Operating System Concepts

Lecture 32: File System Reliability & Examples

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Free space management

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- need to maintain a free-inode list too

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  - expensive to find a free block if most blocks are used!
- problem? the bitmap might be too big to keep in memory

block size = 512 bytes

disk size = 2GB

n = $2^{31}/2^{9} = 2^{22}$ blocks -> 2^{22} bits (**512KB!**)

Linked free-space list

- link together all free disk blocks; each block contains a pointer to the next free block (saving space)
- the head of the list is cached in memory
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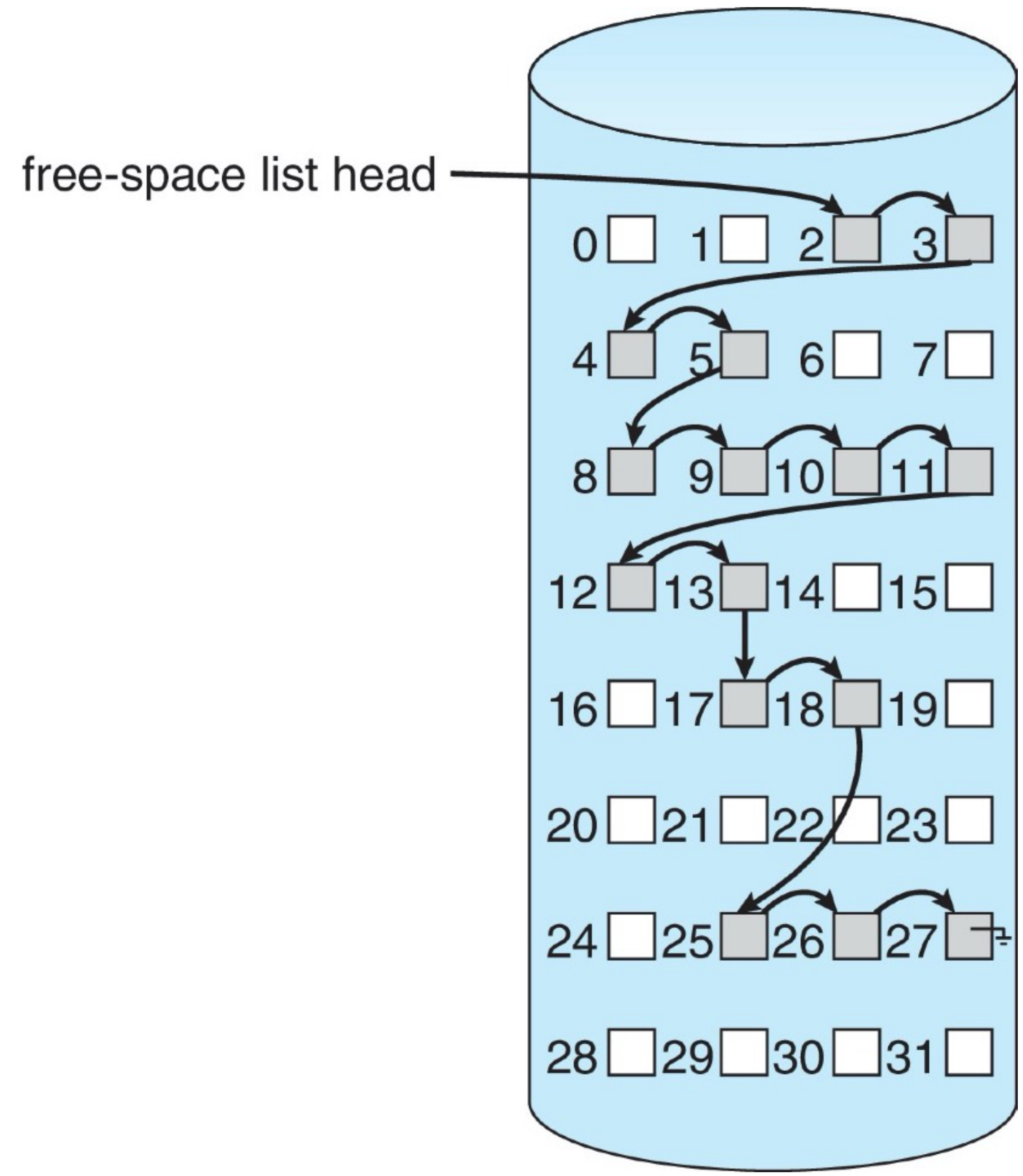

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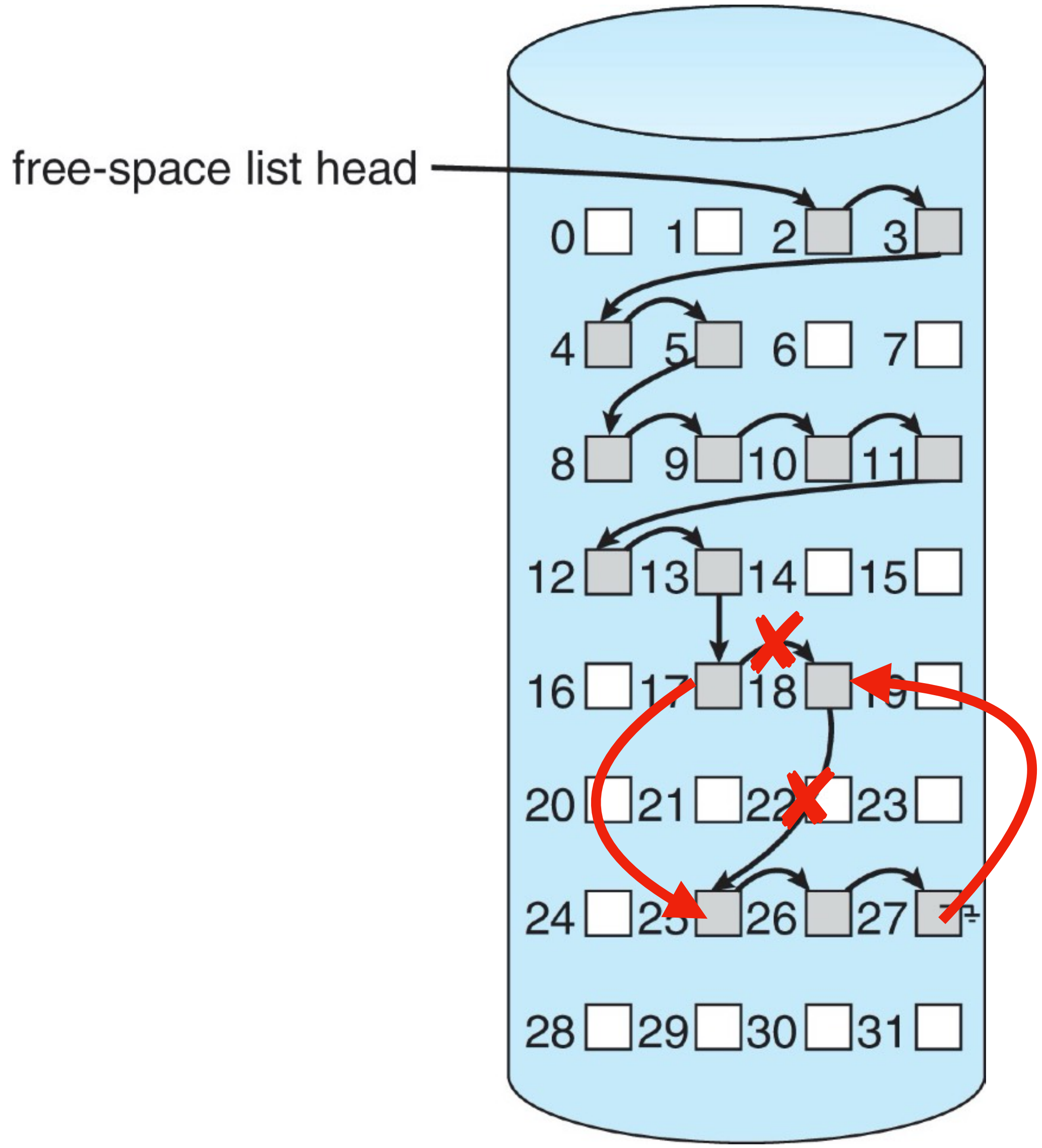
  - linked list gets disorganized over time
  - cannot get contiguous space easily



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- counting
  - space is contiguously used and freed frequently so
    - keep the address of the first free block and the number of following free blocks
    - free-space list has entries containing addresses and counts

Summary

- many of the concerns, tradeoffs, and design decisions discussed for file system are similar to those of virtual memory (and disk as we will see later)
  - contiguous allocation is simple, but suffers from external fragmentation, the need for compaction, and the need to move files as they grow
  - indexed allocation is very similar to page tables
    - a mapping from logical file blocks to physical disk blocks
  - free space can be managed using a bitmap or a linked list

Today's class

- How to make sure that data and metadata previously stored can be retrieved regardless of software crashes and hardware failures?
  - data consistency
  - metadata consistency
- How real file systems are implemented?
  - FFS
  - NTFS

File System Reliability

File system reliability problem

- a single file system operation can involve updates to multiple physical disk blocks (inode, data blocks, bitmap, etc.)
  - to move a file between directories, it has to be deleted from the old directory and added to the new directory
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- **Goal:** guarantee consistency regardless of when crash occurs

Data consistency

- UNIX file system uses the write-back strategy (i.e., delaying writing the modified data back to disk) with periodic forced writes to disk (e.g., every 30 seconds)
  - so other processes read data from cache instead of disk
  - potential for loss of 30 seconds worth of cached changes
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  - user can use the `sync` system call to flush buffer cache to disk immediately
- how to write changes to a file onto disk?
  - naive approach:
    - delete old version; create new version
  - correct approach:
    - write new version in temp file; move old version to another temp file; move new version into real file; unlink old version
    - on a crash look at temp area; if there is any files out there notify user that there might be a problem

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  - run a consistency checker (called `fsck` in UNIX) which scans the entire disk for internal consistency
  - this approach is used in FAT and UNIX file system
- disadvantages:
  - post-crash recovery is time consuming (can take minutes or hours) and may not be possible
  - difficult to reduce every operation to a safely interruptible sequence of writes
  - difficult to achieve consistency when multiple operations occur concurrently

Example

- let’s say you want to extend a given file by one block; the necessary operations are as follows

  1. find a free block
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- so in the case of a crash
  - if a bit is set in the bitmap but a pointer to this block is not added to any inode, writing inode must have been in progress when system crashed
  - if a bit is set in the bitmap and a pointer to this block is added to an inode but file data is not written to that block, writing data must have been in progress when system crashed

Transaction concept

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  - durable: future failures do not affect/corrupt previously committed transactions
- **Basic idea**: do a set of metadata updates tentatively; if you don’t get to commit (due to crash or failure), then roll-back the operations as if the transaction never happened
  - commit makes transaction durable by writing a single sector on disk (we assume this happens atomically)

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- **Note**: sequential I/O is faster than random I/O, and therefore, can be done synchronously

Log-based transaction-oriented file system

- almost all new file systems such as NTFS, ext3, and ext4 use **journaling** (or **write-ahead logging**)
    - write all changes in a transaction to log (update directory, allocate block, etc.) before sending any changes to disk
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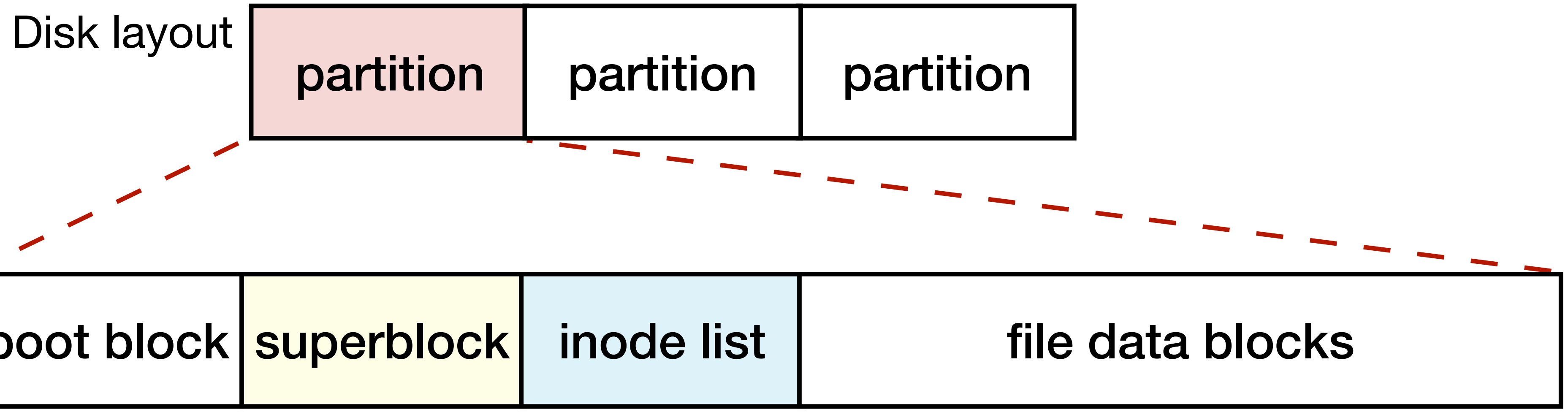
- journaling eliminates the need for doing post-crash file system consistency check (e.g., via `fsck`)
- advantage: a general solution to reliability problem
- disadvantage: data is written twice!

File System Examples

Traditional UNIX file system



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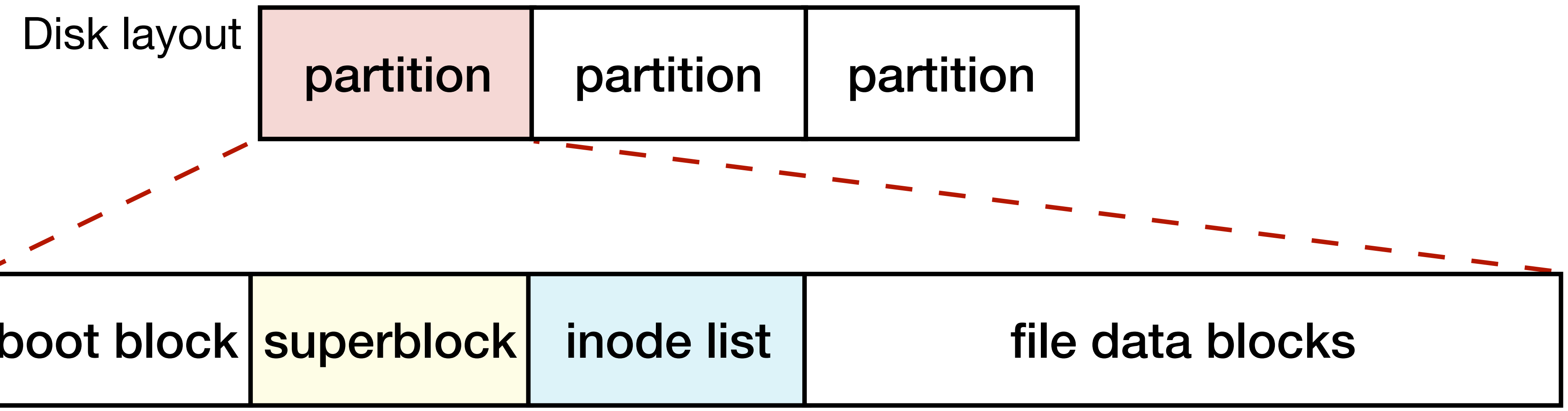

- boot block contains the bootstrap program that runs at boot time to load the OS from that partition
- superblock defines a file system (there is only one per file system)
  - size of the file system and size of the inode list
  - list of free disk blocks (and index of the next free block)
  - list of free inodes (and index of the next free inode)
  - location of the inode of the root directory (inode #2)

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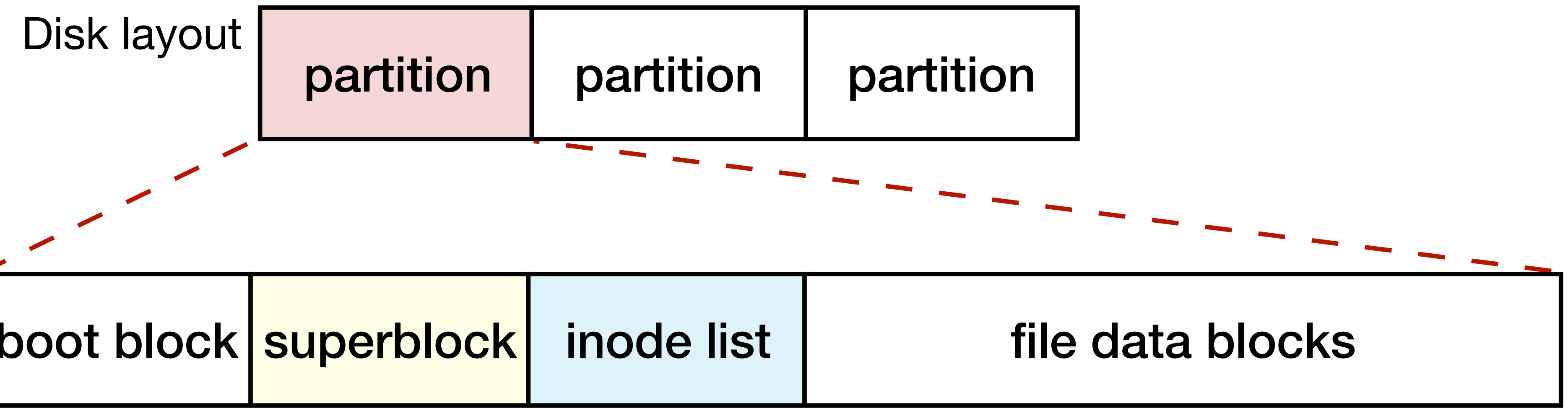

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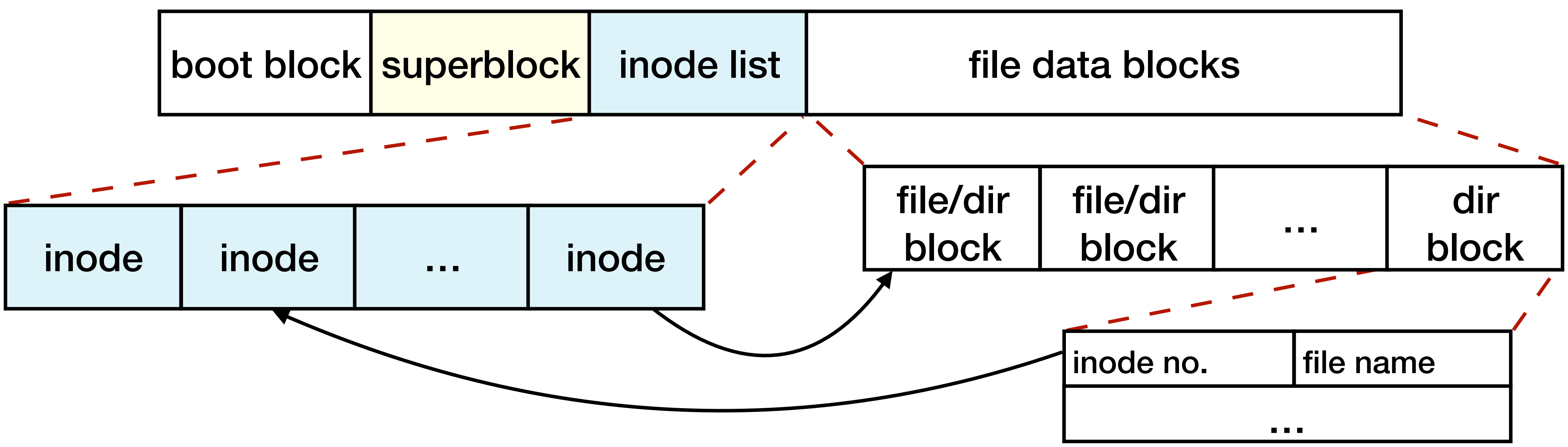
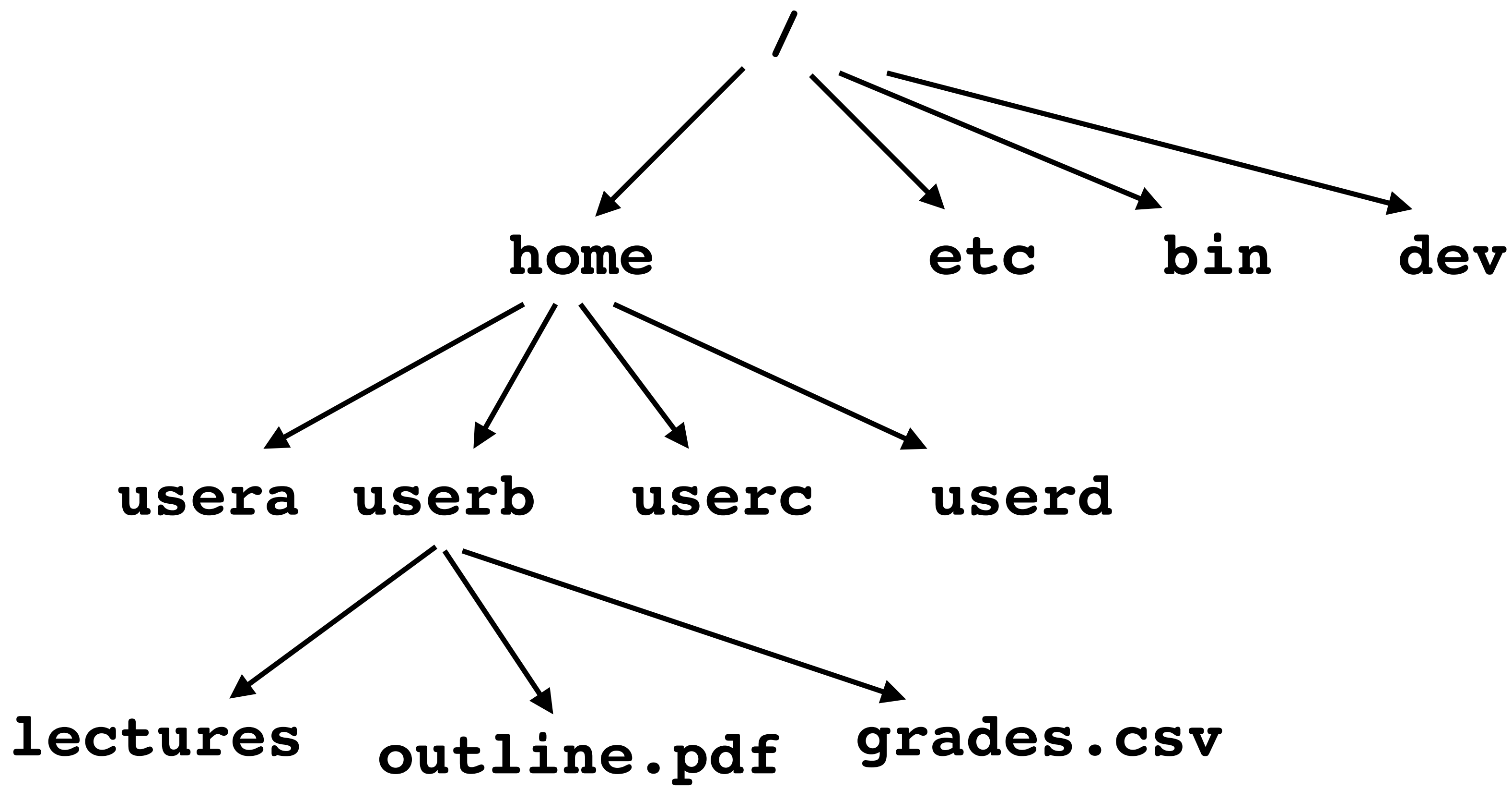
  - list of free inodes (and index of the next free inode)
  - location of the inode of the root directory (inode #2)
- inodes contain file metadata; each inode is identified by a nonnegative integer (i.e., the inode number)
  - can translate the inode number to a location on the disk (inode contains pointers to file data blocks)
  - inodes are either put together as one group (in the inode list) or spread across the disk

Naming and directory structure

- a directory entry (dentry) is a collection of (name, inode number) pairs for files and directories therein
  - is stored as a regular file (its inode has a special flag bit set)
  - only OS can modify directory; users can just read them
  - . and .. are stored as ordinary file names with inode numbers pointing to the inodes of the same directory and the parent directory respectively



A tree-structured hierarchy



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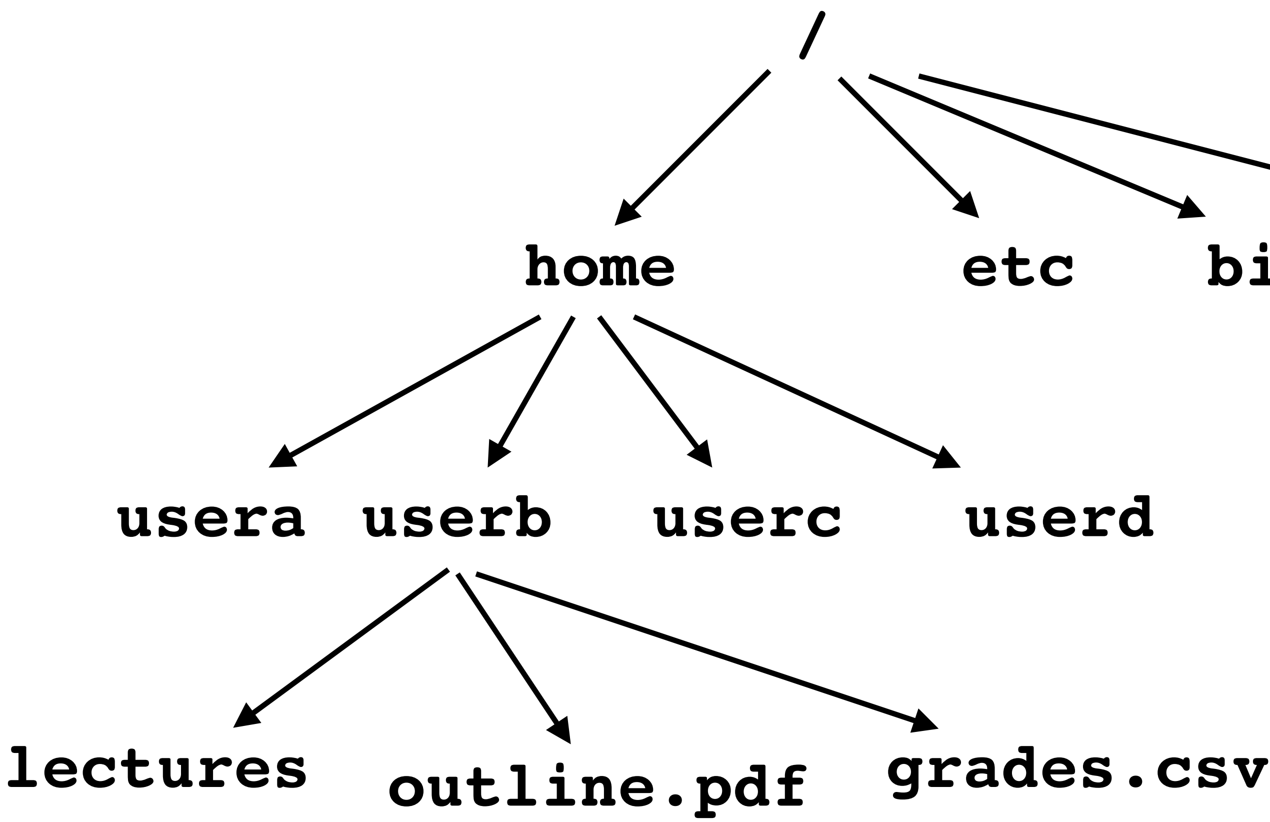


home's dentry contains

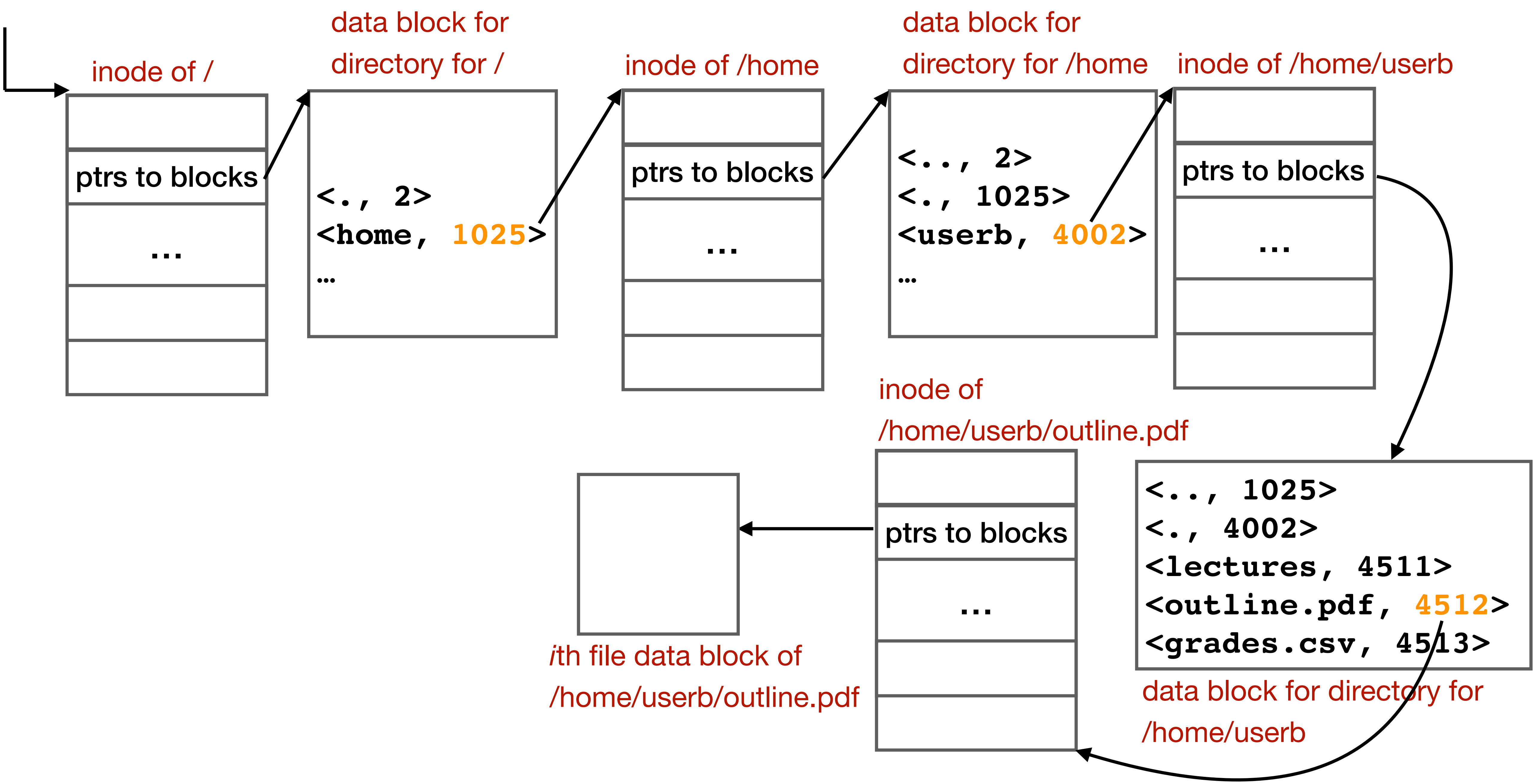
<.., 2>
<., 1025>
<usera, 4001>
<userb, 4002>
<userc, 4003>
<userd, 4004>

userb's dentry contains

<.., 1025>
<., 4002>
<lectures, 4511>
<outline.pdf, 4512>
<grades.csv, 4513>

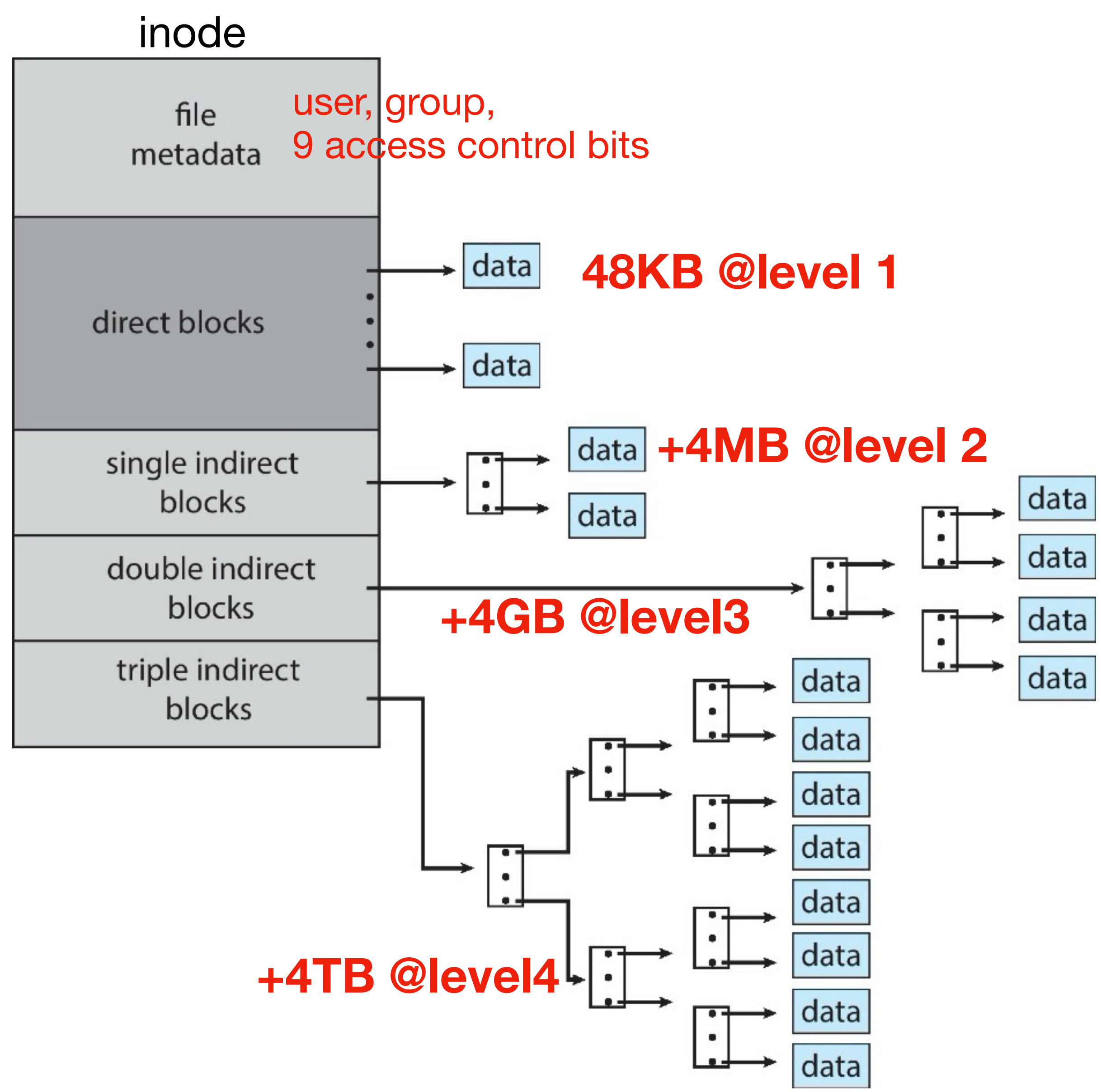
Resolving file location

Where are data blocks of `/home/userb/outline.pdf`?



Asymmetric tree

- original inode format appeared in BSD 4.1 (and later in BSD 4.2)
- each inode contains 15 block pointers (with 32-bit file pointer)
    - the first 12 pointers point to data blocks
        - small files (up to 48KB) use direct blocks only
    - the 13th pointer points to a block of 1024 pointers to 4KB data blocks (1-level indirection)
    - the 14th pointer points to a block of pointers to indirect blocks (2-level indirection)
    - the 15th pointer points to a block of pointers to indirect blocks (3-level indirection)
- shallow tree for small files
    - efficient storage for small files
- deep tree for large files
    - efficient lookup for random access in large files



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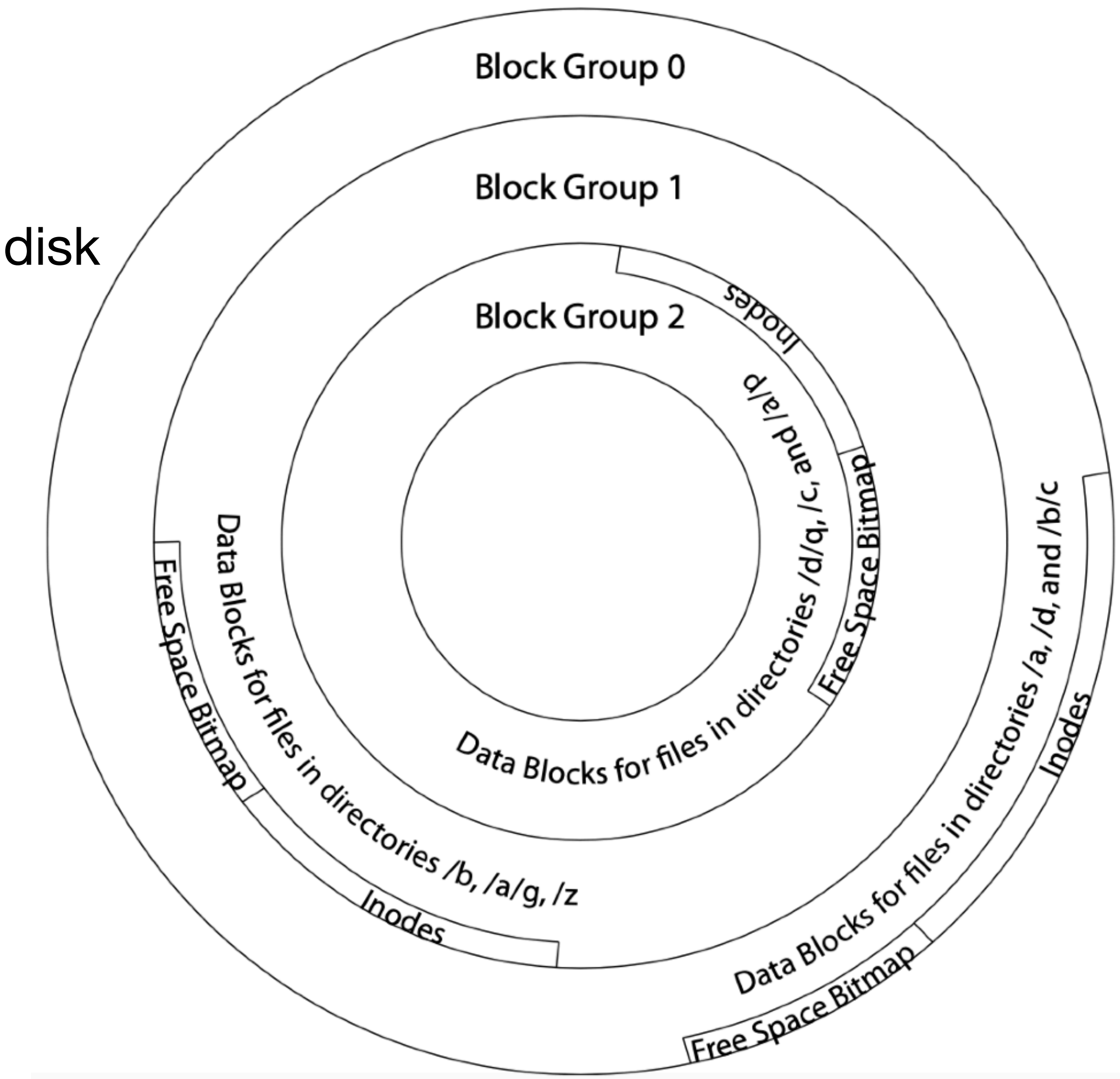
- Fast File System (FFS) proposed allocation and placement policies for BSD 4.2 addressing these problems

Achieving data locality in FFS

- block group is a set of nearby cylinders
  - fast seek between cylinders in same block group
- block group allocation
  - files in same directory are located in same group
  - subdirectories are located in different block groups
- inode list and bitmap are spread throughout disk
  - near file blocks



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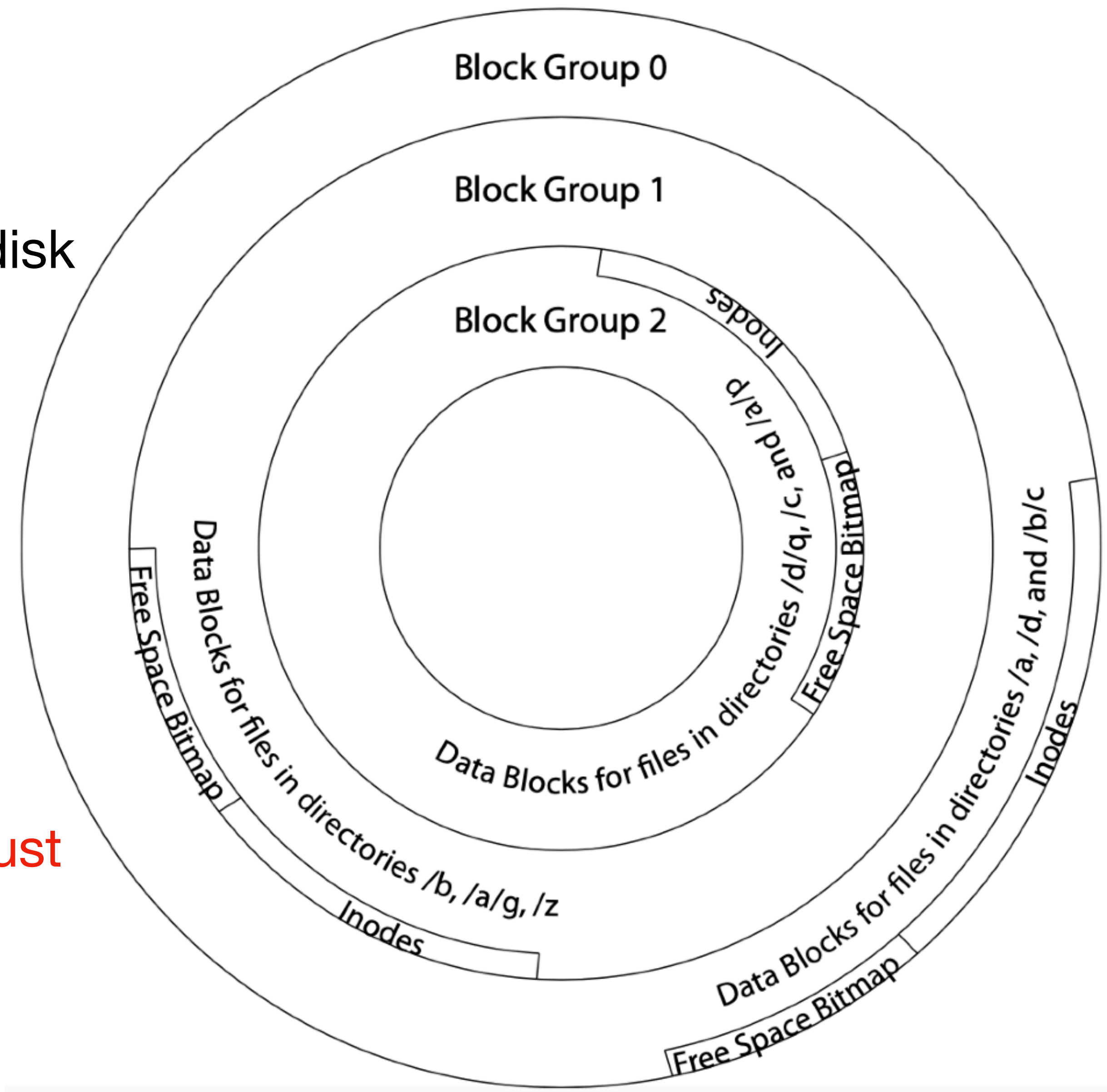

to allocate according to cylinder groups, disk must have free space scattered across cylinders (10% of disk space is reserved for this purpose)

FFS first-fit block allocation

- when allocating space to a new file, search for a free block from the start of the block group
- when extending a file, search for a free block from the last block allocated to that file
  - if there is not enough free blocks in that range, allocate the remaining blocks from a new range
- there will be few little holes at start and a big hole at end of a block group
  - so small files will be fragmented, and large files will be mostly contiguous

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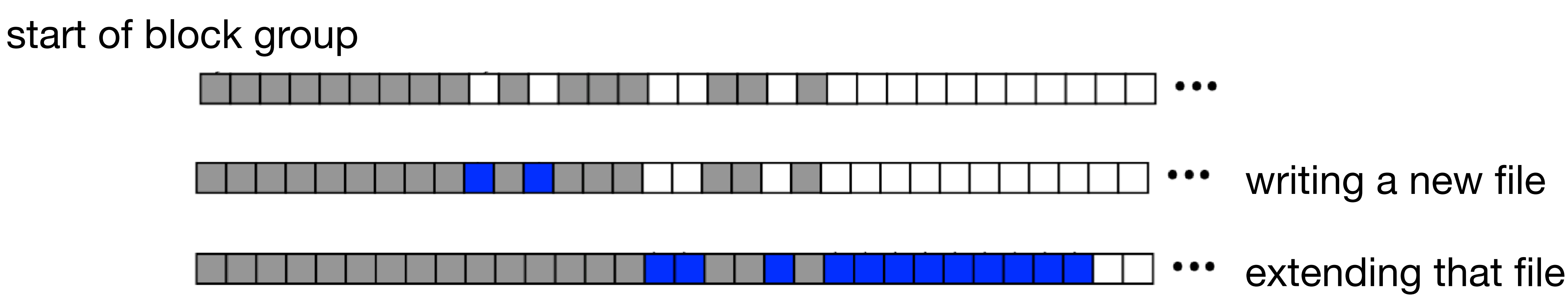
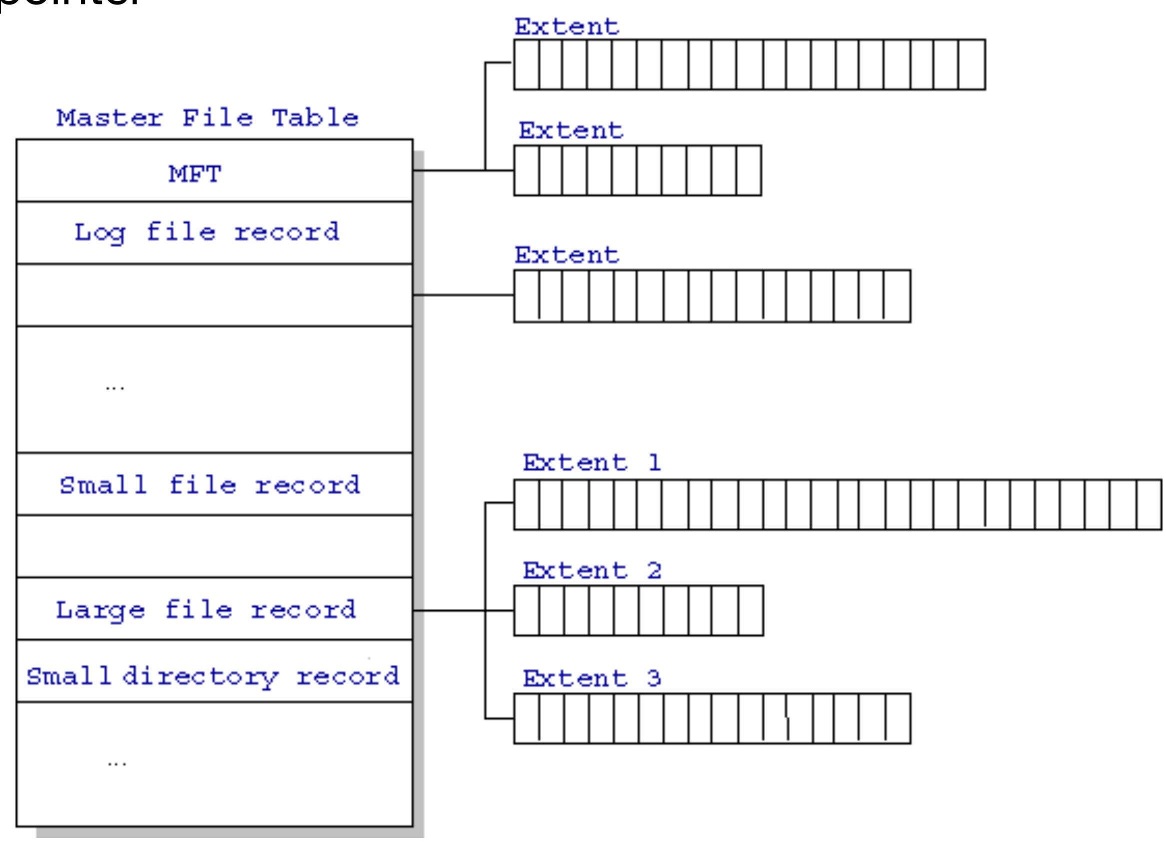


NTFS

- master file table is a flexible (1KB to 4KB) storage for metadata and data
- directories organized using B-trees
- index structure is a variable-depth tree
  - mixes direct and indirect block pointers
- variable-length extents (i.e., adjacent disk blocks)
  - have to store start and length of each extent in block pointer
  - user can provide hint as to size of file being created
- journalling for consistency checking
  - all metadata changes are written sequentially to a log



to learn more visit: http://ntfs.com/ntfs_basics.htm