Chapter 4
Files and Directories

Cheng-Hsin Hsu
National Tsing Hua University
Department of Computer Science

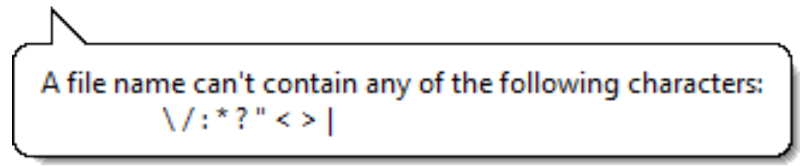
Parts of the course materials are courtesy of Prof. Chun-Ying Huang

Outline

- Introduction
- File Information
- File Permissions
- File Systems
- Directory Operations
- Device Special Files

Filename

- Any characters except slash (/) and null (\0)
  - Compared to Windows



- Usually up to 255 characters (the PATH_MAX constant)
- Every directory contains two filenames
  - Single dot (.), and
  - Double dots (. .)
  - Even in the root directory
- Filenames are independent of language encodings
  - It is interpreted by the user terminals ← for different languages

Pathname

- A sequence of one or more filenames
- Absolute pathname – with a leading slash
  - `/usr/bin/gcc`
- Relative pathname – without a leading slash or with a dot
  - Suppose the current working directory is /usr
  - All the followings points to the same file
    - `bin/gcc`
    - `./bin/gcc`
    - `../usr/bin/gcc`

Directory

- Working Directory
  - Every process has a working directory
  - Also called the *current working directory* (cwd)
  - Can be changed using the `chdir(2)` function ← will it affect the cwd of the shell?
- Home Directory
  - The initial working directory when a user logged in
  - Obtained from the `/etc/passwd` file

```
root:x:0:0:root:/root:/bin/bash
bear:x:1000:1000:Cheng-Hsin Hsu,,,:/home/bear:/bin/bash
```

File Information

stat, fstat, and lstat(2) Functions

Return information about a file

Synopsis

- `int stat(const char *path, struct stat *buf);`
- `int fstat(int fd, struct stat *buf);`
- `int lstat(const char *path, struct stat *buf);`
- Returns: 0 if OK, -1 on error

`stat` and `lstat` are basically equivalent, except `lstat` does not follow a symbolic link ← do a ls –l /var

- It returns the information of the symbolic link itself

`fstat` do the same thing for an opened file

Common File Information

- File type and permissions
- Number of hard links
- User ID and group ID
- Device number (of the containing file system)
- Device number for special files
- File size
- Block size and number of used blocks
- Timestamps: access, modification, and change

The stat Structure

- ```
  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 512B blocks allocated */
    time_t    st_atime;        /* time of last access */
    time_t    st_mtime;        /* time of last modification */
    time_t    st_ctiem;        /* time of last status change */
  };
  ```

Left as exercise: check the latest Linux kernel code to see how is it different from this legacy version?
  ```

File Types

- Regular file
- Directory file
- Block special file
- Character special file
- FIFO
- Socket
- Symbolic link

File Permissions

UIDs and GIDs Associated with a Process

- Real user ID and real group ID
  - UID and GID – Who we really are
  - Taken from the password file when login
- Effective user ID and effective group ID
  - EUID and EGID
  - Used for file access permission checks
- Saved set-user-ID and saved set-group-ID
  - SUID and SGID
  - Saved by the `exec` function
  - The effective user ID and effective group ID when a program is executed

Relationships Between UIDs/GIDs

- Normally, the EUID equals the UID and the EGID equals the GID
- EUID and EGID can be set by the running program using `setuid(2)` and `setgid(2)`, respectively ← won't affect shell process
- Special permission set with SUID and SGID
  - If a program *P* owned by *UserA* has a SUID permission
  - Any one who executes the program *P* will be automatically `setuid` to *UserA*
  - SGID does similar to SUID, but is applied to group id
  - Only root is able to set SUID/SGID permissions for a file

Applications of SUID and SGID

- An example – The `passwd` program
  - The program used to change user's password

```
$ ls -la /usr/bin/passwd
-rwsr-xr-x 1 root root 32988 2008-12-08 17:17 /usr/bin/passwd
```

  - Changing a user password requires to modify the `/etc/shadow` file, which is only accessible to the superuser
  - With the SGID permission, a user is able to run the `passwd` program with root's permission (EUID=0)

File Access Permissions (1/3)

- A file is always associated with a user ID (the owner) and a group ID
- 9-bit permissions
  - user-read, user-write, user-execute
  - group-read, group-write, group-execute
  - other-read, other-write, other-execute
  - Permissions are usually represented in octal
    - For example, 0755
    - Convert 0755 to binary: `111` `101` `101`

```
$ ls -la /bin/bash
-rwxr-xr-x 1 root root 725136 2008-05-13 02:48 /bin/bash
```

File Access Permissions (2/3)

- Rules
  - We can only access files in a directory with valid execute permissions
  - We can open a file for read if we have valid read permissions
  - We can open a file for write and truncate if we have valid write permissions
  - To delete an existing file in a directory, we only need valid write and execute permissions of the directory
  - An executable must have valid execute permissions

File Access Permissions (3/3)

- File access test precedence
  - If the EUID of the process is 0, access is allowed
  - If the EUID of the process equals the owner ID of the file, access is allowed if the appropriate user access permission bits are set
  - If the EGID or supplementary GIDs of the process equals the group ID, access is allowed if the appropriate group access permission bits are set
  - If the appropriate other access permission bits are set, access is allowed
- Access is allowed if one of the above checks passes ← sequentially

Ownership of New Files and Directories

The user ID of a new file is set to the EUID of the creating process

The group ID of a new file can be set either by:

- The EGID of the creating process, or
- The GID of the parent directory

The choice of group ID depends on the OS …

- FreeBSD 5.2.1/Mac OS X 10.3 – by the parent directory
- Linux – depends on a mount option (`grpid`)
  - If `grpid` is set or directory has SGID – by the parent directory
  - Otherwise – by the EGID of the creating process

The access(2) Function

- Check accessibility of a file
- From a real user's perspective
- Synopsis
  - `int access(const char *path, int mode);`
  - Returns: 0 if OK, -1 on error
- The mode can be the bitwise OR of the following constants
  - `R_OK, W_OK, X_OK` – Test for read, write, and execute permissions
  - `F_OK` – Test for the existence of the file

An Example for access(2) Function

```
#include "apue.h"
#include <fcntl.h>

int main(int argc, char *argv[]) {
    if (argc != 2)
        err_quit("usage: a.out <pathname>");
    if (access(argv[1], R_OK) < 0)
        err_ret("access error for %s", argv[1]);
    else
        printf("read access OK\n");
    if (open(argv[1], O_RDONLY) < 0)
        err_ret("open error for %s", argv[1]);
    else
        printf("open for reading OK\n");
    exit(0);
}
```

An Example for access(2) Function (Cont'd)

```
$ ls -l a.out
-rwxrwxr-x 1 sar 15945 Nov 30 12:10 a.out
$ ./a.out a.out
read access OK
open for reading OK
$ ls -l /etc/shadow
-r-------- 1 root 1315 Jul 17 2002 /etc/shadow
$ ./a.out /etc/shadow
access error for /etc/shadow: Permission denied
open error for /etc/shadow: Permission denied
$ sudo su -                 become superuser
Password:                   enter superuser password
# chown root a.out              change file's user ID to root
# chmod u+s a.out               and turn on set-user-ID bit
# ls -l a.out                   check owner and SUID bit
-rwsrwxr-x 1 root 15945 Nov 30 12:10 a.out
# exit                      go back to normal user
$ ./a.out /etc/shadow
access error for /etc/shadow: Permission denied
open for reading OK
```

The umask(2) Function

- Sets the file mode creation mask for the process
- Synopsis
  - `mode_t umask(mode_t cmask);`
  - Returns: previous file mode creation mask
- Changing the umask of a process doesn't affect the umask of its parent
- See examples in the next page

The umask(2) Function (Cont’d)

```
#define RWRWRW (S_IRUSR|S_IWUSR|S_IRGRP|S_IWGRP|S_IROTH|S_IWOTH)
int main(void) {
    umask(0);
    if (creat("foo", RWRWRW) < 0)
        err_sys("creat error for foo");
    umask(S_IRGRP | S_IWGRP | S_IROTH | S_IWOTH);
    if (creat("bar", RWRWRW) < 0)
        err_sys("creat error for bar");
}
```

```
$ umask              first print the current file mode creation mask
002
$ ./a.out
$ ls -l foo bar
-rw------- 1 sar 0 Dec 7 21:20 bar
-rw-rw-rw- 1 sar 0 Dec 7 21:20 foo
$ umask              see if the file mode creation mask changed
002
```

Functions to Set File Modes and Ownerships

- File modes
  - `int chmod(const char *path, mode_t mode);`
  - `int fchmod(int fd, mode_t mode);`
- File ownerships
  - `int chown(const char *path, uid_t owner, gid_t group);`
  - `int fchown(int fd, uid_t owner, gid_t group);`
  - `int lchown(const char *path, uid_t owner, gid_t group);`
  - Note: `lchown` will not follow symbolic links ← commonly seen in many of the functions mentioned in this chapter

The Sticky Bit

Can be used on an executable or a directory

For an executable with the sticky bit, the system

- Caches the executable in swap area after execution ← actually the text portion of it
- Increases performance of loading the executable

For a directory with the sticky bit

- A file in the directory can be only deleted or renamed by …
  - The user owns the file
  - The user owns the directory
  - The superuser
- Usually set for global accessible directories, such as /tmp

Revisit Special File Permissions

- setuid

  -rwsr-xr-x 1 root root 54256 Mar 29 2016 /usr/bin/passwd

- setgid

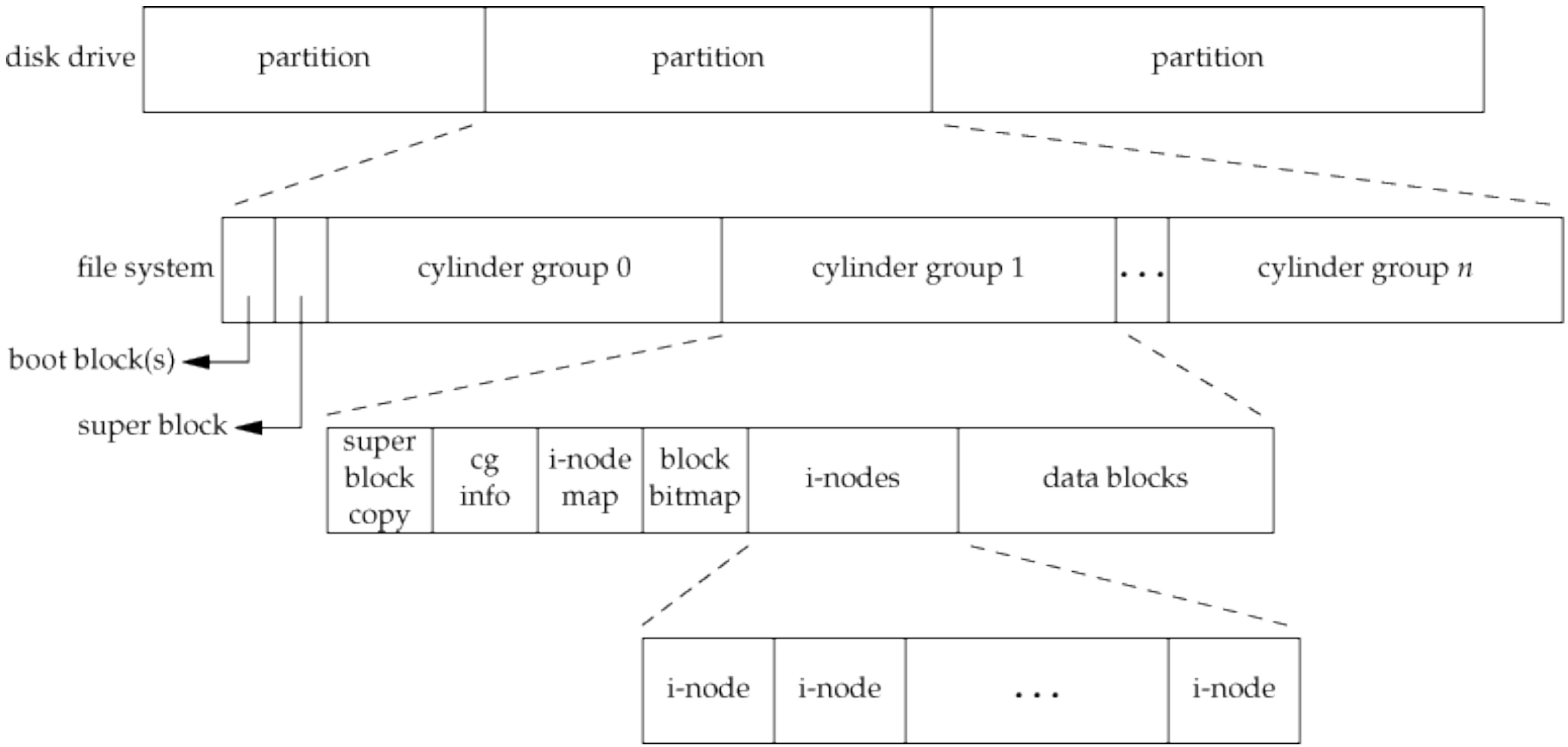
  -rwxr-sr-x 1 root mail 14856 Dec 7 2013 /usr/bin/dotlockfile

- sticky bit

  drwxrwxrwt 10 root root 4096 Oct 24 13:42 /tmp

File Systems

Disk Drives, Partitions, and File System

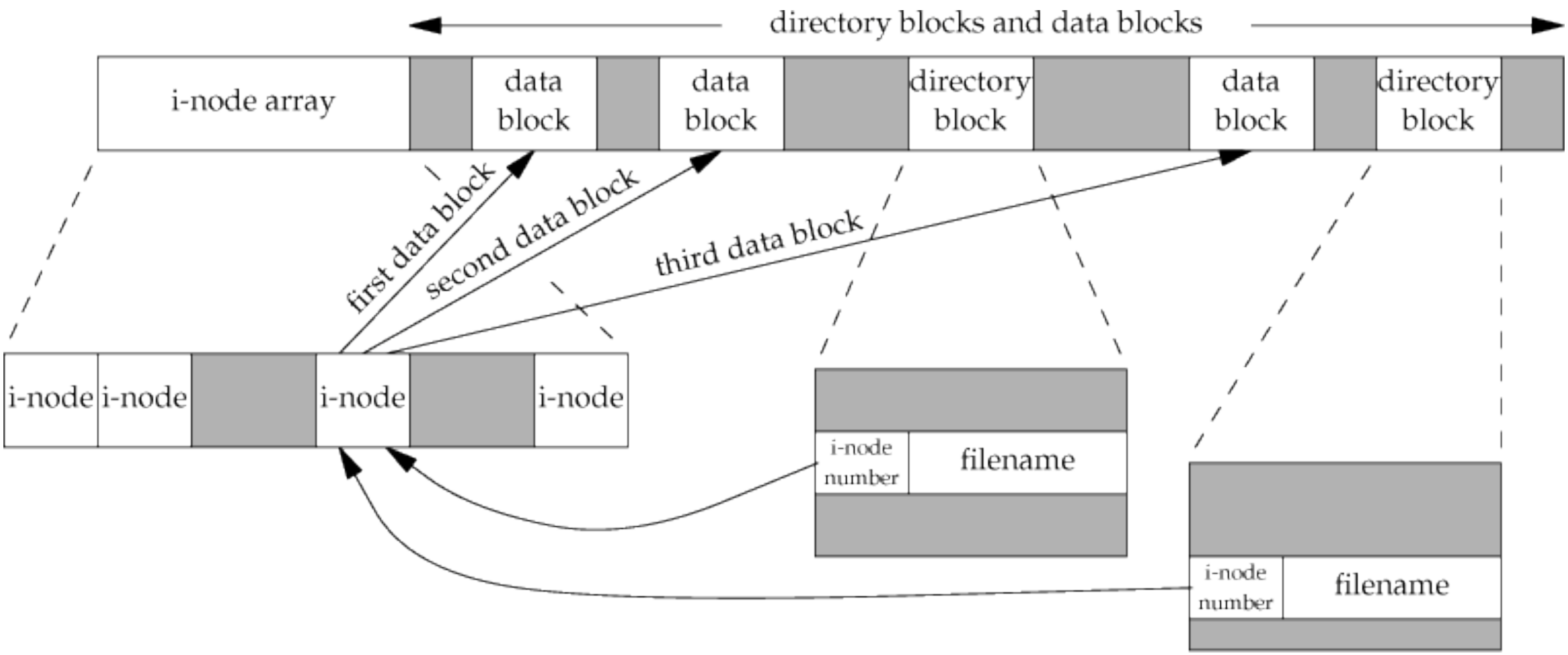


Cylinder Group's i-nodes and Data Blocks

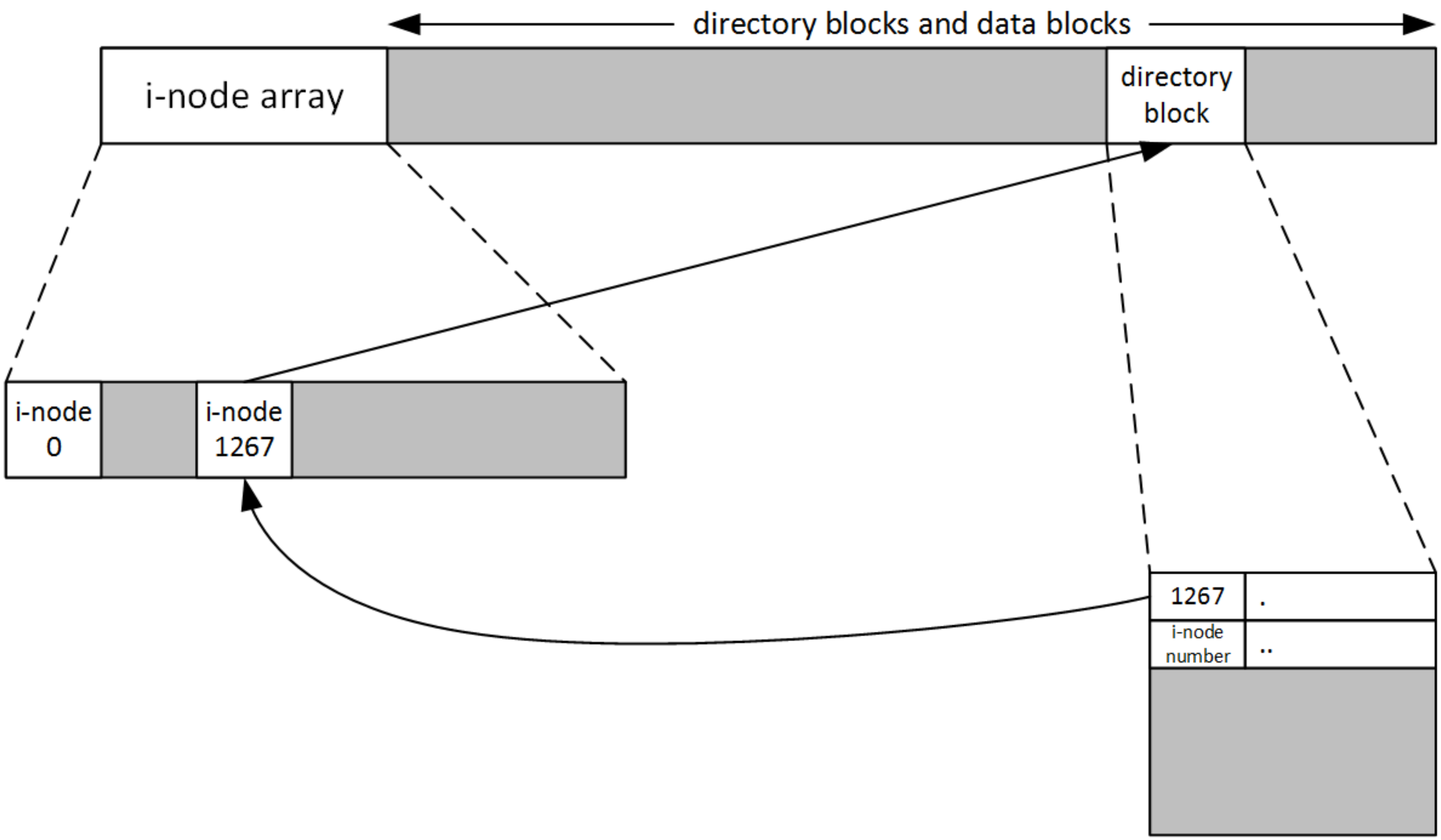
- i-node – describe (meta) information about a file
  - type, permission, data blocks, timestamps, reference counts, …, etc.
- i-node are often indexed using a positive integer number
- Some i-node numbers has special purpose
  - 0 – reserved, or does not exist
  - 1 – list of bad/defective blocks
  - 2 – root directory of a partition

i-nodes and Data Blocks

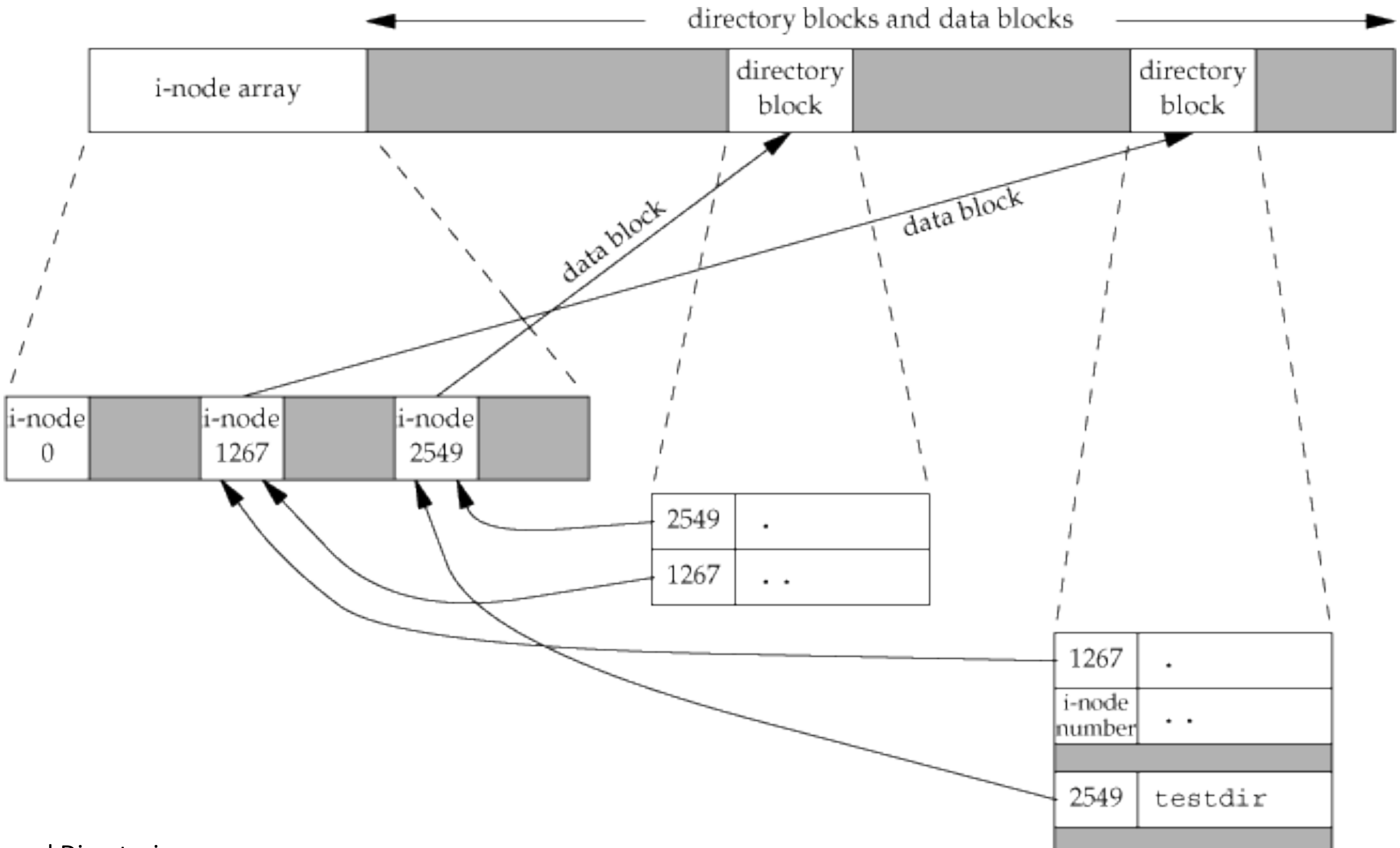
- Two filenames can point to the same i-node ← Why?



Sample Cylinder Group *Before* Creating a Dir



Sample Cylinder Group *After* Creating a Dir



Reference Counts

- The number of pointers that points to an i-node
- Common file operations to work with reference counts
  - Link, unlink, and remove
- Usually a newly created file has a reference count of 1
  - Pointed by the containing directory
- A reference count increases on being link(2)'ed
  - Create a *hard-link*
  - Hard links must reside in *the same* partition
- A reference count decreases on being unlink(2)'ed
- What is the ref. count of i-node 1267 in previous slide?

link, unlink, remove, and rename

- Synopsis
  - `int link(const char *existingpath, const char *newpath);`
  - `int unlink(const char *pathname);`
  - `int remove(const char *pathname);`
  - `int rename(const char *oldname, const char *newname);`
  - Returns: 0 if OK, -1 on error
- Relevant Commands
  - `ls -l` # long listing format, check the reference count
  - `ls -ls` # show file sizes in 1KB blocks
  - `ls -li` # show i-node numbers

Symbolic links

- It is also called soft-links (in contrast to hard-links)
- The ln(1) –s command
- The size of a symbolic link is the length of its target's name

```
$ mkdir foo                          make a new directory
$ touch foo/a                        create a zero-length file
$ ln -s ../foo foo/testdir           create a symbolic link
$ ls -l foo
total 0
-rw-r----- 1 sar 0 Jan 22 00:16 a
lrwxrwxrwx 1 sar 6 Jan 22 00:16 testdir -> ../foo
```

In the above example, the foo/testdir symbolic link causes a loop!

Symbolic Links (Cont'd)

- Symbolic links is able to point to an nonexistence file

```
$ ln -s /no/such/file myfile    create a symbolic link
$ ls myfile
myfile                          ls says it's there
$ cat myfile                    so we try to look at it
cat: myfile: No such file or directory
$ ls -l myfile                  try -l option
lrwxrwxrwx 1 sar 13 Jan 22 00:26 myfile -> /no/such/file
```

Treatments of Symbolic Links by Various Functions

Function	Not follow symbolic link	Follow symbolic link	Function	Not follow symbolic link	Follow symbolic link
access		•	open		•
chdir		•	opendir		•
chmod		•	pathconf		•
chown		•	readlink	•	
creat		•	remove	•	
exec		•	rename	•	
lchown	•		stat		•
link		•	truncate		•
lstat	•		unlink	•	

symlink and readlink

Synopsis

- `int symlink(const char *actualpath, const char *sympath);`
- Returns: 0 if OK, -1 on error
- `ssize_t readlink(const char *path, char *buf, size_t bufsize);`
- Returns: number of bytes placed in the buffer, -1 on error

symlink create a symbolic link *sympath* points to the *actualpath*

- *sympath* and *actualpath* need not reside in the same file system

readlink reads the targeted pathname of the given symbolic link *path*

- The function combines *open*, *read*, and *close*.

File Times

Field	Description	Example	ls(1) option
st_atime	last access time	read	-u
st_mtime	last modification time (file content)	write	default
st_ctime	last change time (i-node)	chmod, chown	-c

Effect of various functions on the access, modification, and change times

Function	Referenced file or dir			Parent directory			Function	Referenced file or dir			Parent directory		
	a	m	c	a	m	c		a	m	c	a	m	c
[f]chmod			•				pipe	•	•	•			
[f]chown			•				read	•					
creat (new)	•	•	•		•	•	remove (file)			•		•	•
creat (trunc)		•	•				remove (dir)					•	•
exec	•						rename			•		•	•
lchown			•				rmdir					•	•
link			•		•	•	[f]truncate		•	•			
mkdir	•	•	•		•	•	unlink			•		•	•
mkfifo	•	•	•		•	•	utime	•	•	•			
open (new)	•	•	•		•	•	write		•	•			
open (trunc)		•	•										

utime Function: Update Time

Synopsis

- `int utime(const char *filename, const struct utimbuf *times);` ← 1 sec resolution
- Returns: 0 if OK, -1 on error
- `futimens(…)` ← for higher resolution!

Time utimbuf data structure

```
struct utimbuf {
    time_t actime;
    time_t modtime;
};
```

Change the access time and modification time of a file

If *times* is *NULL*, the access time and modification time is set to the current time

Directory Operations

mkdir and rmdir Functions

Synopsis

- `int mkdir(const char *pathname, mode_t mode);`
- `int rmdir(const char *pathname);`
- Returns: 0 if OK, -1 on error

Create or remove a directory

When removing a directory …

- If a directory is not empty, the function fails
- If a directory is empty and no process has the directory open, it is removed and freed
- If a directory is empty, but a process has opened the directory, it is removed but not freed
  - No new file can be created in the to-be-removed directory
  - It is freed when the process close the directory ← Similar to unlink!

Reading Directories

Access permissions for directories

- Read: must have read and execute permission
- Create/write: must have write and execute permission

Synopsis

- `DIR *opendir(const char *name);`
- Returns: pointer to the directory if OK, NULL on error
- `struct dirent *readdir(DIR *dir);`
- Returns: pointer to a dirent structure if OK, NULL on reaching *EOF* or error
- `int closedir(DIR *dir);`
- Returns: 0 if OK, -1 on error

readdir Function

The dirent structure

```
struct dirent {
    ino_t          d_ino;       /* inode number */
    off_t          d_off;       /* offset to the next dirent */
    unsigned short d_reclen;    /* length of this record */
    unsigned char  d_type;      /* type of file */
    char           d_name[256]; /* filename */
};
```

The data returned by readdir() may be overwritten by subsequent calls to readdir() for the same directory stream.

Seek in an Opened Directory

- Synopsis
  - `void rewinddir(DIR *dir);`
  - `off_t telldir(DIR *dir);`
  - Returns: current location of the opened dir
  - `void seekdir(DIR *dir, off_t offset);`
- rewinddir resets the position of the directory stream to the beginning
- seekdir set the location in the directory stream

A Sample Program – Filename Enumeration

- Enumerate all files and directories in a given directory
- Usage
  - `./a.out {directory_name}`

```c
#include "mylib.h"
#include <dirent.h>

int
main(int argc, char *argv[]) {
        DIR *dp;
        struct dirent *dirp;
        if(argc != 2)
                err_quit("usage: ls directory_name\n");
        if((dp = opendir(argv[1])) == NULL)
                err_sys("cannot open %s\n", argv[1]);
        while((dirp = readdir(dp)) != NULL)
                printf("%s\n", dirp->d_name);
        closedir(dp);
        return(0);
}
```

chdir, fchdir, and getcwd Functions

Every *process* has a current working directory
- The current working directory is inherited from the parent
- The current working directory for each process is independent

The default working directory for a user is his home directory (configured in the /etc/passwd file)

Current working directory can be changed

Synopsis
- `int chdir(const char *path);`
- `int fchdir(int fd);`
- Returns: 0 if OK, 1 on error
- `char *getcwd(char *buf, size_t size);`
- Returns: *buf* if OK, NULL on error

```
$ pwd
/usr/lib
$ mycd
chdir to /tmp succeeded
$ pwd
/usr/lib
```

Device Special Files

Device Special Files

- Every file system is known by its major and minor device numbers, *encoded* in the system type dev_t
  - The major number identifies the device driver
  - The minor number identifies the specific sub device
  - The major number can be extracted by the macro major(dev_t)
  - The minor number can be extracted by the macro minor(dev_t)
- Recall the stat(2) function, which returns a file status structure
  - The st_dev and the st_rdev value, what's the difference?
  - Let's see an example

An Example of Retrieving Device Numbers

```
int main(int argc, char *argv[]) {
    int i;
    struct stat buf;
    for (i = 1; i < argc; i++) {
        printf("%s: ", argv[i]);
        if (stat(argv[i], &buf) < 0) {
            err_ret("stat error");
            continue;
        }
        printf("dev=%d/%d", major(buf.st_dev), minor(buf.st_dev));
        if (S_ISCHR(buf.st_mode) || S_ISBLK(buf.st_mode)) {
            printf(" (%s) rdev = %d/%d",
                (S_ISCHR(buf.st_mode)) ? "character" : "block",
                major(buf.st_rdev), minor(buf.st_rdev));
        }
        printf("\n");
    }
    exit(0);
}
```

st_dev and st_rdev

- Every file has a *st_dev* number, which indicates the container file system
- Only device files have *st_rdev* numbers, which indicates the device/sub-device
- Running the example in the previous slide

```
$ ./a.out / /dev /home/bear /dev/tty0 /dev/sda2
/: dev = 8/2
/dev: dev = 0/14
/home/chuang: dev = 8/2
/dev/tty0: dev = 0/14 (character) rdev = 4/0
/dev/sda2: dev = 0/14 (block) rdev = 8/2
```

The /dev File System

- Stores device special files
- It can be a real file system
  - Each device special file is created with the *mknod(1)* command
- It can be a pseudo file system
  - Device special files are automatically generated when a device driver is registered

```
$ ls -la /dev/tty0 /dev/sda* /dev/null
crw-rw-rw- 1 root root 1, 3 2008-12-04 10:02 /dev/null
brw-rw---- 1 root disk 8, 0 2009-02-09 18:39 /dev/sda
brw-rw---- 1 root disk 8, 1 2009-02-09 18:39 /dev/sda1
brw-rw---- 1 root disk 8, 2 2009-02-09 10:39 /dev/sda2
crw-rw---- 1 root root 4, 0 2009-02-09 18:39 /dev/tty0
```

Common Device Special Files

/dev/hda*N*? – IDE disks and partitions

/dev/sda*N?* – SCSI or SATA disks and partitions

/dev/scd*N* – CD/DVD-ROMs

/dev/tty*N* – terminals

/dev/ttyS*N* – COM ports

/dev/pts/*N* – pseudo terminals

/dev/null

/dev/zero ← cat /dev/zero | head -c 12 > /tmp/zero.bytes

/dev/urandom ← head -c 30 /dev/urandom > /tmp/rnd.bytes

Assignment #3 (5%)

- (3%) Write a utility like cp(1), say lcp, that copies a file containing holes, without writing the bytes of 0 to the output file.
- (2%) In Section 4.22, our version of ftw, called ftw8.c, never changes its directory. Modify this routine so that each time it encounters a directory, it uses the chdir function to change to that directory, allowing it to use the filename and not the pathname for each call to lstat. When all the entries in a directory have been processed, execute chdir(".."). Compare the time used by this version and the version in the text.
- Submit your lcp.c, ftw8.c, Makefile, and a readme.txt files through iLMS.
- Due date: November 1st