File Systems: Memory Management, Naming, and Reliability

CS 111

Operating System Principles

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Outline

- Managing disk space for file systems
- File naming and directories
- File volumes
- File system performance issues
- File system reliability

Free Space and Allocation Issues

- How do I keep track of a file system's free space?
- How do I allocate new disk blocks when needed?
  - And how do I handle deallocation?

The Allocation/Deallocation Problem

- File systems usually aren't static
- You create and destroy files
- You change the contents of files
  - Sometimes extending their length in the process
- Such changes convert unused disk blocks to used blocks (or visa versa)
- Need correct, efficient ways to do that
- Typically implies a need to maintain a free list of unused disk blocks

Creating a New File

- Allocate a free file control block
  - For UNIX
    - Search the super-block free I-node list
    - Take the first free I-node
  - For DOS
    - Search the parent directory for an unused directory entry
- Initialize the new file control block
  - With file type, protection, ownership, ...
- Give the new file a name

Extending a File

- Application requests new data be assigned to a file
  - May be an explicit allocation/extension request
  - May be implicit (e.g., write to a currently non-existent block – remember sparse files?)
- Find a free chunk of space
  - Traverse the free list to find an appropriate chunk
  - Remove the chosen chunk from the free list
- Associate it with the appropriate address in the file
  - Go to appropriate place in the file or extent descriptor
  - Update it to point to the newly allocated chunk

Deleting a File

- Release all the space that is allocated to the file
  - For UNIX, return each block to the free block list
  - DOS does not free space
    - It uses garbage collection
    - So it will search out deallocated blocks and add them to the free list at some future time
- Deallocate the file control lock
  - For UNIX, zero inode and return it to free list
  - For DOS, zero the first byte of the name in the parent directory
    - Indicating that the directory entry is no longer in use

Free Space Maintenance

- File system manager manages the free space
- Getting/releasing blocks should be fast operations
  - They are extremely frequent
  - We'd like to avoid doing I/O as much as possible
- Unlike memory, it matters what block we choose
  - Best to allocate new space in same cylinder as file's existing space
  - User may ask for contiguous storage
- Free-list organization must address both concerns
  - Speed of allocation and deallocation
  - Ability to allocate contiguous or near-by space

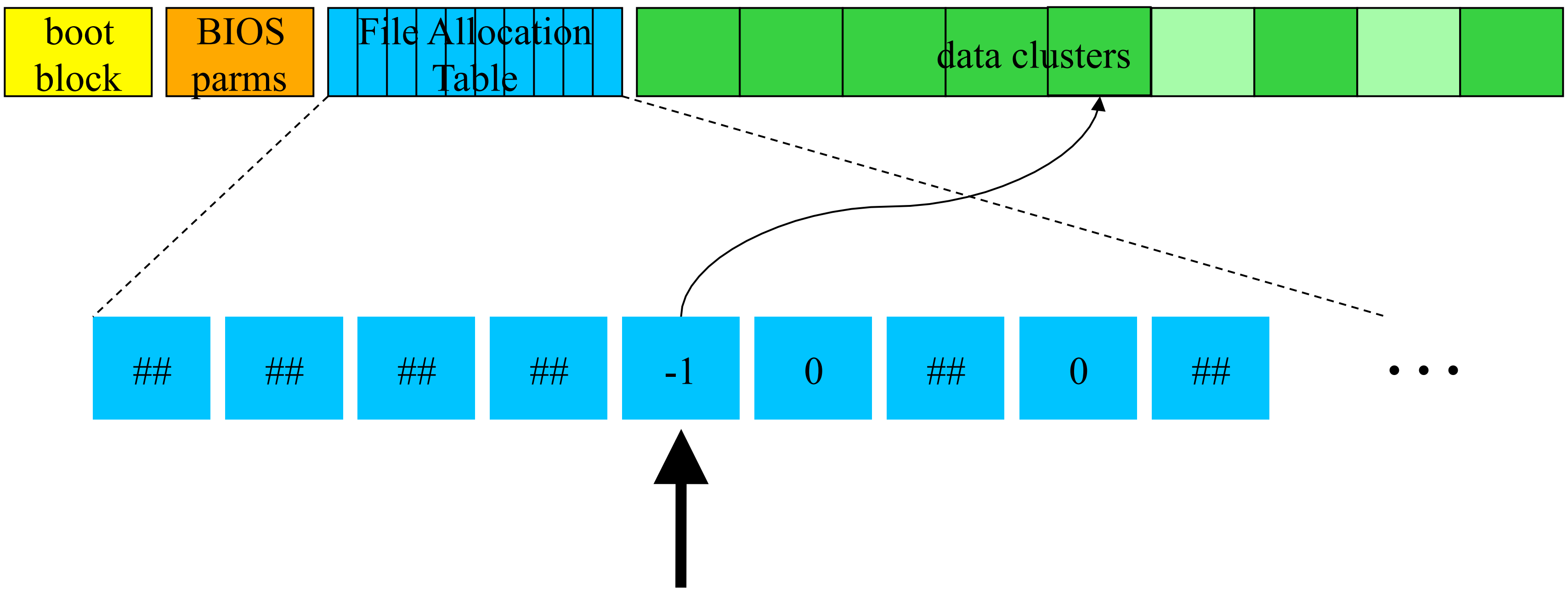
DOS File System Free Space Management

- Search for free clusters in desired cylinder
  - We can map clusters to cylinders
    - The BIOS Parameter Block describes the device geometry
  - Look at first cluster of file to choose the desired cylinder
  - Start search at first cluster of desired cylinder
  - Examine each FAT entry until we find a free one
- If no free clusters, we must garbage collect
  - Recursively search all directories for existing files
  - Enumerate all of the clusters in each file
  - Any clusters not found in search can be marked as free
  - This won’t be fast . . .

Extending a DOS File

- Note cluster number of current last cluster in file
- Search the FAT to find a free cluster
  - Free clusters are indicated by a FAT entry of zero
  - Look for a cluster in the same cylinder as previous cluster
  - Put -1 in its FAT entry to indicate that this is the new EOF
  - This has side effect of marking the new cluster as “not free”
- Chain new cluster on to end of the file
  - Put the number of new cluster into FAT entry for last cluster

DOS Free Space



Each FAT entry corresponds to a cluster, and contains the number of the next cluster.

A value of zero indicates a cluster that is not allocated to any file, and is therefore free.

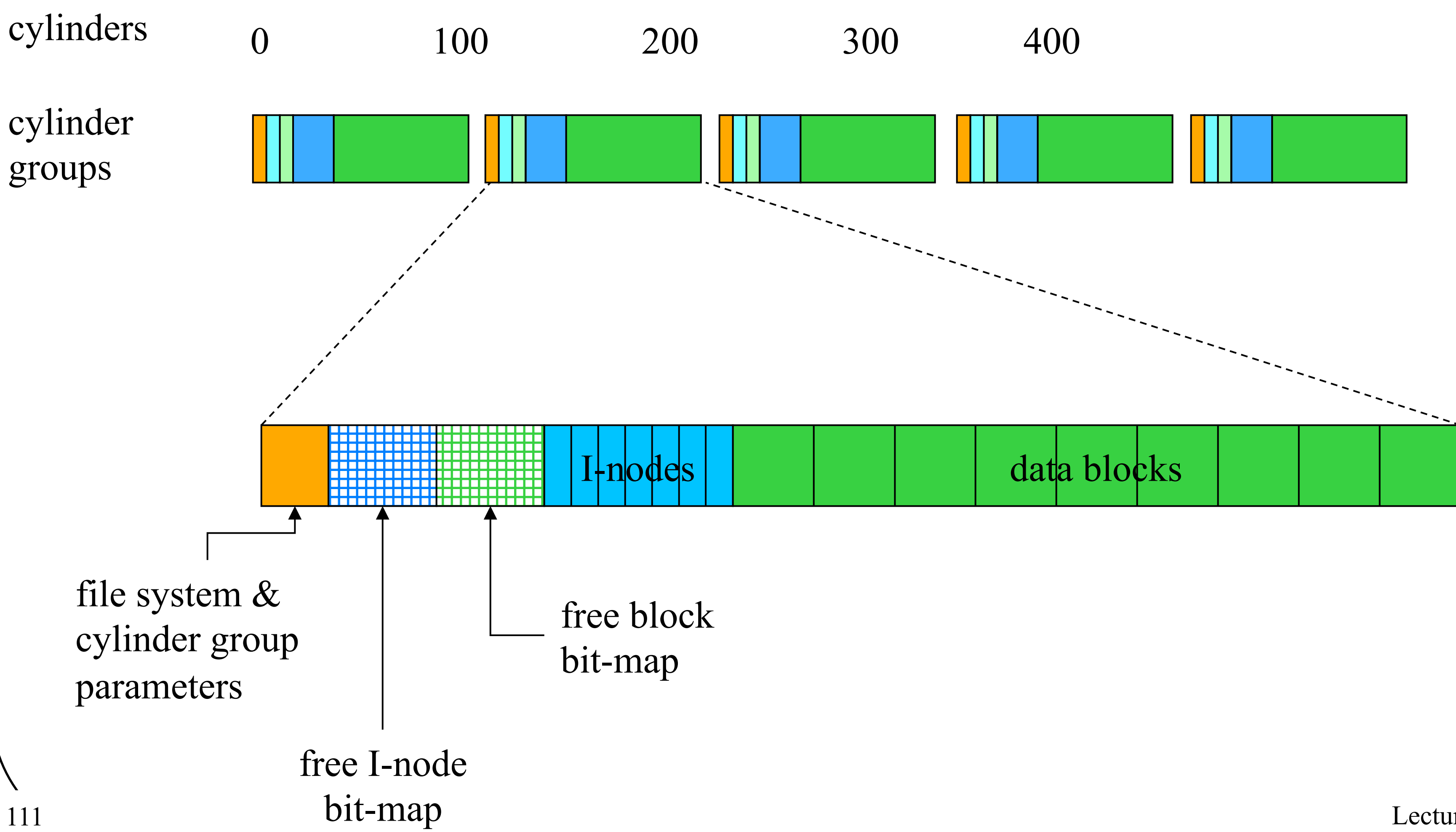
The BSD File System Free Space Management

- BSD is another version of Unix
- The details of its inodes are similar to those of Unix System V
  - As previously discussed
- Other aspects are somewhat different
  - Including free space management
  - Typically more advanced
- Uses bit map approach to managing free space
  - Keeping cylinder issues in mind

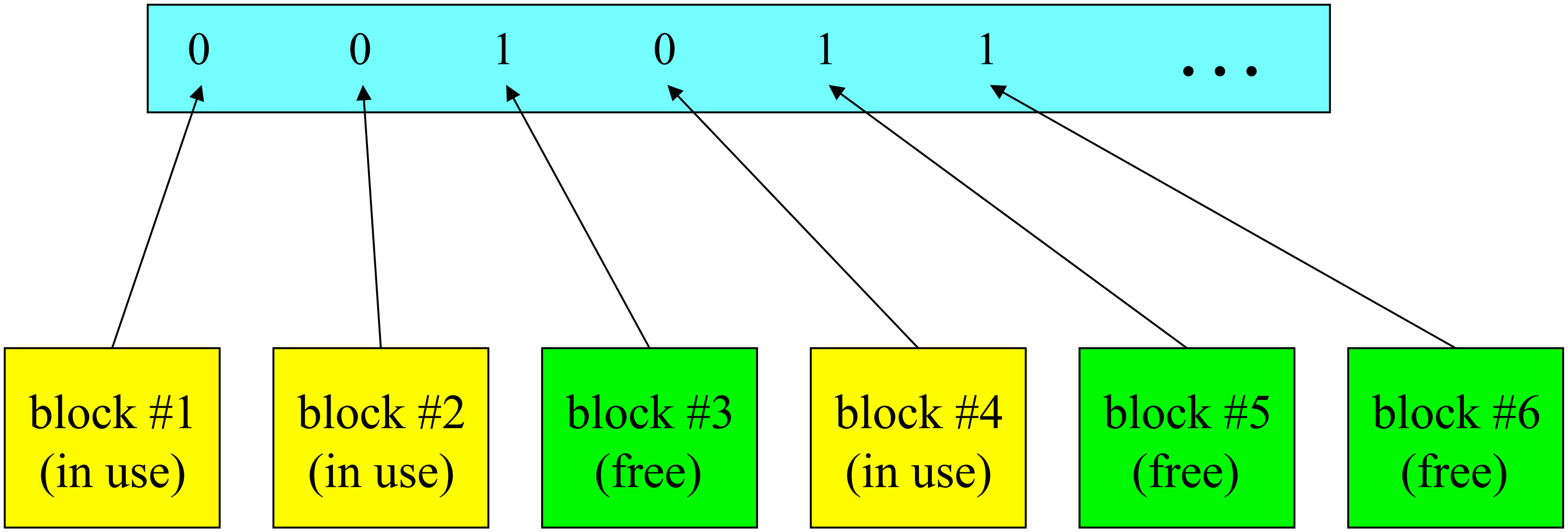
The BSD Approach

- Instead of all control information at start of disk,
- Divide file system into cylinder groups
  - Each cylinder group has its own control information
    - The *cylinder group summary*
  - Active cylinder group summaries are kept in memory
  - Each cylinder group has its own inodes and blocks
  - Free block list is a bit-map in cylinder group summary
- Enables significant reductions in head motion
  - Data blocks in file can be allocated in same cylinder
  - Inode and its data blocks in same cylinder group
  - Directories and their files in same cylinder group

BSD Cylinder Groups and Free Space



Bit Map Free Lists



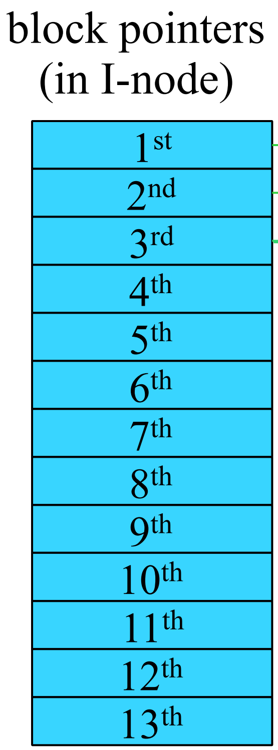
Actual data blocks

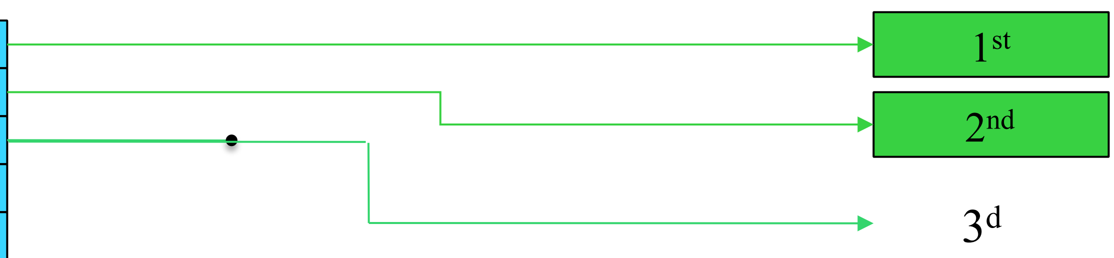
BSD Unix file systems use bit-maps to keep track of both free blocks and free I-nodes in each cylinder group

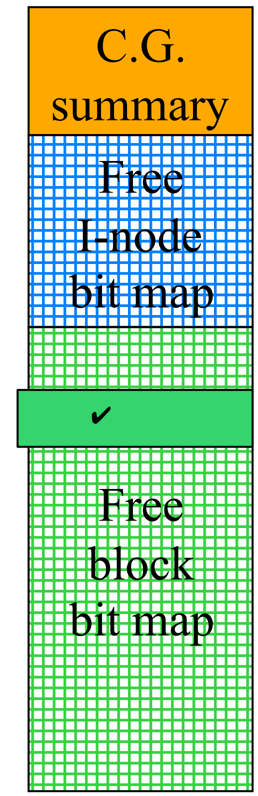
Extending a BSD/Unix File

- Determine the cylinder group for the file's inode
  - Calculated from the inode's identifying number
- Find the cylinder for the previous block in the file
- Find a free block in the desired cylinder
  - Search the free-block bit-map for a free block in the right cylinder
  - Update the bit-map to show the block has been allocated
- Update the inode to point to the new block
  - Go to appropriate block pointer in inode/indirect block
  - If new indirect block is needed, allocate/assign it first
  - Update inode/indirect to point to new block

Unix File Extension







1. Determine cylinder group and get its information
2. Consult the cylinder group free block bit map to find a good block
3. Allocate the block to the file
   3.1 Set appropriate block pointer to it
   3.2 Update the free block bit map

Naming in File Systems

- Each file needs some kind of handle to allow us to refer to it
- Low level names (like inode numbers) aren't usable by people or even programs
- We need a better way to name our files
  - User friendly
  - Allowing for easy organization of large numbers of files
  - Readily realizable in file systems

File Names and Binding

- File system knows files by descriptor structures
- We must provide more useful names for users
- The file system must handle name-to-file mapping
  - Associating names with new files
  - Finding the underlying representation for a given name
  - Changing names associated with existing files
  - Allowing users to organize files using names
- *Name spaces* – the total collection of all names known by some naming mechanism
  - Sometimes all names that *could* be created by the mechanism

Name Space Structure

- There are many ways to structure a name space
  - Flat name spaces
    - All names exist in a single level
  - Hierarchical name spaces
    - A graph approach
    - Can be a strict tree
    - Or a more general graph (usually directed)
- Are all files on the machine under the same name structure?
- Or are there several independent name spaces?

Some Issues in Name Space Structure

- How many files can have the same name?
  - One per file system ... flat name spaces
  - One per directory ... hierarchical name spaces
- How many different names can one file have?
  - A single “true name”
  - Only one “true name”, but aliases are allowed
  - Arbitrarily many
  - What’s different about “true names”?
- Do different names have different characteristics?
  - Does deleting one name make others disappear too?
  - Do all names see the same access permissions?

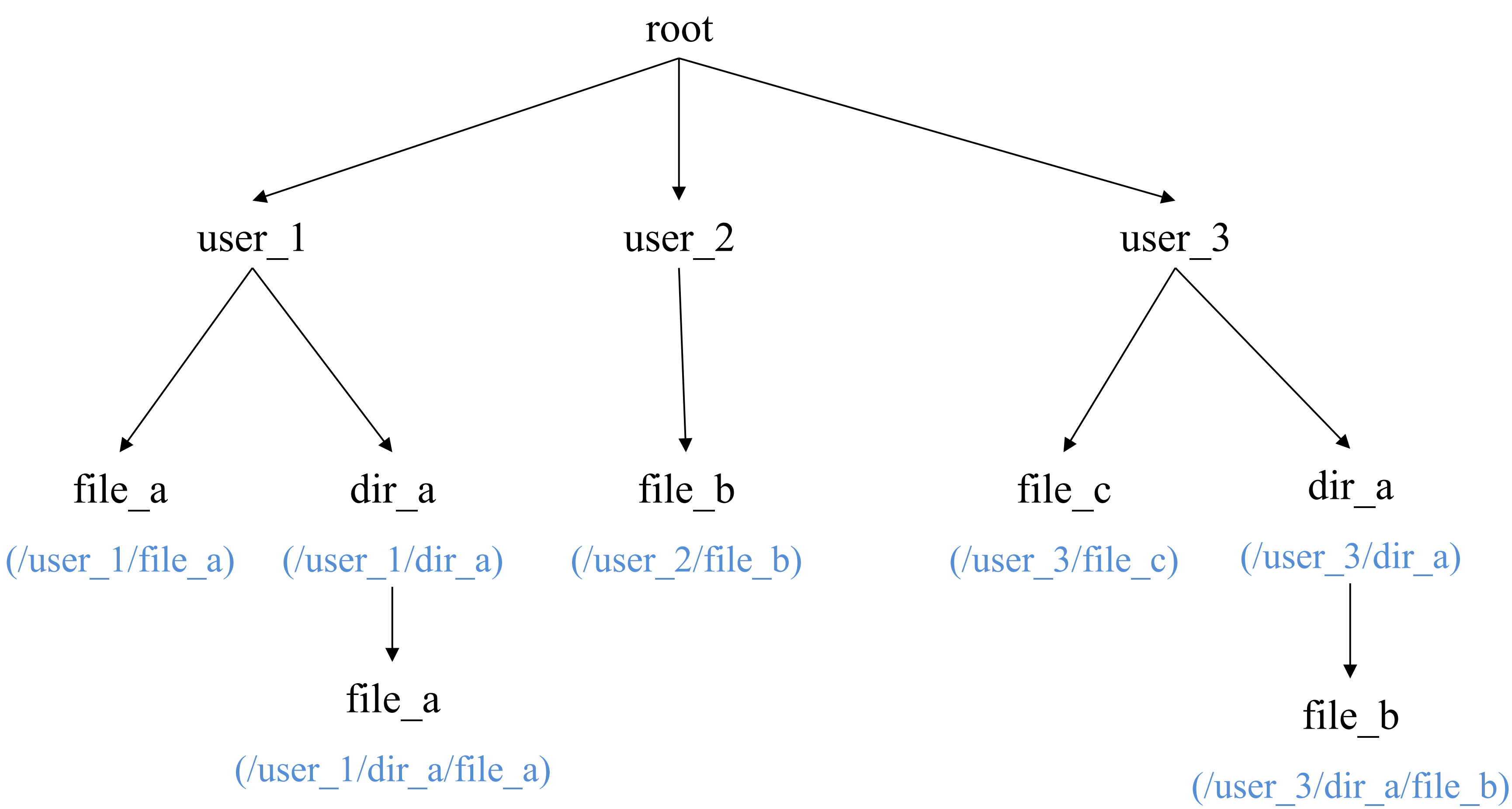
Flat Name Spaces

- There is one naming context per file system
  - All file names must be unique within that context
- All files have exactly one true name
  - These names are probably very long
- File names may have some structure
  - E.g., CAC101.CS111.SECTION1.SLIDES.LECTURE_11
  - This structure may be used to optimize searches
  - The structure is very useful to users but has no meaning to the file system
- Not widely used in modern file systems

Hierarchical Name Spaces

- Essentially a graphical organization
- Typically organized using directories
  - A file containing references to other files
  - A non-leaf node in the graph
  - It can be used as a naming context
    - Each process has a *current directory*
    - File names are interpreted relative to that directory
- Nested directories can form a tree
  - A file name describes a path through that tree
  - The directory tree expands from a “root” node
    - A name beginning from root is called “fully qualified”
  - May actually form a directed graph
    - If files are allowed to have multiple names

A Rooted Directory Tree



Directories Are Files

- Directories are a special type of file
  - Used by OS to map file names into the associated files
- A directory contains multiple directory entries
  - Each directory entry describes one file and its name
- User applications are allowed to read directories
  - To get information about each file
  - To find out what files exist
- Usually only the OS is allowed to write them
  - Users can cause writes through special system calls
  - The file system depends on the integrity of directories

Traversing the Directory Tree

- Some entries in directories point to child directories
  - Describing a lower level in the hierarchy
- To name a file at that level, name the parent directory and the child directory, then the file
  - With some kind of delimiter separating the file name components
- Moving up the hierarchy is often useful
  - Directories usually have special entry for parent
  - Many file systems use the name ".." for that

Example: The DOS File System

- File & directory names separated by back-slashes
  - E.g., `\user_3\dir_a\file_b`
- Directory entries are the file descriptors
  - As such, only one entry can refer to a particular file
- Contents of a DOS directory entry
  - Name (relative to this directory)
  - Type (ordinary file, directory, ...)
  - Location of first cluster of file
  - Length of file in bytes
  - Other privacy and protection attributes

DOS File System Directories

Root directory, starting in cluster #1

file name	type	length	…	1^{st} cluster
`user_1`	DIR	256 bytes	…	9
`user_2`	DIR	512 bytes	…	31
`user_3`	DIR	284 bytes	…	114

Directory `\user_3`, starting in cluster #114

file name	type	length	…	1^{st} cluster
..	DIR	256 bytes	…	1
`dir_a`	DIR	512 bytes	…	62
`file_c`	FILE	1824 bytes	…	102

File Names Vs. Path Names

- In flat name spaces, files had “true names”
  - That name is recorded in some central location
  - Name structure (a.b.c) is a convenient convention
- In DOS, a file is described by a directory entry
  - Local name is specified in that directory entry
  - Fully qualified name is the path to that directory entry
    - E.g., start from root, to user_3, to dir_a, to file_b
  - But DOS files still have only one name
- What if files had no intrinsic names of their own?
  - All names came from directory paths

Example: Unix Directories

- A file system that allows multiple file names
  - So there is no single "true" file name, unlike DOS
- File names separated by slashes
  - E.g., `/user_3/dir_a/file_b`
- The actual file descriptors are the inodes
  - Directory entries only point to inodes
  - Association of a name with an inode is called a *hard link*
  - Multiple directory entries can point to the same inode
- Contents of a Unix directory entry
  - Name (relative to this directory)
  - Pointer to the inode of the associated file

Unix Directories

But what's this "." entry?

It's a directory entry that points to the directory itself!

Root directory, inode #1

inode #	file name
1	.
1	..
9	`user_1`
31	`user_2`
114	`user_3`

Directory `/user_3`, inode #114

inode #	file name
114	.
1	..
194	`dir_a`
307	`file_c`

Here's a ".." entry, pointing to the parent directory

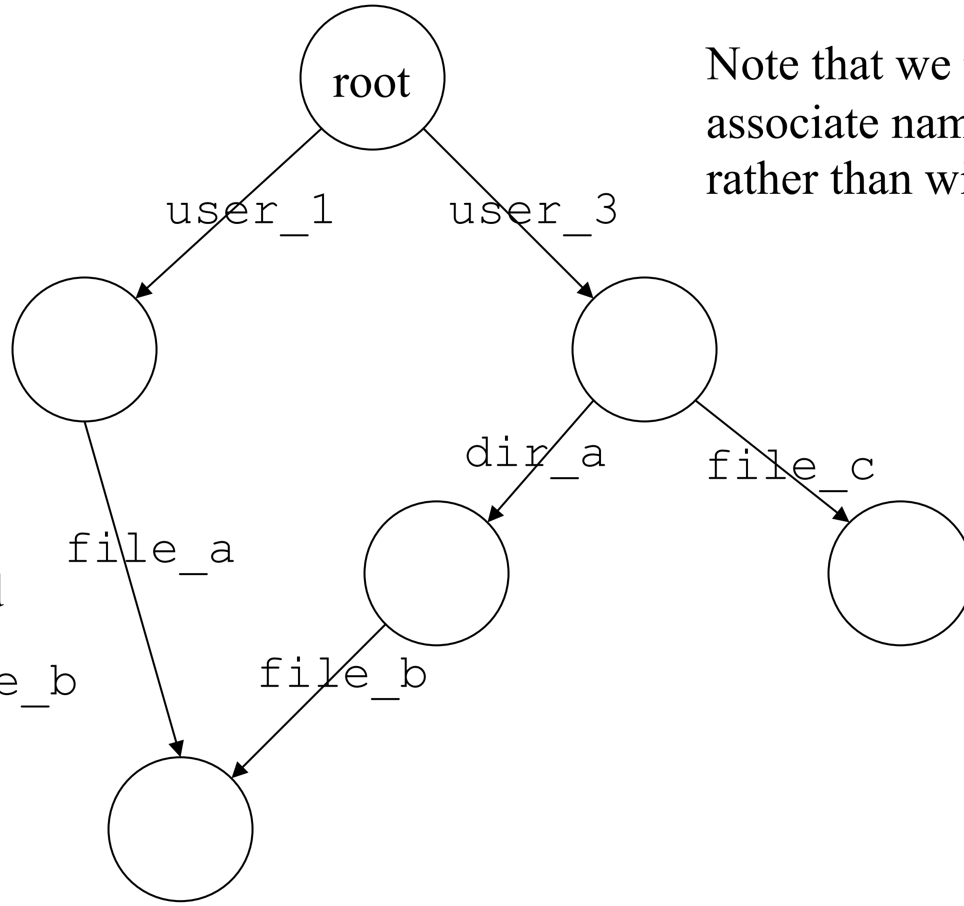
Multiple File Names In Unix

- How do links relate to files?
  - They're the names only
- All other metadata is stored in the file inode
  - File owner sets file protection (e.g., read-only)
- All links provide the same access to the file
  - Anyone with read access to file can create new link
  - But directories are protected files too
    - Not everyone has read or search access to every directory
- All links are equal
  - There is nothing special about the first (or owner's) link

Links and De-allocation

- Files exist under multiple names
- What do we do if one name is removed?
- If we also removed the file itself, what about the other names?
  - Do they now point to something non-existent?
- The Unix solution says the file exists as long as at least one name exists
- Implying we must keep and maintain a reference count of links
  - In the file inode, not in a directory

Unix Hard Link Example



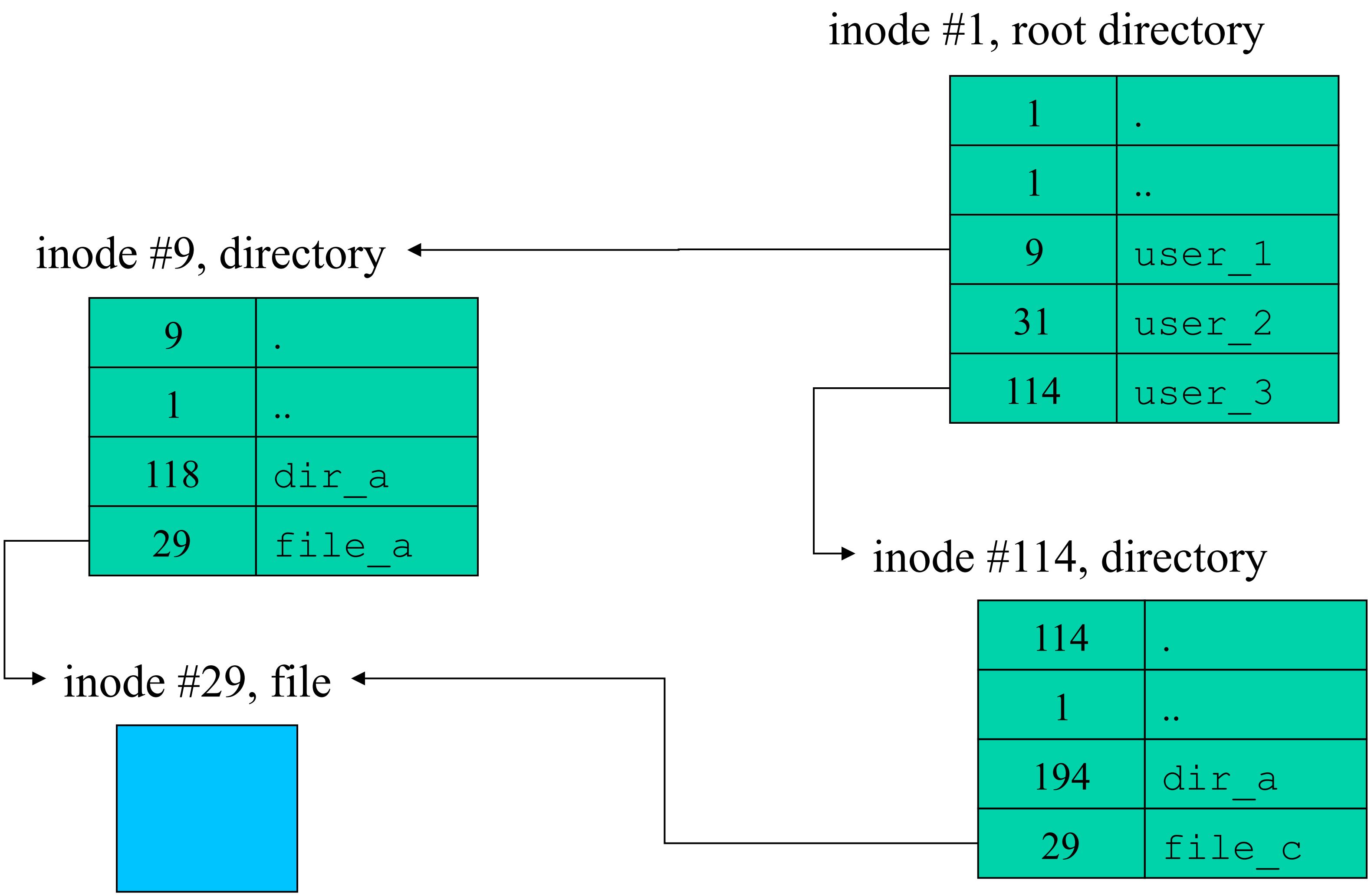
Note that we now associate names with links rather than with files.

`/user_1/file_a` and

`/user_3/dir_a/file_b`

are both links to the same inode

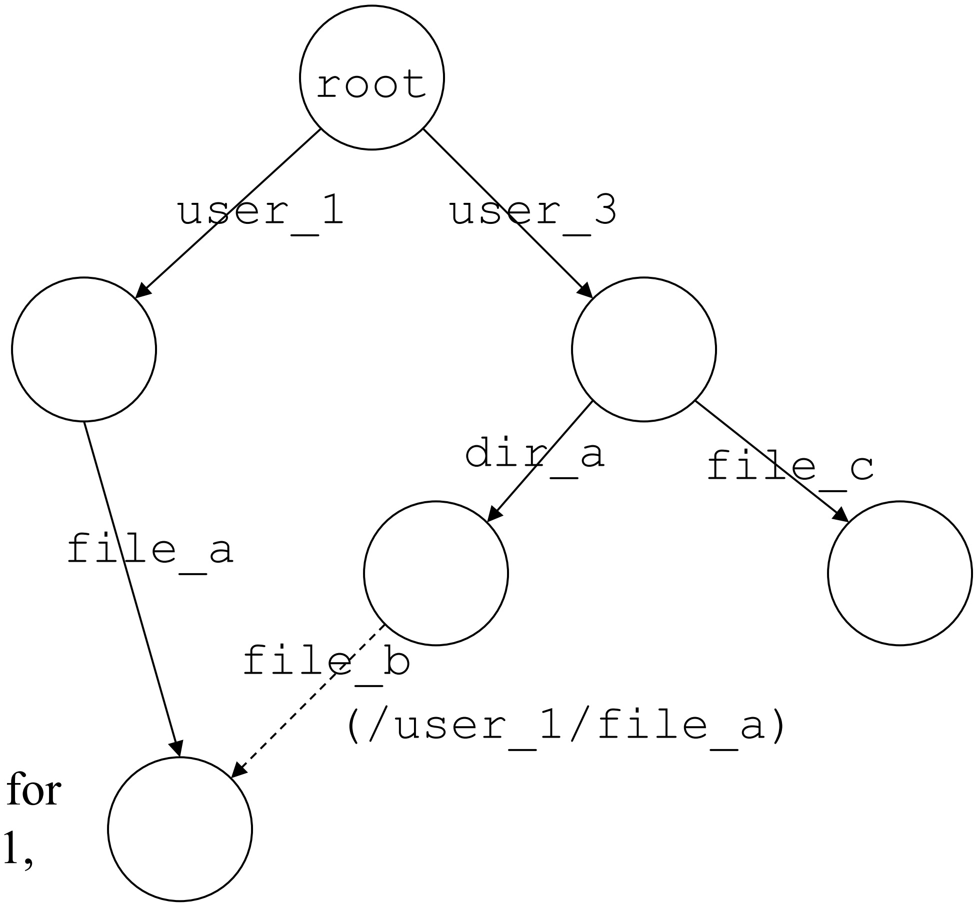
Hard Links, Directories, and Files



Symbolic Links

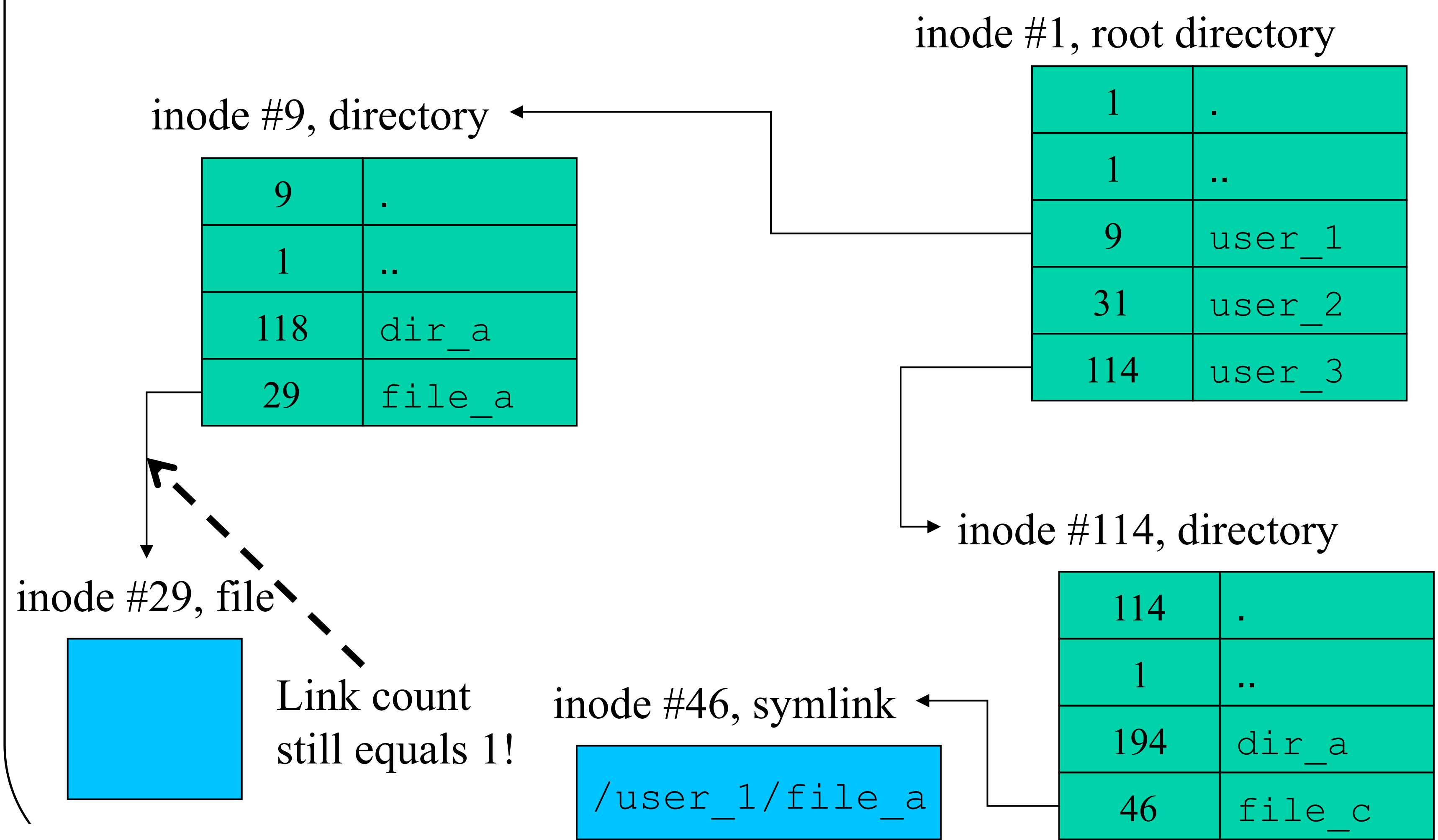
- A different way of giving files multiple names
- Symbolic links implemented as a special type of file
  - An indirect reference to some other file
  - Contents is a path name to another file
- OS recognizes symbolic links
  - Automatically opens associated file instead
  - If file is inaccessible or non-existent, the open fails
- Symbolic link is <u>not</u> a reference to the inode
  - Symbolic links will not prevent deletion
  - Do not guarantee ability to follow the specified path
  - Internet URLs are similar to symbolic links

Symbolic Link Example



The link count for this file is still 1, though

Symbolic Links, Files, and Directories



File Systems and Multiple Disks

- You can usually attach more than one disk to a machine
  - And often do
- Would it make sense to have a single file system span the several disks?
  - Considering the kinds of disk-specific information a file system keeps
  - Like cylinder information
- Usually more trouble than it's worth
  - With the exception of RAID . . .
- Instead, put separate file system on each disk

How About the Other Way Around?

- Multiple file systems on one disk
- Divide physical disk into multiple logical disks
  - Often implemented within disk device drivers
  - Rest of system sees them as separate disk drives
- Typical motivations
  - Permit multiple OSes to coexist on a single disk
    - E.g., a notebook that can boot either Windows or Linux
  - Separation for installation, back-up and recovery
    - E.g., separate personal files from the installed OS file system
  - Separation for free-space
    - Running out of space on one file system doesn't affect others

Working With Multiple File Systems

- So you might have multiple independent file systems on one machine
  - Each handling its own disk layout, free space, and other organizational issues
- How will the overall system work with those several file systems?
- Treat them as totally independent namespaces?
- Or somehow stitch the separate namespaces together?
- Key questions:
  1. How does an application specify which file it wants?
  2. How does the OS find that file?

Finding Files With Multiple File Systems

- Finding files is easy if there is only one file system
  - Any file we want must be on that one file system
  - Directories enable us to name files within a file system
- What if there are multiple file systems available?
  - Somehow, we have to say which one our file is on
- How do we specify which file system to use?
  - One way or another, it must be part of the file name
  - It may be implicit (e.g., same as current directory)
  - Or explicit (e.g., every name specifies it)
  - Regardless, we need some way of specifying which file system to look into for a given file name

Options for Naming With Multiple Partitions

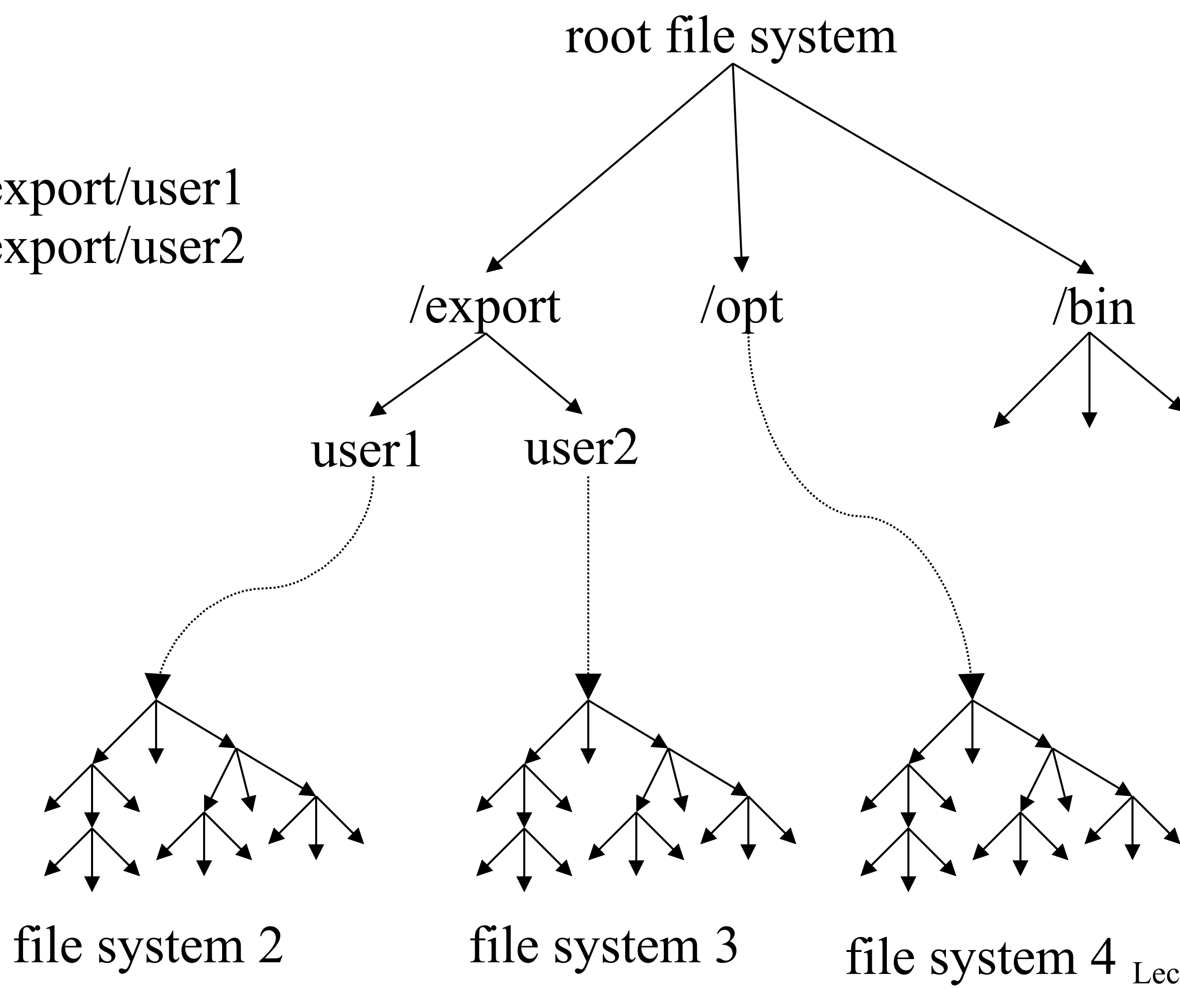
- Could specify the physical device it resides on
  - E.g., `/devices/pci/pci1000,4/disk/lun1/partition2`
    - That would get old real quick
- Could assign logical names to our partitions
  - E.g., "A:", "C:", "D:"
    - You only have to think physical when you set them up
    - But you still have to be aware multiple volumes exist
- Could weave a multi-file-system name space
  - E.g., Unix mounts

Unix File System Mounts

- Goal:
  - To make many file systems appear to be one giant one
  - Users need not be aware of file system boundaries
- Mechanism:
  - *Mount* device on directory
  - Creates a warp from the named directory to the top of the file system on the specified device
  - Any file name beneath that directory is interpreted relative to the root of the mounted file system

Unix Mounted File System Example

mount filesystem2 on /export/user1
mount filesystem3 on /export/user2
mount filesystem4 on /opt



How Does This Actually Work?

- Mark the directory that was mounted on
- When file system opens that directory, don't treat it as an ordinary directory
  - Instead, consult a table of mounts to figure out where the root of the new file system is
- Go to that device and open its root directory
- And proceed from there

File System Performance Issues

- Key factors in file system performance
  - Disk issues
    - Head movement
    - Sector size
- Possible optimizations for file systems
  - Read-ahead
  - Delayed writes
  - Caching (general and special purpose)

File Systems and Disk Drives

- The physics of disk drives impact the performance of file systems
  - Which is unfortunate
- OS designers want to hide that impact
- To do so, they must hide variable disk delays
  - Preferably without making everything experience the largest possible delay
- This requires many optimizations
  - Often based on having a queue of outstanding disk requests

Optimizing Disk I/O

- Don't start I/O until disk is on-cylinder or near sector
  - I/O ties up the controller, locking out other operations
  - Other drives seek while one drive is doing I/O
- Minimize head motion
  - Do all possible reads in current cylinder before moving
  - Make minimum number of trips in small increments
- Encourage efficient data requests
  - Have lots of requests to choose from
  - Encourage cylinder locality
  - Encourage largest possible sector sizes
  - All by OS design choices, not influencing programs/users

Head Motion and File System Performance

- File system organization affects head motion
  - If sectors in a single file are spread across the disk
  - If files are spread randomly across the disk
  - If files and "meta-data" are widely separated
- All files are not used equally often
  - 5% of the files account for 90% of disk accesses
  - File locality should translate into head cylinder locality
- How can these factors to reduce head motion?

Ways To Reduce Head Motion

- Keep sectors of a file together
  - Easiest to do on original write
  - Try to allocate each new sector close to the last one
  - Especially keep them in the same cylinder
- Keep metadata close to files
  - Again, easiest to do at creation time
- Keep files in the same directory close together
  - On the assumption directory implies locality of reference
- If performing compaction, move popular files close together

File System Performance and Sector Size

- Larger sector sizes result in efficient transfers
  - DMA is very fast, once it gets started
  - Per request set-up and head-motion is substantial
- They also result in internal fragmentation
  - Expected waste: ½ sector per file
- As disks get larger, speed outweighs wasted space
  - File systems support ever-larger sector sizes
  - 4K common today
- Clever schemes can reduce fragmentation
  - E.g., use smaller sector size for the last sector of a file

Read Early, Write Late

- If we read blocks before we actually need them, we don't have to wait for them
  - But how can we know which blocks to read early?
- If we write blocks long after we told the application it was done, we don't have to wait
  - But are there bad consequences of delaying those writes?
- Some optimizations depend on good answers to these questions

Read-Ahead

- Request blocks from the disk before any process asked for them
- Reduces process wait time
- When does it make sense?
  - When client specifically requests sequential access
  - When client seems to be reading sequentially
- What are the risks?
  - May waste disk access time reading unwanted blocks
  - May waste buffer space on unneeded blocks

Delayed Writes

- Don’t wait for disk write to complete to tell application it can proceed
- Written block is in a buffer in memory
- Wait until it’s “convenient” to write it to disk
  - Handle reads from in-memory buffer
- Benefits:
  - Applications don’t wait for disk writes
  - Writes to disk can be optimally ordered
  - If file is deleted soon, may never need to perform disk I/O
- Potential problems:
  - Lost writes when system crashes
  - Buffers holding delayed writes can’t be re-used

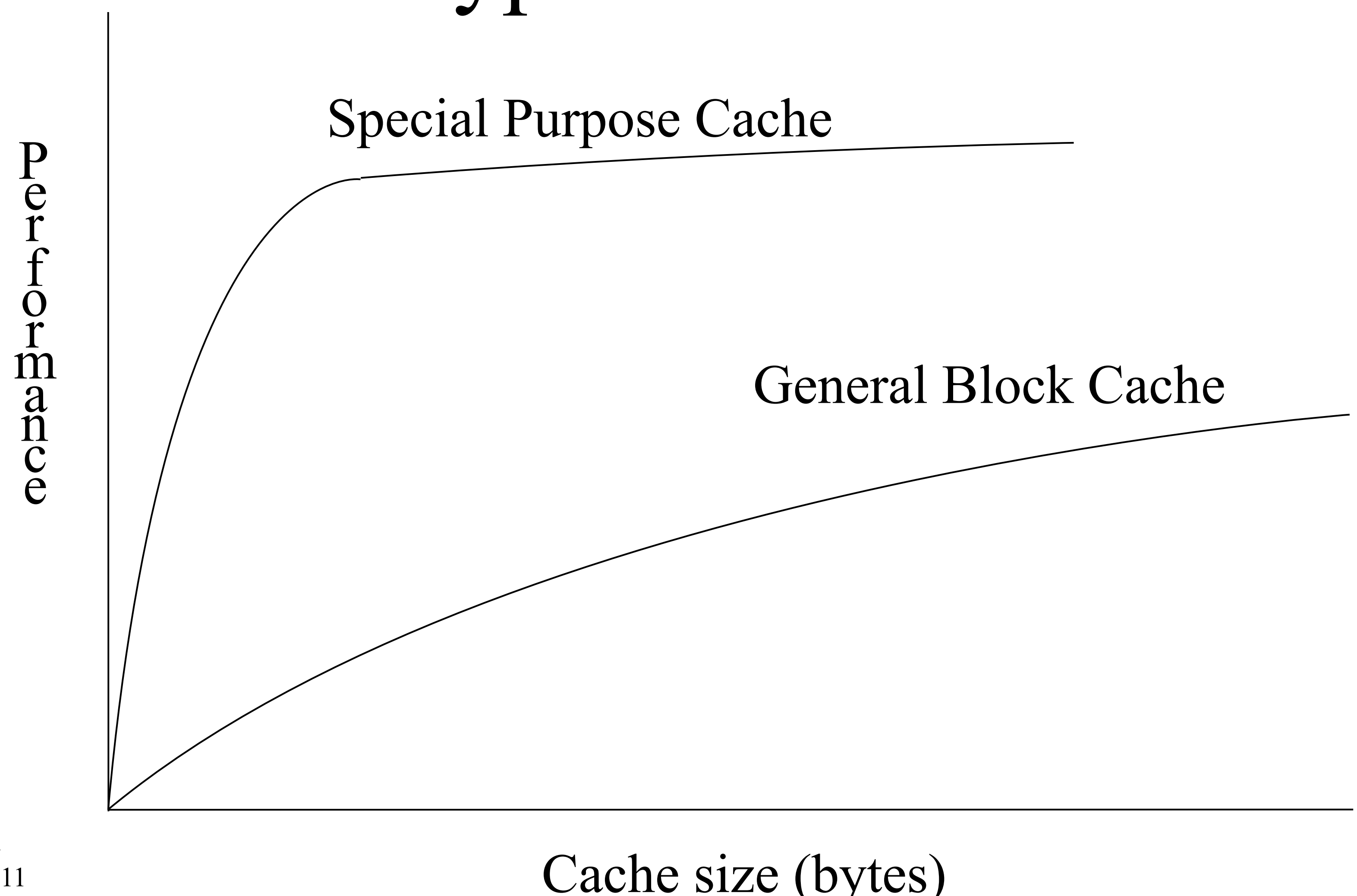
Caching and Performance

- Big performance wins are possible if caches work well
  - They typically contain the block you're looking for
- Should we have one big LRU cache for all purposes?
- Should we have some special-purpose caches?
  - If so, is LRU right for them?

Common Types of Disk Caching

- General block caching
  - Popular files that are read frequently
  - Files that are written and then promptly re-read
  - Provides buffers for read-ahead and deferred write
- Special purpose caches
  - Directory caches speed up searches of same dirs
  - Inode caches speed up re-uses of same file
- Special purpose caches are more complex
  - But they often work much better

Performance Gain For Different Types of Caches



Why Are Special Purpose Caches More Effective?

- They match caching granularity to their need
  - E.g., cache inodes or directory entries
  - Rather than full blocks
- Why does that help?
- Consider an example:
  - A block might contain 100 directory entries, only four of which are regularly used
  - Caching the other 96 as part of the block is a waste of cache space
  - Caching 4 entries allows more popular entries to be cached
  - Tending to lead to higher hit ratios

File Systems Reliability

- File systems are meant to store data persistently
- Meaning they are particularly sensitive to errors that screw things up
  - Other elements can sometimes just reset and restart
  - But if a file is corrupted, that's really bad
- How can we ensure our file system's integrity is not compromised?

Causes of System Data Loss

- OS or computer stops with writes still pending
  - .1-100/year per system
- Defects in media render data unreadable
  - .1 – 10/year per system
- Operator/system management error
  - .01-.1/year per system
- Bugs in file system and system utilities
  - .01-.05/year per system
- Catastrophic device failure
  - .001-.01/year per system

Dealing With Media Failures

- Most media failures are for a small section of the device, not huge extents of it
- Don't use known bad sectors
  - Identify all known bad sectors (factory list, testing)
  - Assign them to a “never use” list in file system
  - Since they aren't free, they won't be used by files
- Deal promptly with newly discovered bad sectors
  - Most failures start with repeated “recoverable” errors
  - Copy the data to another sector ASAP
  - Assign new sector to file in place of failing sector
  - Assign failing sector to the “never use” list

Problems Involving System Failure

- Delayed writes lead to many problems when the system crashes
- Other kinds of corruption can also damage file systems
- We can combat some of these problems using ordered writes
- But we may also need mechanisms to check file system integrity
  - And fix obvious problems

Deferred Writes – Promise and Dangers

- Deferring disk writes can be a big performance win
  - When user updates files in small increments
  - When user repeatedly updates the same data
- It may also make sense for meta-data
  - Writing to a file may update an indirect block many times
  - Unpacking a zip creates many files in same directory
  - It also allocates many consecutive inodes
- But deferring writes can also create big problems
  - If the system crashes before the writes are done
  - Some user data may be lost
  - Or even some meta-data updates may be lost

Performance and Integrity

- It is very important that file systems be fast
  - File system performance drives system performance
- It is absolutely vital that they be robust
  - Files are used to store important data
    - E.g., student projects, grades, video games, …
- We must know that our files are safe
  - That the files will not disappear after they are written
  - That the data will not be corrupted

Deferred Writes – A Worst Case Scenario

- Process allocates a new block for file A
  - We get a new block (x) from the free list
  - We write the updated inode for file A
    - Including a pointer to x
  - We defer free-list write-back (which happens all the time)
- The system crashes, and after it reboots
  - A new process wants a new block for file B
  - We get block x from the (stale) free list
- Two different files now contain the same block
  - When file A is written, file B gets corrupted
  - When file B is written, file A gets corrupted

Ordering Writes

- Many file system corruption problems can be solved by carefully ordering related writes
- Write out data before writing pointers to it
  - Unreferenced objects can be garbage collected
  - Pointers to incorrect data/meta-data are much more serious
- Write out deallocations before allocations
  - Disassociate resources from old files ASAP
  - Free list can be corrected by garbage collection
  - Improperly shared blocks more serious than unlinked ones
- But it may reduce disk I/O efficiency
  - Creating more head motion than elevator scheduling

Backup – The Ultimate Solution

- All files should be regularly backed up
- Permits recovery from catastrophic failures
- Complete vs. incremental back-ups
- Desirable features
  - Ability to back-up a running file system
  - Ability to restore individual files
  - Ability to back-up w/o human assistance
- Should be considered as part of FS design
  - I.e., make file system backup-friendly