File System Interface

ICS332

Operating Systems

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File System

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- It can mean the component of the OS that knows how to virtualize storage
  - As in “I am using a very fast file system implementation”
  - We’ll talk about the OS component in the next set of lecture notes

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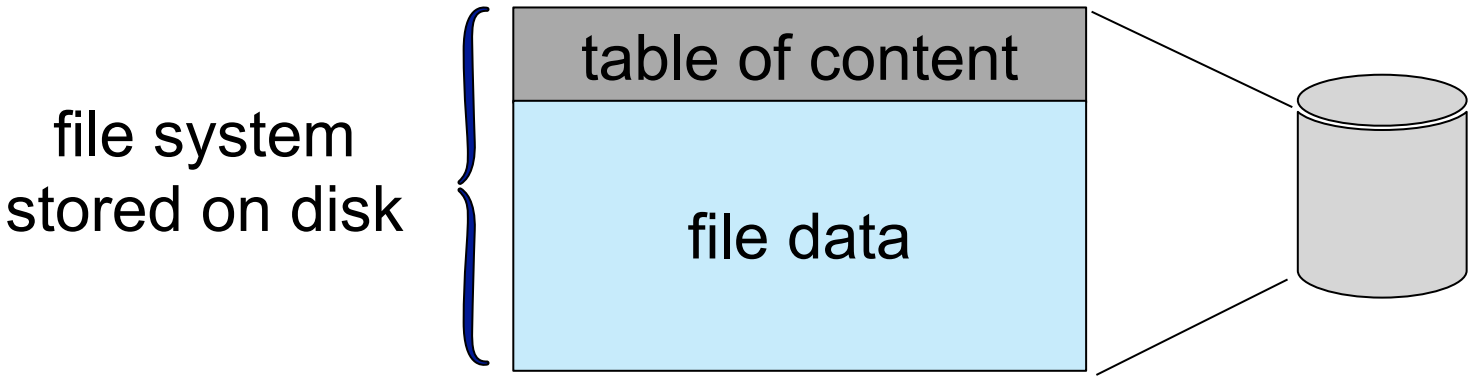
  - As in “my file system was erased”



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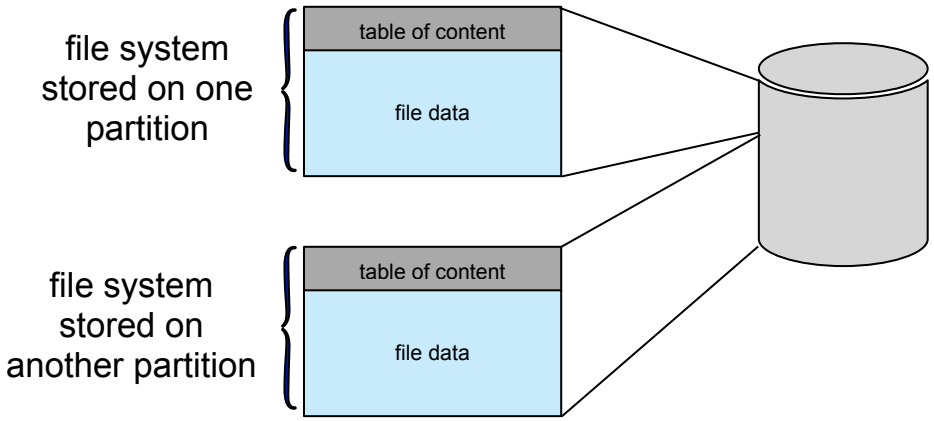


- There can be multiple file systems stored on the same physical disk, in different partitions

Files

- The key abstraction to virtualize storage is a file
  - An array of bytes where each byte can be read or written
  - Has a low-level name (e.g., a number) and a user-level name (e.g., “foo.txt”)
  - Has associated metadata (owner, last write time, read/write/execute permissions)
  - Has some internal type (regular file, symbolic link, hard link, device)
- What about user-level file types?
  - A common practice is to use “file extensions” (like .txt)
  - In some OSes, it is used to figure out what application can open the files
  - But file extensions are typically just conventions
    - In Linux you can name an executable with a .txt extension if you want
    - In Windows you can, but you need to tell Windows about it (PATHEXT)
  - But in general, the type of a file is based on its content, often on the first few bytes (called the “magic number”)
    - The UNIX **`file`** command uses this to display useful file “types”
    - Let’s try it on my **`/usr/bin/local`** directory…

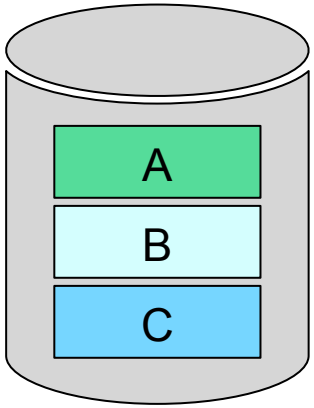
File Operations

- A file is an abstraction, i.e., an abstract data type, on which the OS defines several 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 (a “seek”)
  - Appending at the end of a file
  - Truncating / Deleting
  - Renaming
  - Getting / changing metadata
- OSTEP 39 has **many** examples of using the POSIX file system interface for creating/reading/writing/deleting files
  - I am **not** going to go through all of those here
  - Most of you should be familiar with some of this anyway
  - In these lecture notes we go through some of the ideas/concepts without necessarily showing the corresponding code (see OSTEP for all details)

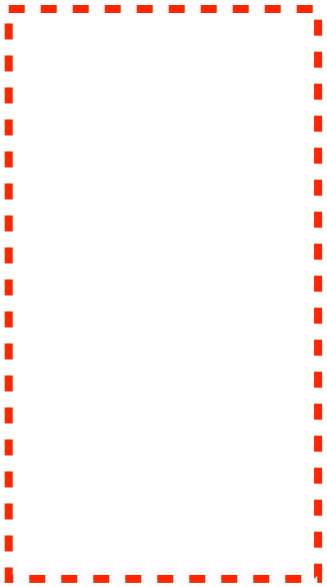
Opening Files

- The OS requires that processes open and close files
  - As you know from writing code in basically any language
- After an open, the OS copies the file system's file entry into an open-file table that is kept in RAM in the kernel
- The OS keeps an open file tables
- A process specifies an open file as an index in its own list of open files
  - The famous "filed" (file descriptor) in Linux
- Let's see an example …

Open File Table

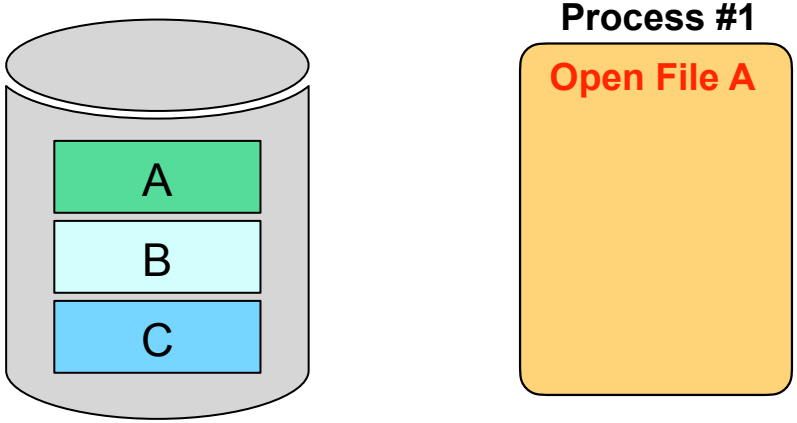


Kernel



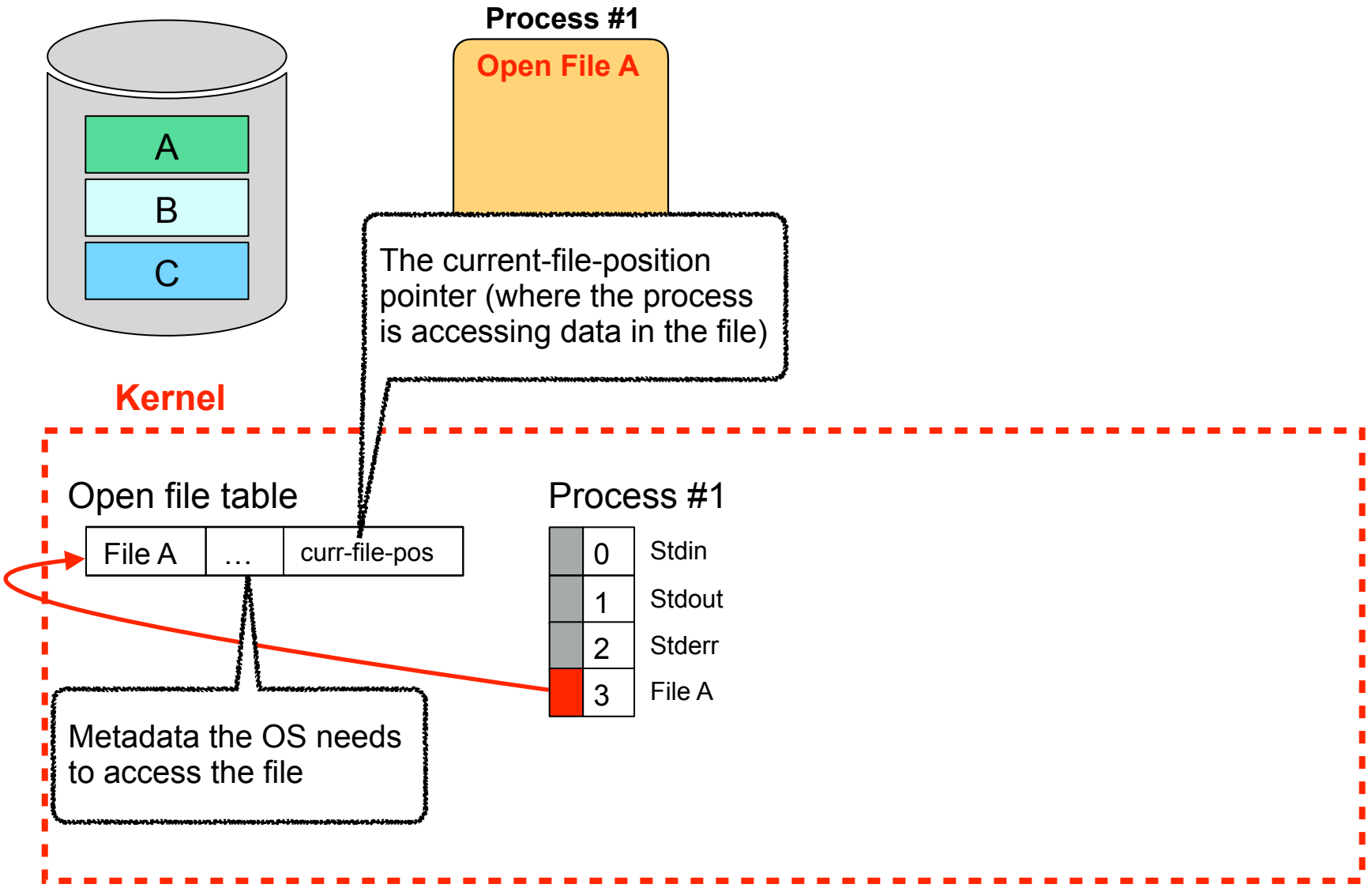
- Consider a system with 3 files on disk

Open File Table

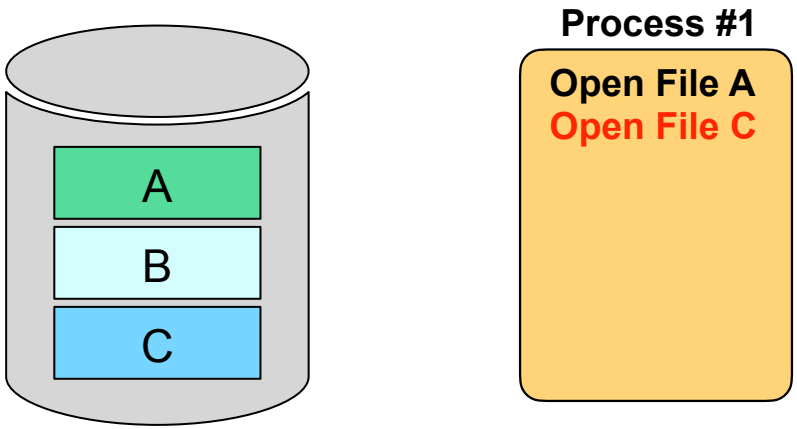


- To open a file a process gives its path to the OS
- The OS asks the file system to use its on-disk "table of content" to locate a data structure that describes the file
  - The index of the first block, the total number of blocks, other useful metadata
- The OS then creates an entry in the open file table
- The OS returns a file descriptor (an integer) to the process, which is an index in its list of opened files
- These stay around until the process closes the file

Open File Table



Open File Table



Kernel

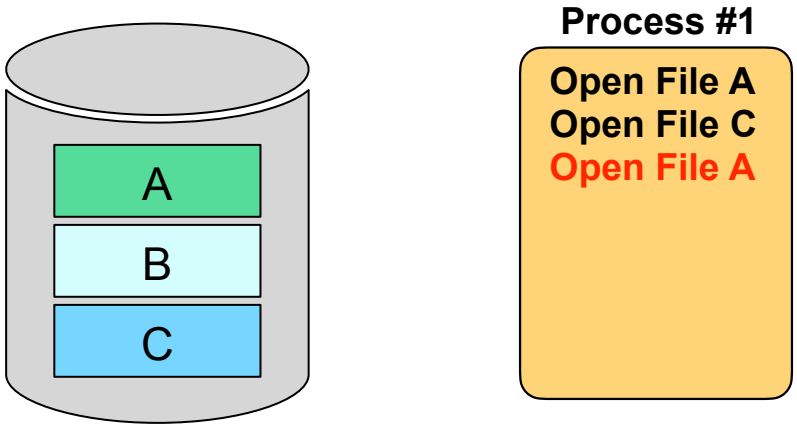
Open file table

File A	…	curr-file-pos
File C	…	curr-file-pos

Process #1

0	Stdin
1	Stdout
2	Stderr
3	File A
4	File C

Open File Table



Process #1

Open File A
Open File C
Open File A

Kernel

Open file table

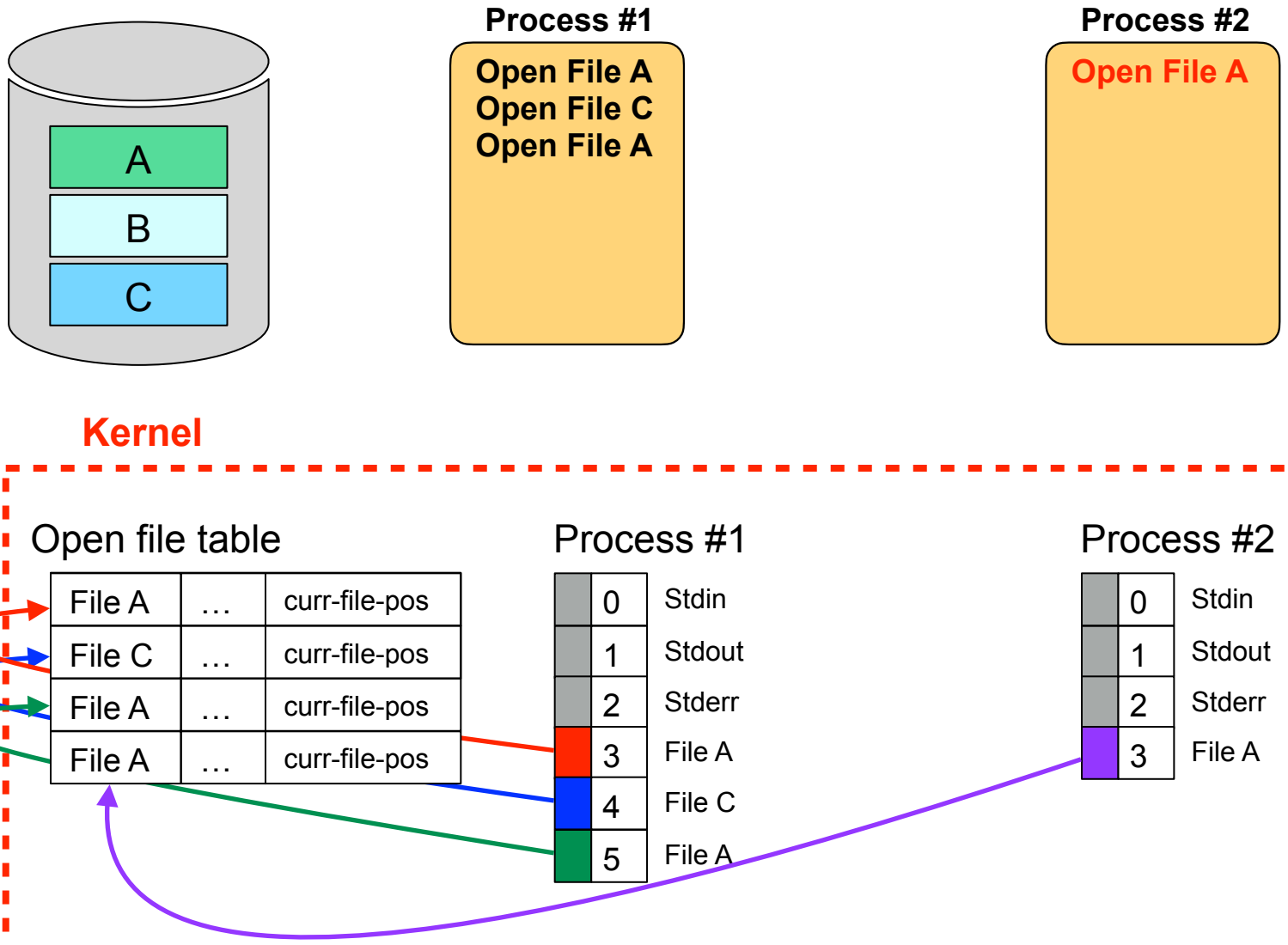
File A	…	curr-file-pos
File C	…	curr-file-pos
File A	…	curr-file-pos

Process #1

0	Stdin
1	Stdout
2	Stderr
3	File A
4	File C
5	File A

A single process can open a file multiple times. It now has more than one current-file-position offsets into the file.

Open File Table



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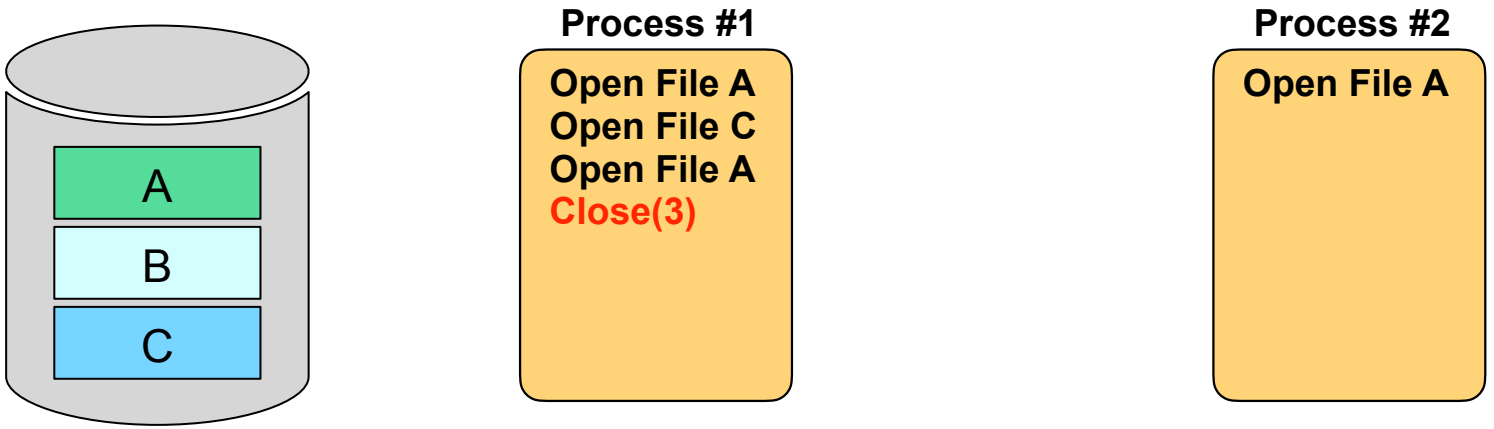

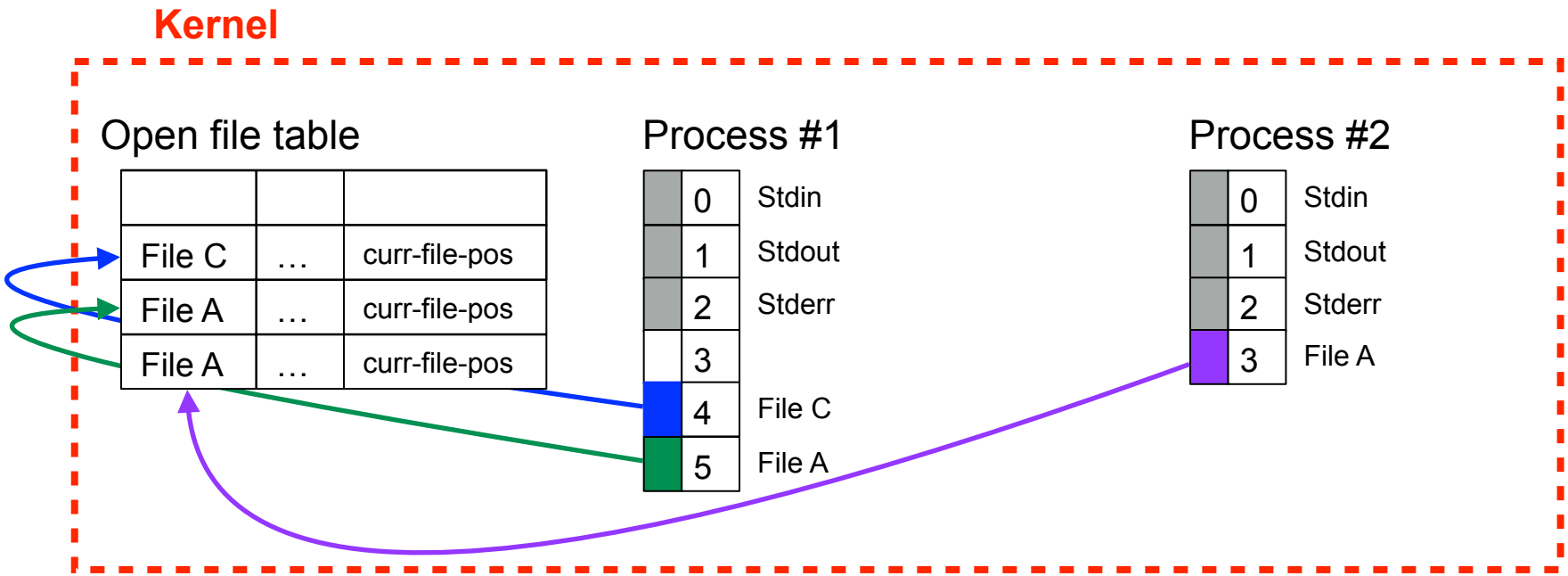

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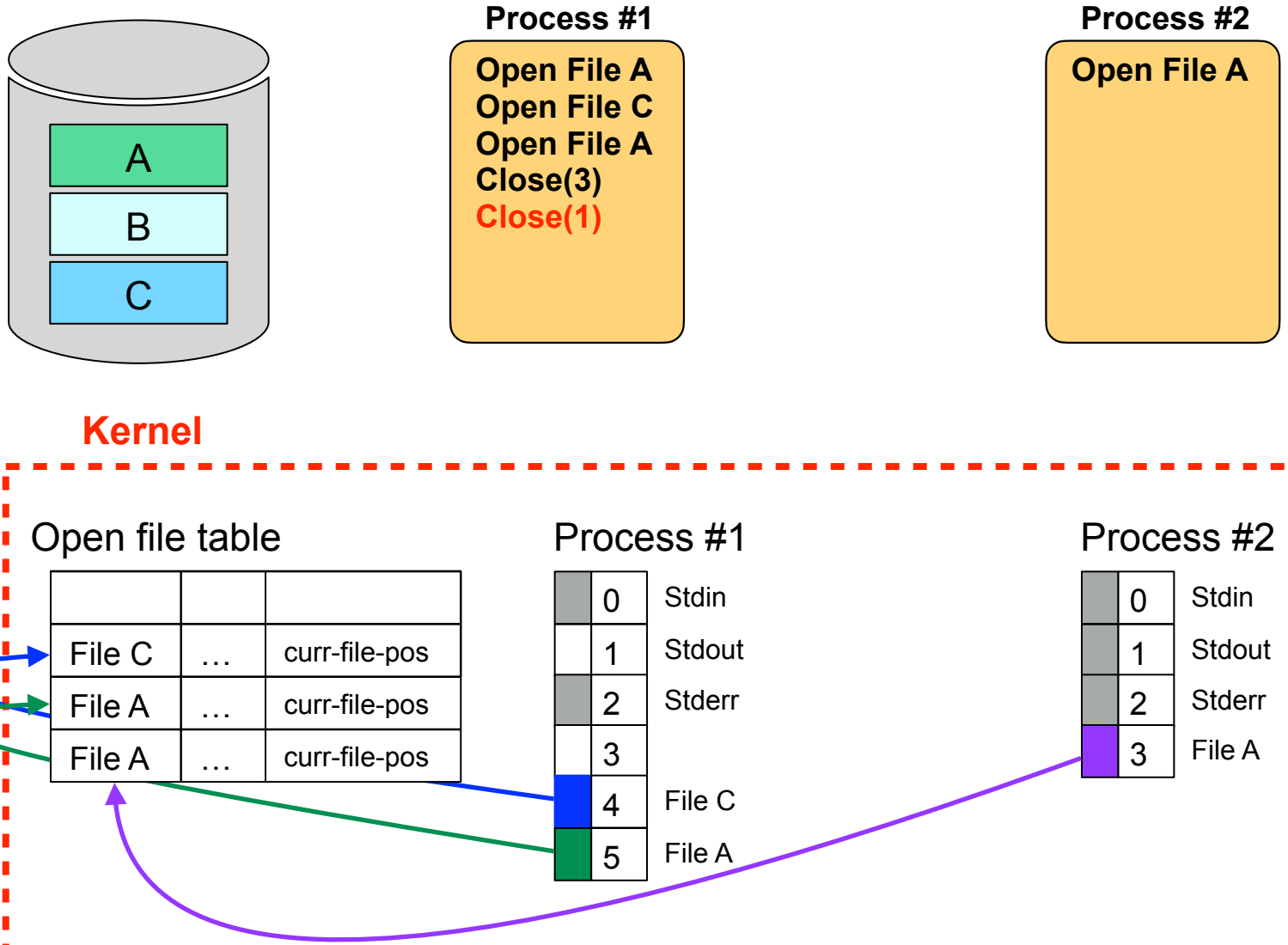

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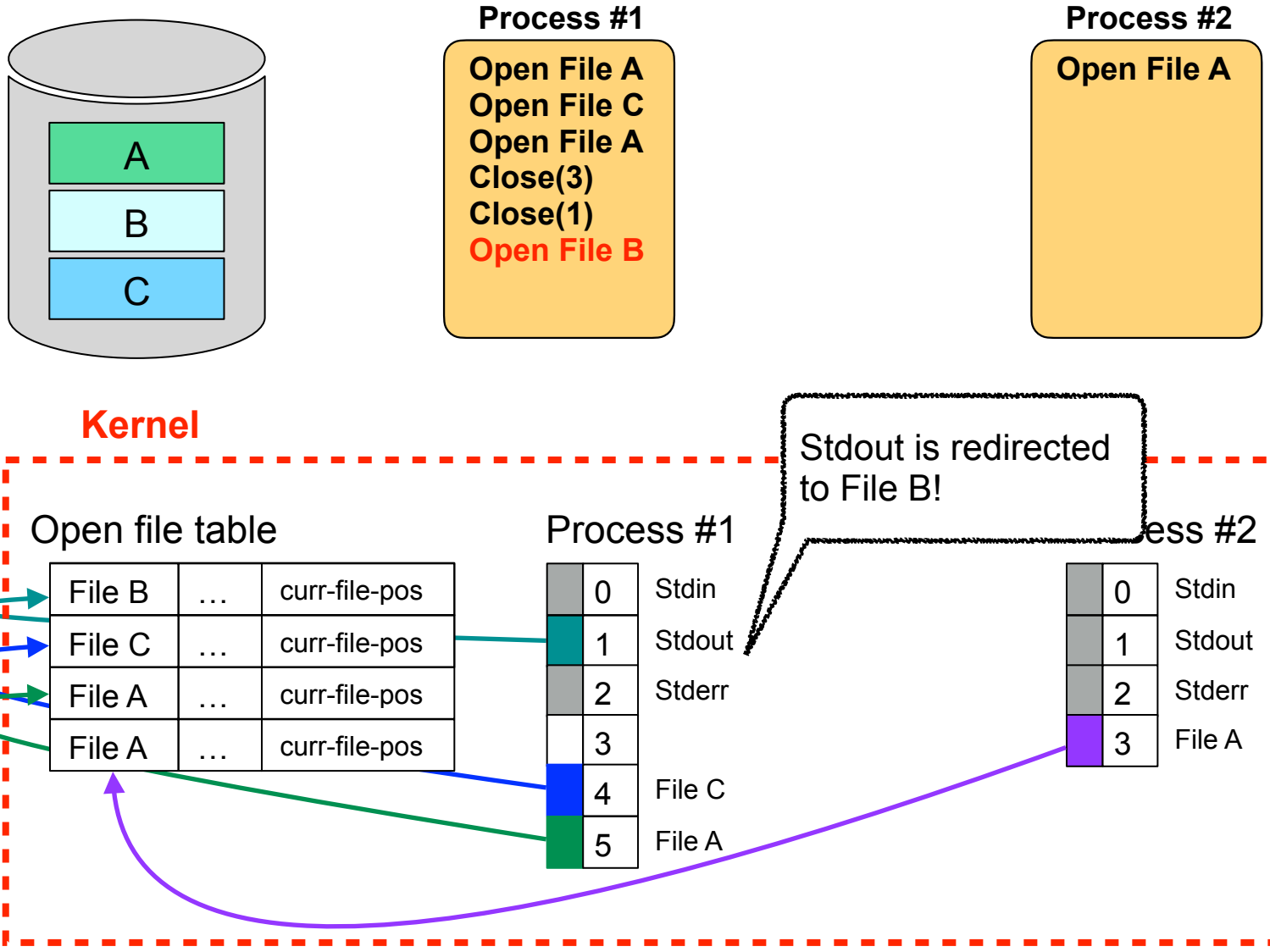


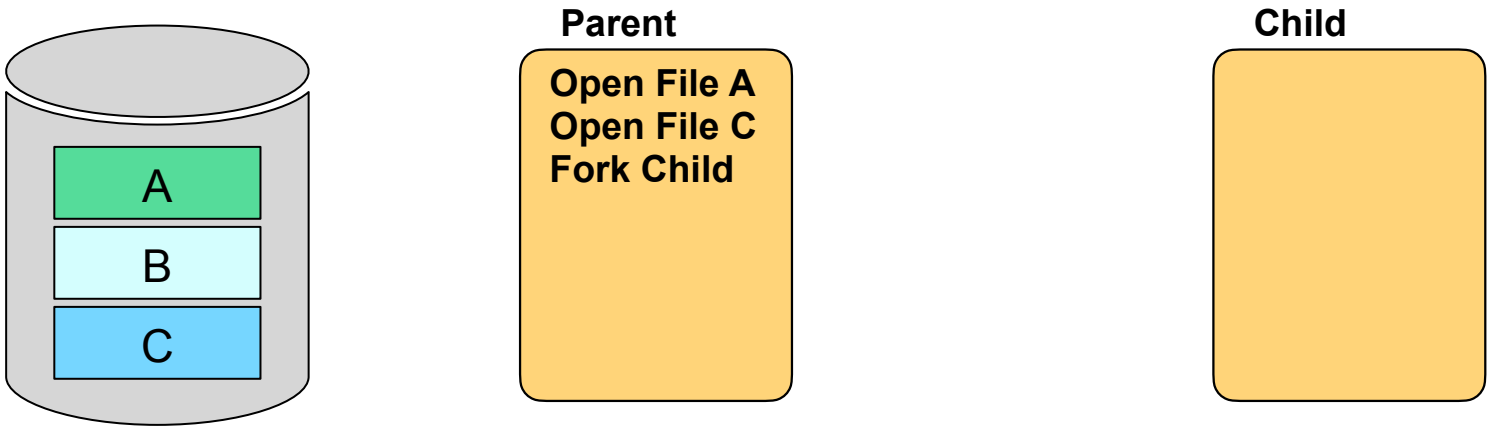
File Locking

- Bad things may happen when multiple processes reference the same file and update its content
  - Just like when threads update the same memory location
- All file systems provides “file locks”
  - 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
- You may have encountered that
  - Let’s try to **`sudo apt update`** in two terminals at the “same” time
- Applications have to implement their own locking
  - From a Shell script on Linux, one can use **`flock`**
  - Java implements **`lock()/release()`** methods as part of the **`java.nio.channels`** package

Shared Open File Table Entries

- Each time a process opens a file, an entry is created in the Kernel's open file table
- But there are ways in which a process can "duplicate" an existing file descriptor (see the Processes module)
  - By being a child of a process with that file descriptor
  - But using the **`dup()`** syscall
- In this case, multiple file descriptors can point to the same open file table entry
- OSTEP Figure 39.2 shows code in which a parent a child shared the same open file table entry
  - The child updates the current-file-position pointer, and the parent "sees" that update!
  - Let's look at that code and also see this on a picture (similar to Figure 39.3 in OSTEP)

Open File Table



Directories

- The other main abstraction provided by the file system is the directory (or folder):
  - A special kind of file: its data is not user data but just as list of files/directories it "contains"
- This makes it possible to create a hierarchy
- In Figure 39.1, the absolute path to the rightmost **`bar.txt`** file is **`/bar/foo/bar.txt`**
  - In UNIX the separator is '/' and the top-level directory is called '/'
  - Paths look different in Windows (**`C:\bar\foo\`**)
- "." and ".." are used to mean "this directory" or "the parent directory"
- Often one talks of the path relative to a working directory
  - In Figure 31.9 **`../bar/foo/bar.txt`** is a relative path to the working directory **`/foo`**

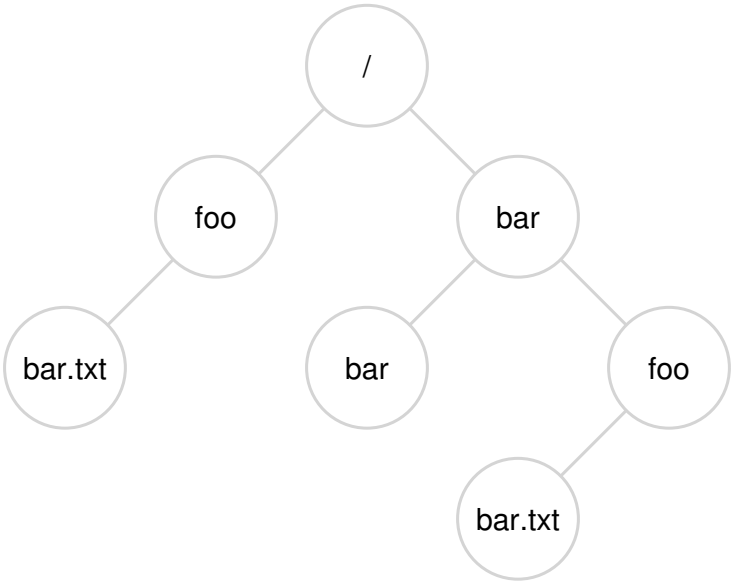


Figure 39.1: **An Example Directory Tree**

Hard Links

- Remember that we said that a file has an internal name and a user-level name
- The internal "name" is really a pointer to some data structure that describes everything about the file
  - That data structure is stored on disk as part of the file system (the famous inode in UNIX systems, see next set of lecture notes)
- But there can be multiple user-level names for the same file!
- A user-level name for a file is called a "link"
- There is a **`link()`** syscall to associate a new name to a file
  - It takes as input an already existing name and the new name
- The UNIX **`ln`** command uses this system call to create new links
  - **`ln <existing name> <new name>`**
- Let's try it, and look the internal file name using **`ls -i`**…

Link Count

- The links we created in the previous slides are called hard links
  - There was no difference between the two files
  - You can remove one without any problem
  - If you remove both, the file disappears
- There is a reference count in the internal file data structure (called the link count), and when it reaches zero the file and its content are deleted
  - We can see the link count using the **`stat`** command
  - Let's try that… (it's very clear on Linux, not as clear on MacOS)

Hard Link

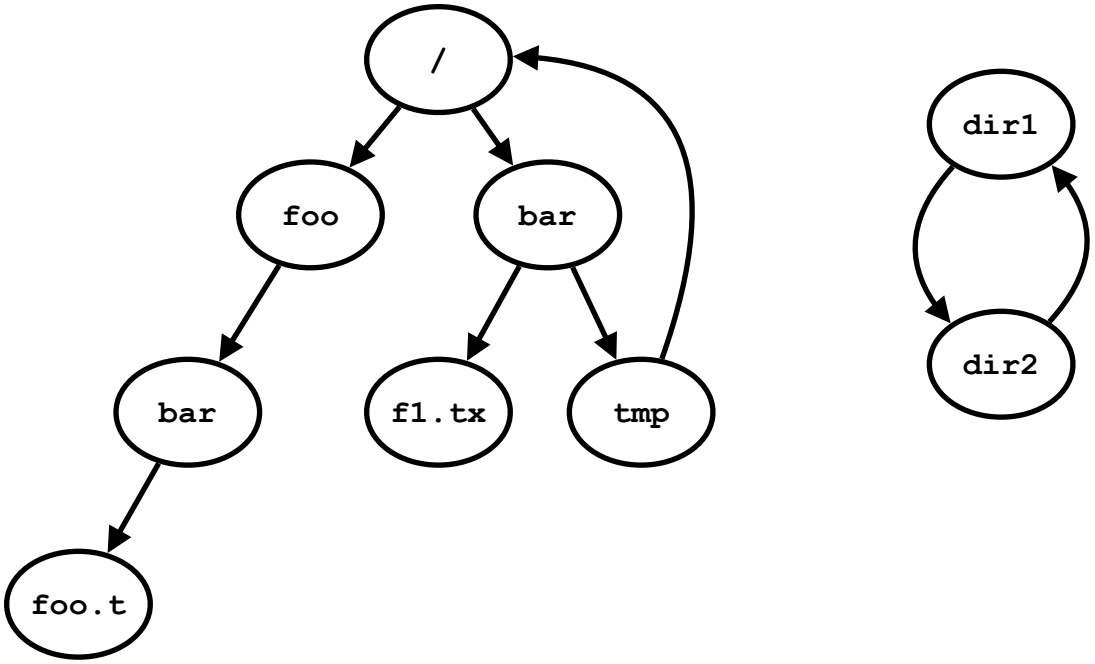
- Hard links can be used for all kinds of purposes, for instance:
- On Linux, whenever a process opens a file, a hard link to is is created
- Say that process with PID 2233 uses calls **`open()`** on **`/home/henric/somefile`**
- **`open()`** returns a file descriptor, i.e., an integer, say 55
- At that point, a hard link to **`/home/henric/somefile`** is created in **`/proc/2233/fd/55`**
- If, while the process is running, **`/bin/rm /home/henric/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...

Soft (or Symbolic) Links

- Soft/Symbolic links are just “shortcuts” that points to a path
- If you remove a soft link, nothing happens to the file
  - i.e., soft links don’t contribute to the link count
- Hard links have limitations, as they only make sense within the same file system, but soft links can point anywhere, to any partition, because they’re just paths
- A soft links is really a special kind of file
  - Just like Desktop shortcuts in Windows for instance
  - If the file pointed to has a longer name, the soft link size will be bigger!
- Soft links are created using **`ln -s`**
  - Let’s try it (and use **`ls -l`**) …
- A soft link can be dangling if its target is removed!
  - That cannot happen with hard link
  - Let’s test that…

Hard-linking Directories?

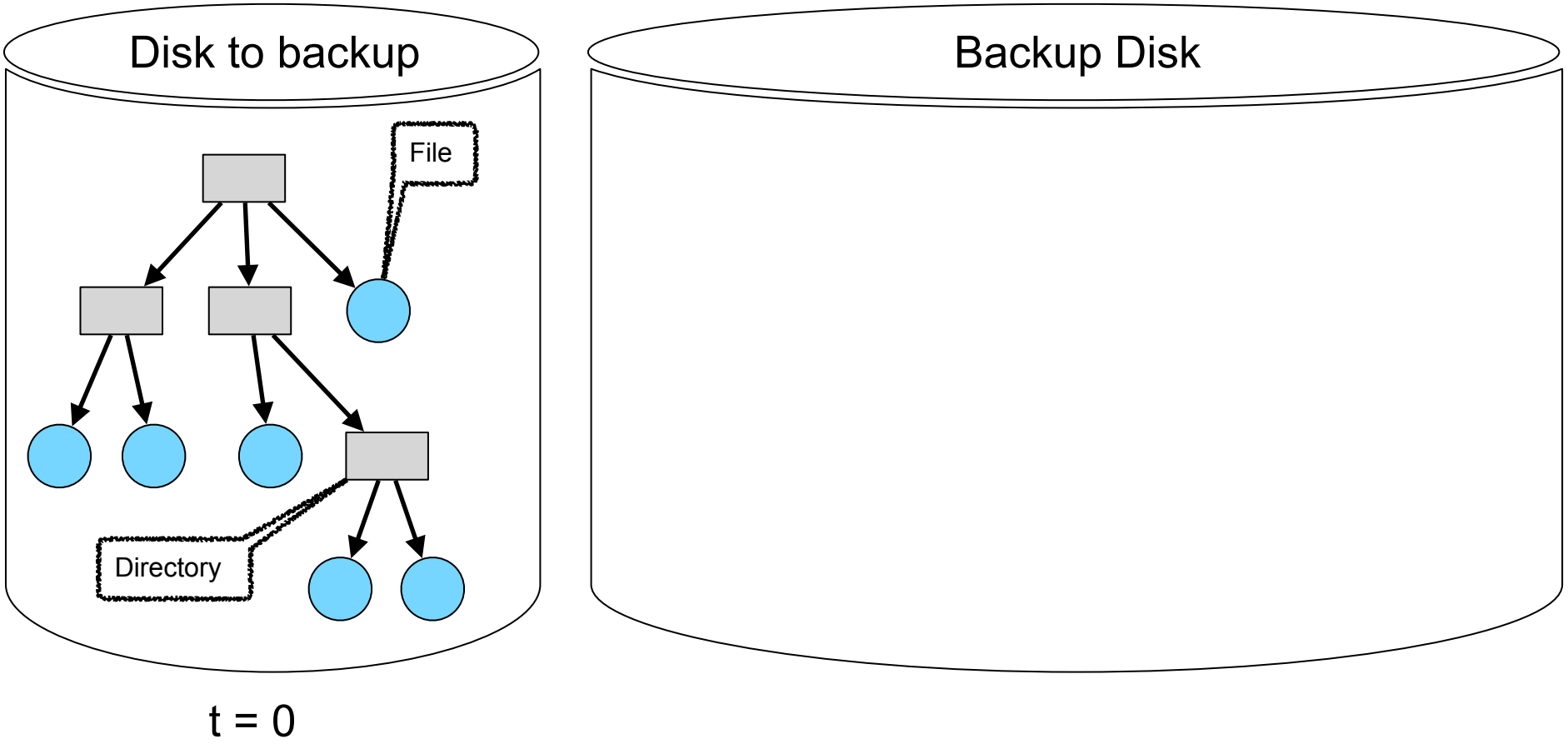
- In Linux, it is not possible to create a hard link to a directory
- This is to avoid cycles in the directory hierarchy!
  - Makes algorithms for traversing the hierarchy more complicated
  - Requires garbage collection of disconnected subgraphs



MacOS Time Machine

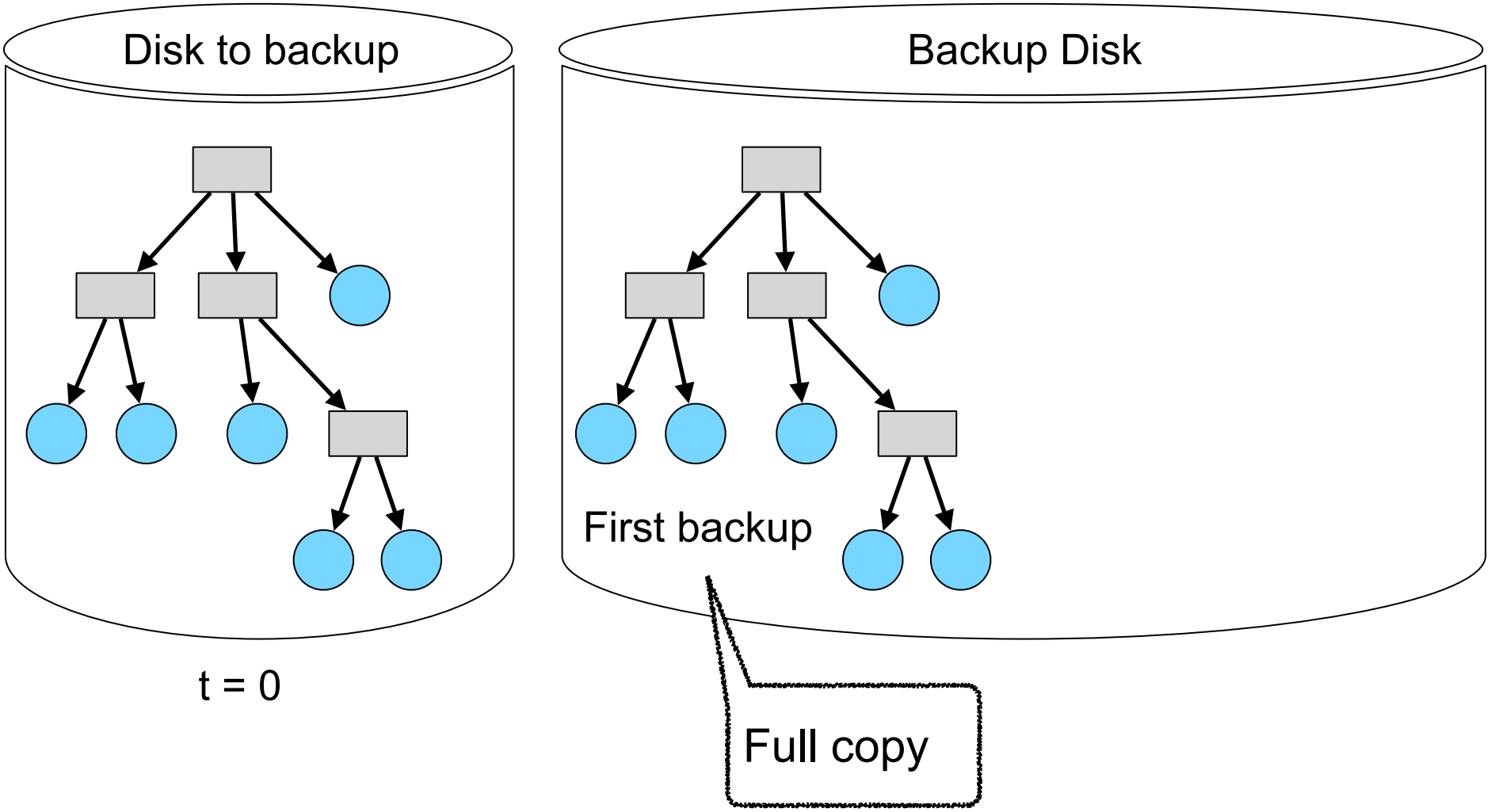
- MacOS allows hard-linking of directories
  - Which makes implementing the file system more complicated
- Time Machine is the backup mechanism for MacOS
- It uses hard links
  - Every time a backup is made, a new backup directory is created that contains a snapshot of the current state of the file system
  - Files that have not been modified are hard links to previously backed up version
    - A new backup should be mostly hard links instead of file copies (major 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)
- Let's see an example….

MacOS Time Machine



t = 0

MacOS Time Machine



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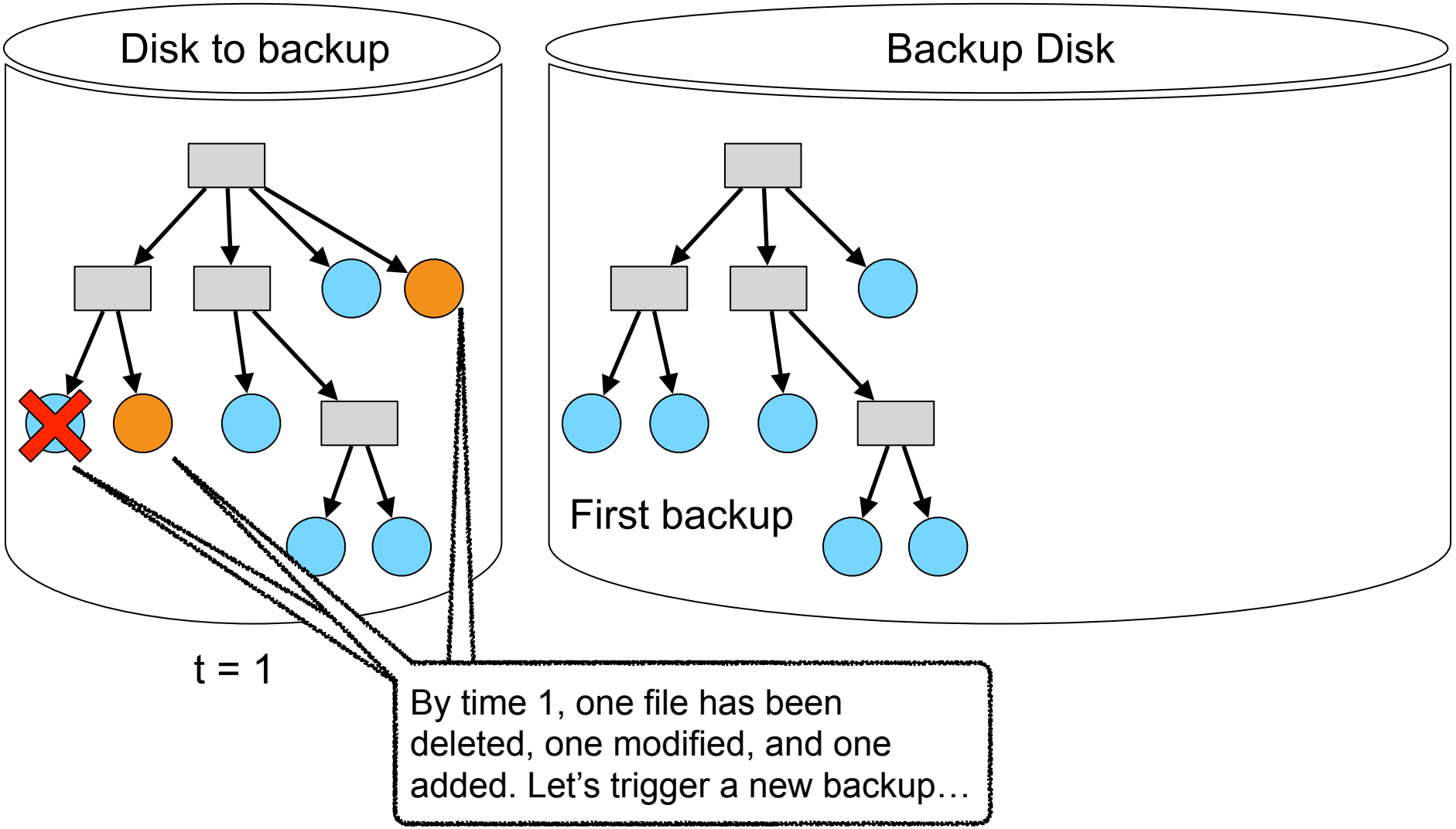

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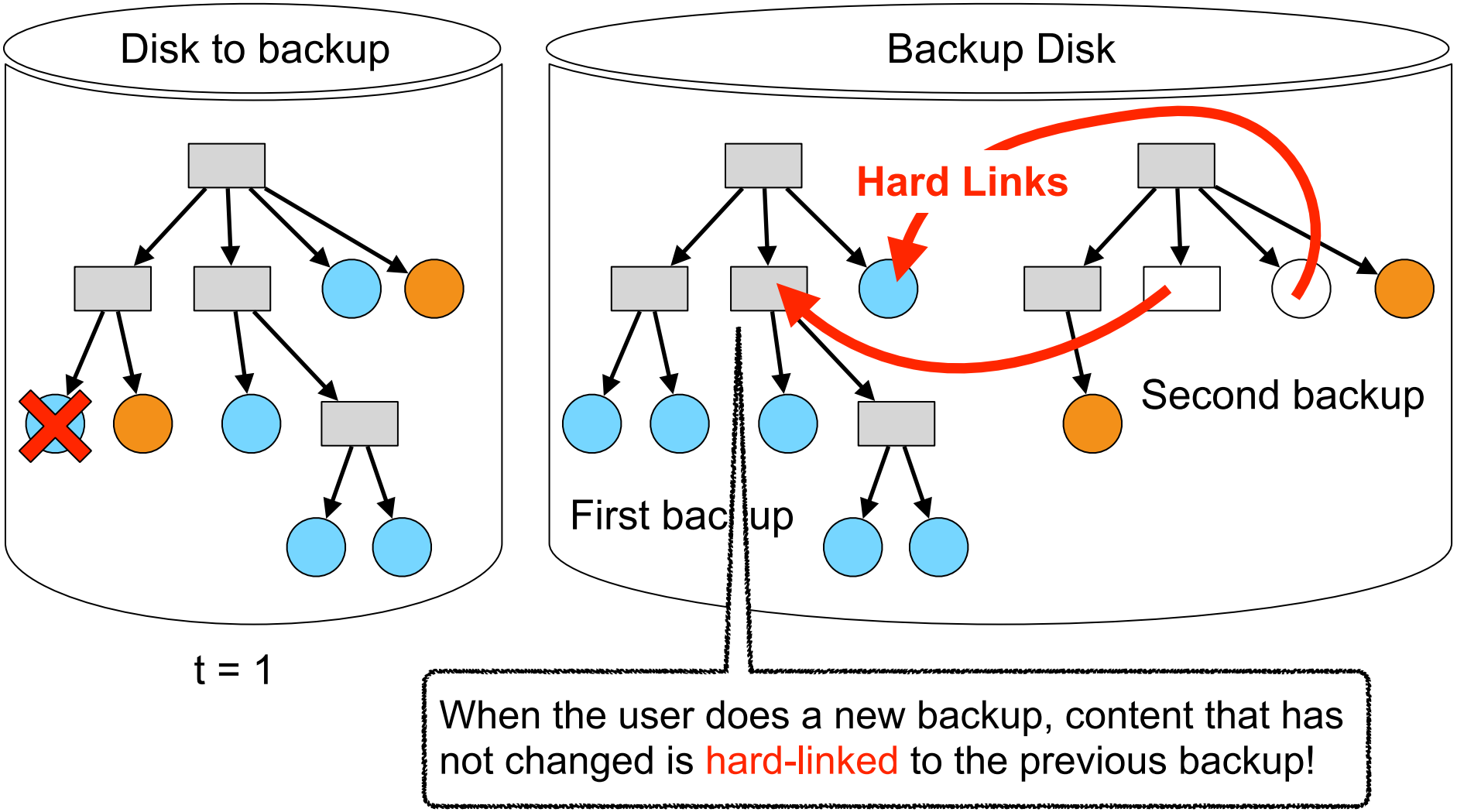
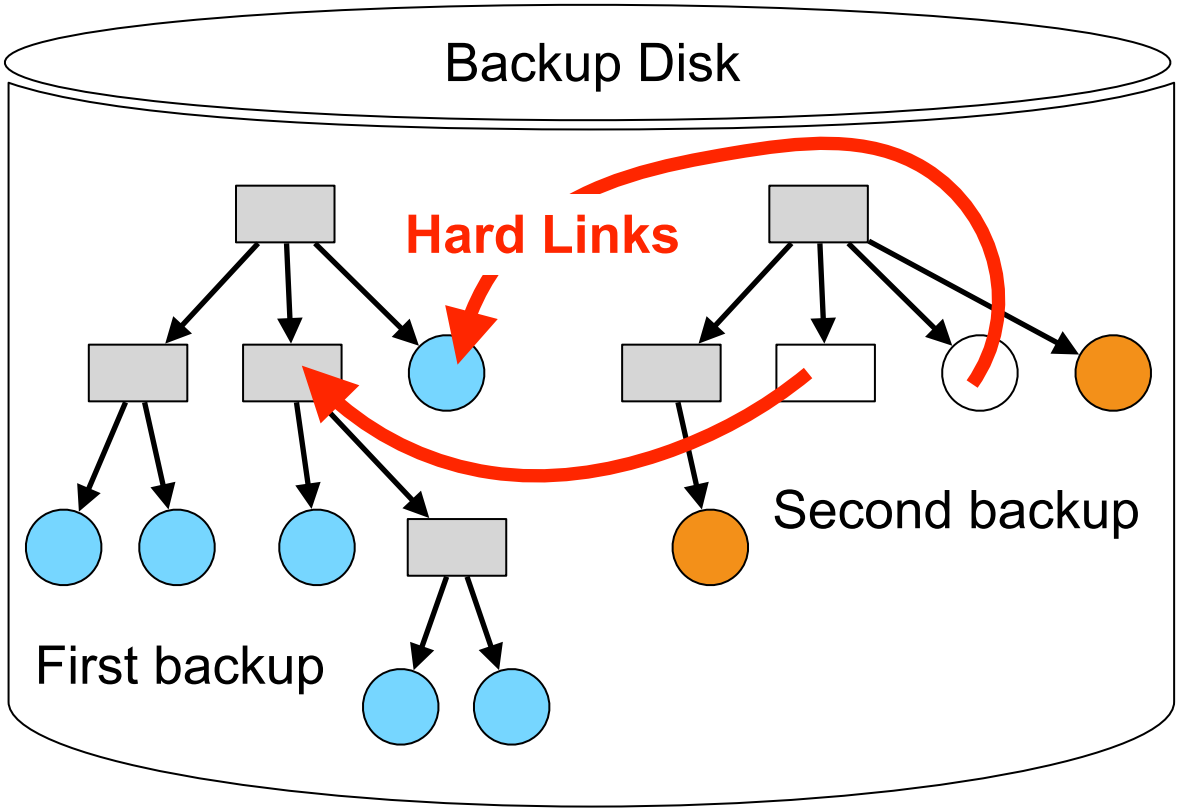
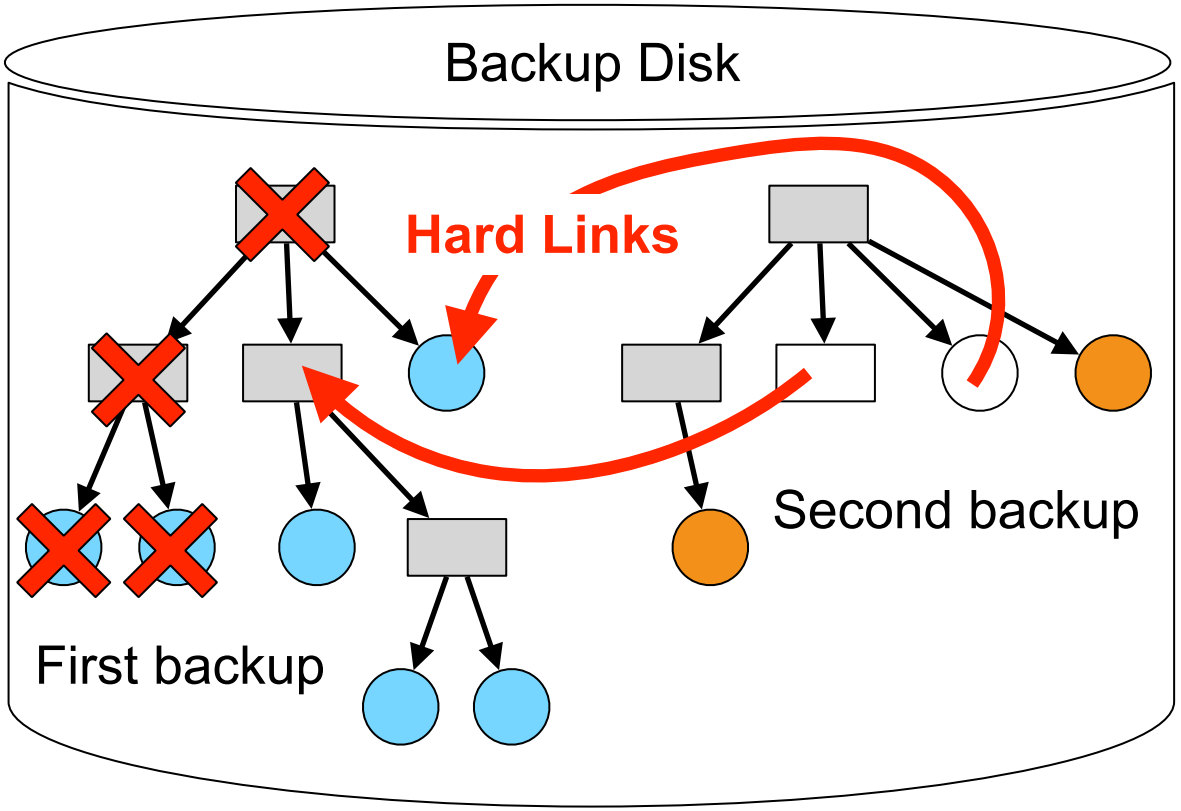


MacOS Time Machine



- The user can now safely delete the first backup by deleting the top-level directory…

MacOS Time Machine



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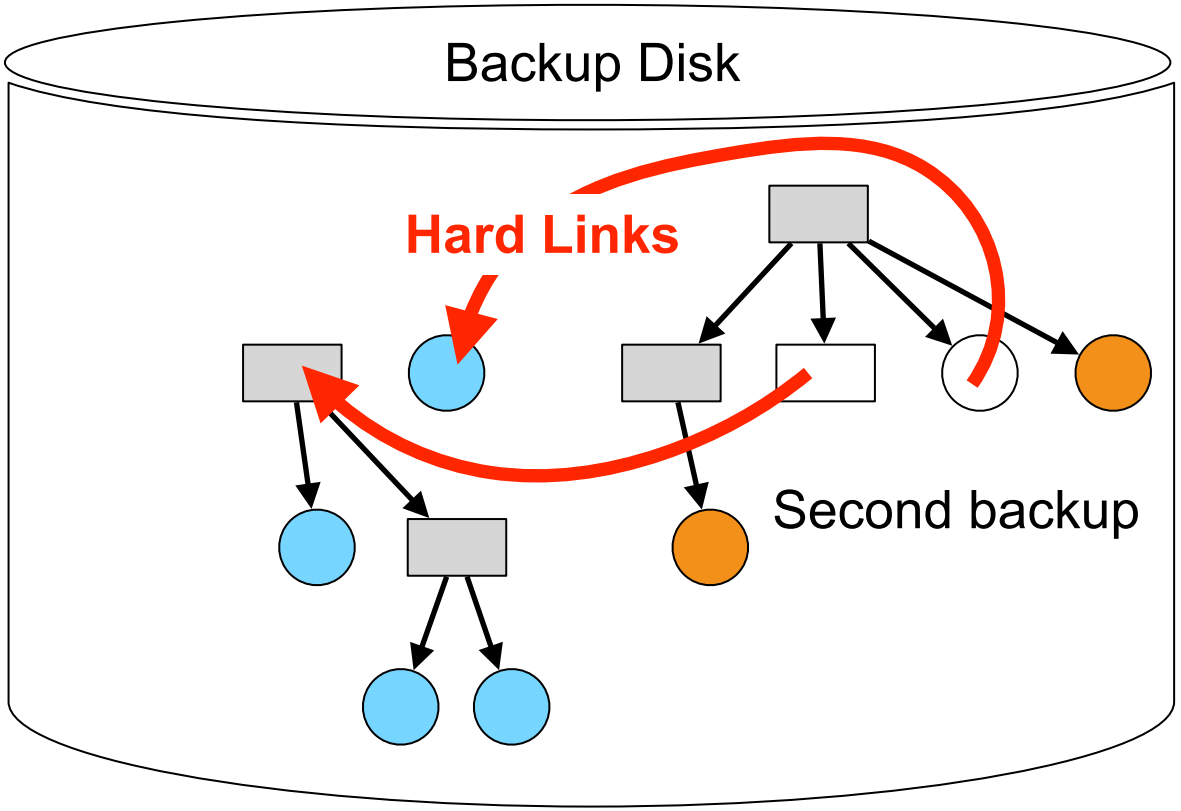

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MacOS Time Machine

- Advantages:
  - Extremely simple to implement
  - The backup can be navigated in all the normal ways, without any specific software!
  - 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 file again
- We can implement this on Linux, but we don’t have hard-linking of directories!
  - So for each backup we have to re-create the whole directory structure and create hard links to all individual files!
  - Such implementations do exist, but they have much higher overhead than Time Machine
    - Unless you install a file system that allows hard-linking of directories

File System Mounting

- There are typically multiple file systems on the same machine
- Each file system is mounted at a special location, the mount point
  - Typically seen as an initially empty directory
- When given a mount point, a volume, a file system type, the OS
  - Asks the device driver to read the volume on the device
  - Checks that the volume does contain a valid file system
  - Makes note of the new file system at the specified mount point, where the content will be seen as if it was just the content of a directory
- 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
  - The **`mount`** command lists all mounted volumes
- Windows: volumes were identified with a letter (e.g., A:, C:), but current versions, like UNIX, allow mounting anywhere

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)

Main Takeaways

- A file system is
  - The implementation of the concept of a file system
  - On-disk content that includes “table of content” + “file data”
- There is an opened file table
- Hardlinks vs. Symbolic (soft) links
- Mac OS Time machine explained
- The term “mounting”

Conclusion

- You have all used file systems before, so these lecture notes attempts to focus on things that some of you may not have been completely familiar with
- See OSTEP 39 for full details

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