File System Interface

ICS332

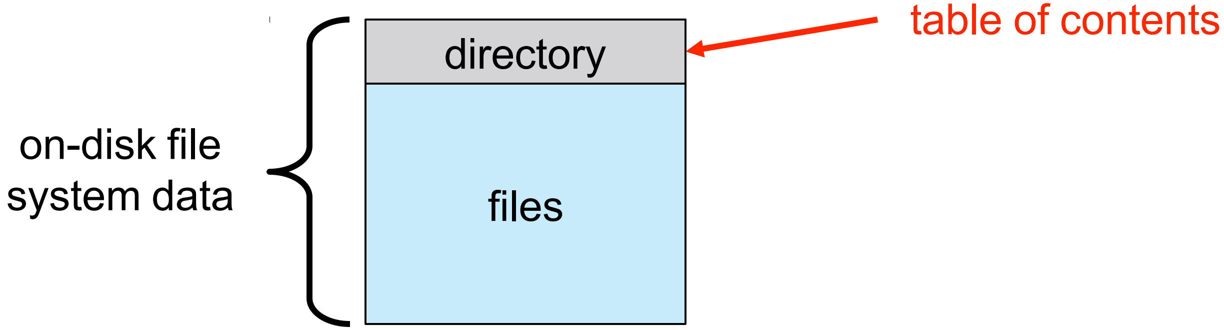
Operating Systems

Files and Directories

- Features
  - A file system implements the file abstraction for secondary storage
  - It also implements the directory abstraction to organize files logically
- Usage
  - It is used for users to organize their data
  - It is used to permit data sharing among processes and users
  - It provides mechanisms for protection

File System

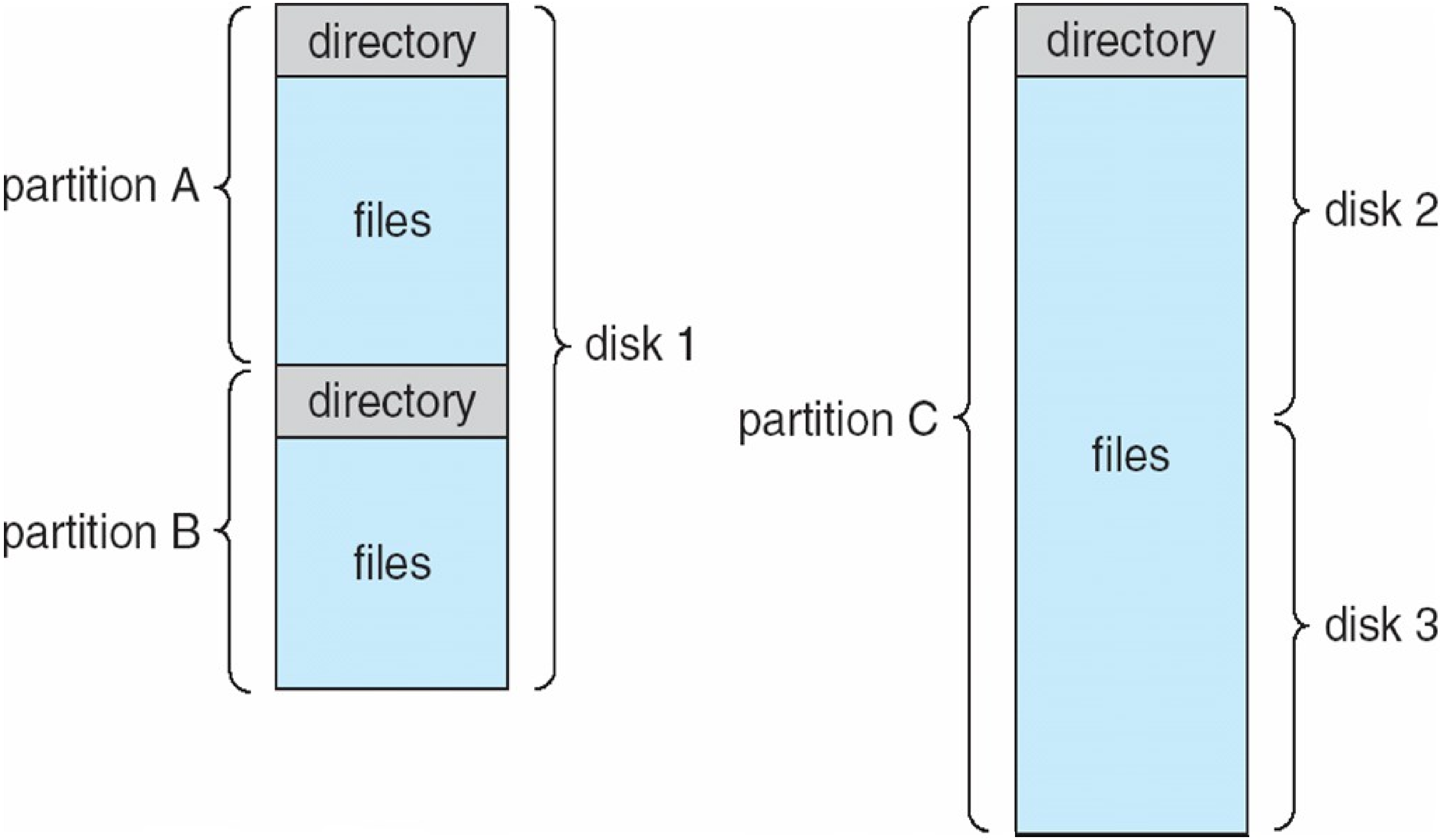
- The term “File System” is a bit confusing
  - The component of the OS that knows how to do “file stuff”
  - A set of algorithms and techniques
  - The content on disk that describes a set of files



- Remember that a disk can be partitioned arbitrarily into logically independent partitions
- Each partition can contain a file system
  - In this case the partition is often called a volume (e.g., C:, A:)
- One can have multiple disks, each with arbitrary partitions, each with a different file system on it

File Systems

- Example with 2 disks, and 3 file systems



File and File Type

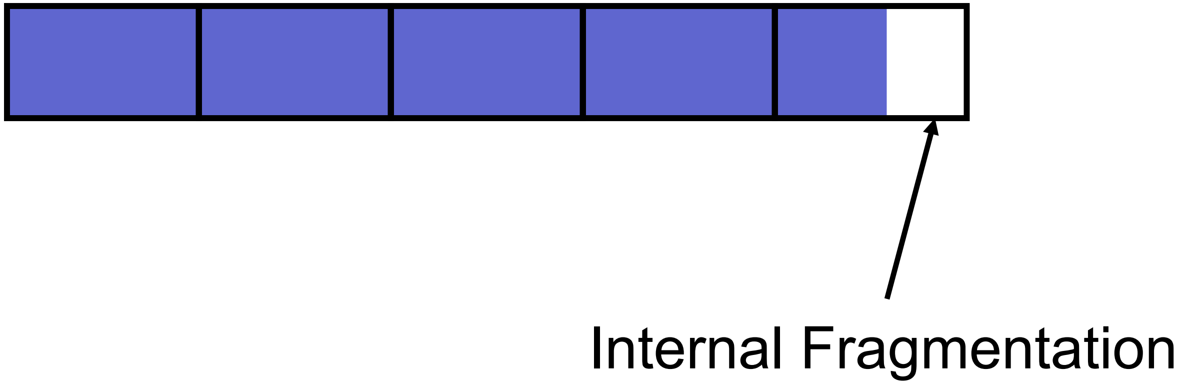
- A file is data + properties (or attributes)
  - Content, size, owner, last read/write time, protection, etc.
- A file can also have a type
  - Understood by the File System
    - e.g., regular file, logical link, device
  - Or understood by the OS
    - Executable, shared library, object file, text, binary, etc.
- In Windows a file type is encoded in its name
  - .com, .exe, .bat, ...
  - Some known to the OS, some just known to applications
- In Mac OS X, each file is associated with a type and the name of the program that created it
  - Done by the create() system call for all files
  - Allows for double clicks to remember which program to use
- In Linux a file type is encoded only in its content
  - “Magic” numbers, first bytes (#!...)
  - Some files have no type and filenames are arbitrary

File Structure

- Question: should the OS know about the structure of a file?
  - The more different structures the OS knows about the more "help" it can provide applications that use particular file types
  - But then, the more complicated the OS code is
    - And it may be too restrictive: e.g., assume all binary files are executable!
- Modern OSes support very few files structures:
  - Files are sequences of bytes that the OS doesn't know about but that have meaning to the applications
  - Certain files are executables and must have a specific format that the OS knows about
    - Executable formats have evolved throughout the years, partly to accommodate dynamic loading
  - The OS may expect a certain directory structure defining an application
    - e.g., Mac OS X "application bundles"

Internal File Structure

- We've seen that the disk provides the OS with a block abstraction (e.g., 512 bytes)
  - All disk I/O is performed in number of blocks
- Each file is stored in a number of blocks



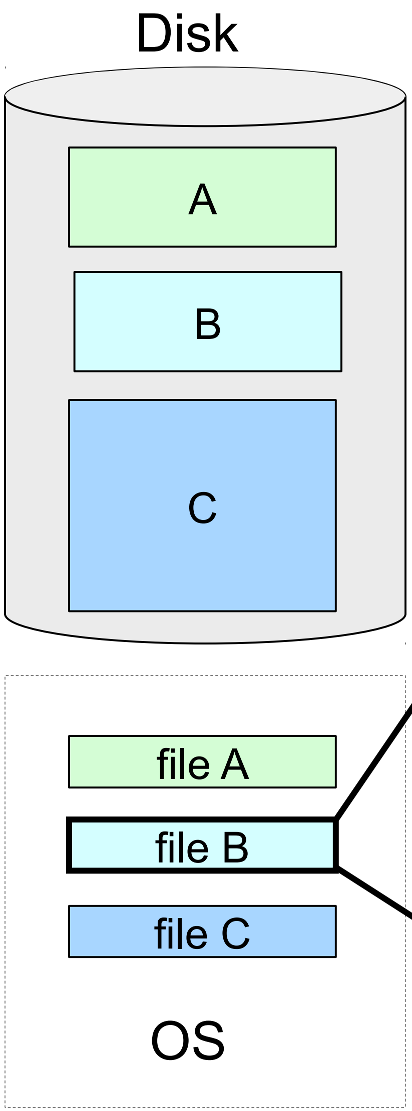
File Operations

- A file is an abstraction, i.e., an abstract data type
- As such the OS defines several file operations
- Basic operations
  - Creating
  - Writing/Reading
    - A current-file-position pointer is kept per process
    - Updated after each write/read operation
  - Repositioning the current-file-position pointer
    - This is called a “seek”
  - Appending at the end of a file
  - Truncating
    - Down to zero size
  - Deleting
  - Renaming

Open Files

- The OS requires that processes open and close files
  - Otherwise, the OS would spend its time searching directories for file names for each file operation
- After an open, the OS copies the file system's file entry (i.e., attributes) into an open-file table that is kept in RAM in the kernel
- The OS keeps two kinds of open-file tables
  - One table per process
  - One global table for all processes
- A process specifies which file the operation is on by giving an index in its local table
  - The famous "filed" (file descriptor) in Linux
- The OS keeps track of a "reference count" for each open file in the global table
  - Incremented each time a process opens the file
  - Decremented each time a process closes the file
- Let's see an example

Open File Tables

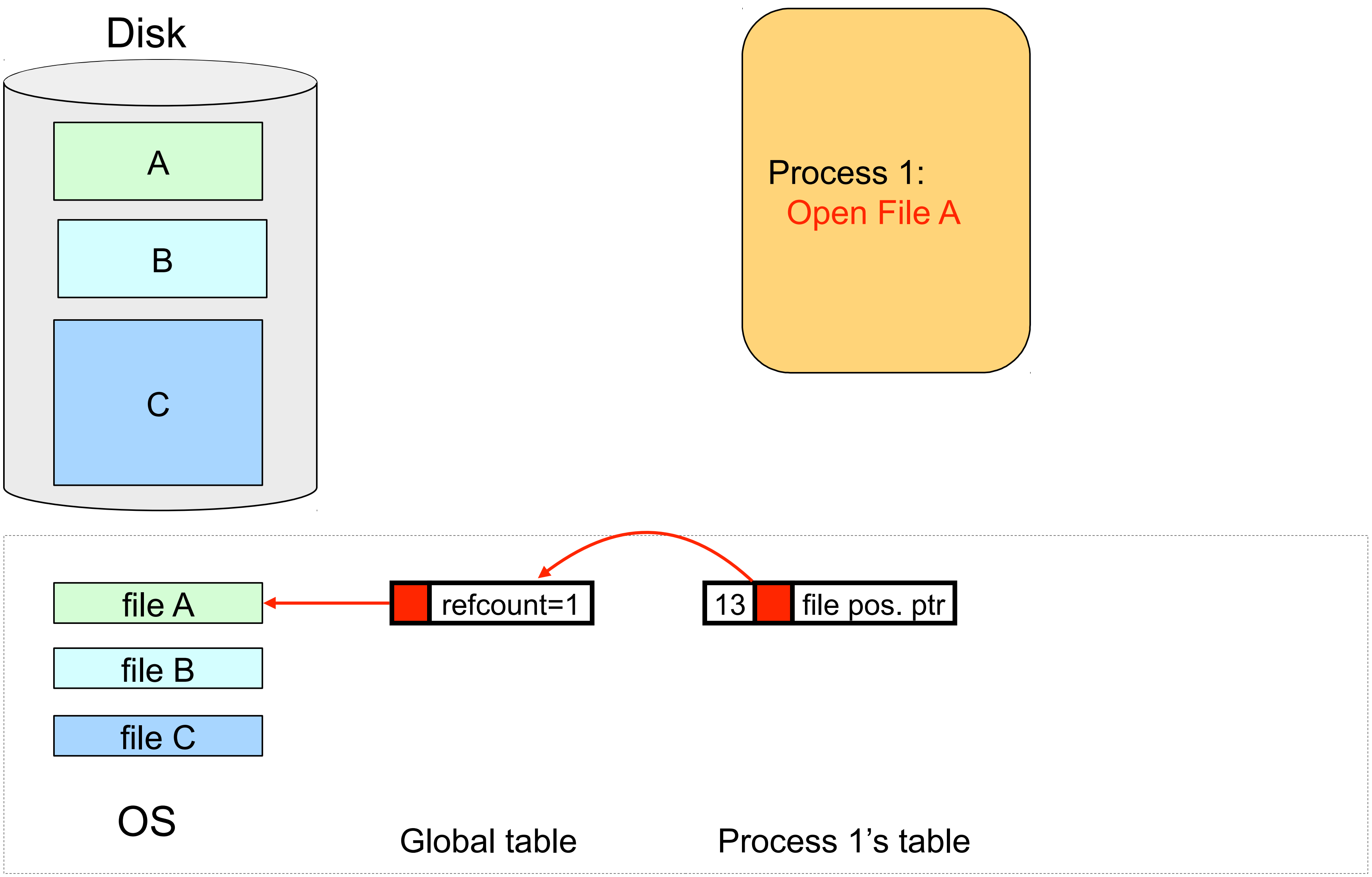


Data structure that contains

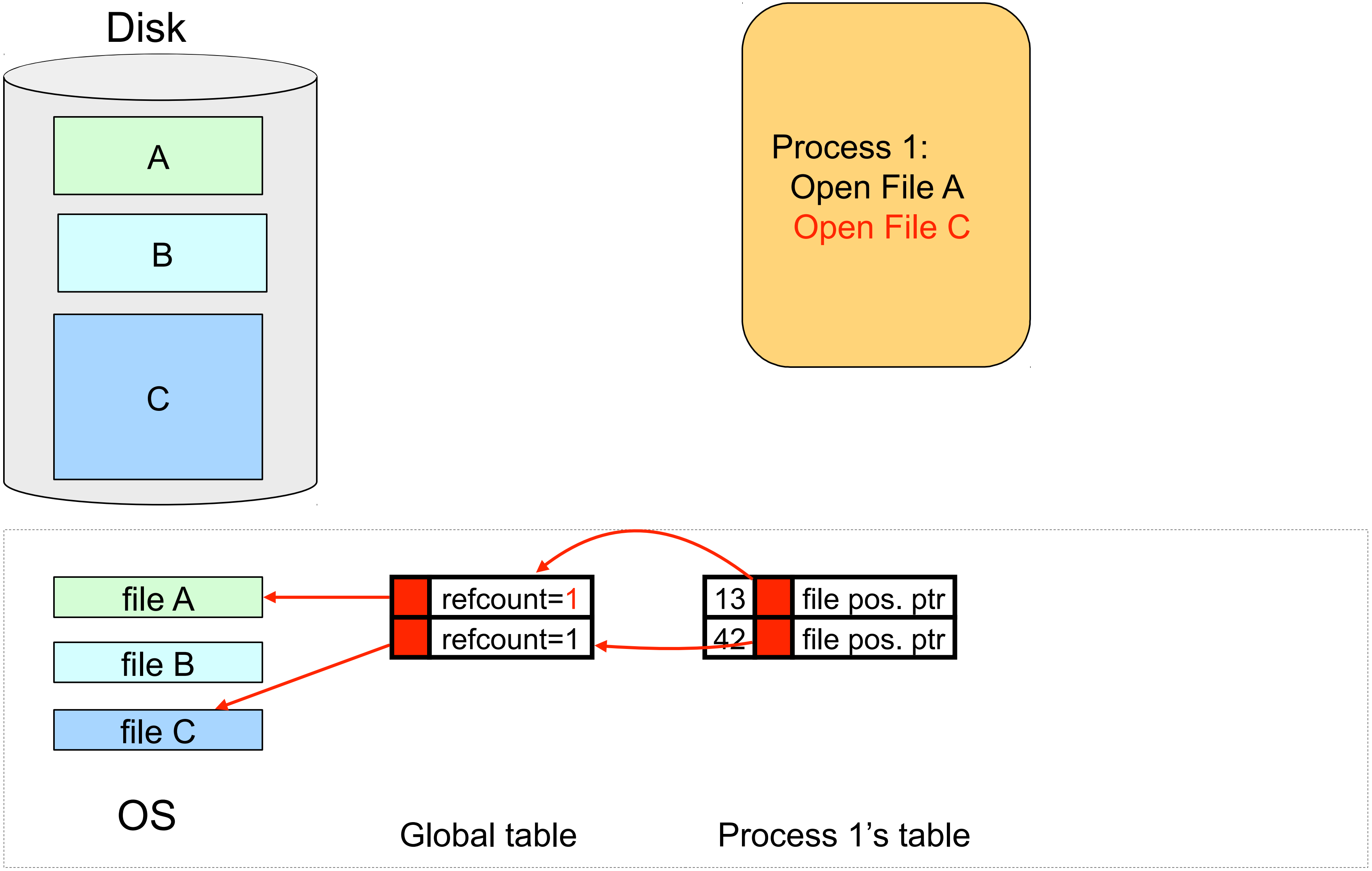
- Location of file on disk
  - Block number of the first block
  - Number of blocks
  - Size in bytes
- Attributes
  - permissions
  - owner
  - time of creation
  - date of last modification
  - ...

- This is kept on disk, but for now we take a logical view of it
  - Let’s just say it’s “in the OS”, or “in the File System”

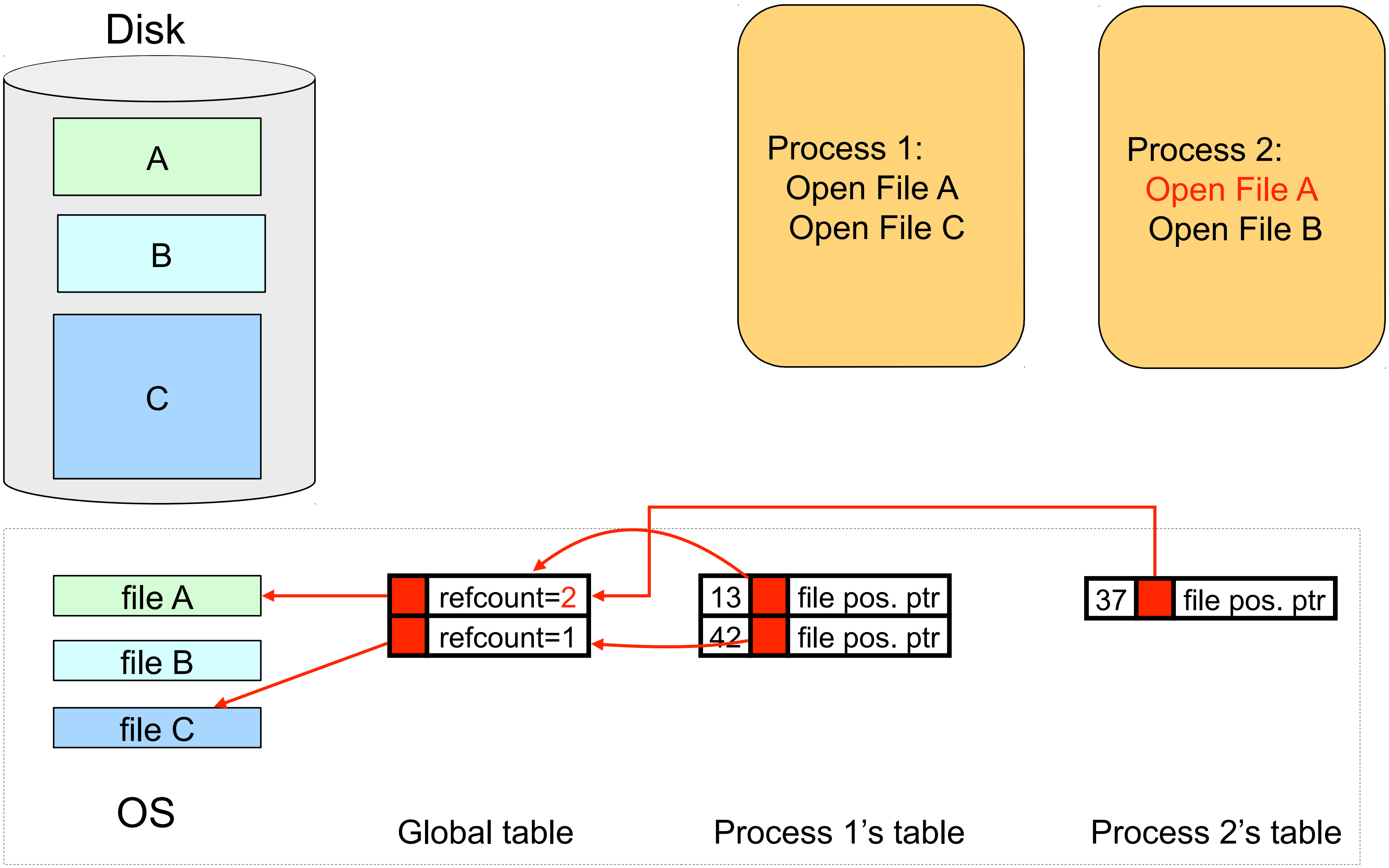
Open File Tables



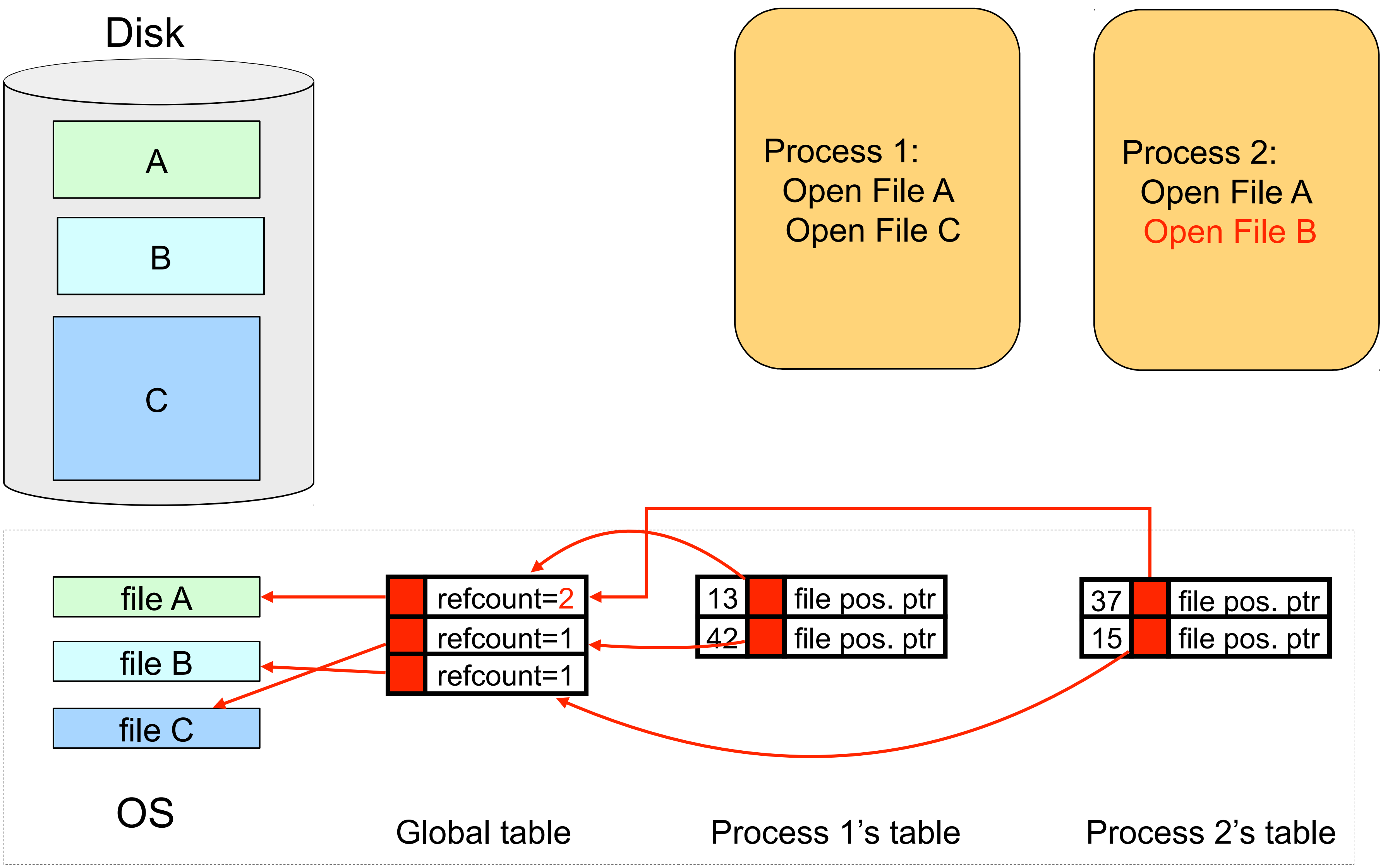
Open File Tables



Open File Tables



Open File Tables



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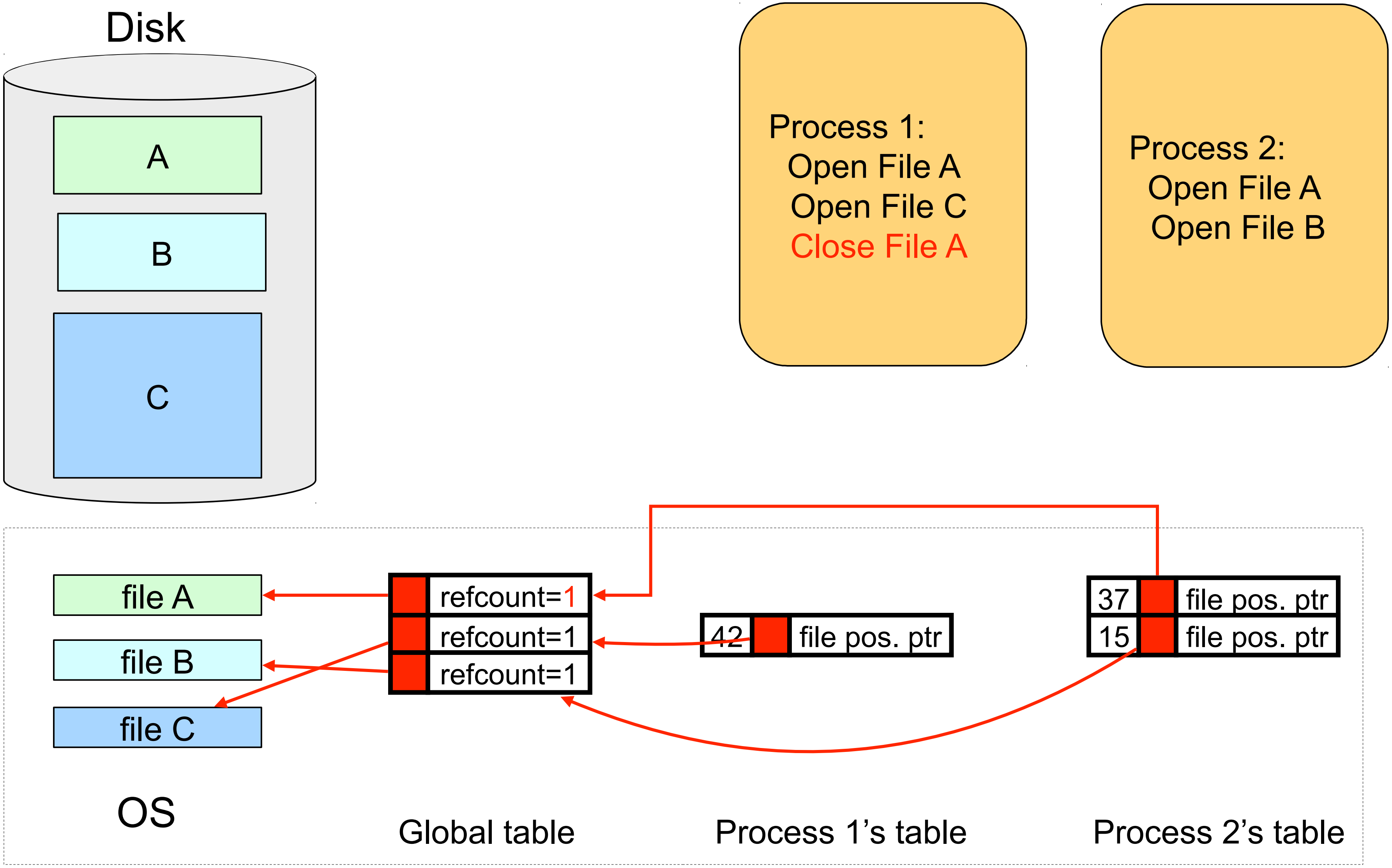
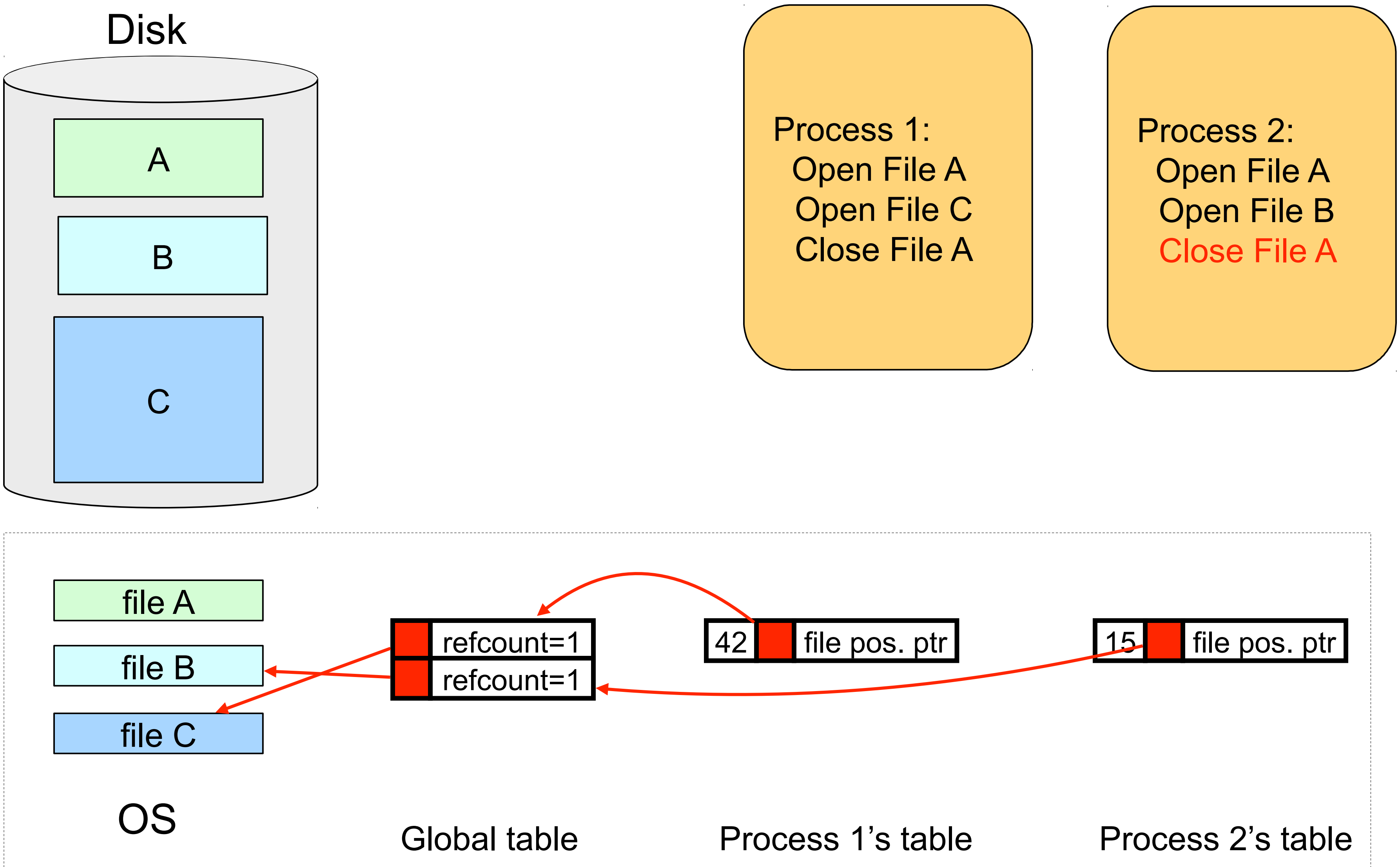


Open File Tables



File Locking

- Bad things may happen when multiple processes reference the same file
  - Just like when threads reference the same memory
- A file lock can be acquired for a full file or for a portion of a file
- The OS may require mandatory locking for some files
  - e.g., for writing for a log file that many system calls write to
- Typically applications have to implement their own locking
- And of courses there can be deadlocks and all the messiness of thread synchronization

- Let’s look at the Java example in Fig. 10.1 in the book

File Locking in Java

```
import java.io.*;
import java.nio.channels.*;
public class LockingExample {
    public static final boolean EXCLUSIVE = false;
    public static final boolean SHARED = true;
    public static void main(String arsg[]) throws IOException {
        FileLock sharedLock = null;
        FileLock exclusiveLock = null;
        try {
            RandomAccessFile raf = new RandomAccessFile("file.txt", "rw");
            FileChannel ch = raf.getChannel();
            // this locks the first half of the file - exclusive  (one writer)
            exclusiveLock = ch.lock(0, raf.length()/2, EXCLUSIVE);
            /** Now modify the data . . . **/
            // release the lock
            exclusiveLock.release();
```

File Locking in Java (cont.)

```
            // this locks the second half of the file - shared (multiple readers)
            sharedLock = ch.lock(raf.length()/2+1, raf.length(), SHARED);
            /** Now read the data . . . **/
            // release the lock
            sharedLock.release();
        } catch (java.io.IOException ioe) {
            System.err.println(ioe);
        } finally {
            if (exclusiveLock != null)
                exclusiveLock.release();
            if (sharedLock != null)
                sharedLock.release();
        }
    }
}
```

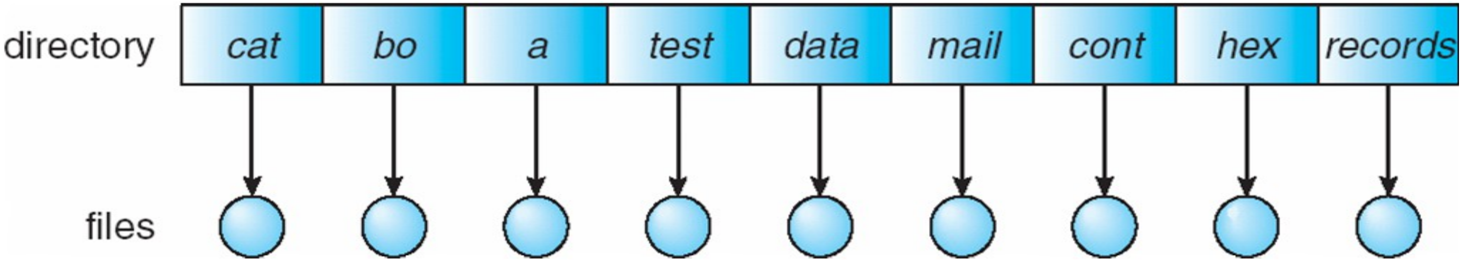
Access Methods

- Sequential Access
  - One byte at a time, in order, until the end
  - Read next, write next, reset to the beginning
- Direct Access
  - Ability to position anywhere in the file
  - Position to block #n, Read next, write next
  - Block number is relative to the beginning of the file
    - Just like a logical page number is relative to the first page in a process' address space
- Indexed Access
  - A file contains an index of "file record" locations
  - One can then look for the object in the index, and then "jump" directly to the beginning of the record
- Linux and Windows: Direct access
  - It's up to you to implement your own application-specific index
  - But internally the FS does some indexing of blocks, as we'll see
- Older OSes provided other, more involved methods, including indexing
  - e.g., you could tell the OS more information about the logical structure of your file

Directories

- We're used to file systems that support
  - multiple directory levels
  - the notion of a *current* directory

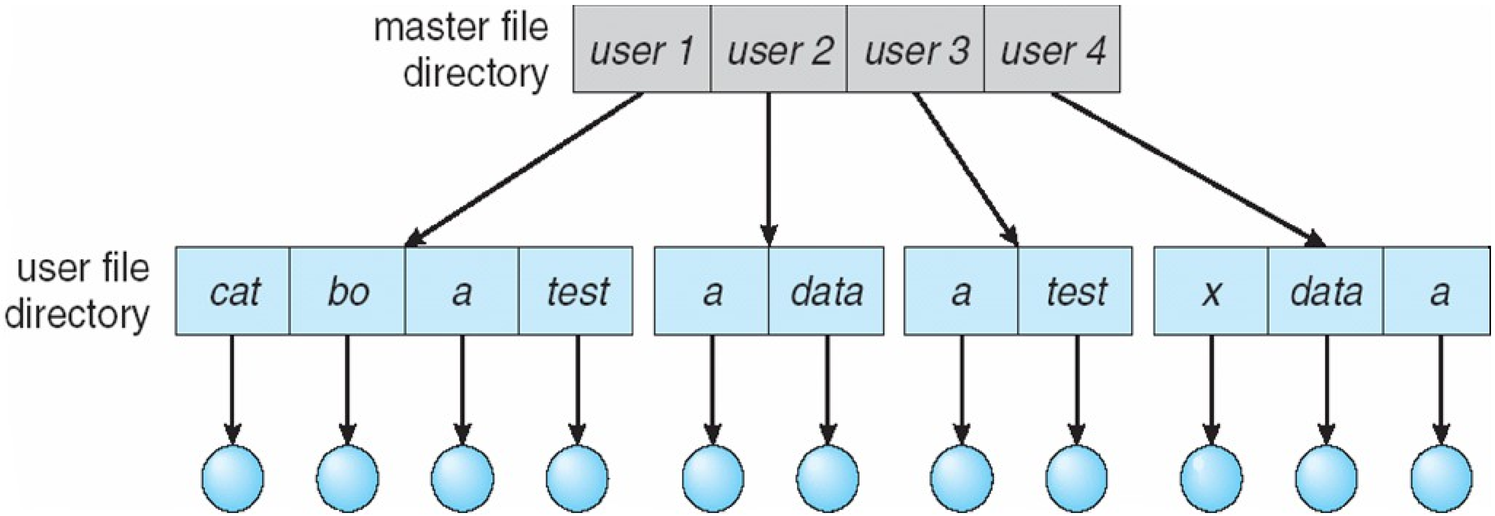
- Single-Level directory



  - Naming conflicts
    - Have to pick longer, and longer unique names
  - Slow searching

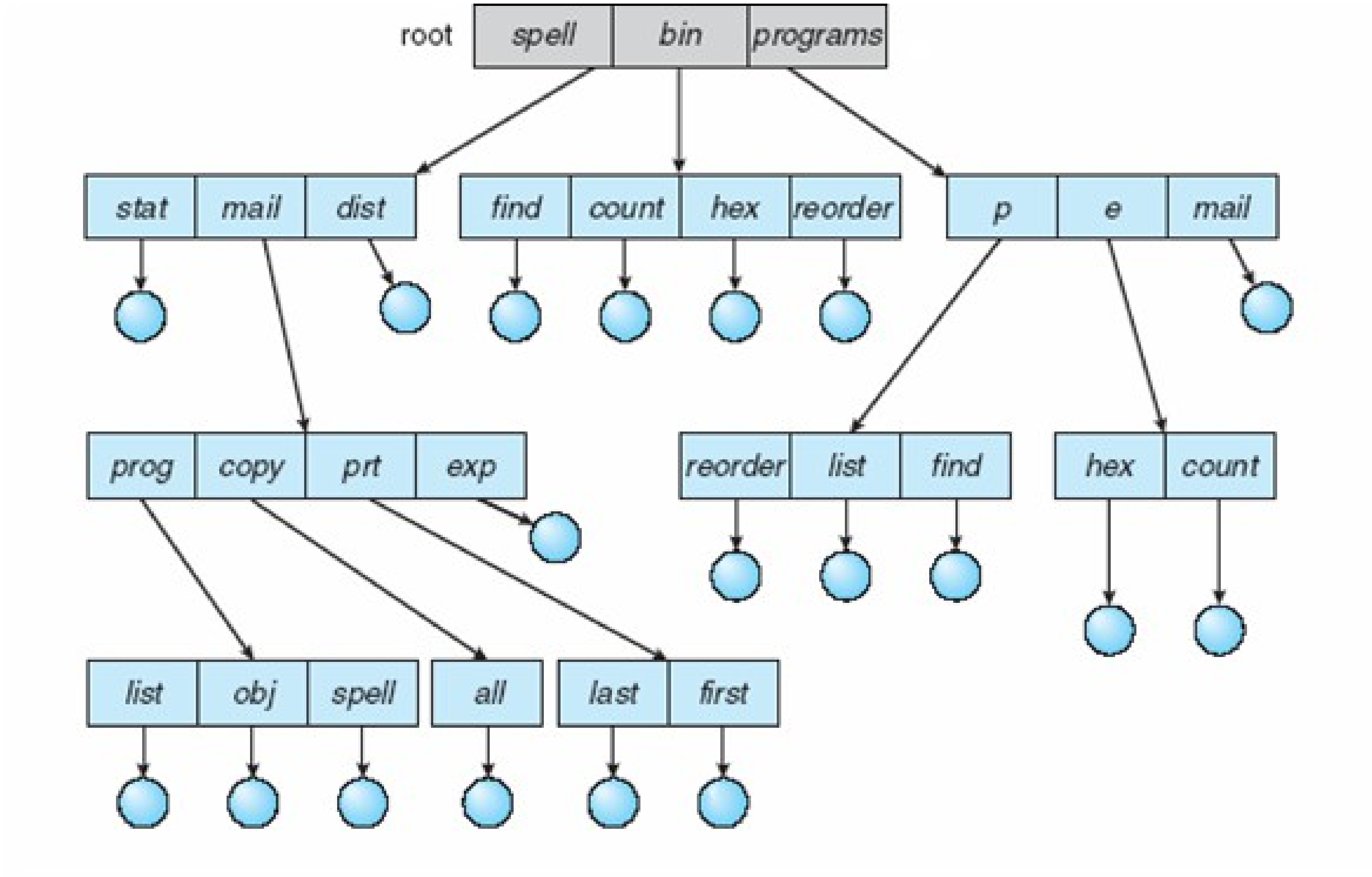
Directories

- Two-Level Directory



  - Faster searching
  - Still naming conflict for each user

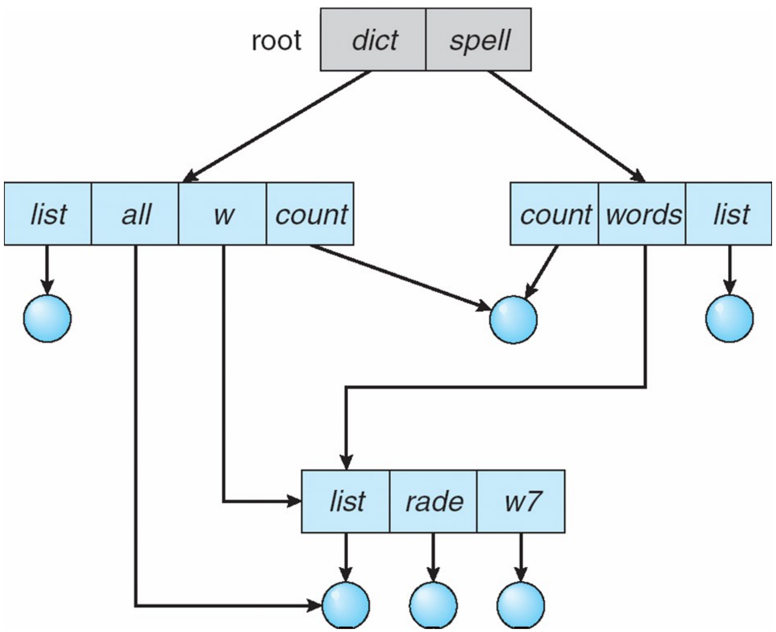
Tree-Structured Directories



Tree-Structured Directories

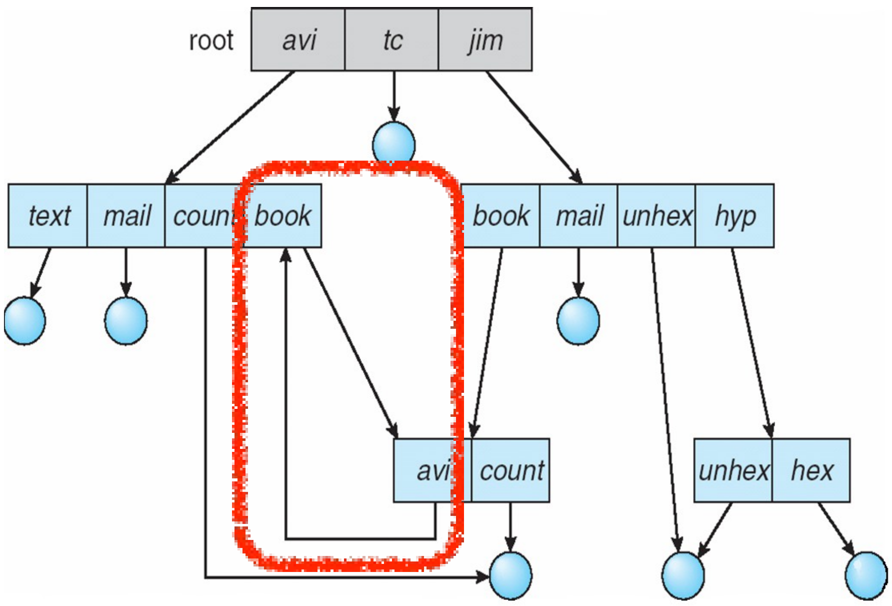
- More general than 1- and 2-level schemes
- Each directory can contain files or directories
  - Differentiated internally by a bit set to 0 for files and 1 for directories
- Each process has a current directory
  - Relative paths
  - Absolute paths
- Path name translation, e.g., for “/one/two/three”
  - Open “/” (the file system knows where that is on disk)
  - Search it for “one” and get its location
  - Open “one”, search it for “two” and get its location
  - Open “two”, search it for “three” and get its location
  - Open “three”
- The OS spends a lot of time walking directory paths
  - Another reason why one separates “open” from “read/write”
  - The OS attempts to cache “common” path prefixes
- But what we have in modern systems is actually more complicated...

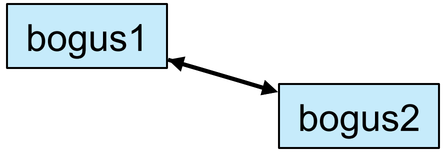
Acyclic Graph Directories



- Files/directories can be shared by directories
- A hard link is created in a directory, to point to or reference another file or directory
  - Identified in the file system as a special file
- The file system keeps track of reference count for each file, and deletes the file when the last reference is removed
- A symbolic link does **not** count toward the reference count
  - You can think of it as an alias for the file (if you remove the alias, nothing happens)
  - If the target file is removed then the alias simply becomes invalid
- This is the UNIX view of links, as implemented by the "In" command
  - No hard-linking of directories
- Acyclic is good for quick/simple traversals
- Simple way to prohibit cycles: no hard linking of directories!
  - Used in Linux

General Graph Directory

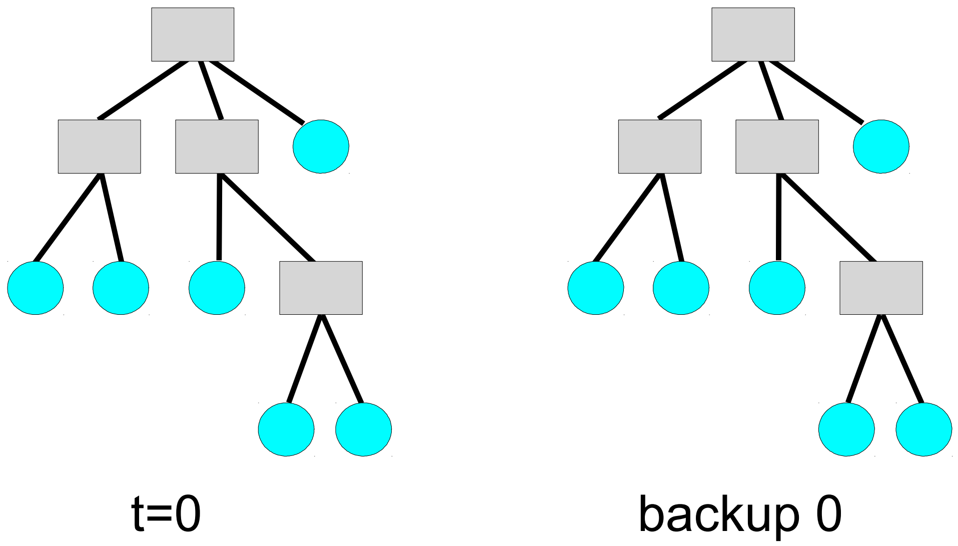




- In this scheme users can do whatever they want
- Directory traversals algorithms must be smarter to avoid infinite loops
- Garbage collection could be useful because ref counts may never reach zero
  - But way too expensive in practice

Mac OSX Time Machine

- Time Machine is the backup mechanism introduced with Leopard
- It uses hard links
  - Every time a new backup is made, a new backup directory is created that contains a snapshot of the current state of the file system
  - Files that haven't been modified are hard links to previously backed up version
    - A new backup should be mostly hard links instead of file copies(space saving)
  - When an old backup directory is wiped out, then whatever files have a reference count of zero are removed (no longer part of more recent data)



At time t=0, the first backup is initialized, meaning that it's a full copy of the directory structure and files

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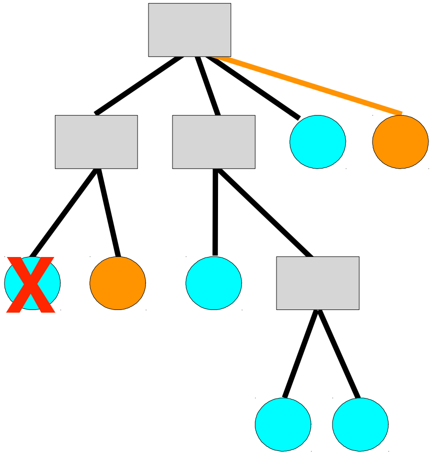
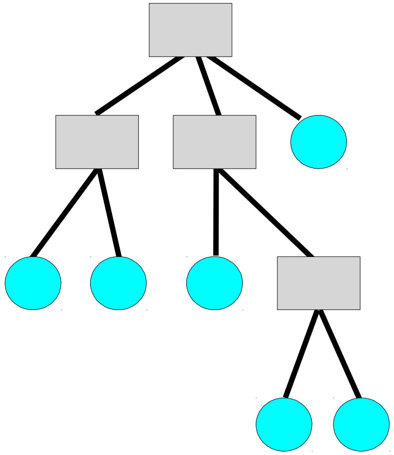


t=1



backup 0

By time t=1, a file has been modified, another one is added, an another one is deleted

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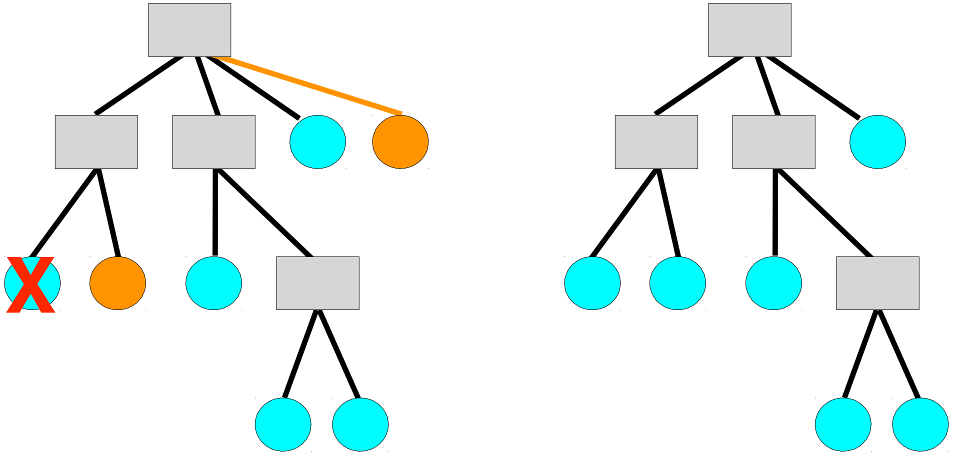

t=1

backup 0

At time t=1, a new backup is triggered by the user

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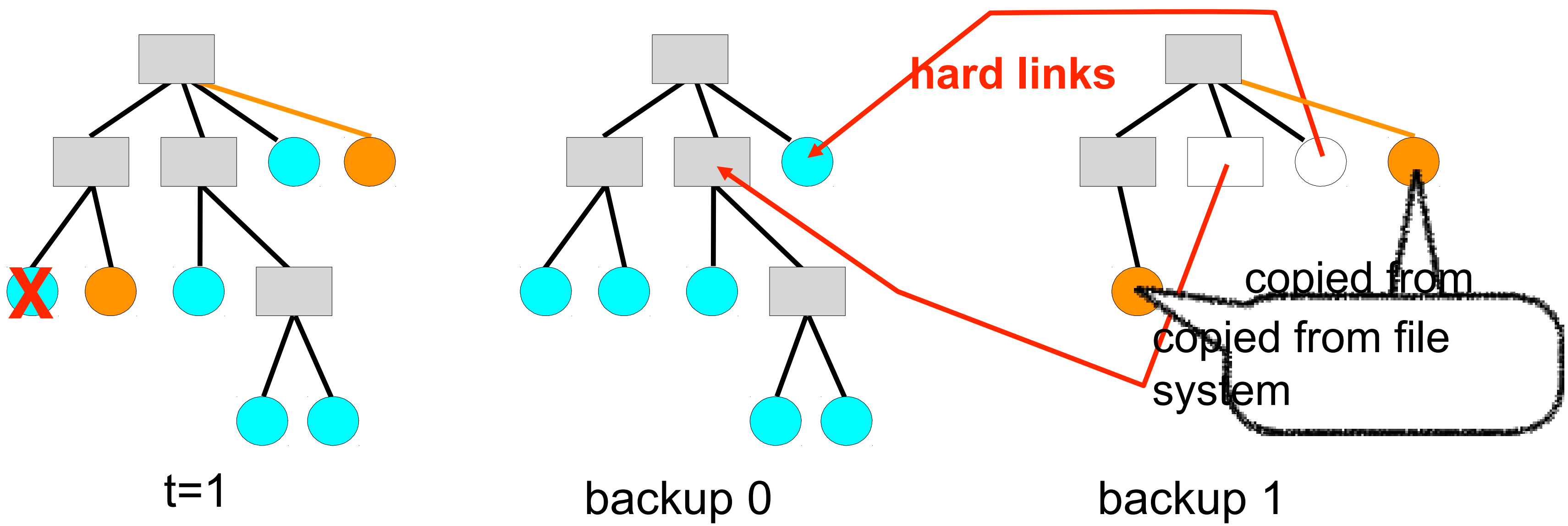

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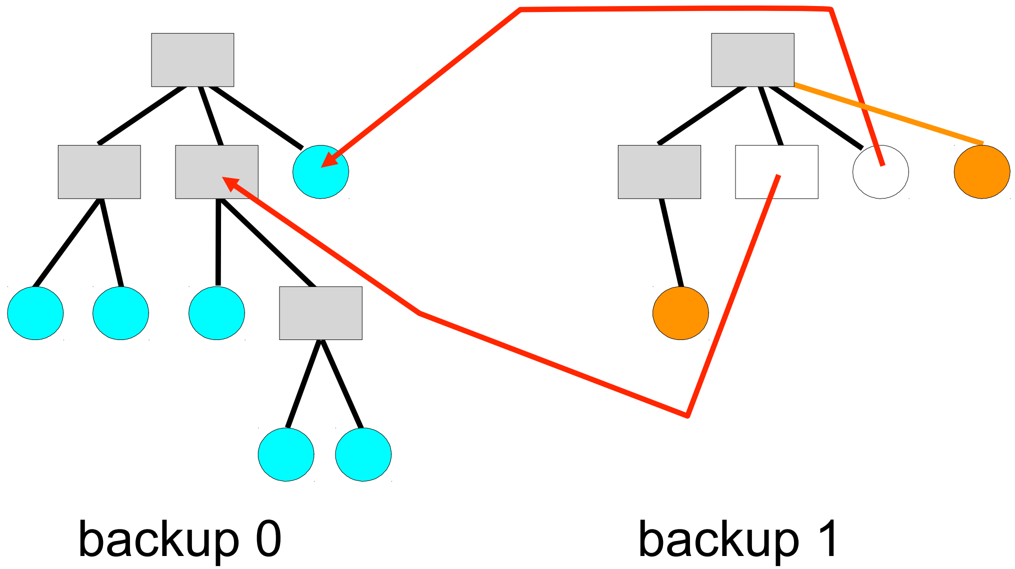

The user can now remove backup 0

Mac OSX Time Machine

- Advantages
  - Extremely simple to implement
  - The back up can be navigated in all the normal ways, without Time Machine
  - Provided backups are frequent, they are done by creating mostly hard links (which is MUCH faster than copying data)
- Drawback
  - If you change 1 byte in a 10GB file, then you copy the whole 10GB
  - But how often does this happen??
- For efficiency, Mac OSX allows hard linking of directories
  - Cycles in the directory hierarchy must be detected, i.e., more complicated file system code
  - Complexity deemed worthwhile by Mac OSX developers

Time Machine on Linux?

- Give how simple and elegant Time Machine is, one may want to implement it on Linux
  - Could be an interesting course project
- But because Linux doesn't allow hard-linking of directories, one would have to recreate the **whole** directory structure for each backup
  - While would take space and, more importantly perhaps, a lot of time
- Such implementations exist, but if you use a standard Linux file system that does not allow cycles in the directory structures, it won't be efficient

Hard Links on Linux

- It turns out that, on Linux, whenever a file is opened by a process, a hard link to the file is created
- Say that process with PID 2233 calls the open() system call to open a file “/home/casanova/somefile”
- open() returns a “file descriptor”, i.e., an integer, say 55
- At that point, a hard link to “/home/casanova/somefile” is created in “/proc/2233/fd/55”
- If, while the process is running, “/bin/rm /home/casanova/somefile” is executed, then the file survives because its reference count is non-zero
  - Essentially, you can’t remove the data for a file while a process is using it, which is probably a good thing
- This allows you to retrieve a file that you’ve erased by mistake as long as some process has it opened
  - You might want to create hard links to your important files anyway
- Let’s try this on a Linux box...

File System Mounting

- There can be multiple file systems
- Each file system is "mounted" at a special location, the mount point
  - Typically seen as an empty directory
- When given a mount point, a volume, a file system type, the OS
  - asks the device driver to read the device's directory
  - checks that the volume does contain a valid file system
  - makes note of the new file system at the specified mount point
    - The OS keeps a list of mount points
- Mac OS X: all volumes are mounted in the /Volumes/ directory
  - Including temporary volumes on USB keys, CDs, etc.
- UNIX: volumes can be mounted anywhere
- Windows: volumes were identified with a letter (e.g., A:, C:), but current versions, like UNIX, allow mounting anywhere
- On Linux the "mount" command lists all mounted volumes

Protection

- File systems provide controlled access
- General approach: Access Control Lists (ACLs)
  - For each file/directory, keep a list of all users and of all allowed accesses for each user
  - Protection violations are raised upon invalid access
- Problem: ACLs can be very large
- Solution: consider only a few groups of users and only a few possible actions
- UNIX:
  - User, Group, Others not in Group, All (ugoa)
  - Read, Write, Execute (rwx)
  - Represented by a few bits
  - chmod command:
    - e.g., chmod g+w foo (add write permission to Group users)
    - e.g., chmod o-r foo (remove read permission to Other users)

Conclusion

- In the next set of lecture notes we'll look at how a file system is implemented...