# Chapters 10, 11 and 12: Free Space Management, File System Reliability

CSCI 3753 Operating Systems

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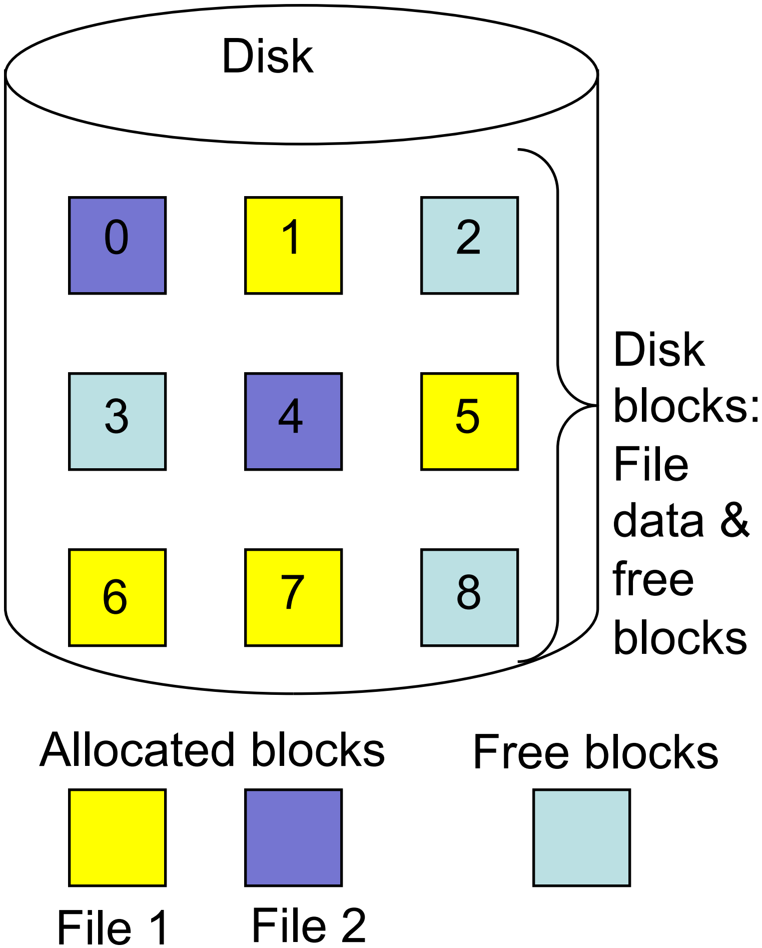
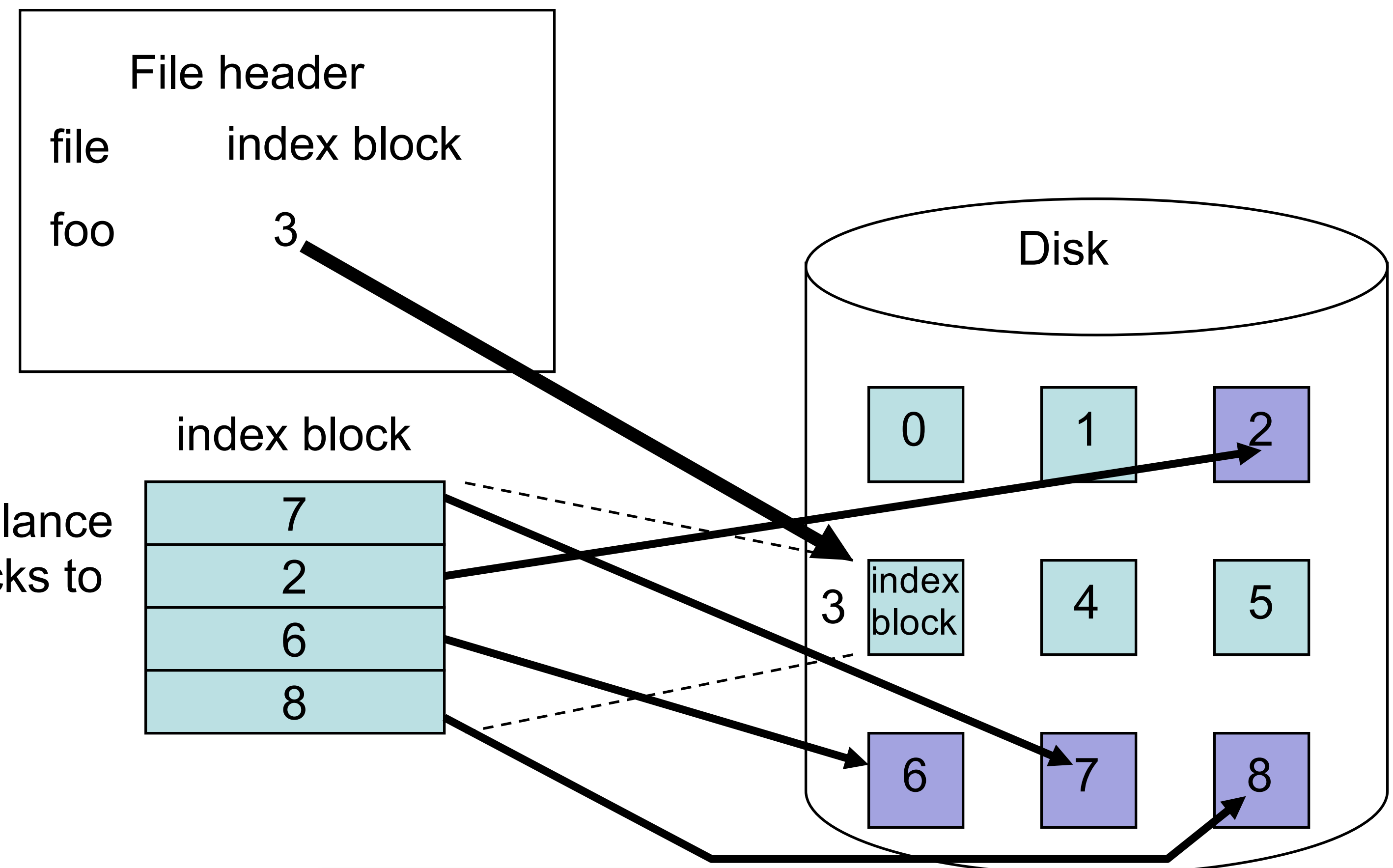
# Recap

- File allocation techniques
  - contiguous allocation
  - Linked allocation
  - FAT
  - Indexed allocation with index block
  - Multi-level indexed allocation
  - UNIX/Linux use hybrid multi-level indexed allocation



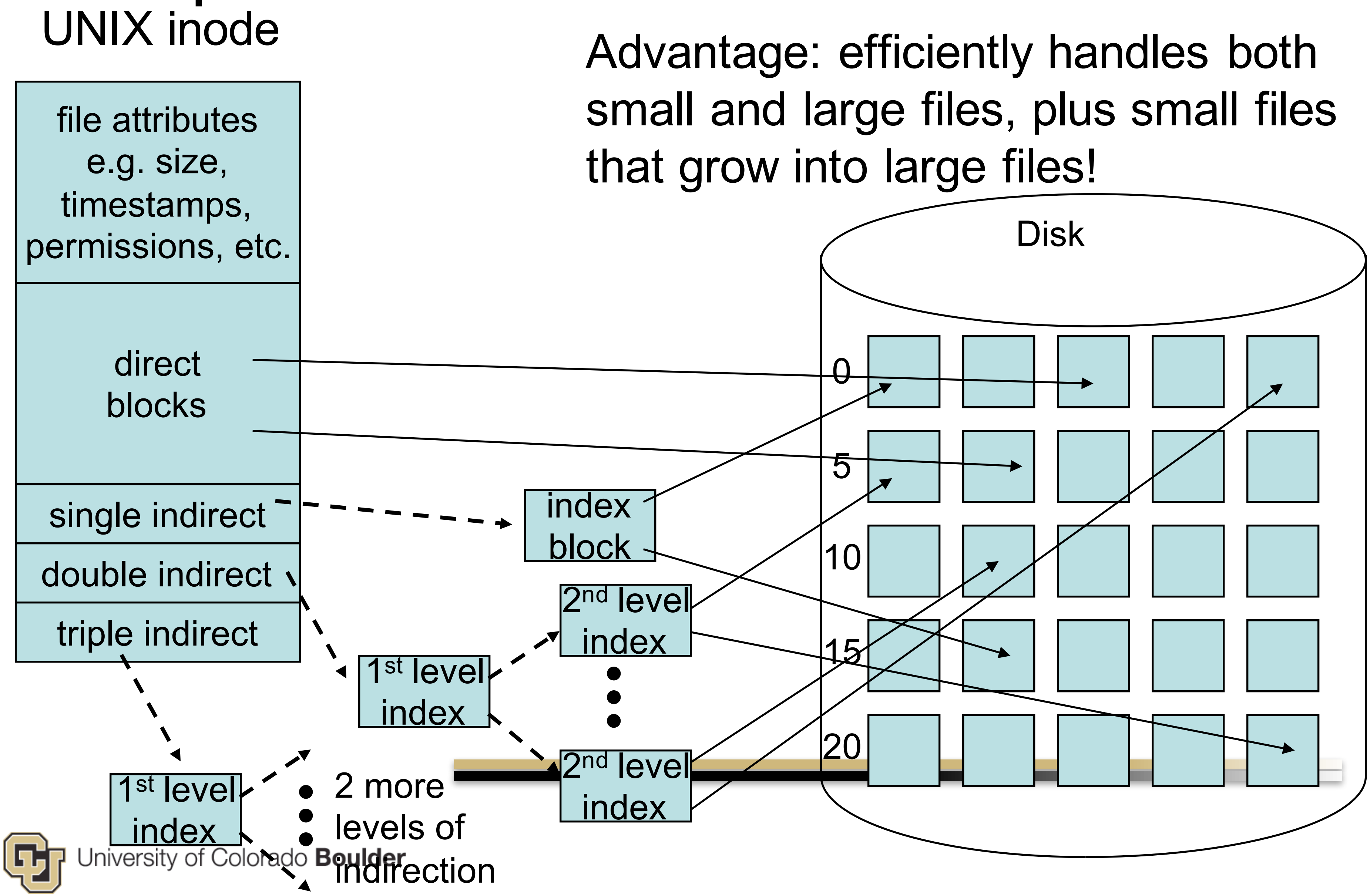
# Recap: Indexed Allocation




note resemblance of index blocks to page tables!

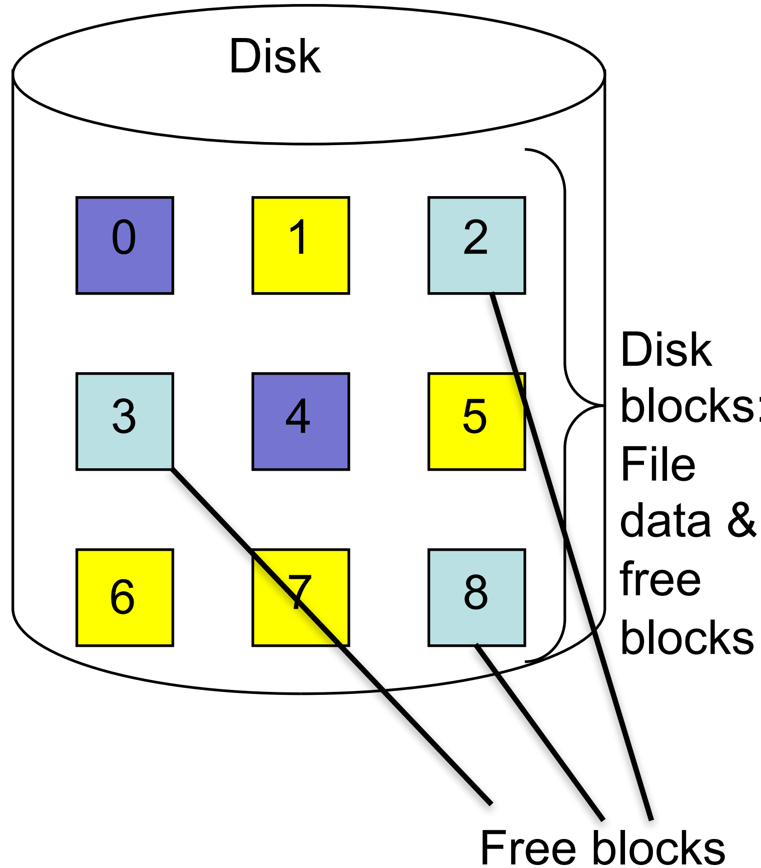
# Recap: UNIX Multilevel Indexed Allocation

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



# 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



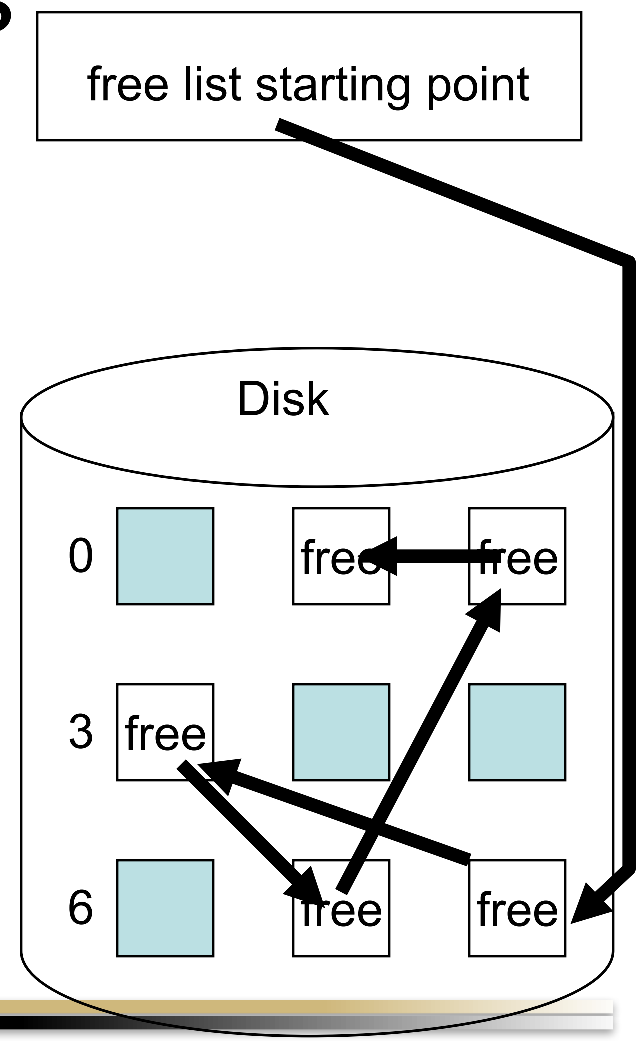
# Free Space Management Approaches

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

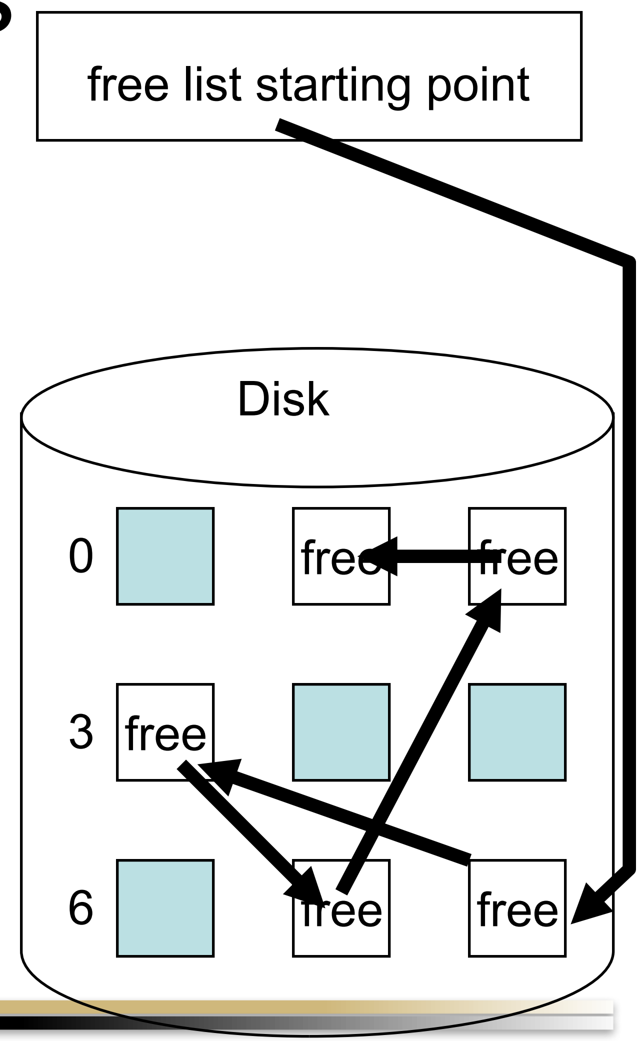
# Free Space Management Approaches

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



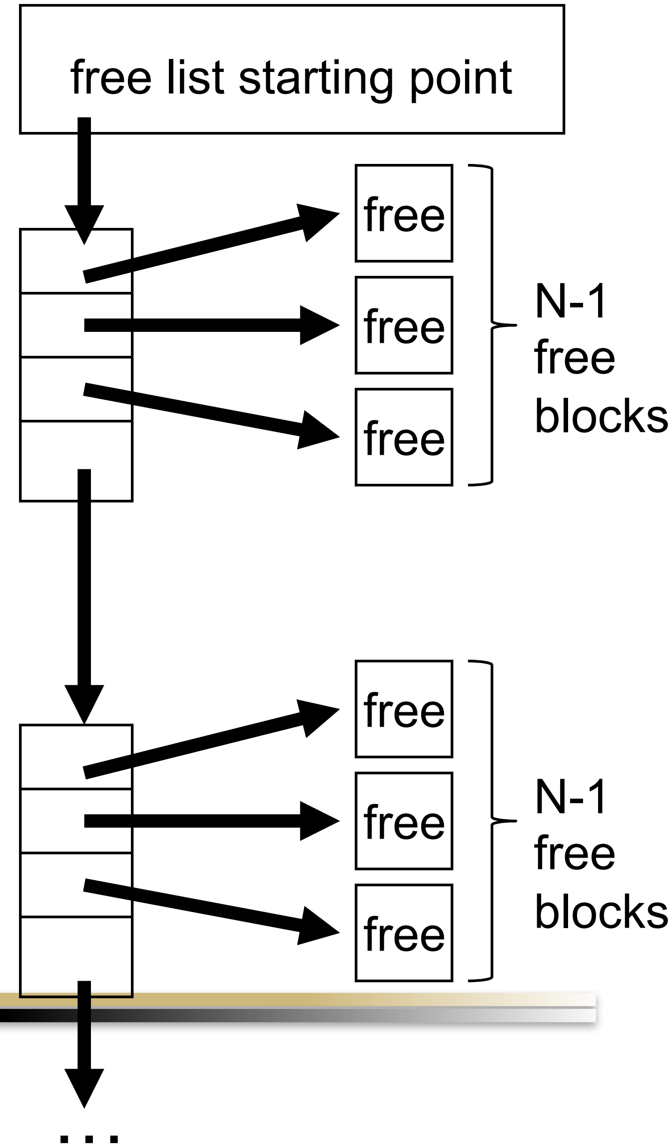
# Free Space Management Approaches

- 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



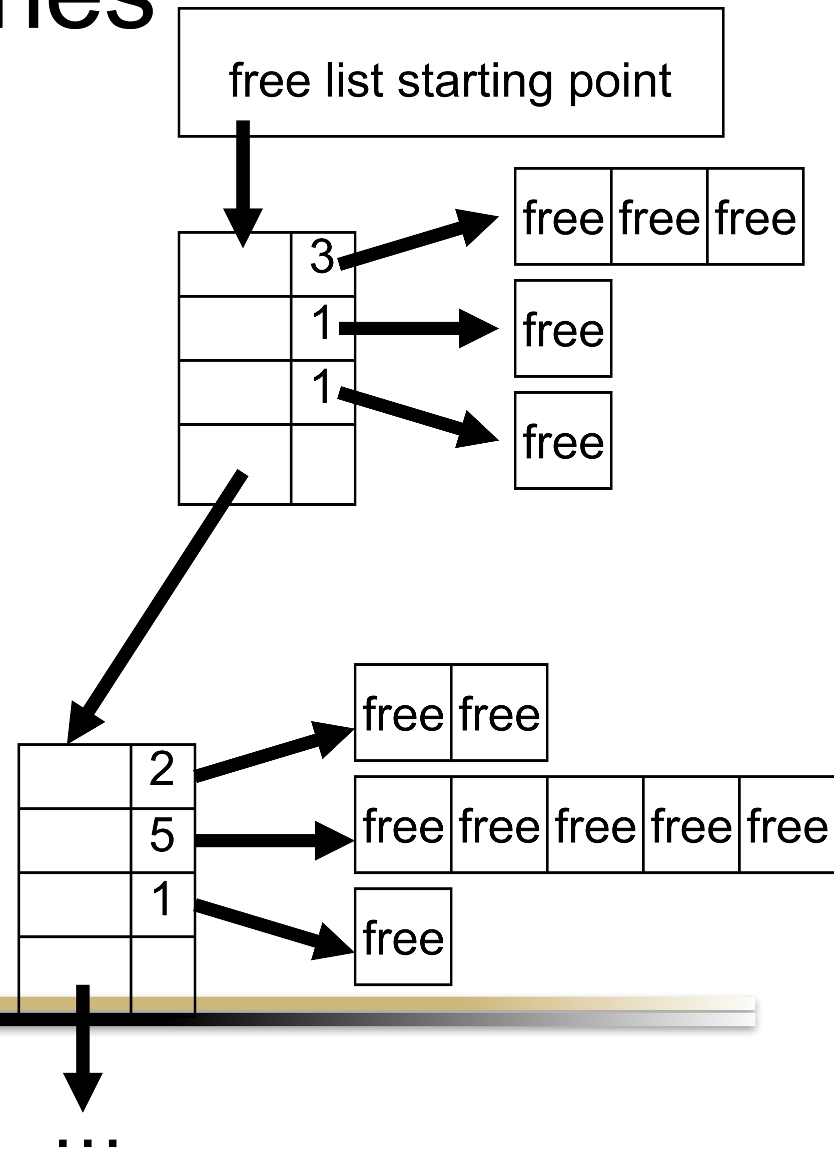
# Free Space Management Approaches

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

- So far, we've seen the following 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

- So far, we've seen the following approaches to improve performance in a file system:
  - 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

- Some 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

# Memory-Mapped Files

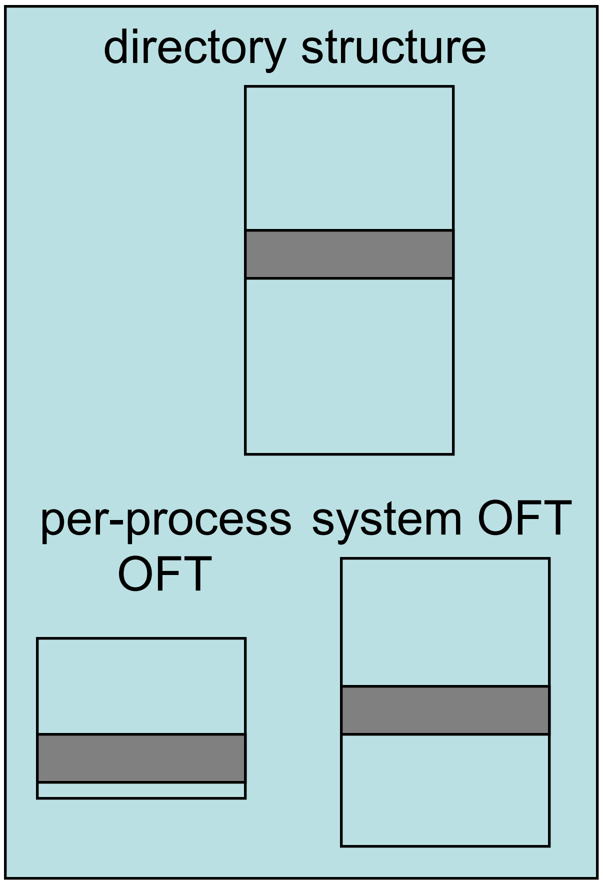
- Review lecture 9.3 slides
- map some parts of a file on disk to pages of virtual memory
  - Use mmap() call
  - First read/write to file data not in memory will on-demand page in the desired blocks of file into main memory pages
  - Subsequent reads/writes to that file data are served quickly by memory
  - Later, flush changes in file to disk
  - Uses virtual memory system – fast compared to read()/write() system calls to change file data contents

# File System Reliability/ Fault Recovery

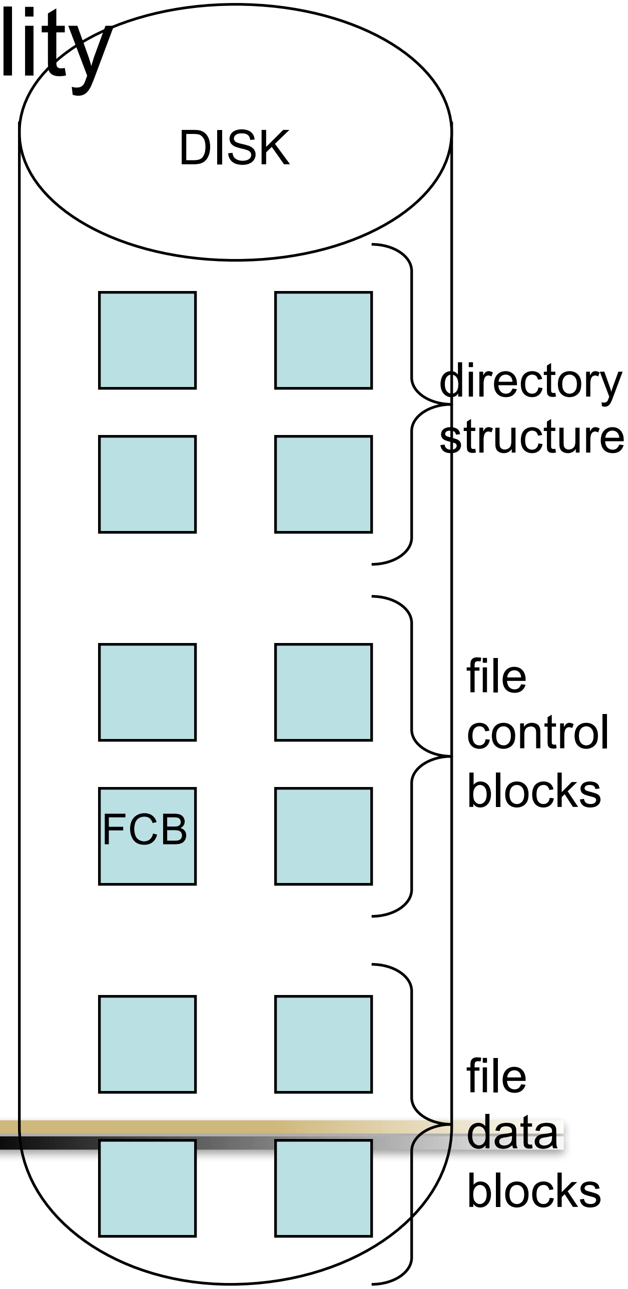
- In general, OS should gracefully recover from hardware or software failure
  - The file system needs to be engineered to ensure reliability/fault recovery
- Problem: File system is quite fragile to system crashes
  - There is a portion of the file system that is cached in memory
  - This portion may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

# File System Fragility

In-Memory OS File Manager




- 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

- 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 fail halfway through the operation, 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 heavyweight, 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 you *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*
- thus, 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.
  - So group the set of steps into a single logical unit that is performed in its entirety or not at all.
- in this way, transactions are viewed as atomic – they 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

LOG

← older — 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

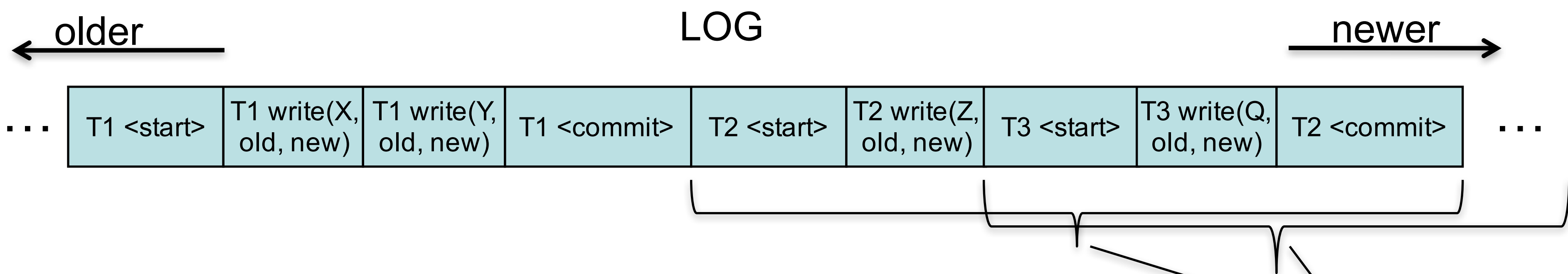
# Log-Based Recovery

← 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




- 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

# Log-Based Recovery

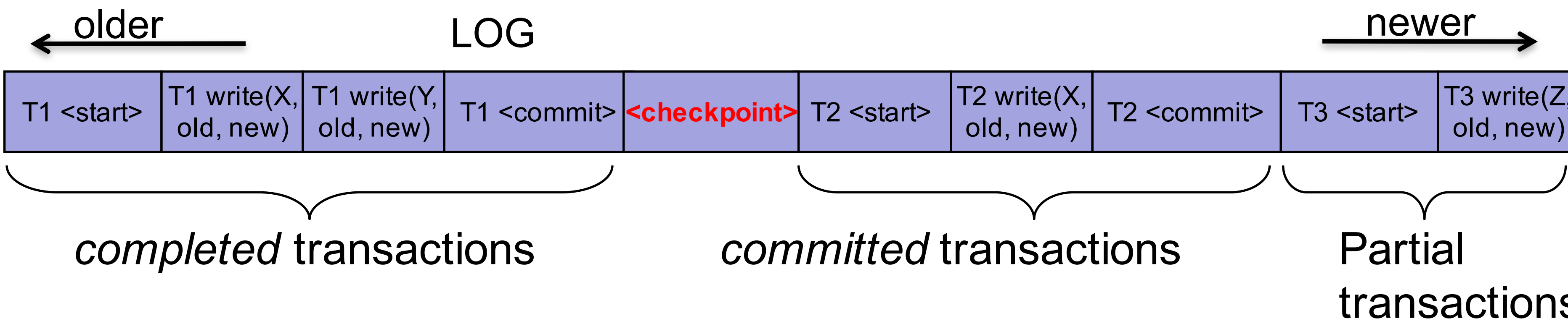
older ← LOG → newer

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 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




- 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-Based Recovery

- Note on an undo(),
  - the log records contain both the old and new data,
  - so there is enough information in the log to restore or roll back a file or object to its old state if the transaction was not completed
- In this way, the OS can cleanly recover the file system

# Journaling File Systems vs. Log-Structured File Systems

- Some file system maintains a separate circular buffer called a journal that records the most recent changes to the file system
  - The journal is separate from the main file system
  - e.g. NTFS, ext3/4fs
- For log-structured file systems, the journal is the file system, i.e. there are no separate data structures, and the journal contains enough information to be entire file system
  - e.g. flash file systems like JFFS, JFFS2, YAFFS. Also LogFS, Sprite LFS, …

# Journaling File Systems

- Some file systems like NTFS only write changes to the metadata of a filesystem to the log
  - e.g. file headers and directory entries only, and not any changes to file data
- Linux's ext4fs can be parameterized to operate in 3 modes:
  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.

# Journaling File Systems

- Linux's ext4fs can be parameterized to operate in 3 modes:
  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 way, you don't have say a file header pointing to a new block of data, yet that data has not yet been written to disk. This is the default on many Linux distributions.
  3. *Writeback 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.