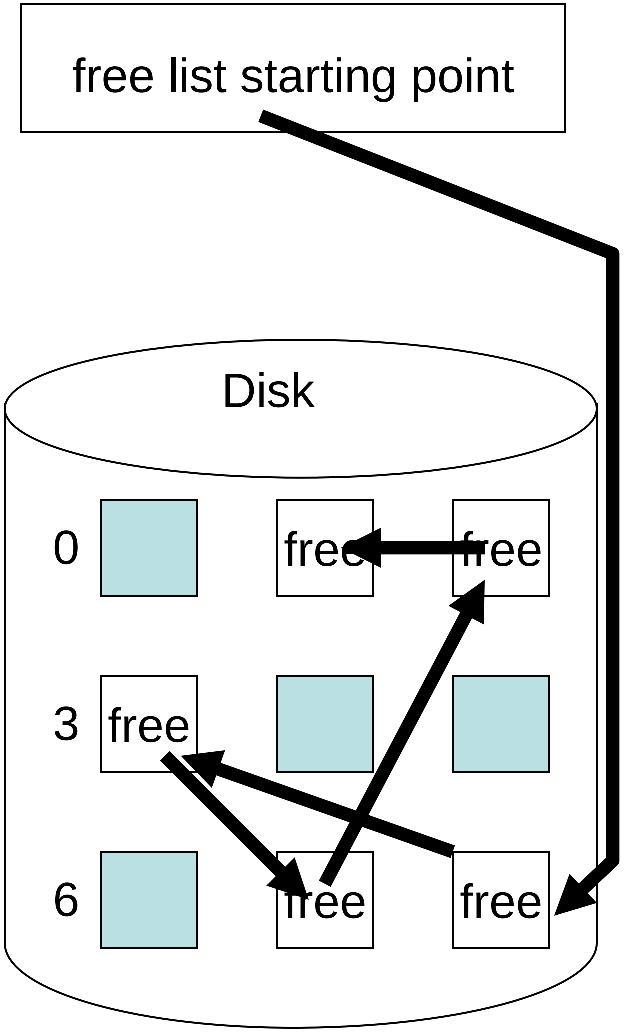
Free Space Management Approaches

2. Linked List
   - link together all free blocks
   - efficient - keeps track of only the free blocks.
     - bitmap has the overhead of tracking both free and allocated blocks - this is wasteful if memory is mostly allocated
   - Faster than bitmap – find 1st free block immediately



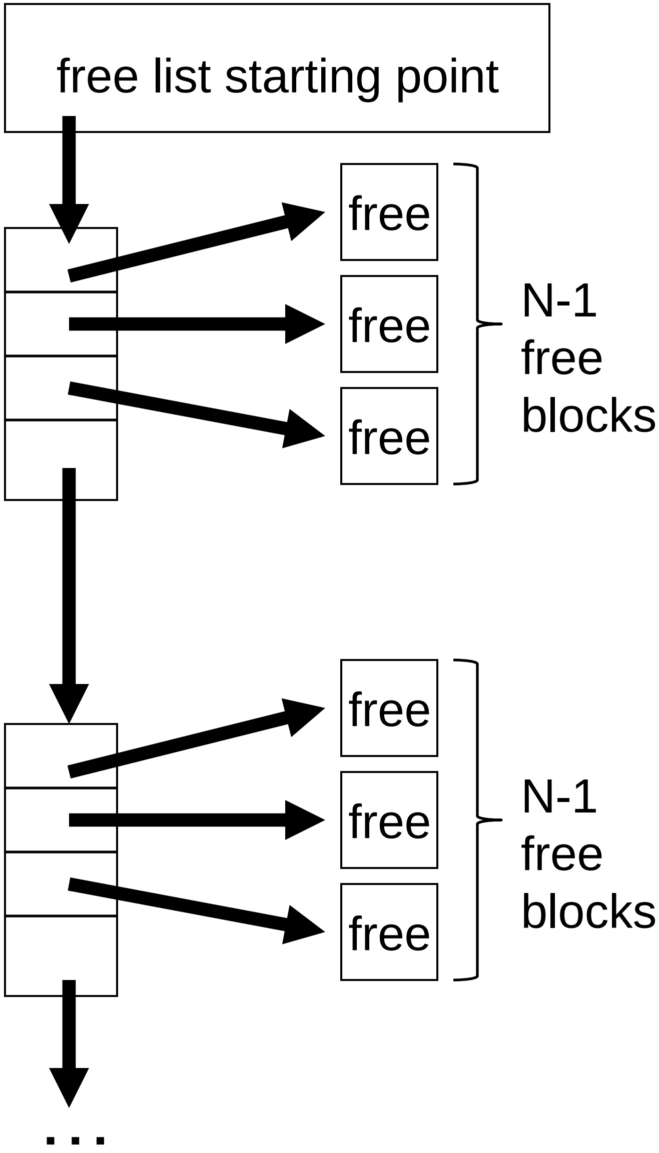
Free Space Management Approaches

- Problem with Linked List free space management:
  - – traversing the free list is slow if you want to allocate a large number of free blocks all at once
    - hopefully this occurs infrequently



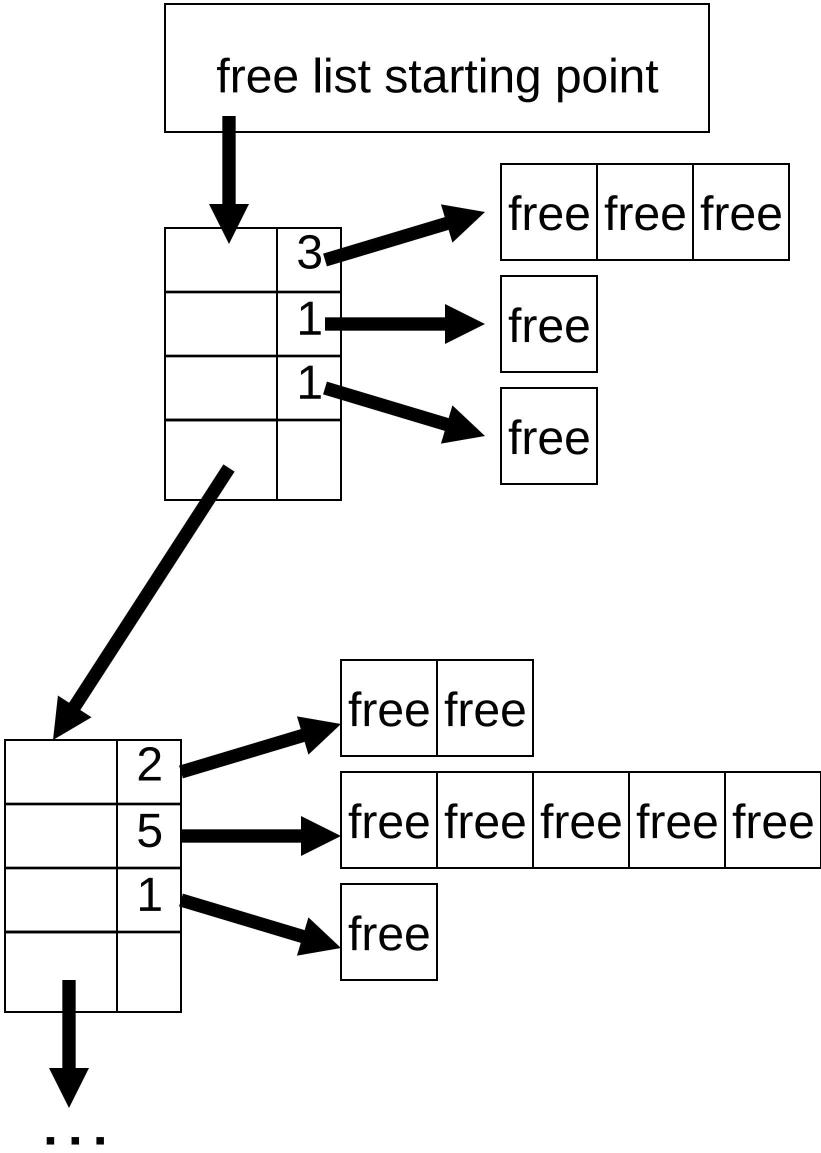
Free Space Management Approaches

3. Grouping
   - linked list, except store n-1 pointers to free blocks in each list block
   - the last block points to the next list block containing more free pointers
   - allows faster allocation of larger numbers of free blocks all at once



Free Space Management Approaches

4. Counting -
   - grouped linked list, but also add a field to each pointer entry that indicates the number of free blocks immediately after the block pointed to
   - even faster allocation of large #' s of free blocks



File System Performance, Reliability, and Fault Recovery

File System Performance

- Approaches to improve performance in a file system:
  - In memory:
    - file header: caching FCB information about open files in memory improves performance (faster access)

    - directory:
      - caching directory entries in memory improves access speed.
      - And hash the directory tree to quickly find an entry and see if it’s in memory.

File System Performance

- On disk:
  - file data: indexed allocation is generally faster than traversing linked list allocation

  - free block list: counting, grouped, linked list allows fast allocation of large # of files

File System Performance

- Other potential optimizations:
  - the disk controller can also have its own cache that stores file data/FCBs/etc. for fast access
  - Cache file data in memory
  - Smarter layout on disk: keep an inode/FCB near file data to reduce disk seeks, and/or file data blocks near each other
  - *read ahead*:

    if the OS knows this is sequential access, then read the requested page and several subsequent pages into main memory cache in anticipation of future reads

File System Performance

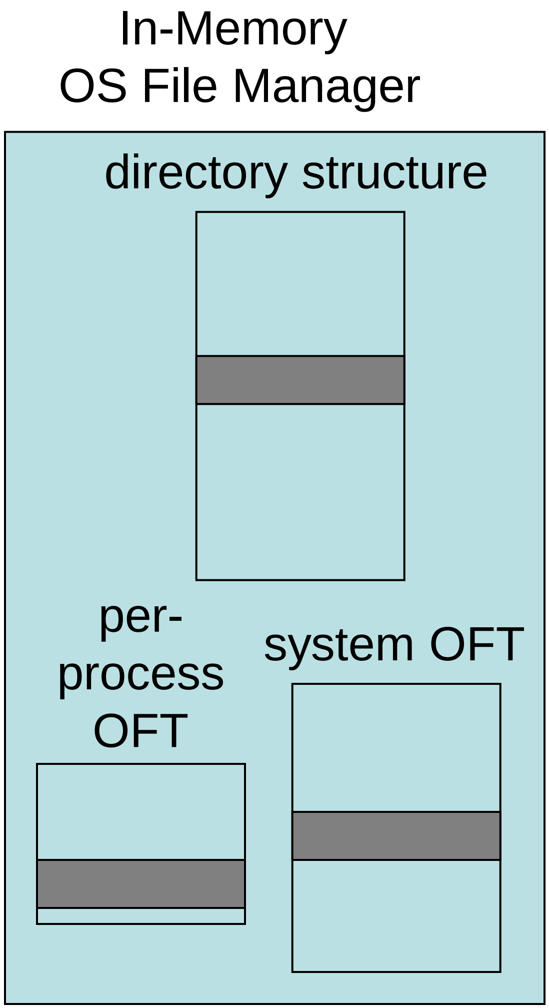
- Some other potential optimizations:
  - *asynchronous writes*: delay writing of file data until sometime later.
  - Advantages:
    - removes disk I/O wait time from the critical path of execution, e.g. a write(X) to a file can return quickly rather than waiting for completion of disk I/O, thereby allowing the program to move forward in its execution
    - This allows a disk to schedule writes efficiently, grouping nearby writes together
    - May avoid a disk write if the data has been changed again soon
    - note that in certain cases, you may prefer to enforce synchronous writes, e.g. when modifying file metadata in the FCB on an open() call

File System Reliability and Fault Recovery

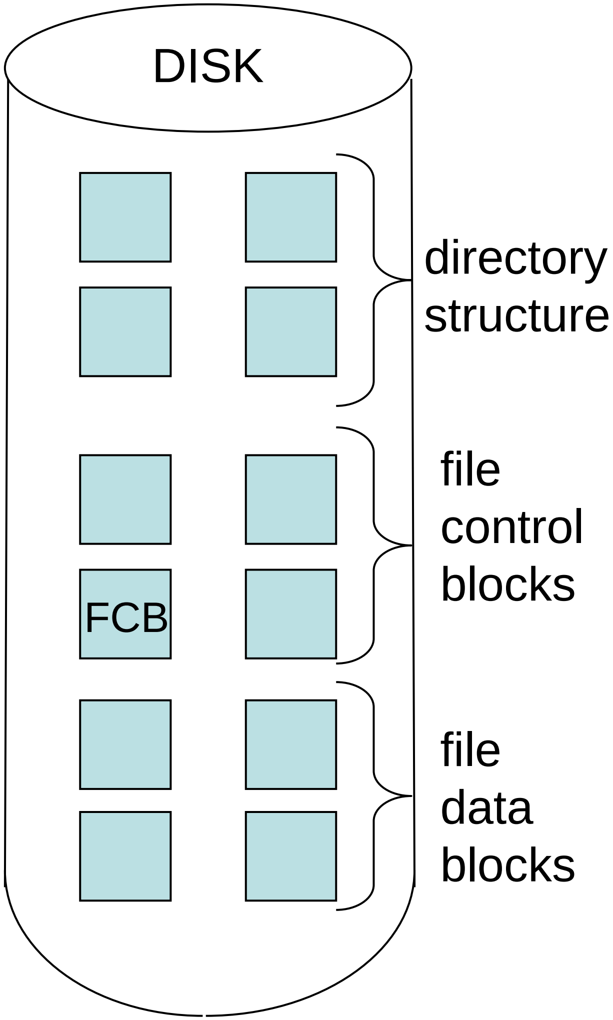
File System Reliability/ Fault Recovery

- **In general, OS should gracefully recover from hardware or software failure**
  - The file system needs to be engineered to ensure reliability/fault recovery
- **Problem: File system is quite fragile to system crashes**
  - There is a portion of the file system that is cached in memory
  - This portion may be inconsistent with the complete file system stored on disk

File System Fragility



- All in-memory file system data are lost on a **power loss**:
  - Directories, file metadata, and file data may all be cached in memory
  - They may all be modified
  - These modifications are lost if they weren't saved to disk



File System Reliability/ Fault Recovery

- Problem #1: **asynchronous writes produce inconsistency between in-memory and on-disk file system**
- Example: promised writes of filed data that were delayed by asynchrony may be lost
- Example: asynchronous writes of directory metadata can create inconsistency between the file system on disk and the writes cached in RAM
    - Directory information in RAM can be more up to date than disk
    - if there is a system failure, e.g. power loss, then the cached writes may be lost
    - in this case, the promised writes will not be executed

File System Reliability & Fault Recovery

- Solution: **To address asynchronous write inconsistency,**
  - UNIX caches directory entries for reads
  - But UNIX does not cache any data write that changes metadata or free space allocation

    These changes to critical metadata are written synchronously (immediately) to disk, before the data blocks are written
- Problem #2: **Even if all writes are synchronous, there is still a consistency problem:**
  - any of the individual synchronous/asynchronous writes to disk can <u>fail halfway through the operation, </u>leaving a half-written directory entry, FCB, or file data block.

File System Reliability & Fault Recovery

- Problem #3: **Complex operations can create inconsistency while waiting for them to complete**
  - – e.g. a file create() involves many operations, and may be interrupted at any time in mid-execution
  - – file create() updates the directory, FCB, file data blocks, and free space management
  - – if there is a failure after creating the FCB, then the file system is in an inconsistent state because the file data has not yet been saved on disk,
    - i.e. the directory says there is a file and points to the FCB, but the FCB is incomplete because its index block hasn’t been fully allocated

Reliability/Fault Recovery Solutions

- **Approach**: file systems can run a consistency checker like fsck in UNIX or chkdsk in MSDOS
  - in linked allocation, would check each linked list and all FCB's to see if they are consistent with the directory structure.
    - similar checks for indexed allocation
  - Check each allocated file data block to see that its checksum is valid
- Disadvantages:
  - This is computational intensive and takes a long time to check the entire file system.
  - This can detect an error, but doesn't ensure recovery or correction

Reliability/Fault Recovery Solutions

- **Approach**: *log-based recovery* is a solution that helps OS *recover* from file system failures:
  - OS maintains a log or journal on disk of each operation on the file system
  - called log-based or journaling file systems,
- The **log on disk is consulted after a failure** to reconstruct the file system
  - In a **journaling file system, the log is seen as a separate entity** from the file data.
  - In a **log-structured system, the log *is* the file system**, and there are no separate structures for storing file data and metadata – it's all in the log.

Log-Based Recovery

- Each operation on the file system is written as a record to the log on disk *before* the operation is actually performed on data on disk
  - this is called *write-ahead logging*
- The file system has a sequence of records of operations in the log about what was intended in case of a crash.
  - The log contains a sequence of statements like **“I’m about to write this directory entry/file header/file data block”,**
  - and **“I just finished writing this directory/FH/data”**.

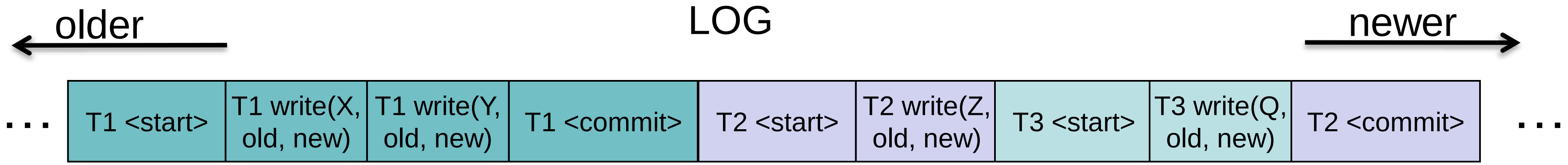
Log-Based Recovery

- operations are grouped in sets called ***transactions***
  - e.g. a file create() has many steps.
    - You either want the entire file created, or not at all if it fails at any step along the way.
  - Need the set of steps into a single logical unit
    - It is performed in its entirety or not at all.
- Transactions are viewed as atomic
  - Either succeed in their entirety or not at all

Log-Based Recovery

- A transaction T_i looks like the following:
  - begins with < T_i starts>
  - followed by a sequence of records like write(X), read(Y), ... needed to complete the transaction, e.g. a file create()
  - ends with < T_i commits>
- Write each of these operations to the log

Log-Based Recovery

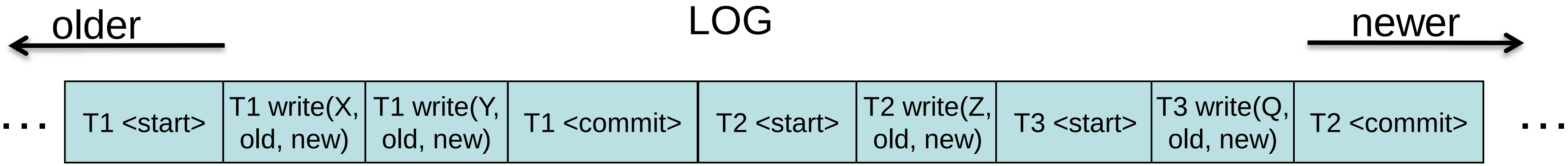


older ← LOG → newer

. . .	T1 <start>	T1 write(X, old, new)	T1 write(Y, old, new)	T1 <commit>	T2 <start>	T2 write(Z, old, new)	T3 <start>	T3 write(Q, old, new)	T2 <commit>	. . .

- Each log record of an operation within a transaction consists of:
  - transaction name T_i
  - data item name, e.g. X
  - old value
  - new value
- Both the old and new values must be saved in order for the system to recover from crashes in mid-transaction

Log-Based Recovery



older

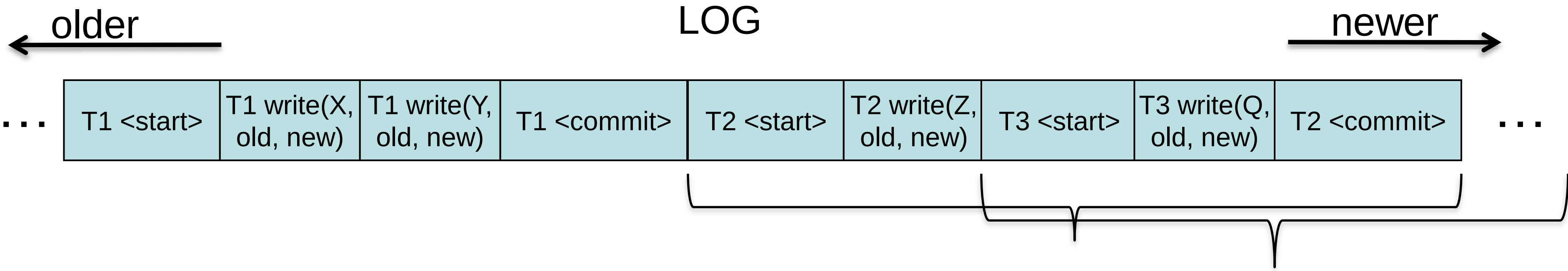
LOG

newer

…	T1 <start>	T1 write(X, old, new)	T1 write(Y, old, new)	T1 <commit>	T2 <start>	T2 write(Z, old, new)	T3 <start>	T3 write(Q, old, new)	T2 <commit>	…

- **A transaction is not considered complete until it is committed in the log**
  - once the <commit> appears in the log, then even if the system crashes after this point, there is enough information in the log to fully execute the transaction upon recovery
  - therefore, once the <commit> appears in the log, it is OK to return from the system call that called file create() or file write()

Log-Based Recovery



older

LOG

newer

…

T1 <start>

T1 write(X, old, new)

T1 write(Y, old, new)

T1 <commit>

T2 <start>

T2 write(Z, old, new)

T3 <start>

T3 write(Q, old, new)

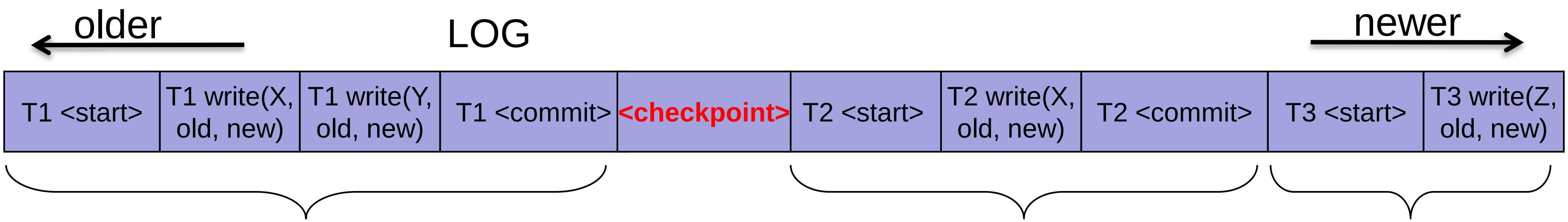
T2 <commit>

…

- Operations in different transactions can overlap in the log

- For asynchronous writes, the actual write(X) to disk may occur much later than the entry written to the log

Log-Based Recovery



older

LOG

newer

T1 <start>	T1 write(X, old, new)	T1 write(Y, old, new)	T1 <commit>	**<checkpoint>**	T2 <start>	T2 write(X, old, new)	T2 <commit>	T3 <start>	T3 write(Z, old, new)

completed transactions are all full transactions prior to a *checkpoint*. All such transactions have been both:

1. committed to the log *and*
2. have been executed by the file system

committed transactions are those that

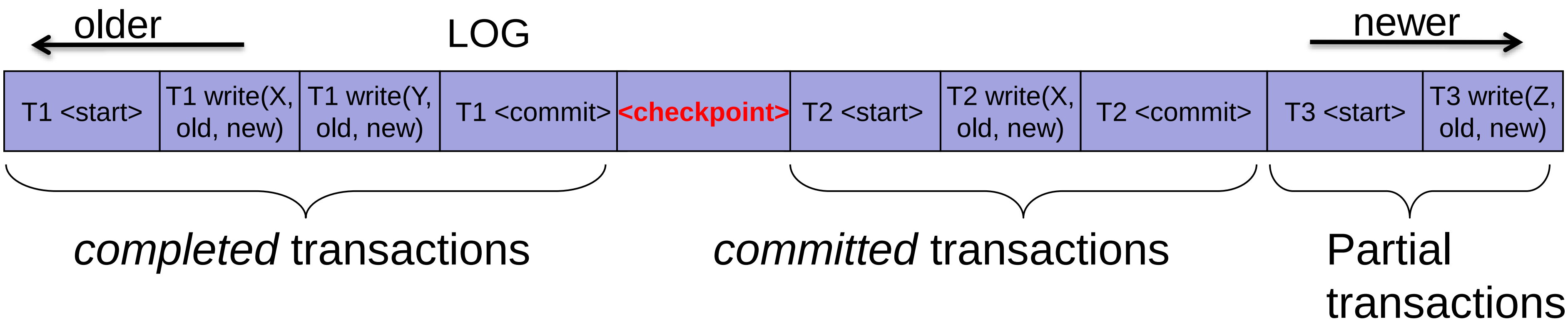
1. have been committed to log but
2. have not yet been executed by the file system (since this is a write-ahead log),

- They are candidates for *redo*() after a crash

Partial transactions are candidates for *undo*() after a crash

Checkpoint: confirm the state of the system: All trans are committed & executed

Log-Based Recovery



older

LOG

newer

T1 <start>	T1 write(X, old, new)	T1 write(Y, old, new)	T1 <commit>	<checkpoint>	T2 <start>	T2 write(X, old, new)	T2 <commit>	T3 <start>	T3 write(Z, old, new)

completed transactions

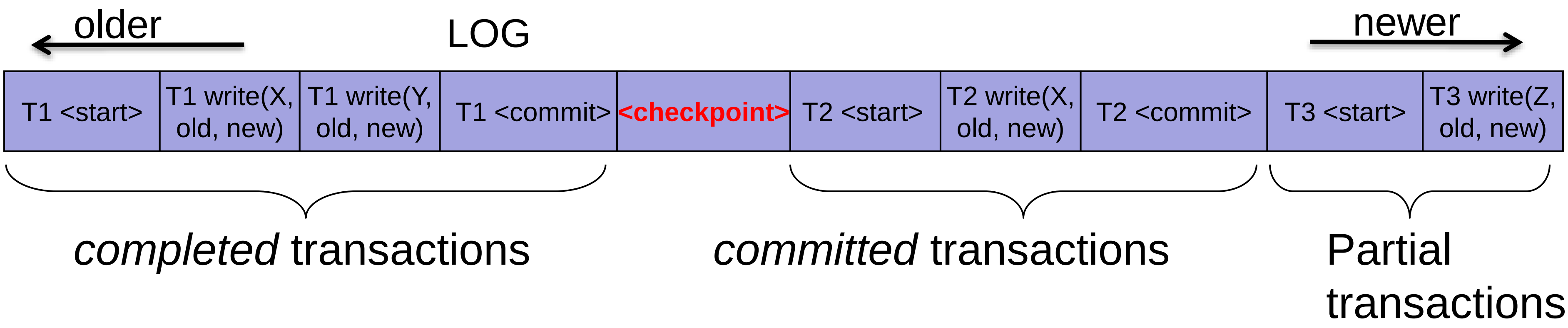
committed transactions

Partial transactions

- The checkpoint indicates that all full transactions (those with a <start> and <commit>) prior to the checkpoint (to the left) have been written to *both* the disk *and* log

- Committed transactions are full transactions in the log that are to the right of the most recent checkpoint, and thus have not been written to disk yet

Log-Based Recovery



older

LOG

newer

T1 <start>	T1 write(X, old, new)	T1 write(Y, old, new)	T1 <commit>	**<checkpoint>**	T2 <start>	T2 write(X, old, new)	T2 <commit>	T3 <start>	T3 write(Z, old, new)

completed transactions

committed transactions

Partial transactions

- In normal operation, the file system will
  - periodically *replay* committed transactions in the log onto disk,
  - Then add a new checkpoint to the log,
  - thus all committed transactions to the left of the newly added checkpoint are converted into completed transactions
  - completed transactions can be removed from the log, or just written over if it’s a circular log

Log-Based Recovery

- On a failure, the OS looks for the latest checkpoint in the log, and redo()'s committed transactions and undo()'s partial transactions from that point on
  - redo() transaction T_i if the log contains both < T_i starts> and < T_i commits> and these transactions appear after a checkpoint
  - undo() transaction T_k if the log contains < T_k starts> but not < T_k commits>
    - this is called an aborted transaction
    - during recovery, such a transaction is rolled back to its former state

Log-structured File Systems

- Assumption:
  - Write is more expensive than read since read can be served very quickly from cache
- Treat the storage as a circular log – Write sequentially to the head of the log
- Advantages:
  - Improve write performance through low seek time (batched write)
  - Allow time-travel or snapshotting
  - Recovery from crash is simpler based on the previous checkpoint.
- Disadvantage:
  - Might make read to be much slower since it fragments files (Optic and Magnetic disk)

Journaling File Systems

- Some file systems like NTFS only write changes to the metadata of a filesystem to the log
  - file headers and directory entries only
  - NOT any changes to file data
  - The journal is separate from the main file system
- Copy-on-write file systems (such as ZFS and Btrfs)
  - Avoid in-place changes to file data by writing out the data in newly allocated blocks
  - Followed by updated metadata that would point to the new data and disown the old
  - Followed by metadata pointing to updated metadata repeatedly to the root of the file system hierarchy
  - Has the same correctness-preserving properties as a journal, without the write-twice overhead
  - Add metadata (checksums) to insure data integrity

Journaling File Systems

- Linux’s ext4fs can be parameterized to operate in 3 modes (cont):

  1. *Journal mode*: both metadata and file data are logged. This is the safest mode, but there is the latency cost of two disk writes for every write.
  2. *Ordered mode:* only metadata is logged, not file data, and it's guaranteed that file contents are written to disk before associated metadata is marked as committed in the journal.
     - This is the default on many Linux distributions.
  3. *Write-back mode:* only metadata is logged, not file data, and no guarantee file data written before metadata, so files can become corrupted.
     - This is riskiest mode/least reliable but fastest.