Operating System Principles: File Systems – Allocation, Naming, Performance, and Reliability

CS 111

Operating Systems

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Outline

- Allocating and managing file system free space
- Other performance improvement strategies
- File naming and directories
- File system reliability issues

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 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

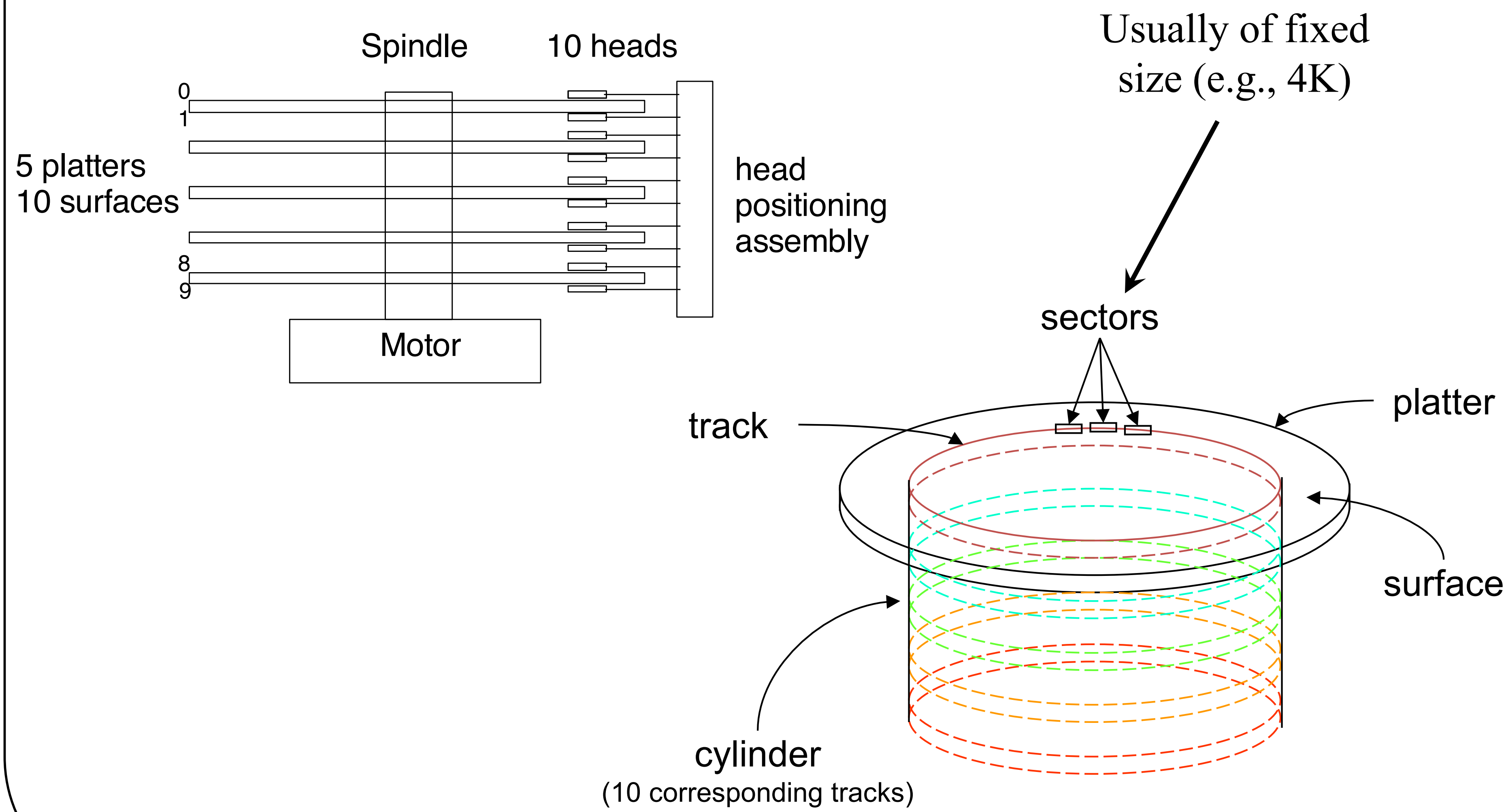
Free Space Maintenance

- 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

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

Disk Drives and Geometry

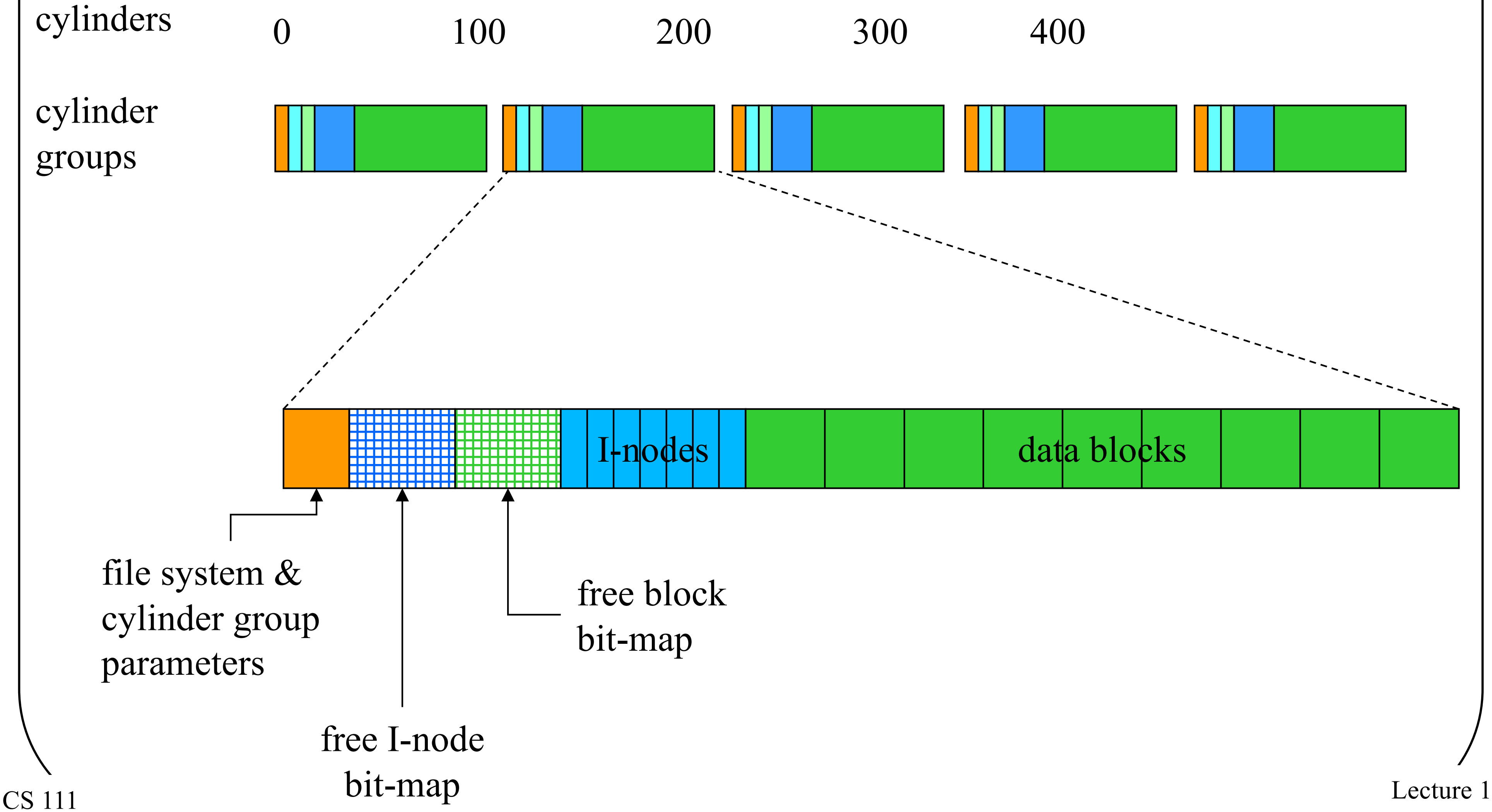


Usually of fixed size (e.g., 4K)

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



cylinders

0

100

200

300

400

cylinder groups

I-nodes

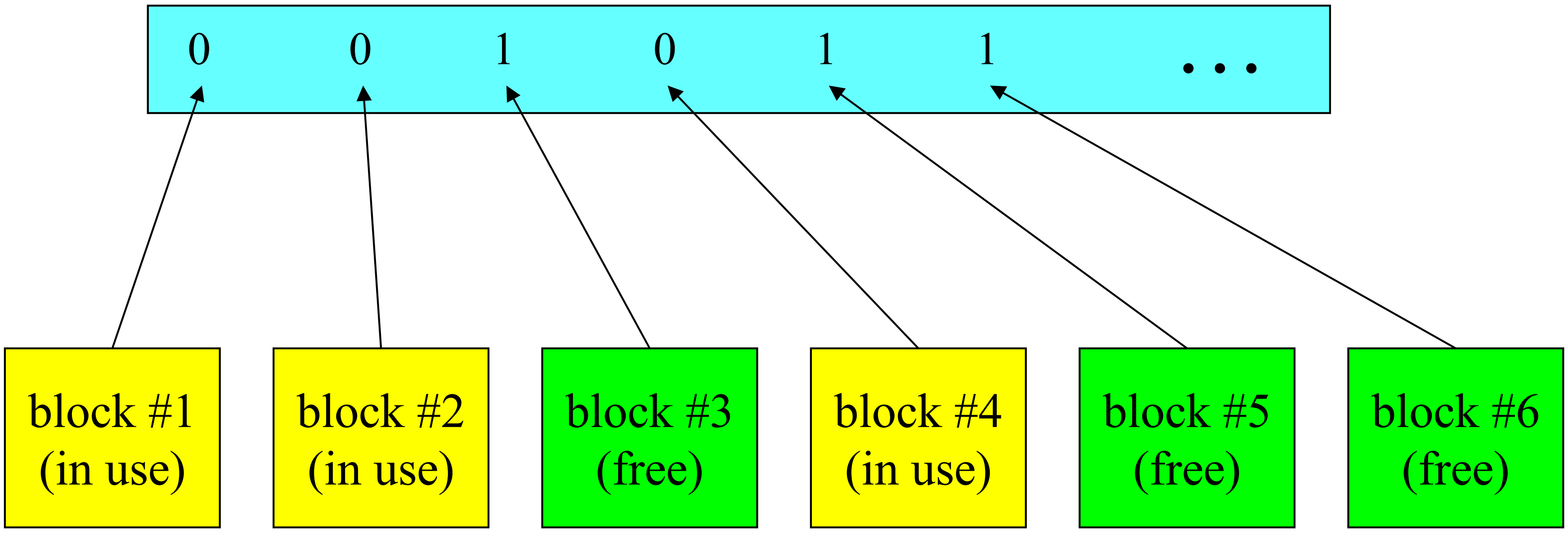
data blocks

file system & cylinder group parameters

free I-node bit-map

free block bit-map

Bit Map Free Lists



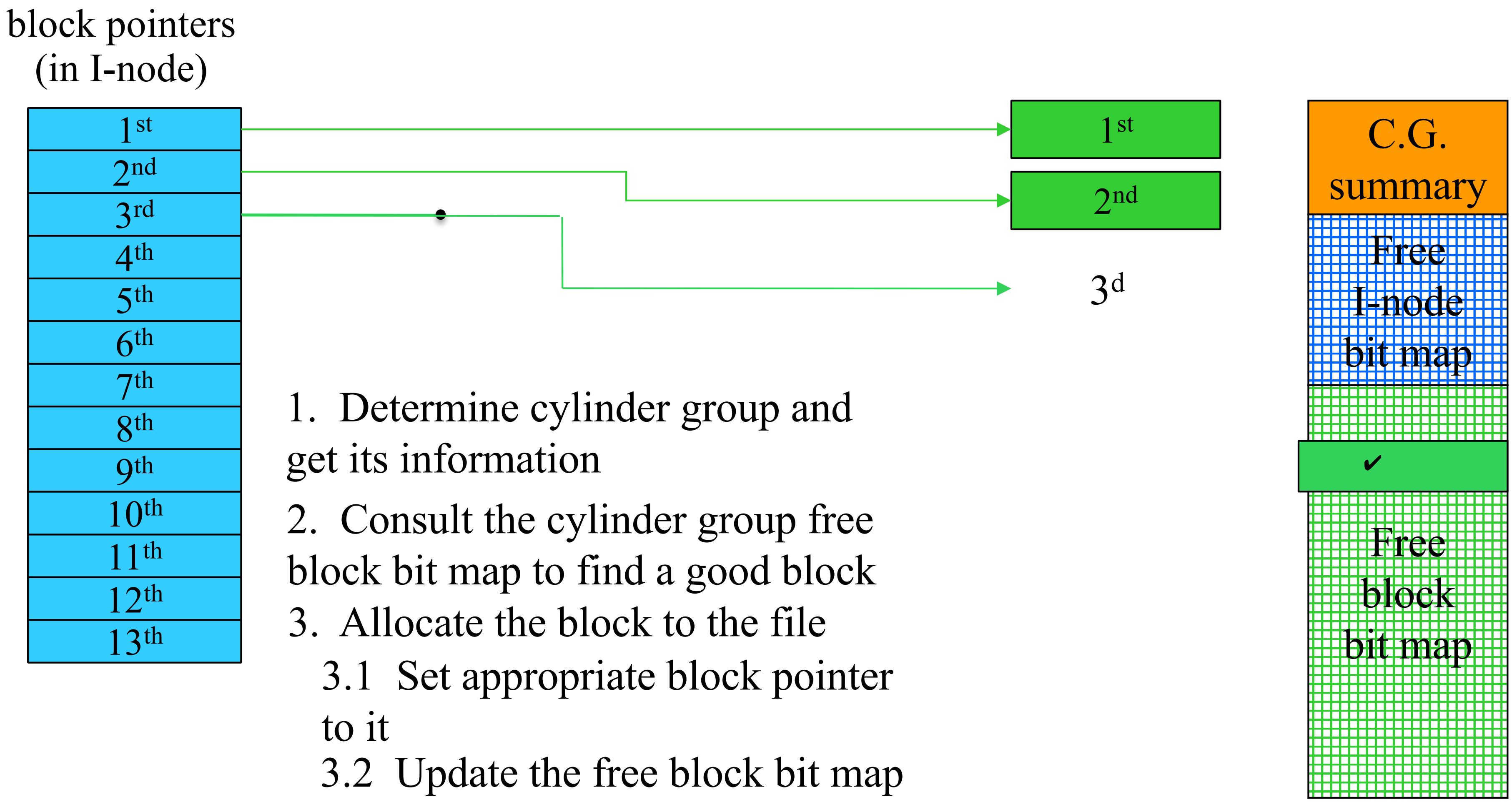
Actual data blocks

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

Other Performance Improvement Strategies

- Beyond disk layout issues
  - Which are only relevant for hard drives, not flash or other solid state devices
- Transfer size
- Caching

Allocation/Transfer Size

- Per operation overheads are high
  - DMA startup, seek, rotation, interrupt service
- Larger transfer units more efficient
  - Amortize fixed per-op costs over more bytes/op
  - Multi-megabyte transfers are very good
- This requires space allocation units
  - Allocate space to files in much larger chunks
  - Large fixed size chunks -> internal fragmentation
  - Therefore we need variable partition allocation

Efficient Disk Allocation

- Allocate space in large, contiguous extents
  - Few seeks, large DMA transfers
- Variable partition disk allocation is difficult
  - More complicated to find something that fits than to always use a single allocation size
  - Many files are allocated for a very long time
- External fragmentation eventually wins
  - New files get smaller chunks, farther apart
  - File system performance degrades with age

Caching

- Caching for reads
- Caching for writes

Read Caching

- Disk I/O takes a very long time
  - Deep queues, large transfers improve efficiency
  - They do not make it significantly faster
- We must eliminate much of our disk I/O
  - Maintain an in-memory cache
  - Depend on locality, reuse of the same blocks
  - Check cache before scheduling I/O

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

Write Caching

- Most disk writes go to a write-back cache
  - They will be flushed out to disk later
- Aggregates small writes into large writes
  - If application does less than full block writes
- Eliminates moot writes
  - If application subsequently rewrites the same data
  - If application subsequently deletes the file
- Accumulates large batches of writes
  - A deeper queue to enable better disk scheduling

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 by matching cache granularities to actual needs

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?

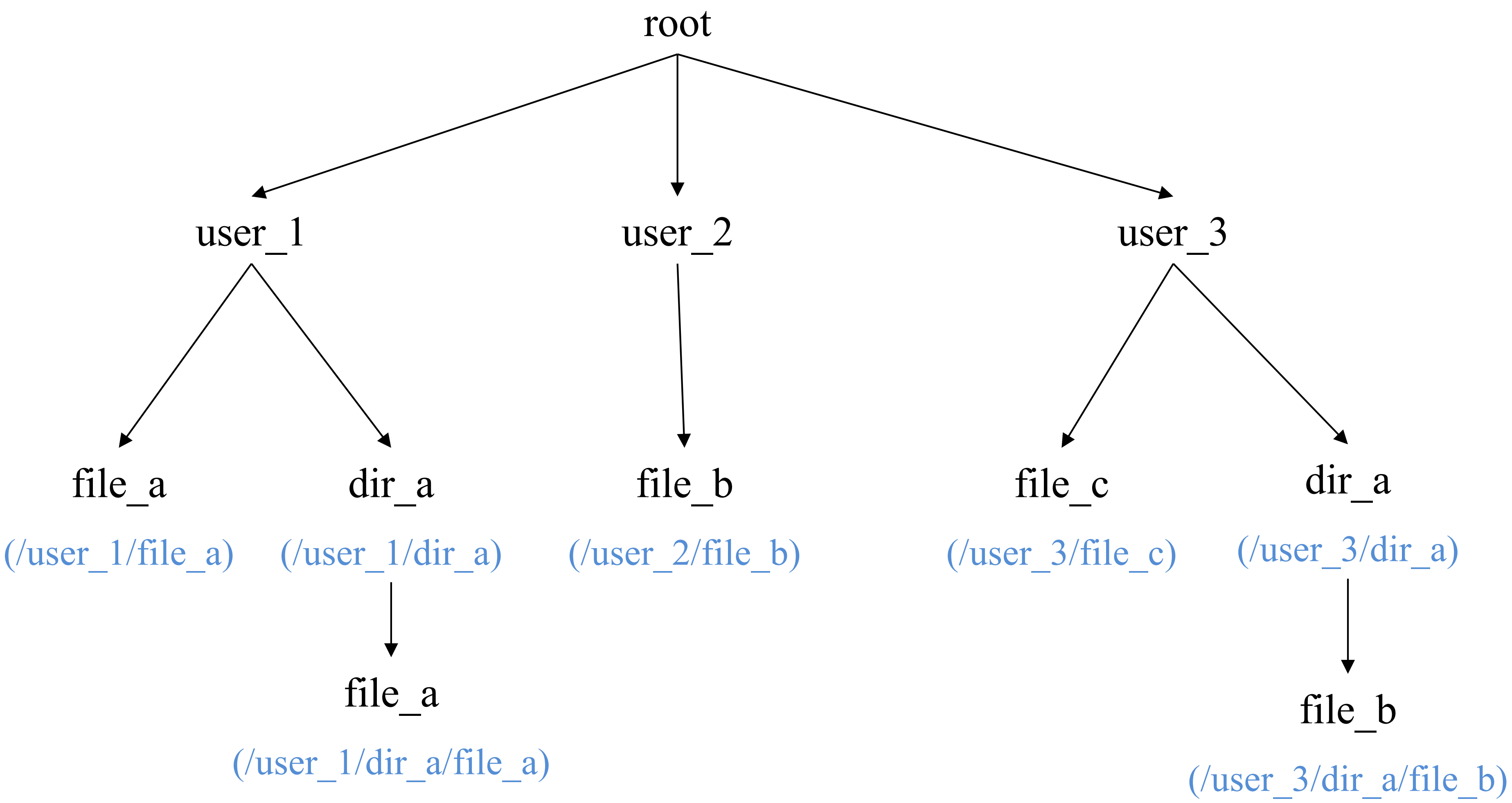
Some Issues in Name Space Structure

- 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?

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

File Names Vs. Path Names

- In some name space systems, files had “true names”
  - Only one possible name for a file,
  - Kept in a record somewhere
- E.g., 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
- What if files had no intrinsic names of their own?
  - All names came from directory paths

Example: Unix Directories

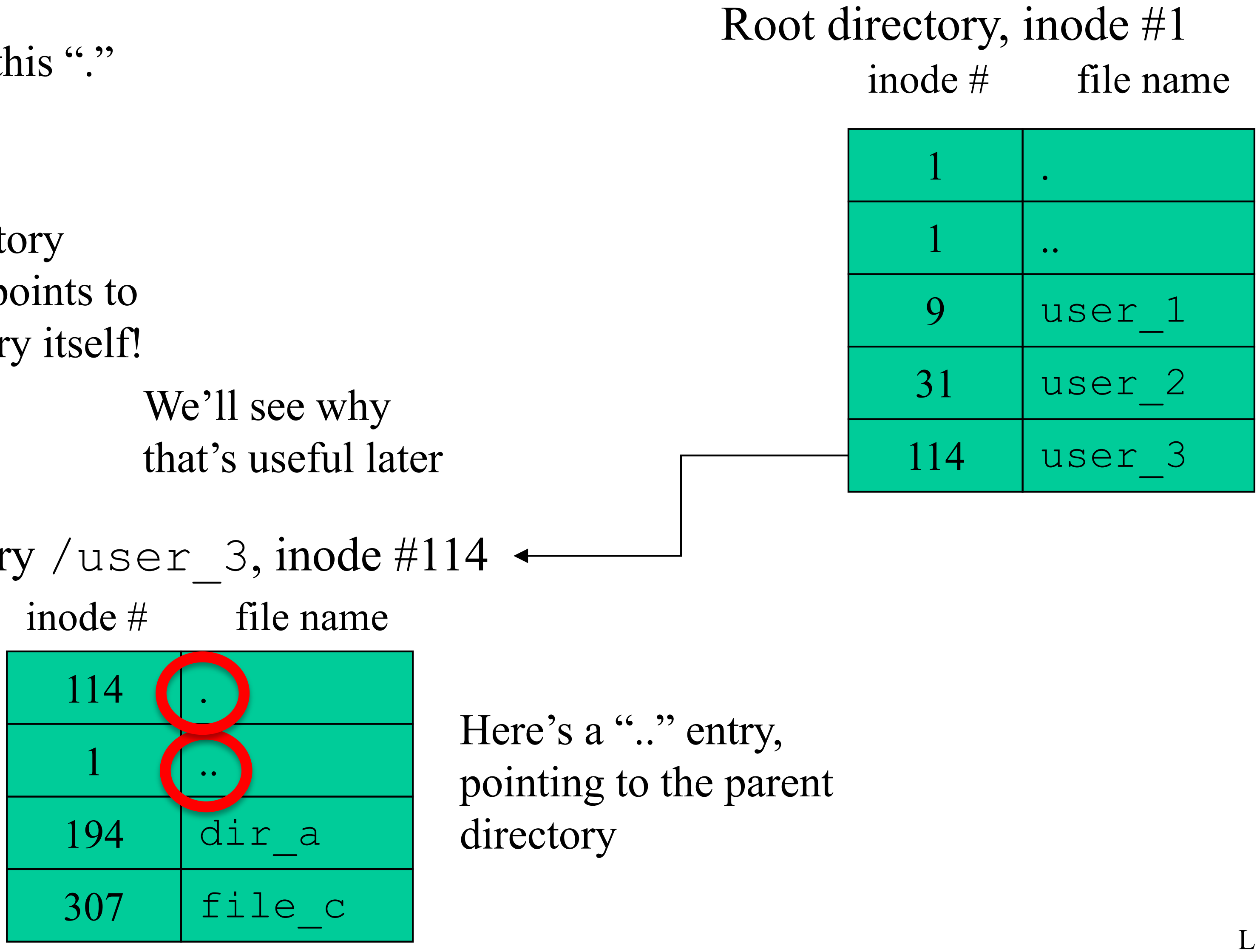
- A file system that allows multiple file names
  - So there is no single “true” file name, unlike DOS
- File names separated by slashes
  - E.g., `/user_3/dir_a/file_b`
- The actual file descriptors are the inodes
  - Directory entries only point to inodes
  - Association of a name with an inode is 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!

We'll see why that's useful later



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

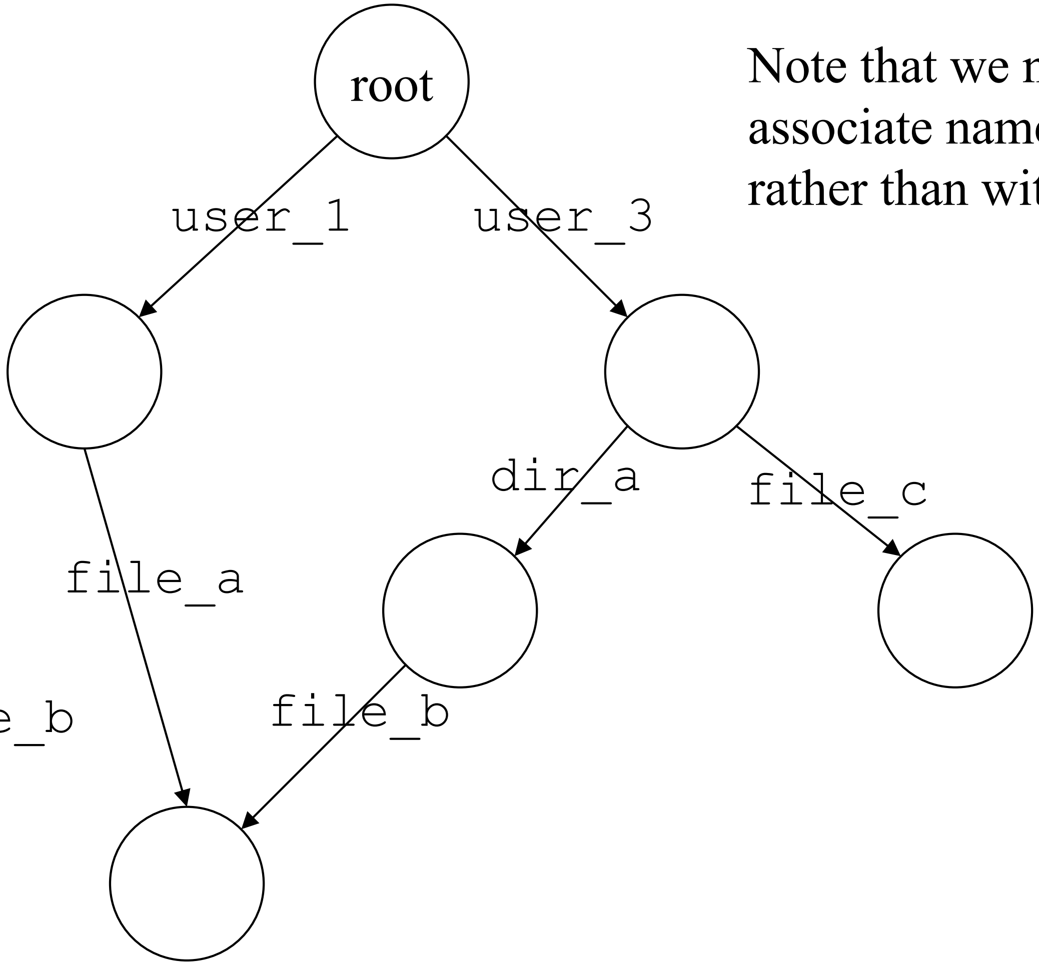
Multiple File Names In Unix

- 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



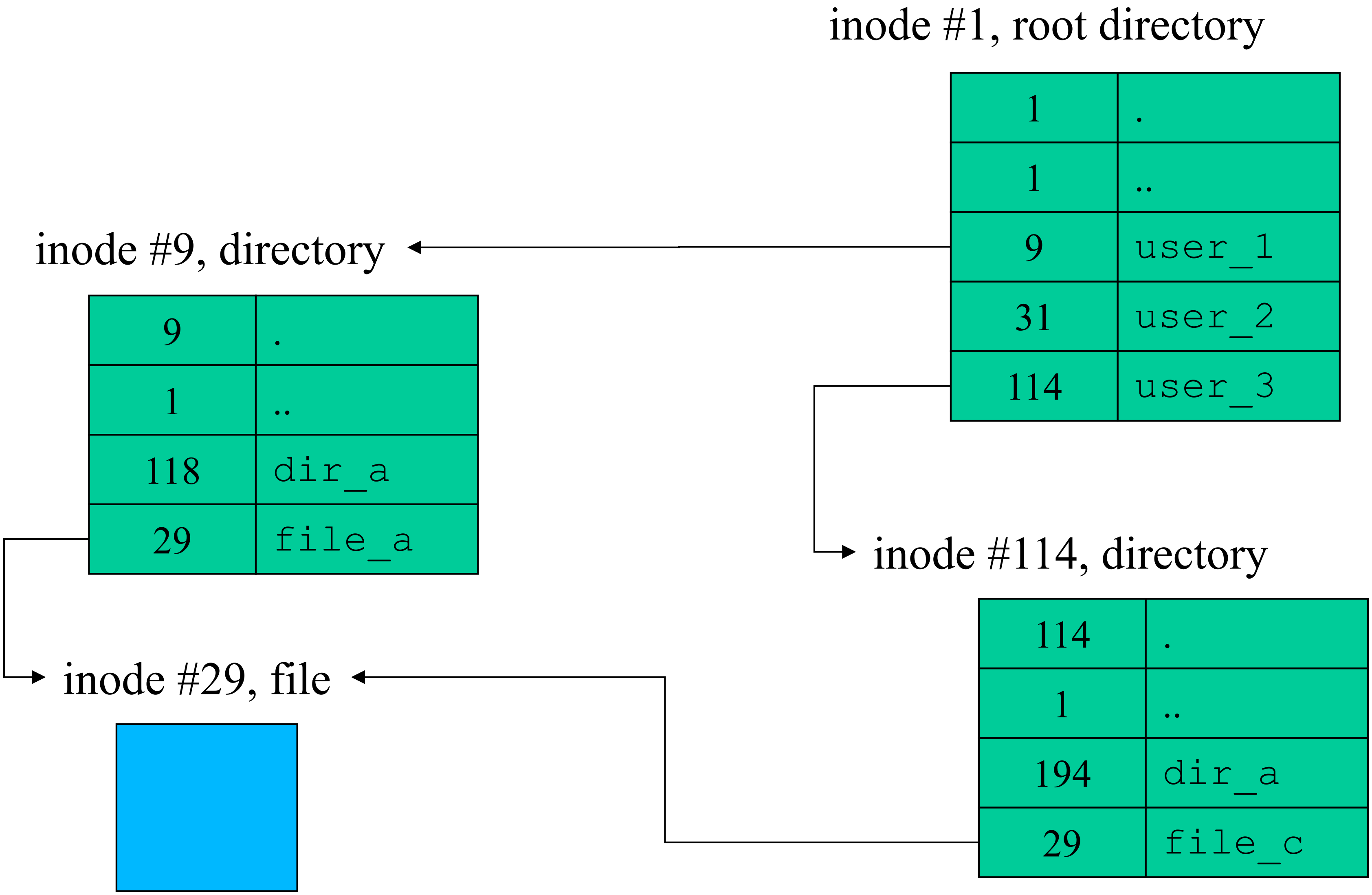
Note that we now associate names with links rather than with files.

`/user_1/file_a` and

`/user_3/dir_a/file_b`

are both links to the same inode

Hard Links, Directories, and Files



inode #1, root directory

1	.
1	..
9	`user_1`
31	`user_2`
114	`user_3`

inode #9, directory

9	.
1	..
118	`dir_a`
29	`file_a`

inode #114, directory

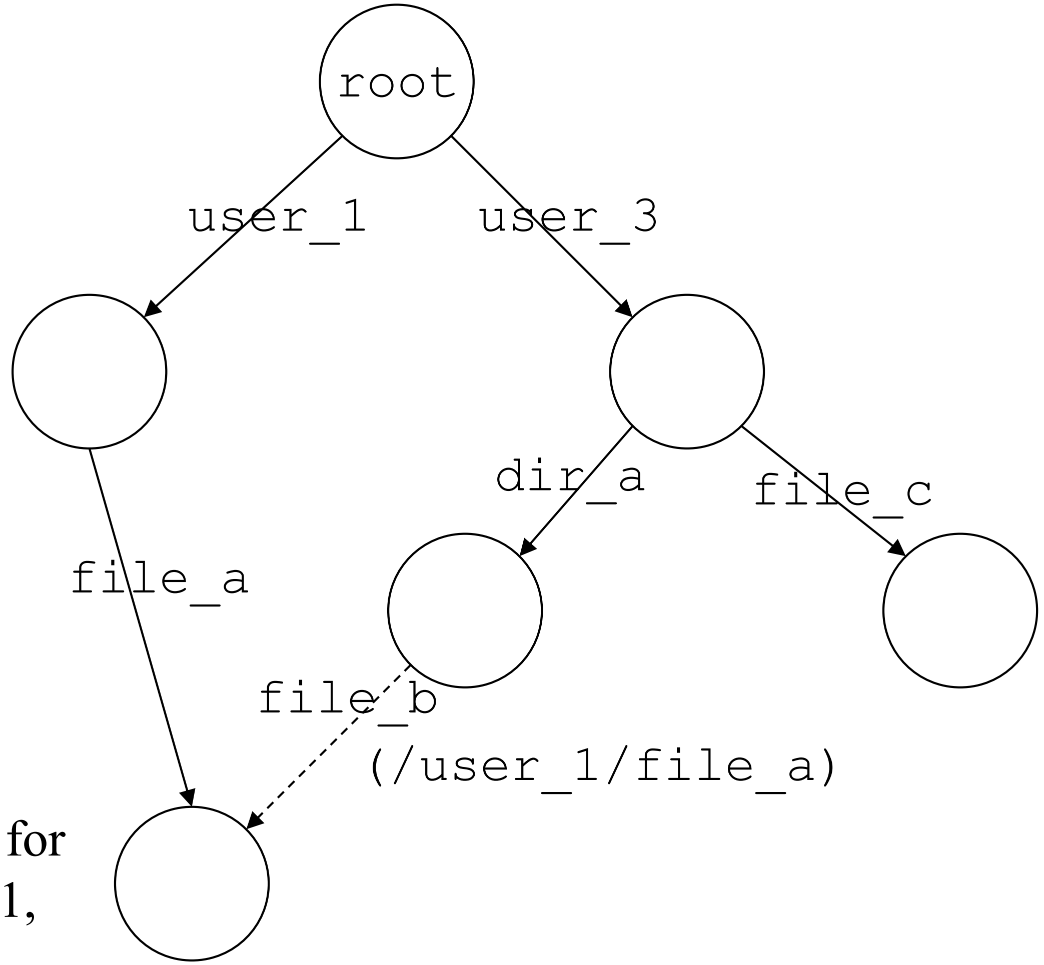
114	.
1	..
194	`dir_a`
29	`file_c`

inode #29, file

Symbolic Links

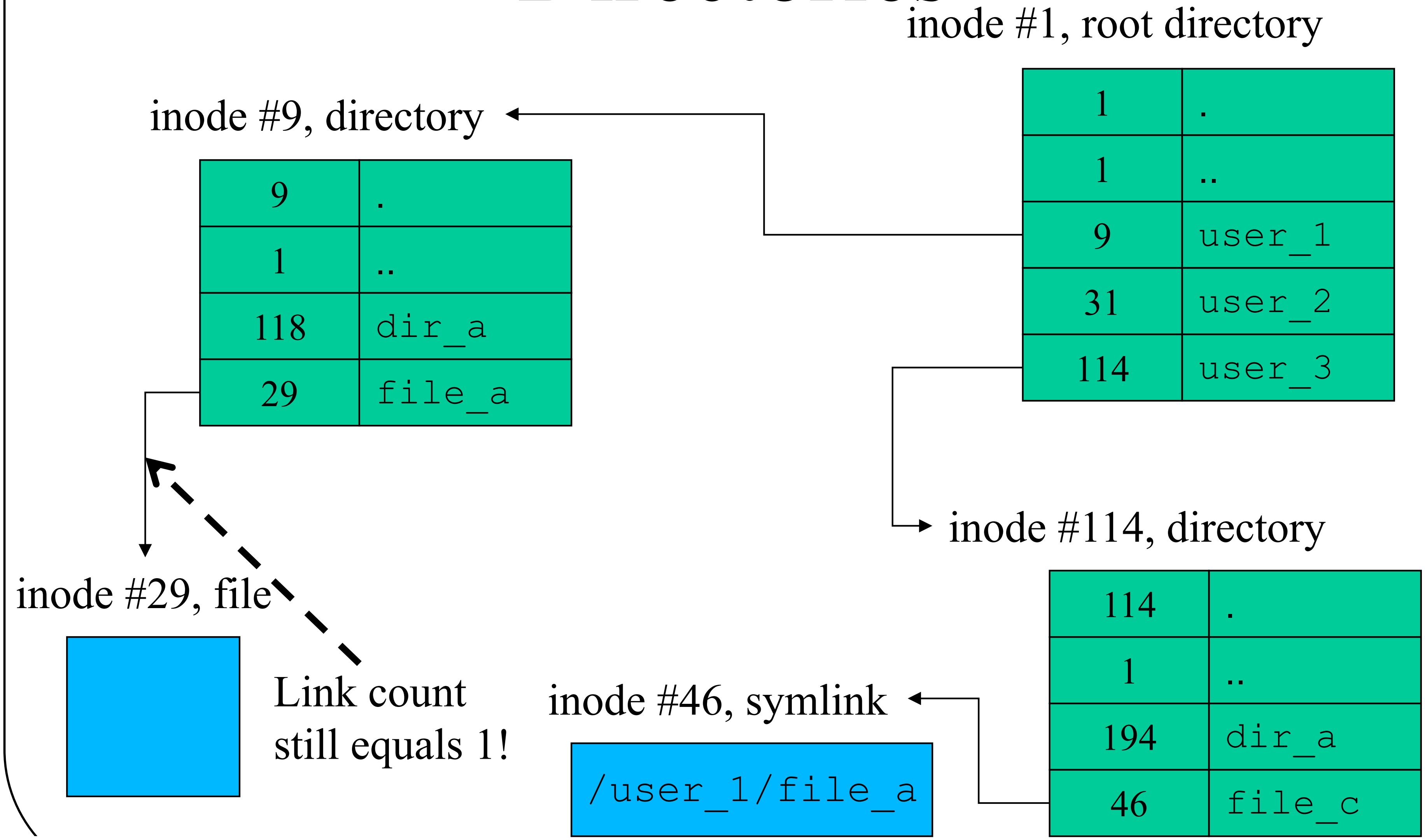
- A different way of giving files multiple names
- Symbolic links implemented as a special type of file
  - An indirect reference to some other file
  - Contents is a path name to another file
- File system recognizes symbolic links
  - Automatically opens associated file instead
  - If file is inaccessible or non-existent, the open fails
- Symbolic link is not 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



inode #1, root directory

1	.
1	..
9	user_1
31	user_2
114	user_3

inode #9, directory

9	.
1	..
118	dir_a
29	file_a

inode #29, file

Link count still equals 1!

inode #114, directory

114	.
1	..
194	dir_a
46	file_c

inode #46, symlink

/user_1/file_a

File Systems Reliability

- What can go wrong in a file system?
- Data loss
  - File or data is no longer present
  - Some/all of data cannot be correctly read back
- File system corruption
  - Lost free space
  - References to non-existent files
  - Corrupted free-list multiply allocates space
  - File contents over-written by something else
  - Corrupted directories make files un-findable
  - Corrupted inodes lose file info/pointers

Storage Device Failures

- Unrecoverable read errors
  - Signal degrades beyond ECC ability to correct
  - Background *scrubbing* can greatly reduce
- Misdirected or incomplete writes
  - Detectable with independent checksums
- Complete mechanical/electronic failures
- All are correctable with redundant copies
  - Mirroring, parity, or erasure coding
  - Individual block or whole volume recovery
  - At worst, backup

File Systems – System Failures

- Caused by system crashes or OS bugs
- Queued writes that don’t get completed
  - Client writes that will not be persisted
  - Client creates that will not be persisted
  - Partial multi-block file system updates
- Can also be caused by power failures
  - Solution: NVRAM disk controllers
  - Solution: Uninterruptable Power Supply (UPS)
  - Solution: super-caps and fast flush

Deferred Writes – A Worst Case Scenario

- Process allocates a new block to file A
  - We get a new block (x) from the free list
  - We write out the updated inode for file A
  - We defer free-list write-back (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

Robustness – Ordered Writes

- Carefully ordered writes can reduce potential damage
- Write out data before writing pointers to it
  - Unreferenced objects can be garbage collected
  - Pointers to incorrect info are more serious
- Write out deallocations before allocations
  - Disassociate resources from old files ASAP
  - Free list can be corrected by garbage collection
  - Shared data is more serious than missing data

Practicality of Ordered Writes

- Greatly reduced I/O performance
  - Eliminates head/disk motion scheduling
  - Eliminates accumulation of near-by operations
  - Eliminates consolidation of updates to same block
- May not be possible
  - Modern disk drives re-order queued requests
- Doesn't actually solve the problem
  - Does not eliminate incomplete writes
  - It chooses minor problems over major ones

Robustness – Audit and Repair

- Design file system structures for audit and repair
  - Redundant information in multiple distinct places
    - Maintain reference counts in each object
    - Children have pointers back to their parents
    - Transaction logs of all updates
  - All resources can be garbage collected
    - Discover and recover unreferenced objects
- Audit file system for correctness (prior to mount)
  - All objects are well formatted
  - All references and free-lists are correct and consistent
- Use redundant info to enable automatic repair

Practicality of Audit and Repair

- Integrity checking a file system after a crash
  - Verifying check-sums, reference counts, etc.
  - Automatically correct any inconsistencies
  - A standard practice for many years (see *fsck(8)*)
- No longer practical
  - Checking a 2TB FS at 100MB/second = 5.5 hours
- We need more efficient partial write solutions
  - File systems that are immune to them
  - File systems that enable very fast recovery

Journaling

- Create a circular buffer journaling device
  - Journal writes are always sequential
  - Journal writes can be batched
  - Journal is relatively small, may use NVRAM
- Journal all intended file system updates
  - Inode updates, block write/alloc/free
- Efficiently schedule actual file system updates
  - Write-back cache, batching, motion-scheduling
- Journal completions when real writes happen

Batched Journal Entries

- Operation is safe after journal entry persisted
  - Caller must wait for this to happen
- Small writes are still inefficient
- Accumulate batch until full or max wait time

```
writer:
    if there is no current in-memory journal page
        allocate a new page
    add my transaction to the current journal page
    if current journal page is now full
        do the write, await completion
        wake up processes waiting for this page
    else
        start timer, sleep until I/O is done
```

```
flusher:
    while true
        sleep()
        if current-in-memory page is due
            close page to further updates
            do the write, await completion
            wake up processes waiting for page
```

Journal Recovery

- Journal is a circular buffer
  - It can be recycled after old ops have completed
  - Time-stamps distinguish new entries from old
- After system restart
  - Review entire (relatively small) journal
  - Note which ops are known to have completed
  - Perform all writes not known to have completed
    - Data and destination are both in the journal
    - All of these write operations are idempotent
  - Truncate journal and resume normal operation

Why Does Journaling Work?

- Journal writes much faster than data writes
  - All journal writes are sequential
  - There is no competing head motion
- In normal operation, journal is write-only
  - File system never reads/processes the journal
- Scanning the journal on restart is very fast
  - It is very small (compared to the file system)
  - It can read (sequentially) with huge (efficient) reads
  - All recovery processing is done in memory

Meta-Data Only Journaling

- Why journal meta-data?
  - It is small and random (very I/O inefficient)
  - It is integrity-critical (huge potential data loss)
- Why not journal data?
  - It is often large and sequential (I/O efficient)
  - It would consume most of journal capacity bandwidth
  - It is less order sensitive (just precede meta-data)
- Safe meta-data journaling
  - Allocate new space, write the data
  - Then journal the meta-data updates

Log Structured File Systems

- The journal is the file system
  - All inodes and data updates written to the log
  - Updates are Redirect-on-Write
  - In-memory index caches inode locations
- Becoming a dominant architecture
  - Flash file systems
  - Key/value stores
- Issues
  - Recovery time (to reconstruct index/cache)
  - Log defragmentation and garbage collection

Navigating a Logging File System

- Inodes point at data segments in the log
  - Sequential writes may be contiguous in log
  - Random updates can be spread all over the log
- Updated inodes are added to end of the log
- Index points to latest version of each inode
  - Index is periodically appended to the log
- Recovery
  - Find and recover the latest index
  - Replay all log updates since then

Redirect on Write

Note: This will work very nicely for flash devices

- Many modern file systems now do this
  - Once written, blocks and inodes are immutable
  - Add new info to the log, and update the index
- The old inodes and data remain in the log
  - If we have an old index, we can access them
  - Clones and snapshots are almost free
- Price is management and garbage collection
  - We must inventory and manage old versions
  - We must eventually recycle old log entries