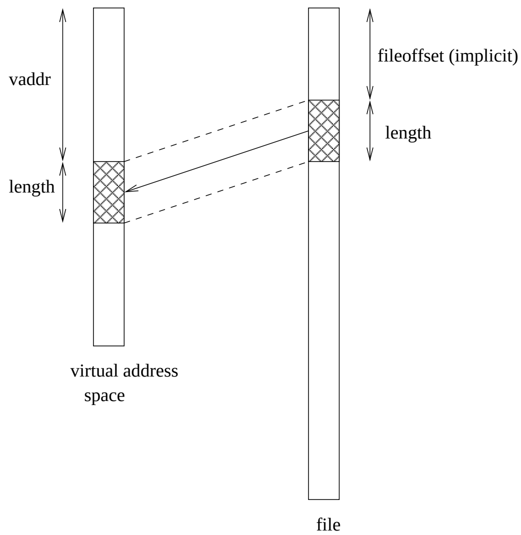
Files and File Systems

- files: persistent, named data objects
  - data consists of a sequence of numbered bytes
  - file may change size over time
  - file has associated meta-data
    - examples: owner, access controls, file type, creation and access timestamps
- file system: a collection of files which share a common name space
  - allows files to be created, destroyed, renamed, . . .

File Interface

- open, close
  - open returns a file identifier (or handle or descriptor), which is used in subsequent operations to identify the file. (Why is this done?)
- read, write, seek
  - read copies data from a file into a virtual address space
  - write copies data from a virtual address space into a file
  - seek enables non-sequential reading/writing
- get/set file meta-data, e.g., Unix `fstat, chmod`

File Read



`read(fileID, vaddr, length)`

File Position

- each file descriptor (open file) has an associated file position
- read and write operations
  - start from the current file position
  - update the current file position
- this makes sequential file I/O easy for an application to request
- for non-sequential (random) file I/O, use:
  - a seek operation (`lseek`) to adjust file position before reading or writing
  - a positioned read or write operation, e.g., Unix `pread, pwrite`:
    `pread(fileId,vaddr,length,filePosition)`

Sequential File Reading Example (Unix)

```
char buf[512];
int i;
int f = open("myfile",O_RDONLY);
for(i=0; i<100; i++) {
  read(f,(void *)buf,512);
}
close(f);
```

Read the first $100 * 512$ bytes of a file, 512 bytes at a time.

File Reading Example Using Seek (Unix)

```
char buf[512];
int i;
int f = open("myfile",O_RDONLY);
for(i=1; i<=100; i++) {
  lseek(f,(100-i)*512,SEEK_SET);
  read(f,(void *)buf,512);
}
close(f);
```

Read the first $100 * 512$ bytes of a file, 512 bytes at a time, in reverse order.

File Reading Example Using Positioned Read

```
char buf[512];
int i;
int f = open("myfile",O_RDONLY);
for(i=0; i<100; i+=2) {
  pread(f,(void *)buf,512,i*512);
}
close(f);
```

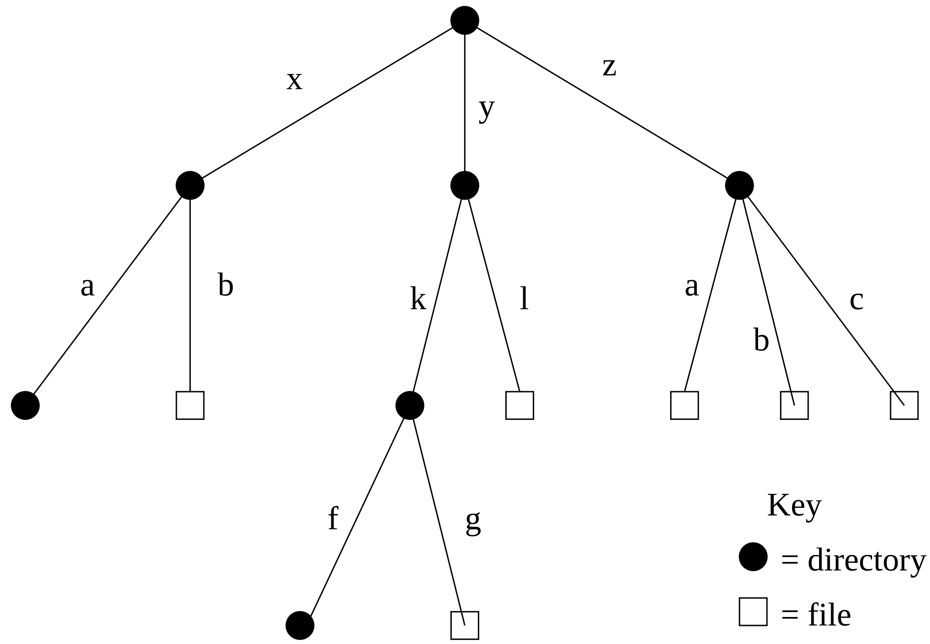
Read every second 512 byte chunk of a file, until 50 have been read.

Directories and File Names

- A directory maps *file names* (strings) to *i-numbers*
  - an i-number is a unique (within a file system) identifier for a file or directory
  - given an i-number, the file system can find the data and meta-data for the file
- Directories provide a way for applications to group related files
- Since directories can be nested, a filesystem's directories can be viewed as a tree, with a single *root* directory.
- In a directory tree, files are leaves
- Files may be identified by *pathnames*, which describe a path through the directory tree from the root directory to the file, e.g.:

  `/home/user/courses/cs350/notes/filesys.pdf`
- Directories also have pathnames
- Applications refer to files using pathnames, not i-numbers

Hierarchical Namespace Example



Hard Links

- a *hard link* is an association between a name (string) and an i-number
  - each entry in a directory is a hard link
- when a file is created, so is a hard link to that file
  - `open(/a/b/c,O_CREAT|O_TRUNC)`
  - this creates a new file if a file called `/a/b/c` does not already exist
  - it also creates a hard link to the file in the directory `/a/b`
- Once a file is created, *additional* hard links can be made to it.
  - example: `link(/x/b,/y/k/h)` creates a new hard link `h` in directory `/y/k`. The link refers to the i-number of file `/x/b`, which must exist.
- linking to an existing file creates a new pathname for that file
  - each file has a unique i-number, but may have multiple pathnames
- Not possible to `link` to a directory (to avoid cycles)

Unlinking and Referential Integrity

- hard links can be removed:
  - `unlink(/x/b)`
- the file system ensures that hard links have *referential integrity*, which means that if the link exists, the file that it refers to also exists.
  - When a hard link is created, it refers to an existing file.
  - There is no system call to delete a file. Instead, a file is deleted when its last hard link is removed.

Symbolic Links

- a *symbolic link*, or *soft link*, is an association between a name (string) and a pathname.
  - `symlink(/z/a,/y/k/m)` creates a symbolic link `m` in directory `/y/k`. The symbolic link refers to the pathname `/z/a`.
- If an application attempts to open `/y/k/m`, the file system will
  1. recognize `/y/k/m` as a symbolic link, and
  2. attempt to open `/z/a` instead
- referential integrity is *not* preserved for symbolic links
  - in the example above, `/z/a` need not exist!

UNIX/Linux Link Example (1 of 3)

```
% cat > file1
This is file1.
<cntl-d>
% ls -li
685844 -rw------- 1 user group 15 2008-08-20 file1
% ln file1 link1
% ln -s file1 sym1
% ln not-here link2
ln: not-here: No such file or directory
% ln -s not-here sym2
```

Files, hard links, and soft/symbolic links.

UNIX/Linux Link Example (2 of 3)

```
% ls -li
685844 -rw------- 2 user group 15 2008-08-20 file1
685844 -rw------- 2 user group 15 2008-08-20 link1
685845 lrwxrwxrwx 1 user group  5 2008-08-20 sym1 -> file1
685846 lrwxrwxrwx 1 user group  8 2008-08-20 sym2 -> not-here
% cat file1
This is file1.
% cat link1
This is file1.
% cat sym1
This is file1.
% cat sym2
cat: sym2: No such file or directory
% /bin/rm file1
```

Accessing and manipulating files, hard links, and soft/symbolic links.

UNIX/Linux Link Example (3 of 3)

```
% ls -li
685844 -rw------- 1 user group 15 2008-08-20 link1
685845 lrwxrwxrwx 1 user group  5 2008-08-20 sym1 -> file1
685846 lrwxrwxrwx 1 user group  8 2008-08-20 sym2 -> not-here
% cat link1
This is file1.
% cat sym1
cat: sym1: No such file or directory
% cat > file1
This is a brand new file1.
<cntl-d>
% ls -li
685847 -rw------- 1 user group 27 2008-08-20 file1
685844 -rw------- 1 user group 15 2008-08-20 link1
685845 lrwxrwxrwx 1 user group  5 2008-08-20 sym1 -> file1
685846 lrwxrwxrwx 1 user group  8 2008-08-20 sym2 -> not-here
% cat link1
This is file1.
% cat sym1
This is a brand new file1.
```

Different behaviour for hard links and soft/symbolic links.

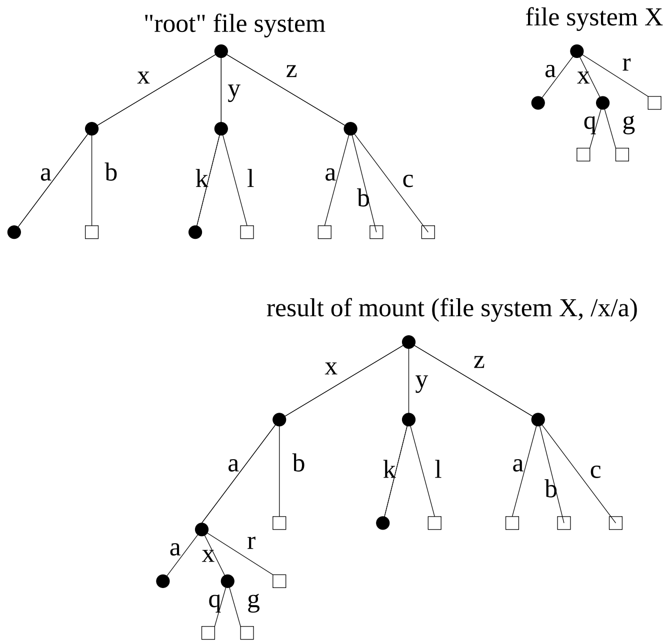
Multiple File Systems

- it is not uncommon for a system to have multiple file systems
- some kind of global file namespace is required
- two examples:

  DOS/Windows: use two-part file names: file system name, pathname within file system
  - example: `C:\user\cs350\schedule.txt`

  Unix: create single hierarchical namespace that combines the namespaces of two file systems
  - Unix `mount` system call does this
- mounting does *not* make two file systems into one file system
  - it merely creates a single, hierarchical namespace that combines the namespaces of two file systems
  - the new namespace is temporary - it exists only until the file system is unmounted

Unix `mount` Example



Links and Multiple File Systems

- hard links cannot cross file system boundaries
  - each hard link maps a name to an i-number, which is unique only *within* a file system
- for example, even after the mount operation illustrated on the previous slide, `link(/x/a/x/g,/z/d)` would result in an error, because the new link, which is in the root file system refers to an object in file system X
- soft links do not have this limitation
- for example, after the mount operation illustrated on the previous slide:
  - `symlink(/x/a/x/g,/z/d)` would succeed
  - `open(/z/d)` would succeed, with the effect of opening `/z/a/x/g`.
- even if the `symlink` operation were to occur *before* the `mount` command, it would succeed

File System Implementation

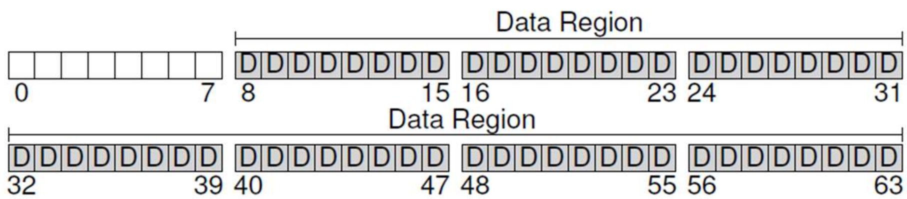
- what needs to be stored persistently?
  - file data
  - file meta-data
  - directories and links
  - file system meta-data
- non-persistent information
  - open files per process
  - file position for each open file
  - *cached* copies of persistent data

File System Example

- Use an extremely small disk as an example:
  - 256 KB disk!
  - Most disks have a sector size of 512 bytes
    - Memory is usually *byte addressable*
    - Disk is usually "sector addressable"
  - 512 total sectors on this disk
- Group every 8 consecutive sectors into a block
  - Better spatial locality (fewer seeks)
  - Reduces the number of block pointers (we'll see what this means soon)
  - 4 KB block is a convenient size for demand paging
  - 64 total blocks on this disk

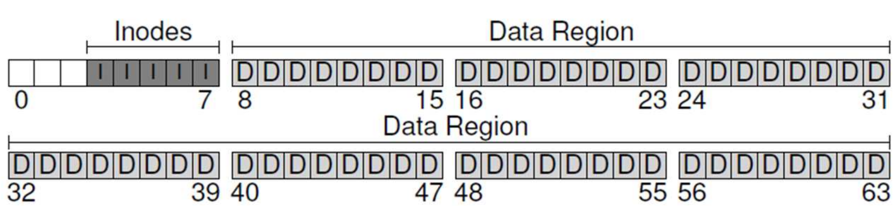
VSFS: Very Simple File System (1 of 5)

- Most of the blocks should be for storing user data (last 56 blocks)



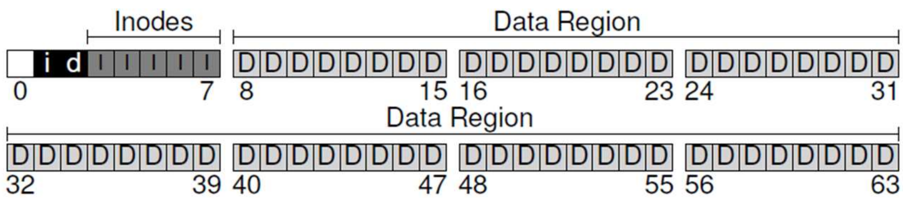
VSFS: Very Simple File System (2 of 5)

- Need some way to map files to data blocks
- Create an array of i-nodes, where each i-node contains the meta-data for a file
  - The index into the array is the file's index number (i-number)
- Assume each i-node is 256 bytes, and we dedicate 5 blocks for i-nodes
  - This allows for 80 total i-nodes/files



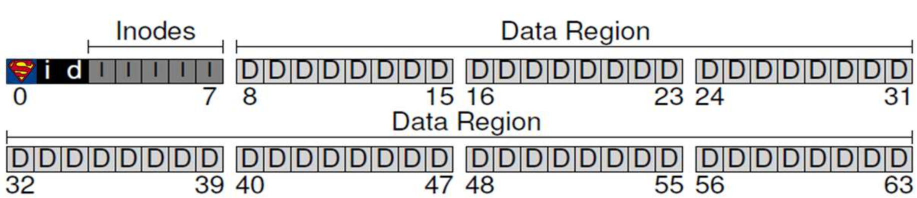
VSFS: Very Simple File System (3 of 5)

- We also need to know which i-nodes and blocks are unused
- Many ways of doing this:
  - In VSFS, we use a bitmap for each
  - Can also use a free list instead of a bitmap
- A block size of 4 KB means we can track 32K i-nodes and 32K blocks
  - This is far more than we actually need

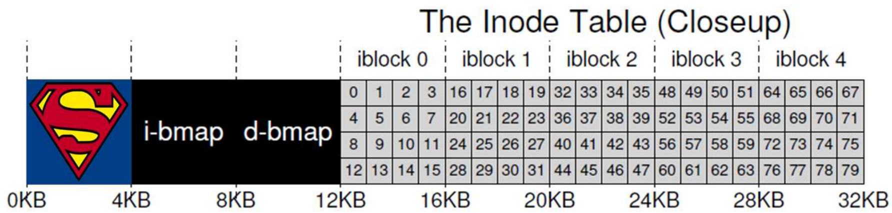


VSFS: Very Simple File System (4 of 5)

- Reserve the first block as the **superblock**
- A superblock contains meta-information about the entire file system
  - e.g., how many i-nodes and blocks are in the system, where the i-node table begins, etc.



VSFS: Very Simple File System (5 of 5)



i-nodes

- An i-node is a *fixed size* index structure that holds both file meta-data and a small number of pointers to data blocks
- i-node fields include:
  - file type
  - file permissions
  - file length
  - number of file blocks
  - time of last file access
  - time of last i-node update, last file update
  - number of hard links to this file
  - direct data block pointers
  - single, double, and triple indirect data block pointers

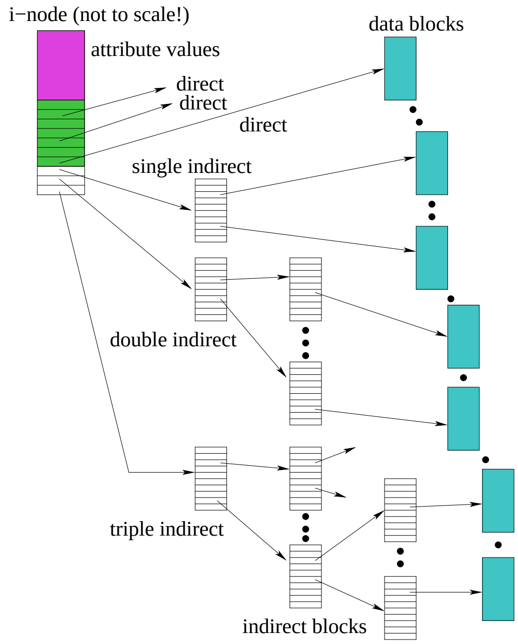
VSFS: i-node

- Assume disk blocks can be referenced based on a 4 byte address
  - 2^{32} blocks, 4 KB blocks
  - Maximum disk size is 16 TB
- In VSFS, an i-node is 256 bytes
  - Assume there is enough room for 12 direct pointers to blocks
  - Each pointer points to a different block for storing user data
  - Pointers are ordered: first pointer points to the first block in the file, etc.
- What is the maximum file size if we only have direct pointers?
  - 12 * 4 KB = 48 KB
- Great for small files (which are common)
- Not so great if you want to store big files

VSFS: Indirect Blocks

- In addition to 12 direct pointers, we can also introduce an **indirect pointer**
  - An indirect pointer points to a block full of direct pointers
- 4 KB block of direct pointers = 1024 pointers
  - Maximum file size is: (12 + 1024) * 4 KB = 4144 KB
- Better, but still not enough
- Add a **double indirect pointer**
  - Points to a 4 KB block of indirect pointers
  - (12 + 1024 + 1024 * 1024) * 4 KB
  - Just over 4 GB in size (is this enough?)

i-node Diagram



File System Design

- File system parameters:
  - *How many i-nodes should a file system have?*
  - *How many direct and indirect blocks should an i-node have?*
  - *What is the "right" block size?*

- For a general purpose file system, design it to be efficient for the common case

Most files are small	Roughly 2K is the most common size
Average file size is growing	Almost 200K is the average
Most bytes are stored in large files	A few big files use most of the space
File systems contains lots of files	Almost 100K on average
File systems are roughly half full	Even as disks grow, file systems remain ~50% full
Directories are typically small	Many have few entries; most have 20 or fewer

Directories

- Implemented as a special type of file.
- Directory file contains directory entries, each consisting of
  - a file name (component of a path name) and the corresponding i-number

name	i-number
.	5
..	2
foo	12
bar	13
foobar	24

- Directory files can be read by application programs (e.g., `ls`)
- Directory files are only updated by the kernel, in response to file system operations, e.g, create file, create link
- Application programs cannot write directly to directory files. (Why not?)

Implementing Hard Links

- hard links are simply directory entries
- for example, consider:

  `link(/y/k/g,/z/m)`
- to implement this:
  1. find out the internal file identifier for `/y/k/g`
  2. create a new entry in directory `/z`
     - file name in new entry is `m`
     - file identifier (i-number) in the new entry is the one discovered in step 1

Implementing Soft Links

- soft links can be implemented as a special type of file
- for example, consider:

  `symlink(/y/k/g,/z/m)`
- to implement this:
  - create a new *symlink* file
  - add a new entry in directory `/z`
    - file name in new entry is `m`
    - i-number in the new entry is the i-number of the new symlink file
  - store the pathname string "/y/k/g" as the contents of the new symlink file

Free Space Management

- Use the bitmaps to find a free i-node and free blocks
  - Each bit represents the availability of an i-node or block
- There are often many free blocks to choose from
  - To improve spatial locality and reduce fragementation, a file system may want to select a free block that is followed by a sequence of other free blocks

Reading From a File (/foo/bar)

- First read the root i-node
  - At "well known" position (i-node 2)
  - i-node 1 is usually for tracking bad blocks

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[1]
open(bar)			read							
						read				
				read						
							read			
					read					
read()					read					
								read		
					write					
read()					read					
									read	
					write					
read()					read					
										read
					write					

Reading From a File (/foo/bar)

- Read the directory information from root
  - Find the i-number for foo
  - Read the foo i-node

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[1]
open(bar)			read							
						read				
				read						
							read			
					read					
read()					read					
								read		
					write					
read()					read					
									read	
					write					
read()					read					
										read
					write					

Reading From a File (/foo/bar)

- Read the directory information from foo
  - Find the i-number for bar
  - Read the bar i-node

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[1]
open(bar)			**read**							
						read				
				read						
							read			
					read					
read()					**read**					
								read		
					write					
read()					**read**					
									read	
					write					
read()					**read**					
										read
					write					

Reading From a File (/foo/bar)

- Permission check (is the user allowed to read this file?)
- Allocate a file descriptor in the per-process descriptor table
- Increment the counter for this i-number in the global open file table

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[1]
open(bar)			**read**							
						read				
				read						
							read			
					read					
read()					**read**					
								read		
					write					
read()					**read**					
									read	
					write					
read()					**read**					
										read
					write					

Reading From a File (/foo/bar)

- Find the block using a direct/indirect pointer and read the data
- Update the i-node with a new access time
- Update the file position in the per-process descriptor table
- Closing a file deallocates the file descriptor and decrements the counter for this i-number in the global open file table

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[1]
open(bar)			read							
						read				
				read						
							read			
					read					
read()					read					
								read		
					write					
read()					read					
									read	
					write					
read()					read					
										read
					write					

Creating a File (/foo/bar)

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[1]
create (/foo/bar)			read							
						read				
				read						
							read			
		read								
		write								
							write			
					read					
					write					
				write						
write()					read					
	read									
	write									
								write		
					write					
write()					read					
	read									
	write									
									write	
					write					
write()					read					
	read									
	write									
										write
					write					

In-Memory (Non-Persistent) Structures

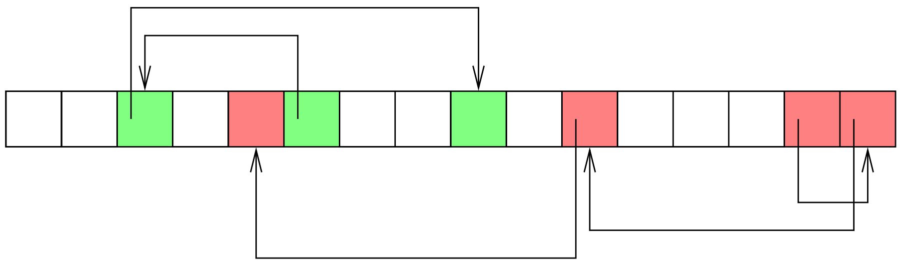
- per process
  - descriptor table
    * which file descriptors does this process have open?
    * to which file does each open descriptor refer?
    * what is the current file position for each descriptor?
- system wide
  - open file table
    * which files are currently open (by any process)?
  - i-node cache
    * in-memory copies of recently-used i-nodes
  - block cache
    * in-memory copies of data blocks and indirect blocks

Chaining

- VSFS uses a per-file index (direct and indirect pointers) to access blocks
- Two alternative approaches:
  - Chaining:
    * Each block includes a pointer to the next block
  - External chaining:
    * The chain is kept as an external structure
    * Microsoft's File Allocation Table (FAT) uses external chaining

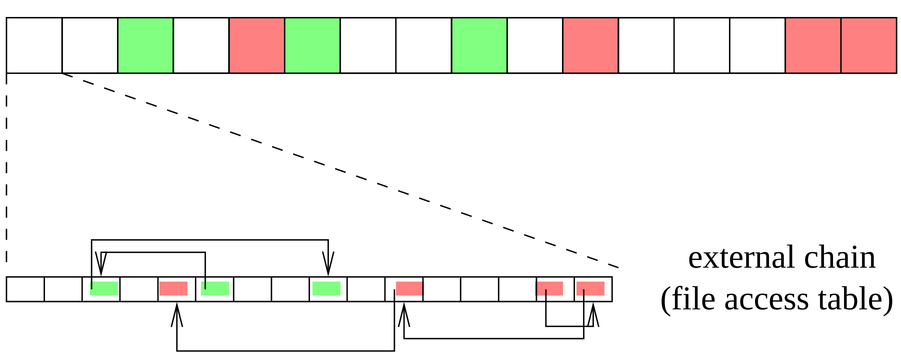
Chaining

- Directory table contains the name of the file, and each file's starting block
- Acceptable for sequential access, very slow for random access (why?)



External Chaining

- Introduces a special file access table that specifies all of the file chains

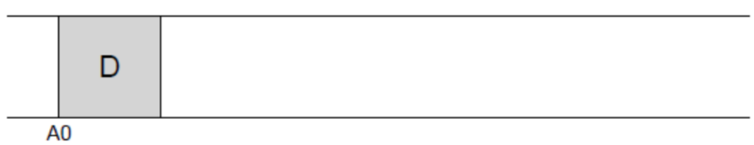


Log-Structured File System (LFS)

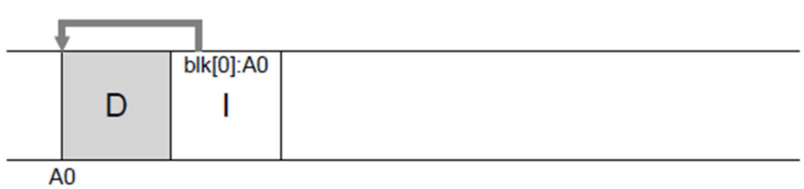
- LFS is built on a very different set of assumptions:
  - Memory sizes are growing
    - Most reads will be served from cache
    - Reads therefore are fast and do not require any seeks
  - Large gap between random I/O and sequential I/O performance
- Main idea: Make all writes sequential writes

Log-Structured File System

- Write data block D at address A0



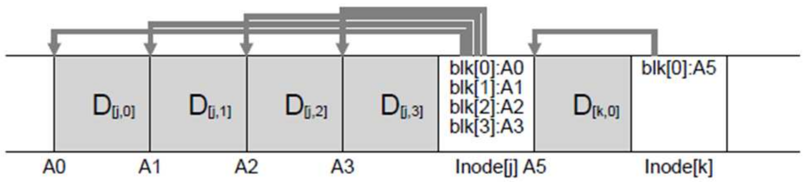
- Write i-node I for the file and point it to block D



- The next block write will be placed after i-node I
- To overwrite data, just write a **new** block and i-node at the next position

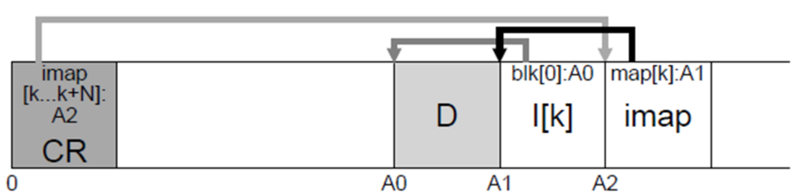
Log-Structured File System

- Write buffering is used to collect multiple writes to the same file together
  - Reduces the number of i-nodes that need to be written



Log-Structured File System

- Problem:
  - How do we find the i-node for a file on a cache miss?
- i-node map (imap) takes an i-node number as an input, and returns the disk address of the most recent version of the i-node
- Write a portion of the i-node map every time an i-node is updated



- How do we find the i-node maps?
  - Maintain a periodically updated checkpoint region with pointers to the latest imaps
  - Checkpoint region always updated during graceful shutdown

Problems Caused by Failures

- a single logical file system operation may require several disk I/O operations
- example: deleting a file
  - remove entry from directory
  - remove file index (i-node) from i-node table
  - mark file's data blocks free in free space index
- what if, because of a failure, some but not all of these changes are reflected on the disk?

- system failure will destroy in-memory file system structures
- persistent structures should be *crash consistent*, i.e., should be consistent when system restarts after a failure

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Fault Tolerance

- special-purpose consistency checkers (e.g., Unix `fsck` in Berkeley FFS, Linux ext2)
  - runs after a crash, before normal operations resume
  - find and attempt to repair inconsistent file system data structures, e.g.:
    - file with no directory entry
    - free space that is not marked as free
- journaling (e.g., Veritas, NTFS, Linux ext3)
  - record file system meta-data changes in a journal (log), so that sequences of changes can be written to disk in a single operation
  - *after* changes have been journaled, update the disk data structures (*write-ahead logging*)
  - after a failure, redo journaled updates in case they were not done before the failure