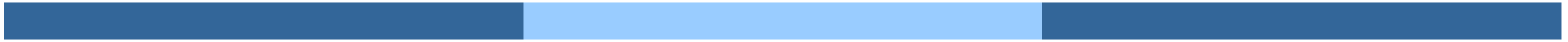
File and Directory in Practice



Operating Systems
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Two Key Abstractions

- File
  - A linear array of bytes, with each you can read/write
  - Has a low-level name (user does not know) - **inode number**
  - Usually OS does not know the exact type of the file
- Directory
  - Has a low-level name
  - Its content is quite specific: contains a list of user-readable name to low-level name. Like ("foo", inode number 10)
  - Each entry either points to file or other directory

Two Key Abstractions

- File
  - External name (visible to user) must be symbolic
    - In hierarchical file system, unique external names are given as pathnames (path from root to the file)
  - Internal names (low-level names): i-node in UNIX
    - Stores information about file system object: file, directory, socket, …
    - Index into array of file descriptors/headers for a volume
- Directory: translation from external to internal name

File System Interface

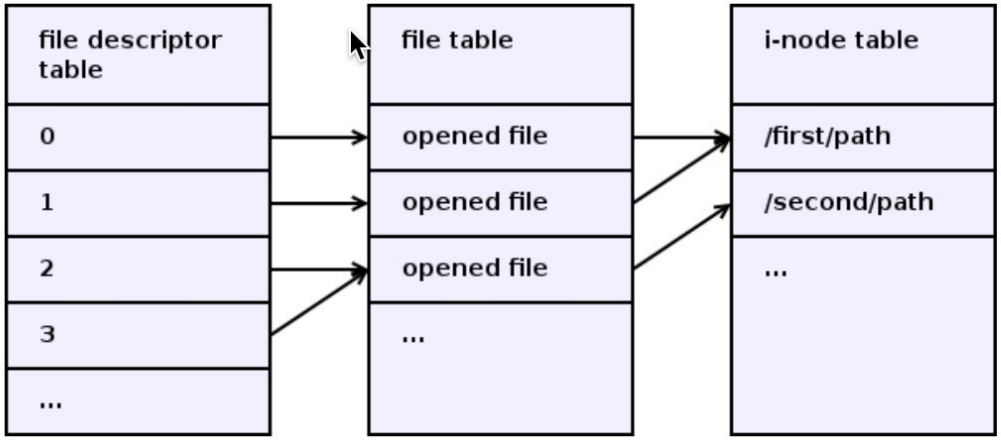
- Create file

```
int fd = open("foo", O_CREAT | O_WRONLY | O_TRUNC);
```

- O_CREAT: create the file if not exists (not ***O_CREATE***)
- O_WRONLY: can only write to the file
- O_TRUNC: if the file exists, truncate it to zero bytes

The return value of **open**() is a file descriptor, a small, nonnegative integer that is used in subsequent system calls (**read**(2), **write**(2), **lseek**(2), **fcntl**(2), etc.) to refer to the open file. The file descriptor returned by a successful call will be the lowest-numbered file descriptor not currently open for the process.

File Descriptor



A *file descriptor* is an index in the per-process file descriptor table (in the left of the picture). Each file descriptor table entry contains a reference to a *file object*, stored in the file table (in the middle of the picture). Each file object contains a reference to an i-node, stored in the i-node table (in the right of the picture).

A file descriptor is just a number that is used to refer a file object from the user space. A file object represents an opened file. It contains things likes current read/write offset, non-blocking flag and another non-persistent state. An i-node represents a filesystem object. It contains things like file meta-information (e.g. owner and permissions) and references to data blocks.

File descriptors created by several `open()` calls for the same file path point to different file objects, but these file objects point to the same i-node. Duplicated file descriptors created by `dup2()` or `fork()` point to the same file object.

A BSD lock and an Open file description lock is associated with a file object, while a POSIX record lock is associated with an `[i-node, pid]` pair. We'll discuss it below.

The cat example

```
os@os:~/temp$ echo hello > foo
os@os:~/temp$ cat foo
hello
os@os:~/temp$
```

```
os@os:~/temp$ strace cat foo
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...}) = 0
open("foo", O_RDONLY)                   = 3
fstat(3, {st_mode=S_IFREG|0664, st_size=6, ...}) = 0
fadvise64(3, 0, 0, POSIX_FADV_SEQUENTIAL) = 0
mmap(NULL, 139264, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f703ea95000
read(3, "hello\n", 131072)              = 6
write(1, "hello\n", 6hello
)                       = 6
read(3, "", 131072)                     = 0
munmap(0x7f703ea95000, 139264)          = 0
close(3)                                = 0
close(1)                                = 0
close(2)                                = 0
exit_group(0)                           = ?
+++ exited with 0 +++
```

write and fsync

- write():
  - please write this data to persistent storage, at some point in the future. The file system, for performance reasons, will buffer such writes in memory for some time (say 5 seconds, or 30); at that later point in time, the write(s) will actually be issued to the storage device
- fsync(): forces all dirty (not yet written) data to disk

```
int fd = open("foo", O_CREAT | O_WRONLY | O_TRUNC);
assert(fd > -1);
int rc = write(fd, buffer, size);
assert(rc == size);
rc = fsync(fd);
assert(rc == 0);
```

Getting Information About Files

- Information is kept in **inode**

```
struct stat {
    dev_t     st_dev;     /* ID of device containing file */
    ino_t     st_ino;     /* inode number */
    mode_t    st_mode;    /* protection */
    nlink_t   st_nlink;   /* number of hard links */
    uid_t     st_uid;     /* user ID of owner */
    gid_t     st_gid;     /* group ID of owner */
    dev_t     st_rdev;    /* device ID (if special file) */
    off_t     st_size;    /* total size, in bytes */
    blksize_t st_blksize; /* blocksize for filesystem I/O */
    blkcnt_t  st_blocks;  /* number of blocks allocated */
    time_t    st_atime;   /* time of last access */
    time_t    st_mtime;   /* time of last modification */
    time_t    st_ctime;   /* time of last status change */
};
```

```
os@os:~/temp$ stat foo
  File: 'foo'
  Size: 6               Blocks: 8          IO Block: 4096   regular file
Device: 801h/2049d      Inode: 1328649     Links: 1
Access: (0664/-rw-rw-r--)  Uid: ( 1000/      os)   Gid: ( 1000/      os)
Access: 2018-12-19 00:24:02.448286431 +0800
Modify: 2018-12-19 00:24:01.316296543 +0800
Change: 2018-12-19 00:24:01.316296543 +0800
 Birth: -
```

Removing Files

```
os@os:~/temp$ strace rm foo
```

- Why we just "remove" or "delete" the file, but using "unlinkat"?

```
newfstatat(AT_FDCWD, "foo", {st_mode=S_IFREG|0664, st_size=6, ...}, AT_SYMLINK_NOFOLLOW) = 0
faccessat(AT_FDCWD, "foo", W_OK)        = 0
unlinkat(AT_FDCWD, "foo", 0)            = 0
lseek(0, 0, SEEK_CUR)                   = -1 ESPIPE (Illegal seek)
close(0)                                = 0
```

Hard link vs soft link

- Link
  - A file may be known by more than one name in one or more directories. Such multiple names are known as links.
  - The two kinds of links are also known as hard links and soft links.
- Hard link
  - a hard link is a directory entry that associates with a file
  - The file name "." in a directory is a hard link to the directory itself
  - The file name ".." is a hard link to the parent directory
- Soft link (a.k.a., symbolic link or symlink)
  - A symbolic link is a file containing the path name of another file
  - Soft links, unlike hard links, may point to directories and may cross file-system boundaries

Hard Links

- link() system call: system call takes two arguments, an old pathname and a new one
  - another way to refer to the same file

```
os@os:~/temp/foo$ echo hello > file
os@os:~/temp/foo$ cat file
hello
os@os:~/temp/foo$ ln file file2
os@os:~/temp/foo$ cat file2
hello
os@os:~/temp/foo$ ls -i file file2
1328650 file  1328650 file2
os@os:~/temp/foo$
```

  - same inode number
  - Even an empty directory has two entries

```
os@os:~/temp/foo$ ls -al
total 8
drwxrwxr-x 2 os os 4096 Dec 20 23:56 .
drwxrwxr-x 3 os os 4096 Dec 20 23:56 ..
```

```
os@os:~/temp/foo$ ls -al
total 8
drwxrwxr-x 2 os os 4096 Dec 20 23:56 .
drwxrwxr-x 3 os os 4096 Dec 20 23:56 ..
```

Why removing a file calls unlink

- Create a file
  - making a structure (the inode) that will track virtually all relevant information about the file
  - **linking** a human-readable name to that file (or inode), and putting that link into a directory
- To remove a file, we **unlink** it

```
unlink() deletes a name from the filesystem.  If that name was the last
link to a file and no processes have the file open, the file is deleted
and the space it was using is made available for reuse.
```

Reference count

```
os@os:~/temp/foo$ rm file
os@os:~/temp/foo$ cat file2
hello
os@os:~/temp/foo$
```

- rm: unlink the file, and check the reference count of the **inode**

```
os@os:~/temp/foo$ echo hello >file
os@os:~/temp/foo$ stat file
  File: 'file'
  Size: 6               Blocks: 8          IO Block: 4096   regular file
Device: 801h/2049d      Inode: 1328650     Links: 1
Access: (0664/-rw-rw-r--)  Uid: ( 1000/      os)   Gid: ( 1000/      os)
Access: 2018-12-21 00:09:14.763058468 +0800
Modify: 2018-12-21 00:09:14.763058468 +0800
Change: 2018-12-21 00:09:14.763058468 +0800
 Birth: -
os@os:~/temp/foo$ ln file file2
os@os:~/temp/foo$ stat file2
  File: 'file2'
  Size: 6               Blocks: 8          IO Block: 4096   regular file
Device: 801h/2049d      Inode: 1328650     Links: 2
Access: (0664/-rw-rw-r--)  Uid: ( 1000/      os)   Gid: ( 1000/      os)
Access: 2018-12-21 00:09:14.763058468 +0800
Modify: 2018-12-21 00:09:14.763058468 +0800
Change: 2018-12-21 00:09:24.247463616 +0800
 Birth: -
os@os:~/temp/foo$ ln file2 file3
os@os:~/temp/foo$ stat file
  File: 'file'
  Size: 6               Blocks: 8          IO Block: 4096   regular file
Device: 801h/2049d      Inode: 1328650     Links: 3
Access: (0664/-rw-rw-r--)  Uid: ( 1000/      os)   Gid: ( 1000/      os)
Access: 2018-12-21 00:09:14.763058468 +0800
Modify: 2018-12-21 00:09:14.763058468 +0800
Change: 2018-12-21 00:09:33.975880487 +0800
 Birth: -
```

```
os@os:~/temp/foo$ rm file
os@os:~/temp/foo$ stat file2
  File: 'file2'
  Size: 6               Blocks: 8          IO Block: 4096   regular file
Device: 801h/2049d      Inode: 1328650     Links: 2
Access: (0664/-rw-rw-r--)  Uid: ( 1000/      os)   Gid: ( 1000/      os)
Access: 2018-12-21 00:09:14.763058468 +0800
Modify: 2018-12-21 00:09:14.763058468 +0800
Change: 2018-12-21 00:09:40.776172622 +0800
 Birth: -
os@os:~/temp/foo$ rm file2
os@os:~/temp/foo$ stat file3
  File: 'file3'
  Size: 6               Blocks: 8          IO Block: 4096   regular file
Device: 801h/2049d      Inode: 1328650     Links: 1
Access: (0664/-rw-rw-r--)  Uid: ( 1000/      os)   Gid: ( 1000/      os)
Access: 2018-12-21 00:09:14.763058468 +0800
Modify: 2018-12-21 00:09:14.763058468 +0800
Change: 2018-12-21 00:09:47.092444491 +0800
 Birth: -
```

Soft links

- rm the target file, the link will be invalided

```
os@os:~/temp/foo$ echo hello > file
os@os:~/temp/foo$ ln -s file file2
```

```
os@os:~/temp/foo$ ls -l
total 4
-rw-rw-r-- 1 os os 6 Dec 21 00:11 file
lrwxrwxrwx 1 os os 4 Dec 21 00:12 file2 -> file
os@os:~/temp/foo$ stat file
  File: 'file'
  Size: 6               Blocks: 8          IO Block: 4096   regular file
Device: 801h/2049d      Inode: 1328650     Links: 1
Access: (0664/-rw-rw-r--)  Uid: ( 1000/      os)   Gid: ( 1000/      os)
Access: 2018-12-21 00:11:54.636605978 +0800
Modify: 2018-12-21 00:11:54.636605978 +0800
Change: 2018-12-21 00:11:54.636605978 +0800
 Birth: -
os@os:~/temp/foo$ stat file2
  File: 'file2' -> 'file'
  Size: 4               Blocks: 0          IO Block: 4096   symbolic link
Device: 801h/2049d      Inode: 1328653     Links: 1
Access: (0777/lrwxrwxrwx)  Uid: ( 1000/      os)   Gid: ( 1000/      os)
Access: 2018-12-21 00:12:02.300152148 +0800
Modify: 2018-12-21 00:12:00.960229971 +0800
Change: 2018-12-21 00:12:00.960229971 +0800
 Birth: -
```

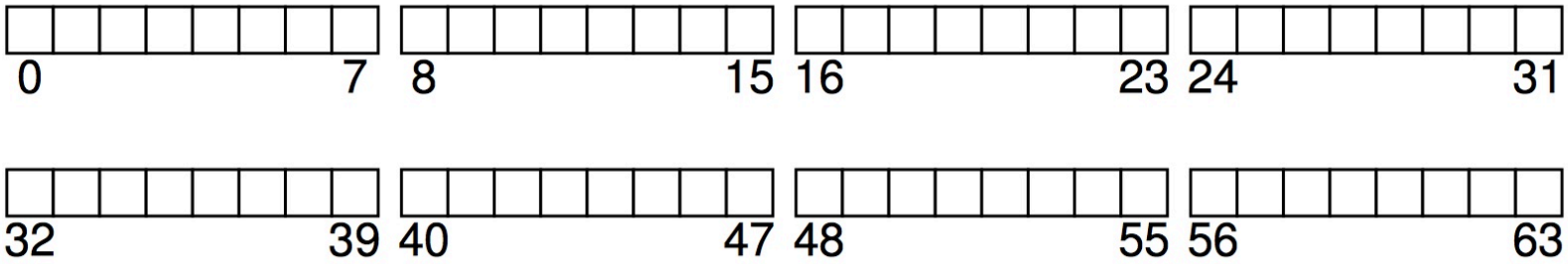
```
os@os:~/temp/foo$ rm file
os@os:~/temp/foo$ cat file2
cat: file2: No such file or directory
os@os:~/temp/foo$ ls -l
total 0
lrwxrwxrwx 1 os os 4 Dec 21 00:12 file2 -> file
os@os:~/temp/foo$
```

Two different aspects of FS

- (on-disk) Structure about FS
  - vs in-memory struct about FS
- Access methods
  - how does the FS maps the calls (open/read/write) onto its structures

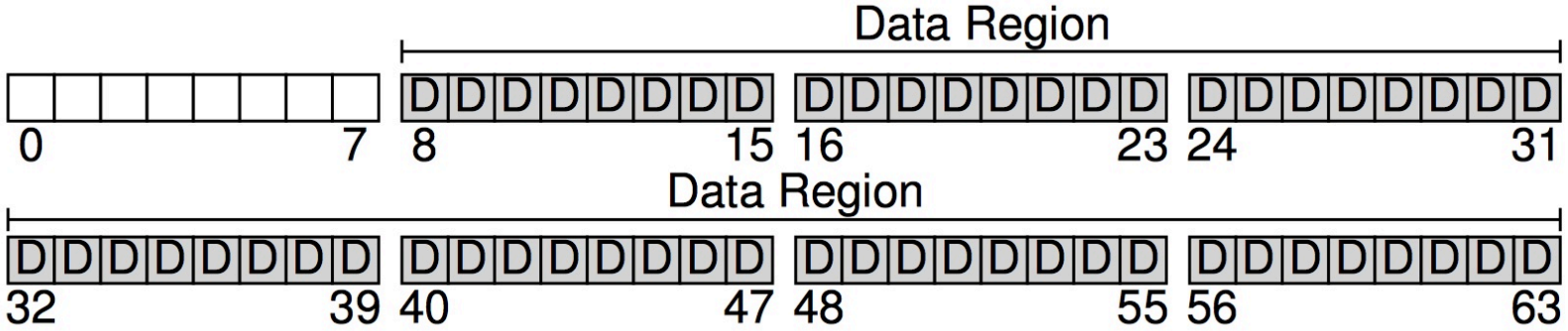
An Example

- Suppose we have a serial of blocks
  - Block size: 4k
  - 64 blocks



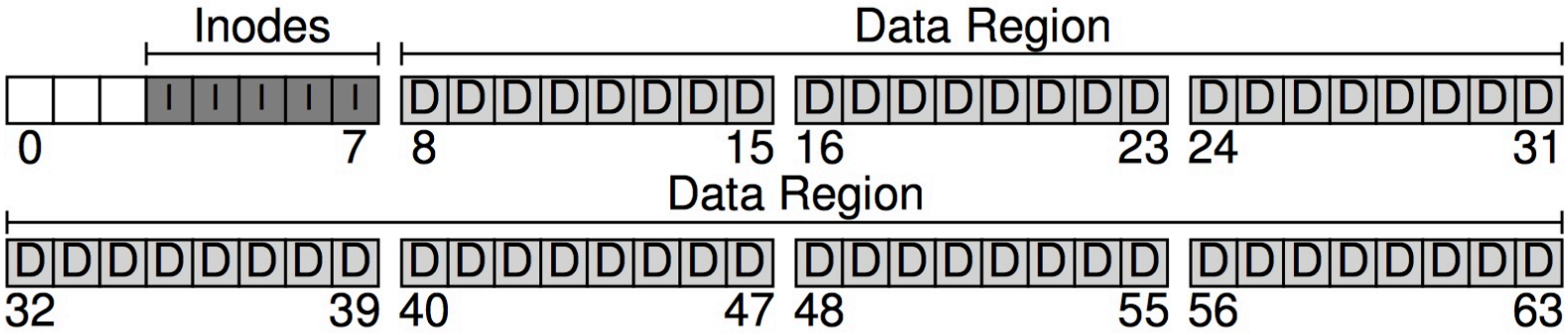
Data Region

- We reserve some blocks for data
  - 56 of 64 blocks



Inodes

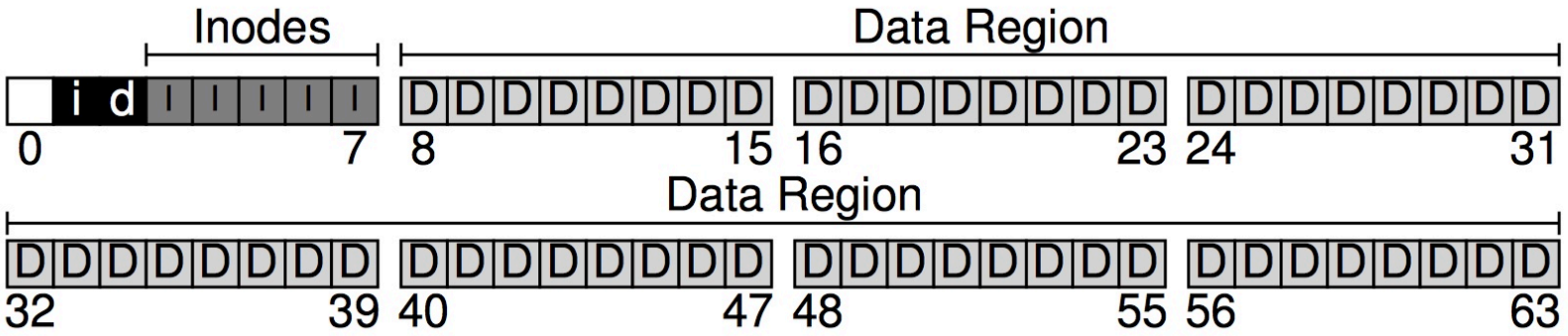
- Inode table: contains inodes
- 5 of 64 blocks are reserved for inodes
  - Suppose inodes are 256 bytes, 4 kb block can hold 16 inodes, then 5 blocks -> 80 inodes -> 80 files (directories)



D: data block
I: inode table

Bitmap

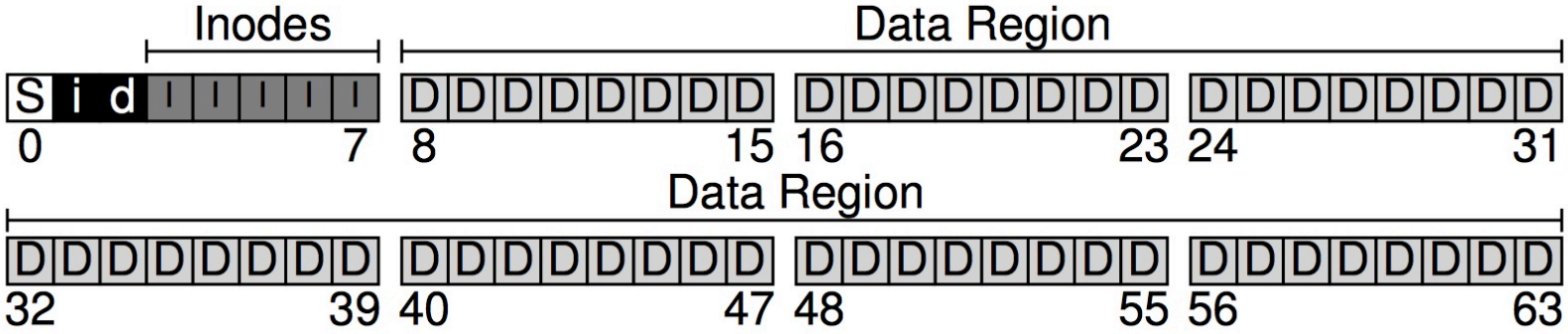
- Suppose we use bitmap to manage the free space
  - One bitmap for free inodes
  - One bitmap for free data region



D: Data block
I: inode
i: inode bitmap
d: data region bitmap

Superblock

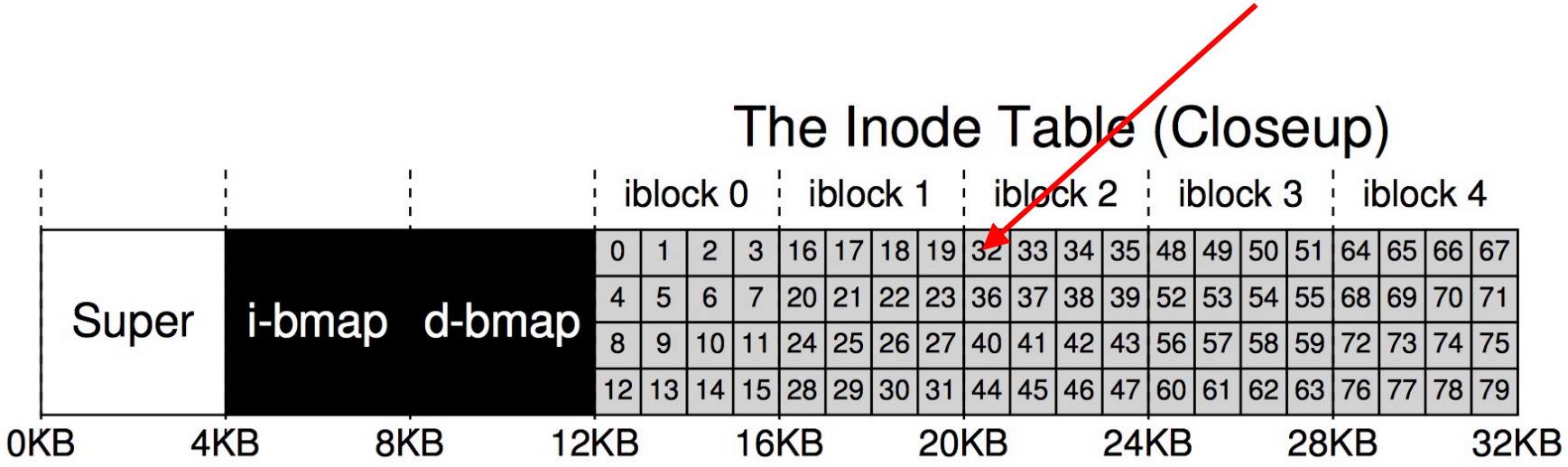
- Superblock
  - Contains information about this file system: how many inodes/data blocks, where the inode table begins, where the data region begins, and **a magic number**



D: Data block
I: inode
i: inode bitmap
d: data region bitmap
S: superblock

Inode address calculation

- Suppose inodes are 256 bytes, 4 kb block can hold 16 inodes, then 5 blocks -> 80 inodes -> 80 files (directories)
- Each inode is identified by a number(inumber)
- To read inode number No. 32
  - 32 * sizeof(inode) = 8k
  - Address: 8k + 4k(super block) + 8k(BITMAP) = 20K



Two different aspects of FS

- VFS data structure
  - inode
- In-memory data structure
  - ext2_inode_info
  - Contain both ext2_node and inode
- On-disk data structure
  - ext2_inode

```
struct inode {
        umode_t                 i_mode;
        unsigned short          i_opflags;
        kuid_t                  i_uid;
        kgid_t                  i_gid;
        unsigned int            i_flags;

#ifdef CONFIG_FS_POSIX_ACL
        struct posix_acl        *i_acl;
        struct posix_acl        *i_default_acl;
#endif

        const struct inode_operations   *i_op;
        struct super_block      *i_sb;
        struct address_space    *i_mapping;
```

```
struct ext2_inode {
        __le16  i_mode;         /* File mode */
        __le16  i_uid;          /* Low 16 bits of Owner Uid */
        __le32  i_size;         /* Size in bytes */
        __le32  i_atime;        /* Access time */
        __le32  i_ctime;        /* Creation time */
        __le32  i_mtime;        /* Modification time */
        __le32  i_dtime;        /* Deletion Time */
        __le16  i_gid;          /* Low 16 bits of Group Id */
        __le16  i_links_count;  /* Links count */
        __le32  i_blocks;       /* Blocks count */
        __le32  i_flags;        /* File flags */
        union {
                struct {
                        __le32  l_i_reserved1;
                } linux1;
                struct {
                        __le32  h_i_translator;
                } hurd1;
                struct {
                        __le32  m_i_reserved1;
                } masix1;
        } osd1;                         /* OS dependent 1 */
        __le32  i_block[EXT2_N_BLOCKS];/* Pointers to blocks */
```

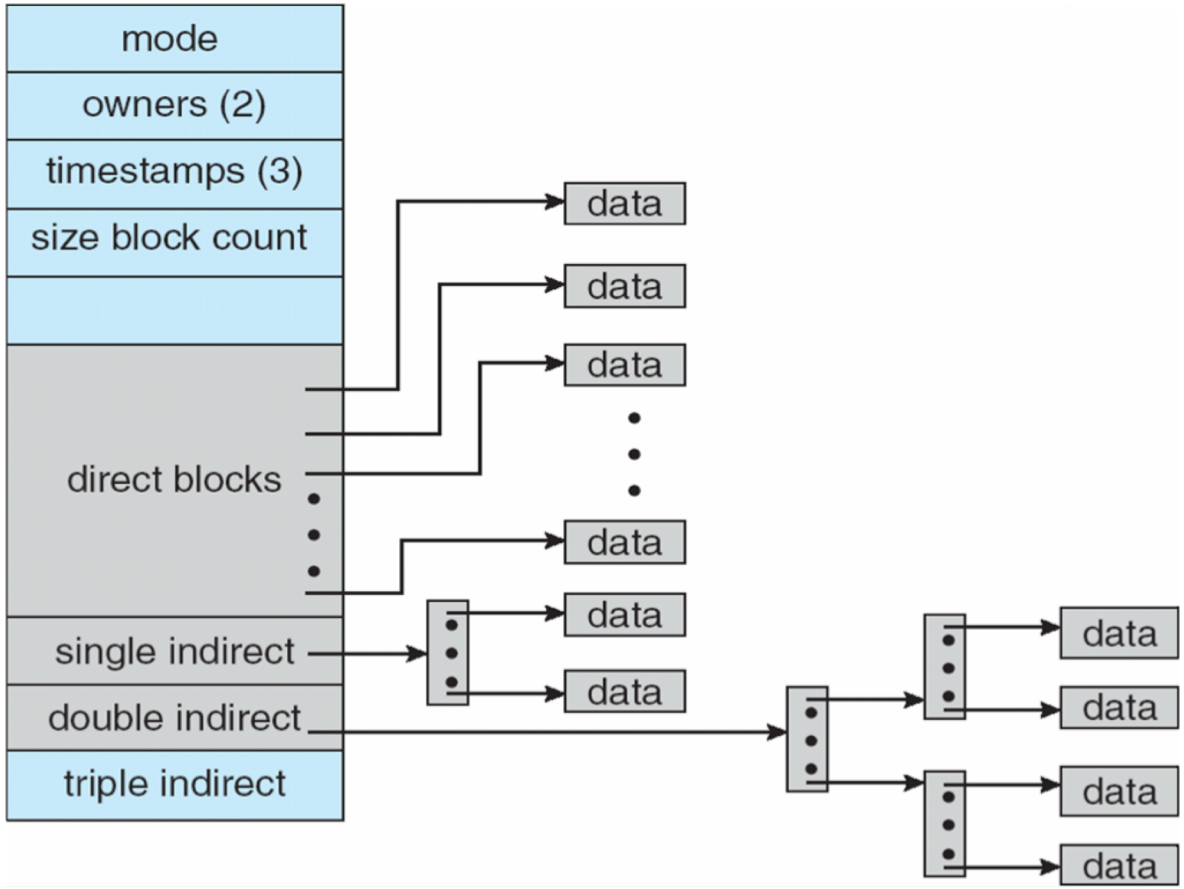
Linux inode

Size	Name	What is this inode field for?
2	mode	can this file be read/written/executed?
2	uid	who owns this file?
4	size	how many bytes are in this file?
4	time	what time was this file last accessed?
4	ctime	what time was this file created?
4	mtime	what time was this file last modified?
4	dtime	what time was this inode deleted?
2	gid	which group does this file belong to?
2	links_count	how many hard links are there to this file?
4	blocks	how many blocks have been allocated to this file?
4	flags	how should ext2 use this inode?
4	osd1	an OS-dependent field
60	block	a set of disk pointers (15 total)
4	generation	file version (used by NFS)
4	file_acl	a new permissions model beyond mode bits
4	dir_acl	called access control lists

Figure 40.1: **Simplified Ext2 Inode**

Multi-Level Index in inode

- To support bigger file, we need multi-level index for the nodes



Directory Organization

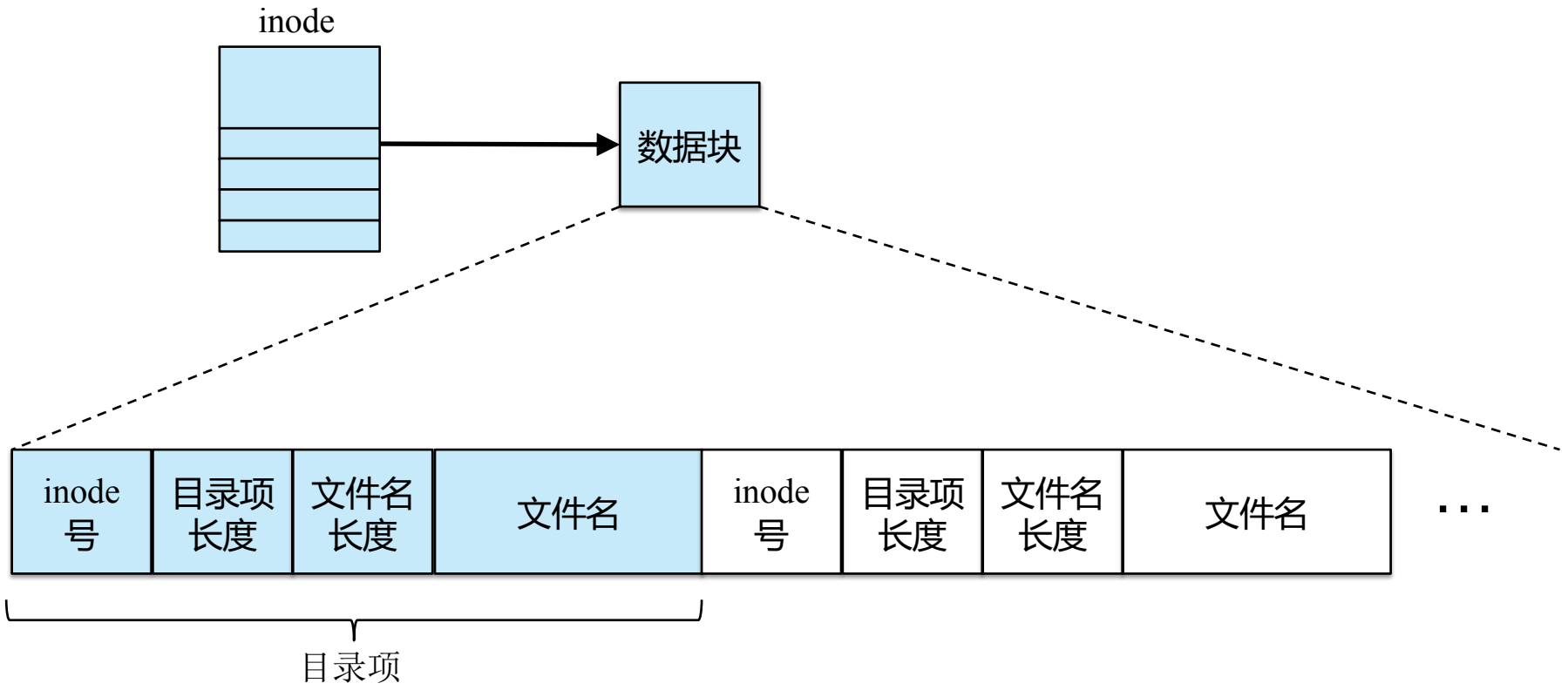
- Suppose a dir (inode number 5) has 3 files: foo, bar, foobar
  - inode number, name;
  - strlen: length of the name
  - reclen: length of the name plus **left over space**
    - For reuse the entry purpose

inum	reclen	strlen	name
5	4	2	.
2	4	3	..
12	4	4	foo
13	4	4	bar
24	8	7	foobar

```
struct ext2_dir_entry {
        __le32  inode;                  /* Inode number */
        __le16  rec_len;                /* Directory entry length */
        __le16  name_len;               /* Name length */
        char    name[];                 /* File name, up to EXT2_NAME_LEN */
};
```

Directory Implementation

- Directory is a special file
  - Store the mapping from file name to inode



Free Space Management

- Bit map
- Some OS will use the pre-allocation policy
  - For instance, when a file is created, a sequence of blocks (say 8) will be allocated
    - This can guarantee that the file on the disk is contiguous

Read /foo/bar

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[2]
open(bar)			**read**			**read**				
				read						
							read			
					read					
read()					**read**					
								read		
					write					
read()					**read**					
									read	
					write					
read()					**read**					
										read
					write					

What about the system-wide/per-process open file table?

Write to Disk: /foo/bar

	data bitmap	inode bitmap	root inode	foo inode	bar inode	root data	foo data	bar data[0]	bar data[1]	bar data[2]
create (/foo/bar)		read write	read	read	read write	read	read	write		
write()	read write				read write			write		
write()	read write				read write				write	
write()	read write				read write					write

Caching and Buffering

- Without caching, each file open would require two reads for each level of the directory
  - One for the inode, and one for data
- Early system allocate a **fixed-size** cache to hold popular blocks
- Morden systems use a **unified page cache** for both virtual memory pages and file system pages
- Write buffering: does not write to disk immediately, instead sync to disk for like 5 - 30 seconds
- Database: direct IO with raw data

Takeaway

- File interfaces
  - External name
  - Internal name (low-level name): inode
- Directory
  - Translate from external name to internal name
- Hard link vs soft link
- On-disk layout of FS