Lecture Note 3.
File Programming

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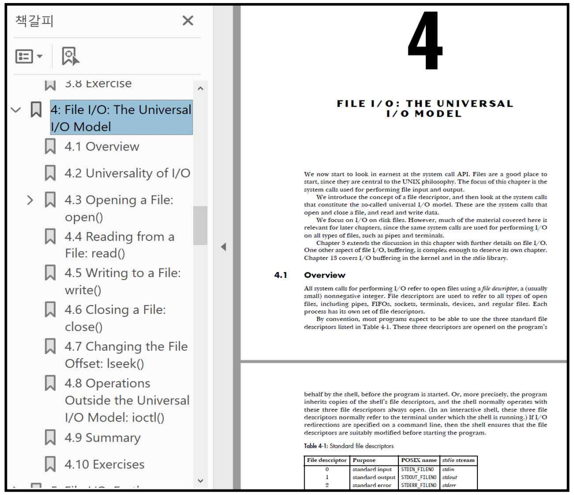
Objectives

- Understand disk geometry
- Discuss system programs for disk (storage)
- Apprehend the internal structure of a file
- Learn how to use file-related system calls
- Make a program (command) that manipulates a file

- Refer to Chapter 4, 5 in the LPI and Chapter 10 in the CSAPP



4

FILE I/O: THE UNIVERSAL I/O MODEL

We now start to look in earnest at the system call API. Files are a good place to start, since they are central to the UNIX philosophy. The focus of this chapter is the system calls used for performing file input and output.

We introduce the concept of a file descriptor, and then look at the system calls that constitute the so-called universal I/O model. These are the system calls that open and close a file, and read and write data.

We focus on I/O on disk files. However, much of the material covered here is relevant for later chapters, since the same system calls are used for performing I/O on all types of files, such as pipes and terminals.

Chapter 5 extends the discussion in this chapter with further details on file I/O. One other aspect of file I/O, buffering, is complex enough to deserve its own chapter. Chapter 13 covers I/O buffering in the kernel and in the *stdio* library.

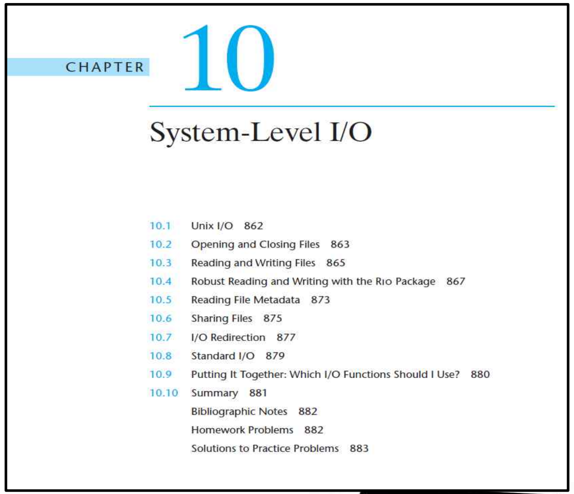
4.1 Overview

All system calls for performing I/O refer to open files using a *file descriptor*, a (usually small) nonnegative integer. File descriptors are used to refer to all types of open files, including pipes, FIFOs, sockets, terminals, devices, and regular files. Each process has its own set of file descriptors.

By convention, most programs expect to be able to use the three standard file descriptors listed in Table 4-1. These three descriptors are opened on the program's behalf by the shell, before the program is started. Or, more precisely, the program inherits copies of the shell's file descriptors, and the shell normally operates with these three file descriptors always open. (In an interactive shell, these three file descriptors normally refer to the terminal under which the shell is running.) If I/O redirections are specified on a command line, then the shell ensures that the file descriptors are suitably modified before starting the program.

Table 4-1: Standard file descriptors

File descriptor	Purpose	POSIX name	*stdio* stream
0	standard input	STDIN_FILENO	*stdin*
1	standard output	STDOUT_FILENO	*stdout*
2	standard error	STDERR_FILENO	*stderr*



CHAPTER 10

System-Level I/O

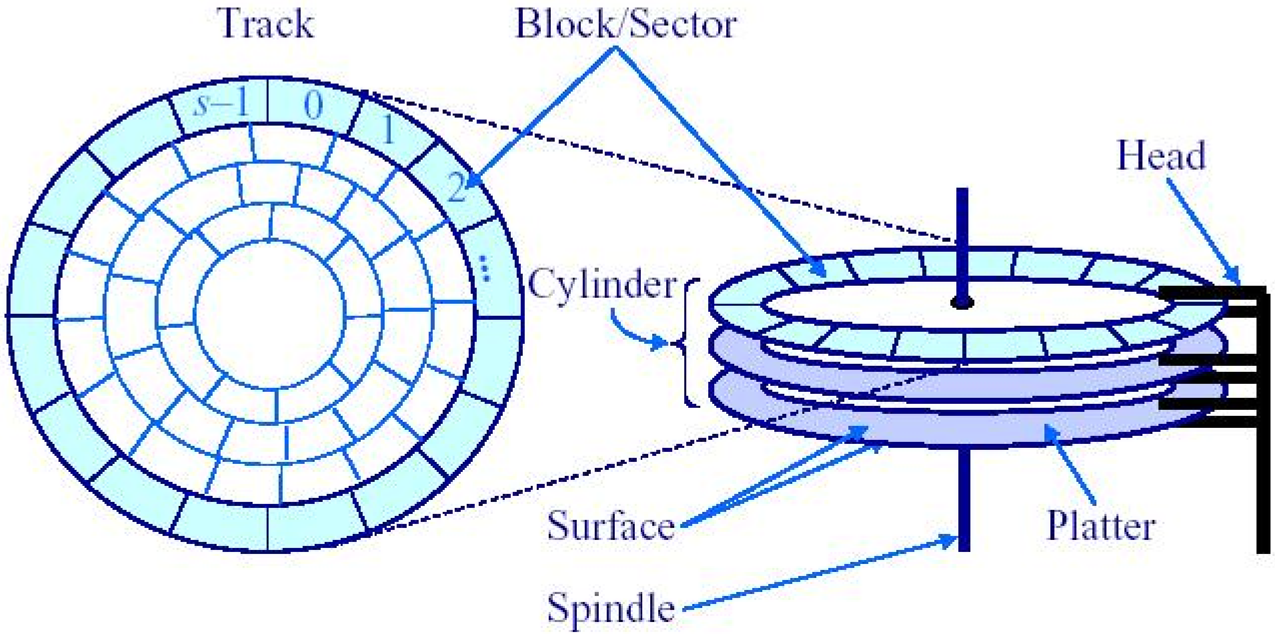
Introduction

- Issues on file
  - File manipulation (create, access, remove, …)
  - Associate a file name with actual data stored in disk
  - Manage file attributes/access control
  - Support hierarchy structure (directory)
  - Support a variety of file types (e.g. device)

- File related system calls
  - open(), creat(): create a file, start accessing a file (authentication)
  - read(), write(): read/write bytes from/to a file
  - close(): finish accessing a file
  - lseek(): jump to a particular offset (location) in a file
  - unlink(), remove() : delete a file
  - fcntl() : control a file (file descriptor)
  - …

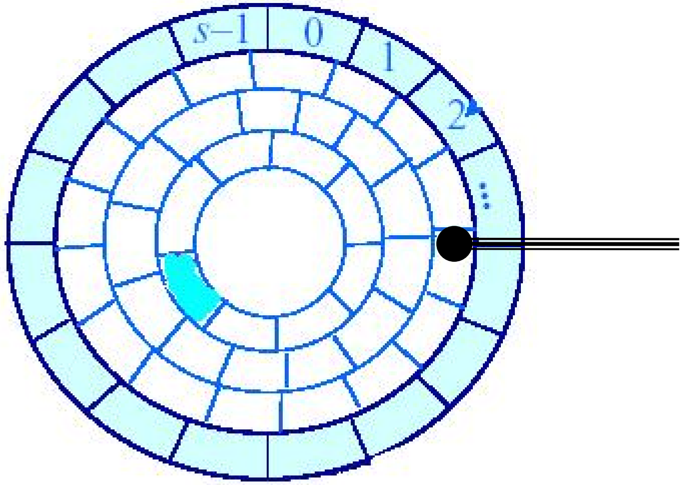
Disk structure (1/4)

- Components
  - ✓ Platter, Spindle, Surface
  - ✓ Track, Sector, Cylinder
  - ✓ Head, ARM



Disk structure (2/4)

- Disk access
  - ✓ Sector addressing : head(surface), track(cylinder), sector
  - ✓ Seek time: move head to appropriate track
  - ✓ Rotational latency: wait for the sector to appear under the head
  - ✓ Transmission time: read/write the request sector(s)



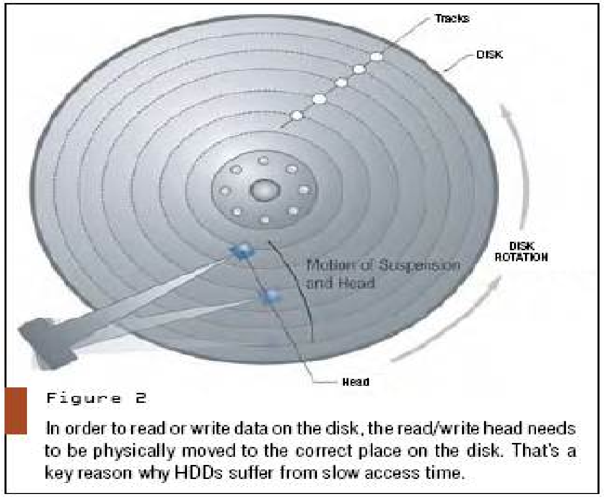


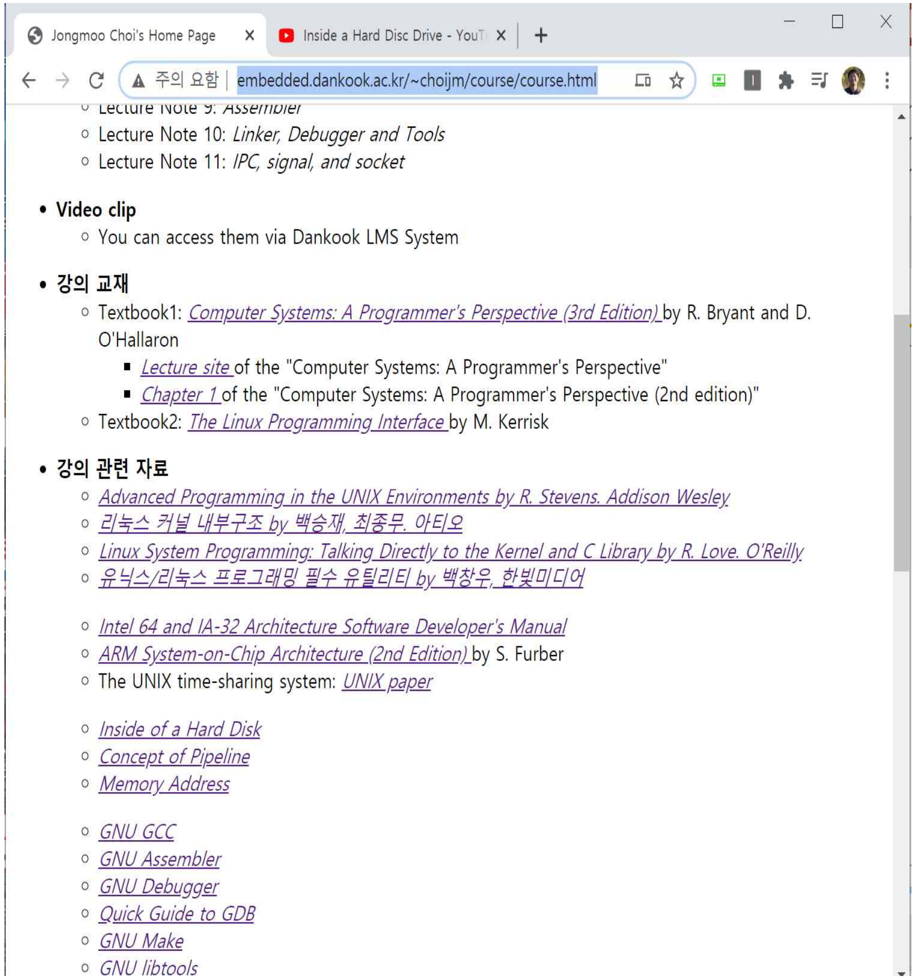
Figure 2

In order to read or write data on the disk, the read/write head needs to be physically moved to the correct place on the disk. That's a key reason why HDDs suffer from slow access time.

- ✓ Try to reduce the Seek time and Rotational latency
  ➔ Make use of various disk scheduling (eg. SCAN or elevator algorithm) and Parallel access techniques (RAID)

Disk structure (3/4)

- Disk access
  - ✓ Disk behaviors (from youtube)


Jongmoo Choi's Home Page
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- Lecture Note 9: *Assembler*
- Lecture Note 10: *Linker, Debugger and Tools*
- Lecture Note 11: *IPC, signal, and socket*

- **Video clip**
  - You can access them via Dankook LMS System

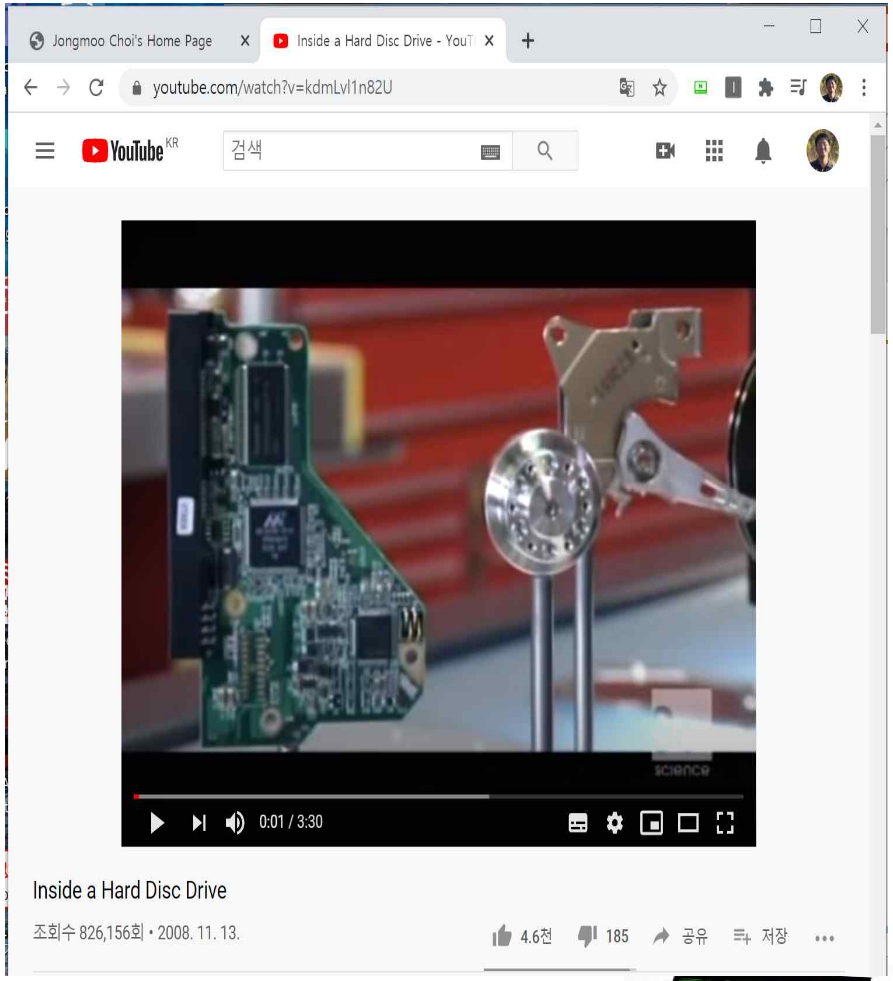
- **강의 교재**
  - Textbook1: *Computer Systems: A Programmer's Perspective (3rd Edition)* by R. Bryant and D. O'Hallaron
    - *Lecture site* of the "Computer Systems: A Programmer's Perspective"
    - *Chapter 1* of the "Computer Systems: A Programmer's Perspective (2nd edition)"
  - Textbook2: *The Linux Programming Interface* by M. Kerrisk

- **강의 관련 자료**
  - *Advanced Programming in the UNIX Environments by R. Stevens. Addison Wesley*
  - *리눅스 커널 내부구조 by 백승재, 최종무. 아티오*
  - *Linux System Programming: Talking Directly to the Kernel and C Library by R. Love. O'Reilly*
  - *유닉스/리눅스 프로그래밍 필수 유틸리티 by 백창우, 한빛미디어*

  - *Intel 64 and IA-32 Architecture Software Developer's Manual*
  - *ARM System-on-Chip Architecture (2nd Edition)* by S. Furber
  - The UNIX time-sharing system: *UNIX paper*

  - *Inside of a Hard Disk*
  - *Concept of Pipeline*
  - *Memory Address*

  - *GNU GCC*
  - *GNU Assembler*
  - *GNU Debugger*
  - *Quick Guide to GDB*
  - *GNU Make*
  - *GNU libtools*



Inside a Hard Disc Drive

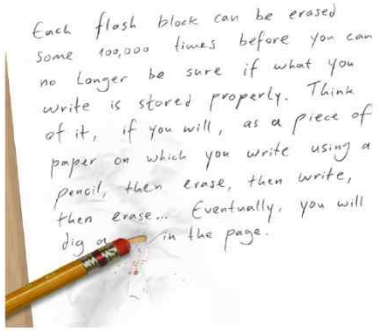
조회수 826,156회 • 2008. 11. 13.

Disk structure (4/4, Optional)

- Disk vs. Flash memory

vs

- ✓ No mechanical part (fast, lightweight)
- ✓ Overwrite limitation (erase before write)
- ✓ Read/Write vs. Erase granularity
- ✓ Endurance, Disturbance, Retention error
- ✓ SLC, MLC, TLC

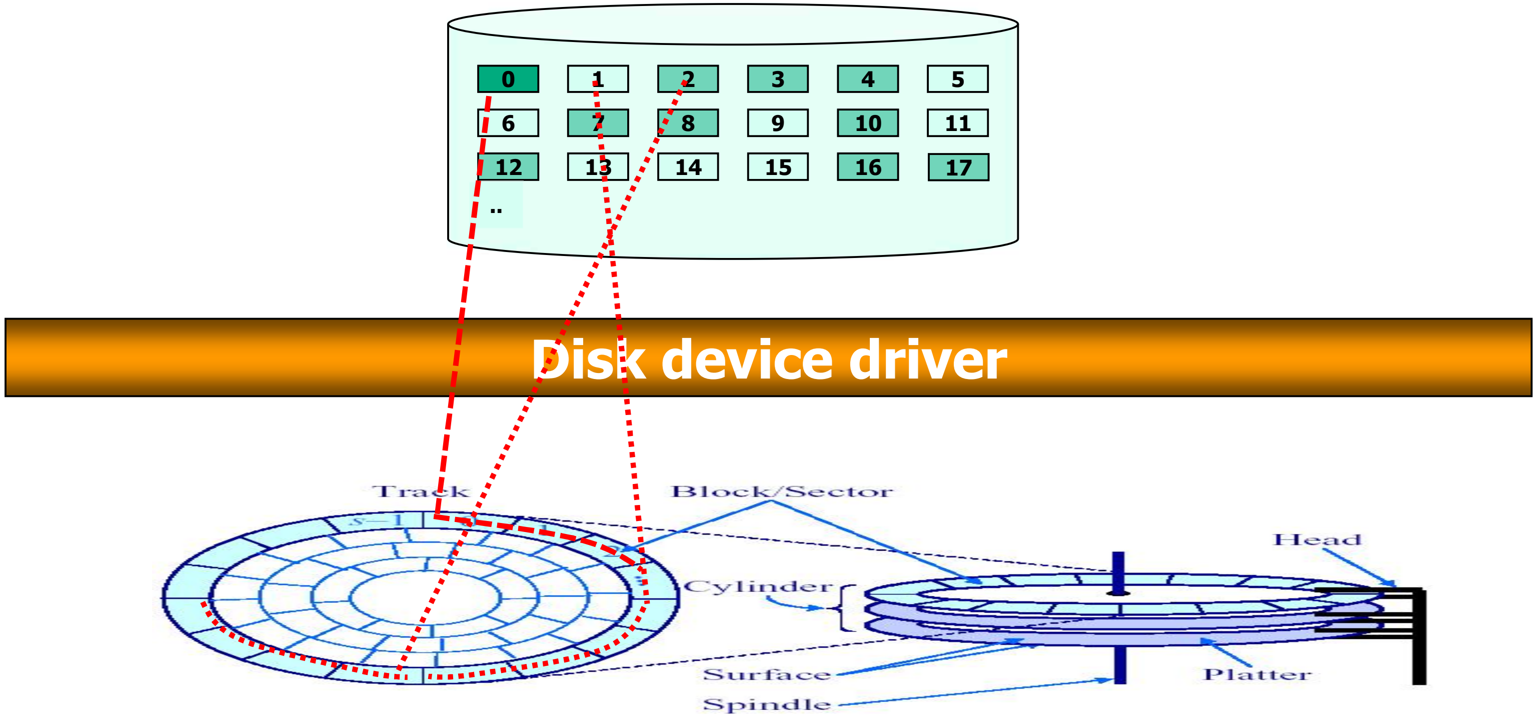


Each flash block can be erased
Some 100,000 times before you can
no Longer be sure if what you
write is stored properly. Think
of it, if you will, as a piece of
paper on which you write using a
pencil, then erase, then write,
then erase... Eventually, you will
dig a [illegible] in the page.

Figure 1: Flash, like paper, can only be erased so many times before it gets used up.

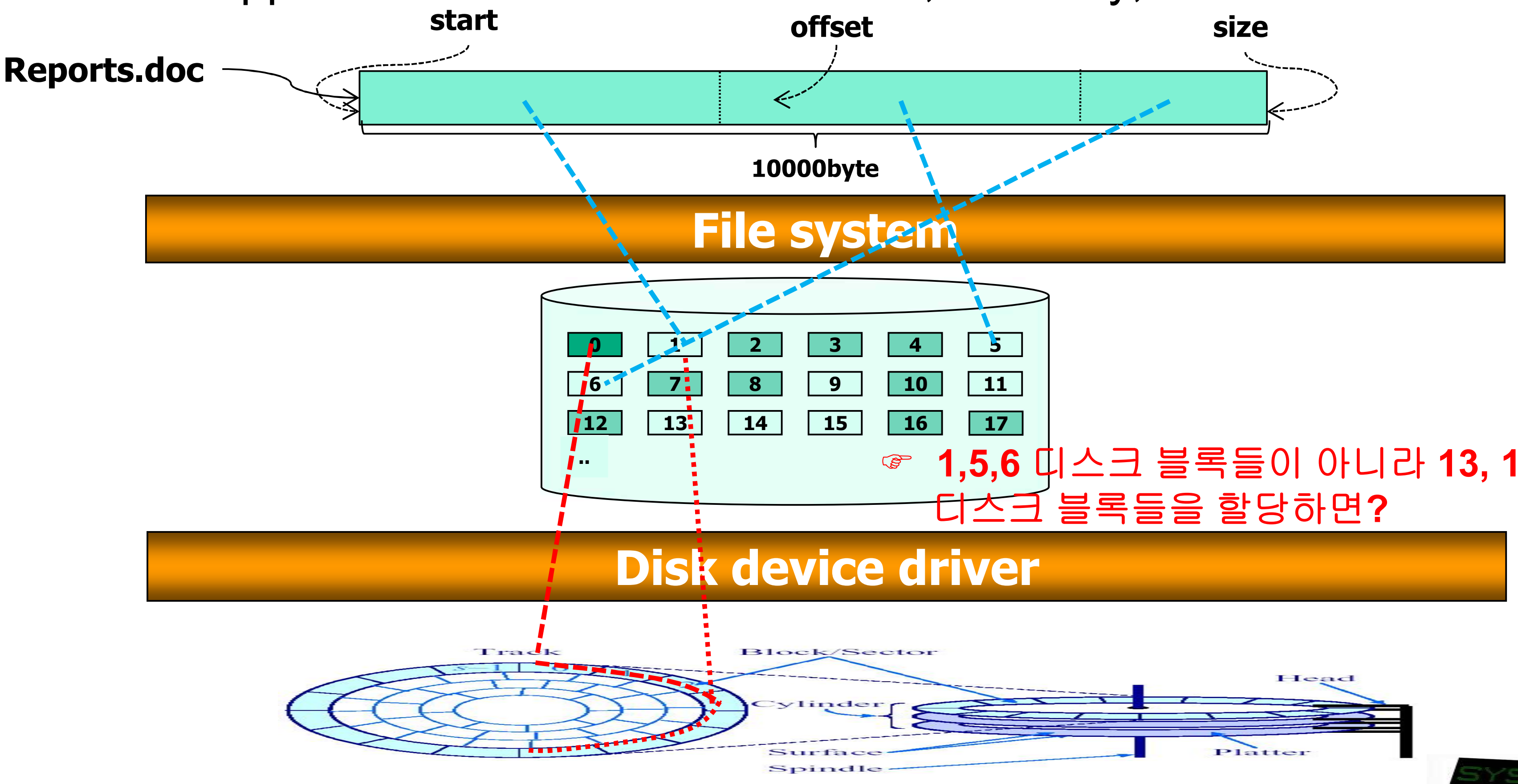
System programs for Disk (1/7)

- Disk device driver
  - ✓ Abstract disk as a logical disk (a collection of disk blocks)
    - The size of a disk block is the same as that of page frame (4 or 8KB)
  - ✓ Disk command handling (ATA command: type, start, size, device, …)
  - ✓ Disk initialization, scheduling, error handling, …



System programs for Disk (2/7)

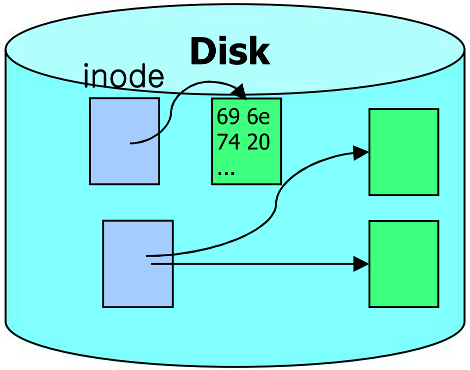
- File system
  - ✓ Support file abstraction: stream of bytes
  - ✓ Associate a file with disk blocks (inode, FAT)
  - ✓ Support file attribute/access control, directory, …



☞ **1,5,6** 디스크 블록들이 아니라 **13, 14, 15** 디스크 블록들을 할당하면**?**

System programs for Disk (3/7)

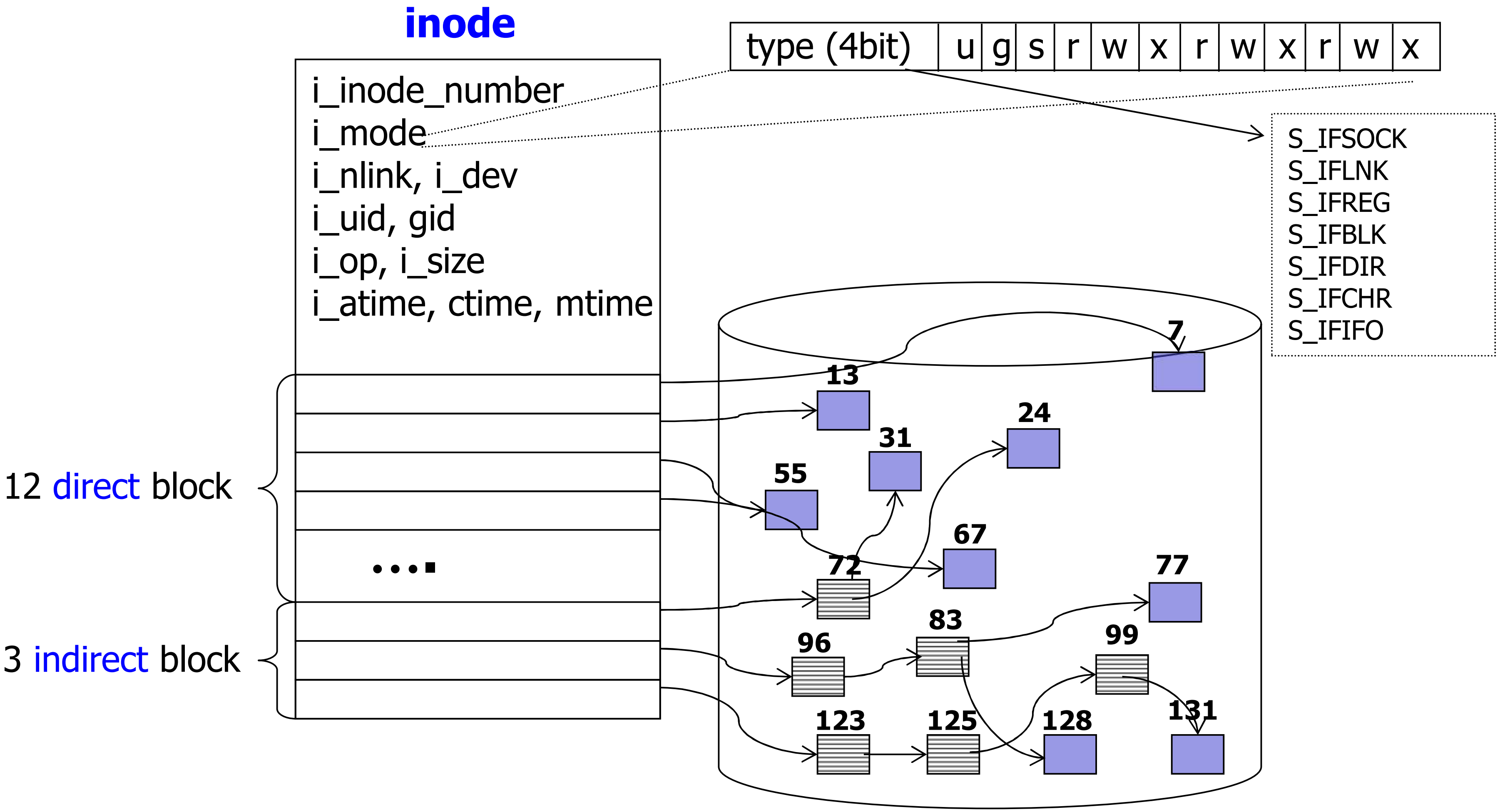
- File system
  - ✓ inode concept
    - An object for managing a file in a file system (metadata)
    - Used by various file systems such as UFS, FFS, Ext2/3/4, LFS, …
    - Maintain information for a file (e.g. “ls –l”)
      - file size
      - locations of disk blocks for a file
      - file owner, access permission
      - time information
      - file type: regular, directory, device, pipe, socket, …
    - Stored in disk
    - Constructed when a file is created



(from LN1)

System programs for Disk (4/7)

- File system
  - ✓ inode structure



inode

i_inode_number
i_mode
i_nlink, i_dev
i_uid, gid
i_op, i_size
i_atime, ctime, mtime
....

type (4bit)	u	g	s	r	w	x	r	w	x	r	w	x

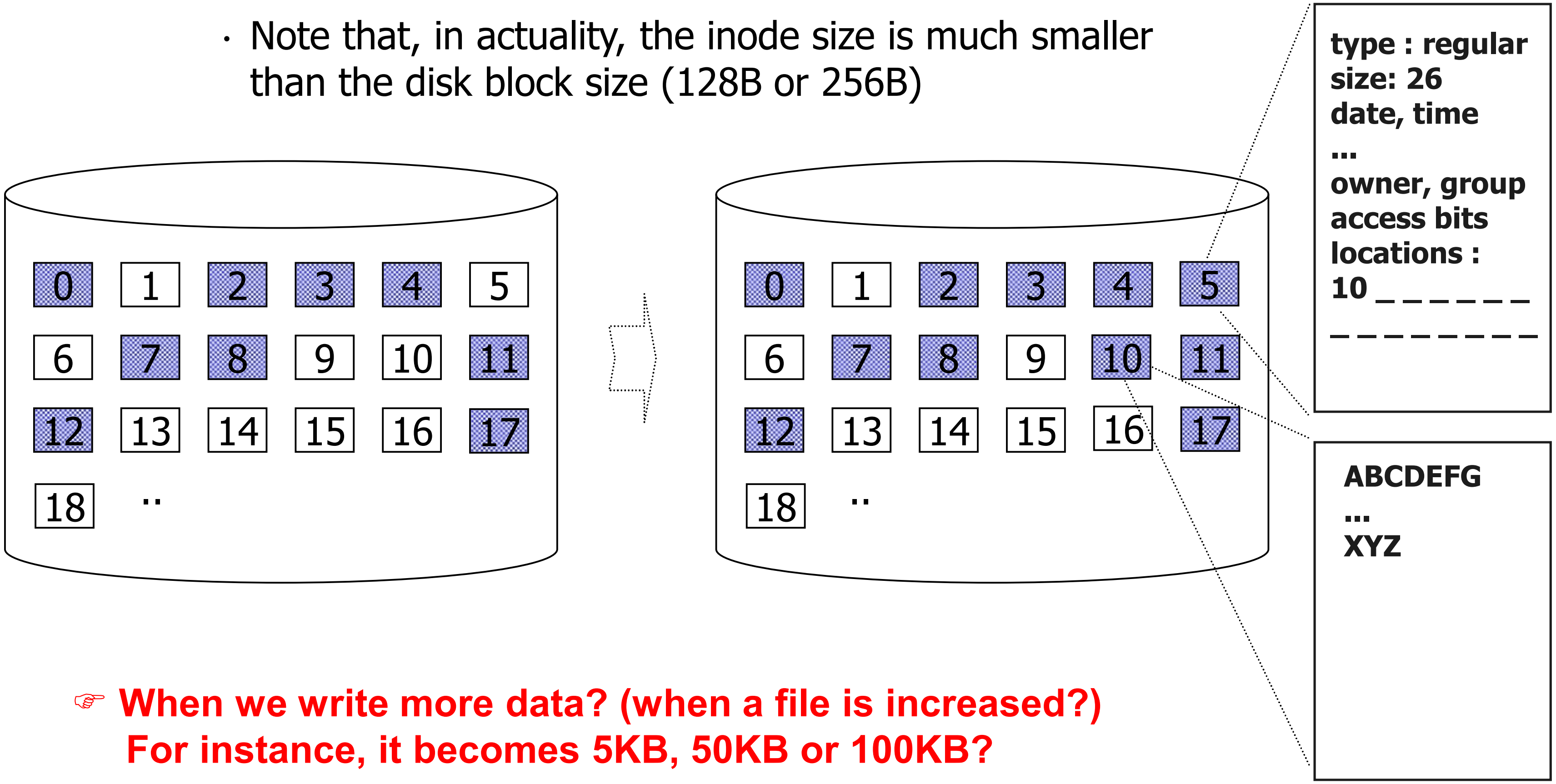
S_IFSOCK
S_IFLNK
S_IFREG
S_IFBLK
S_IFDIR
S_IFCHR
S_IFIFO

12 direct block

3 indirect block

System programs for Disk (5/7)

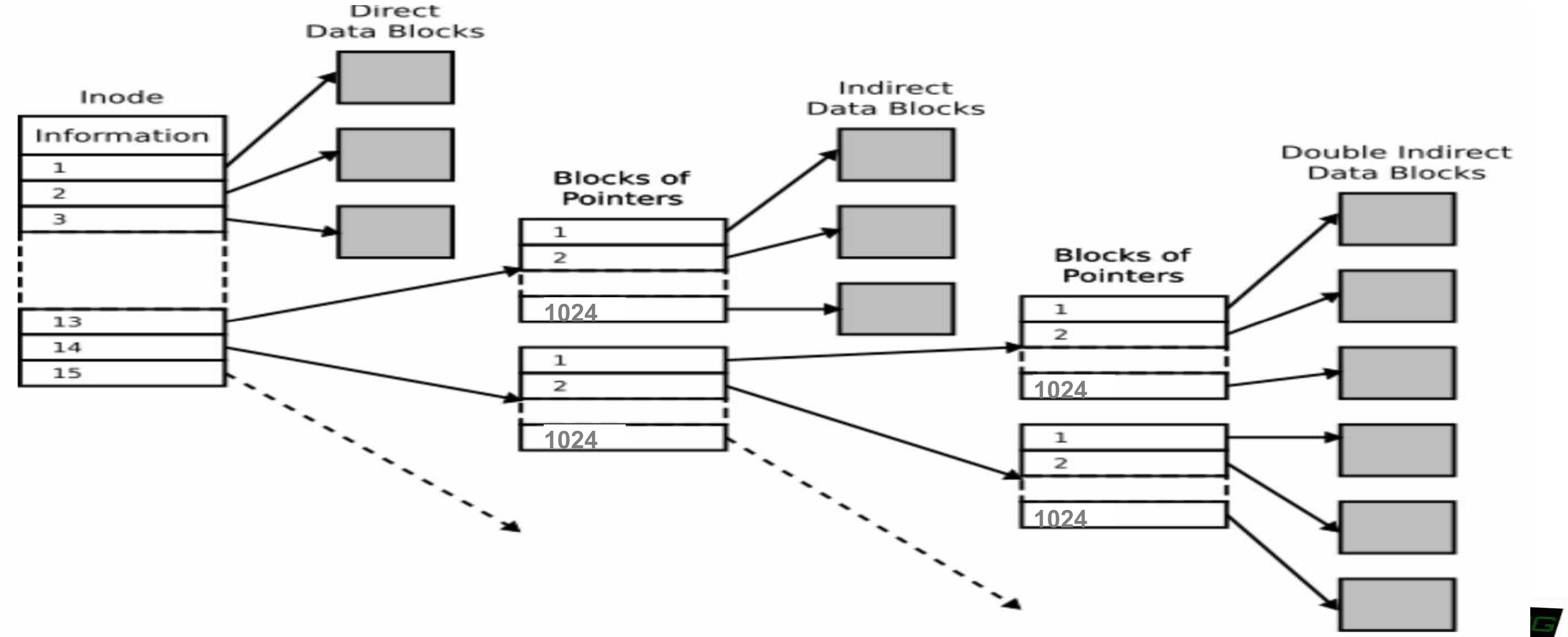
- File system
  - ✓ inode example
    - When we create a new file, named “alphabet.txt”, whose contents include “AB…Z”.
      - Note that, in actuality, the inode size is much smaller than the disk block size (128B or 256B)



☞ **When we write more data? (when a file is increased?)**
For instance, it becomes 5KB, 50KB or 100KB?

Quiz for 4th-Week 2nd-Lesson

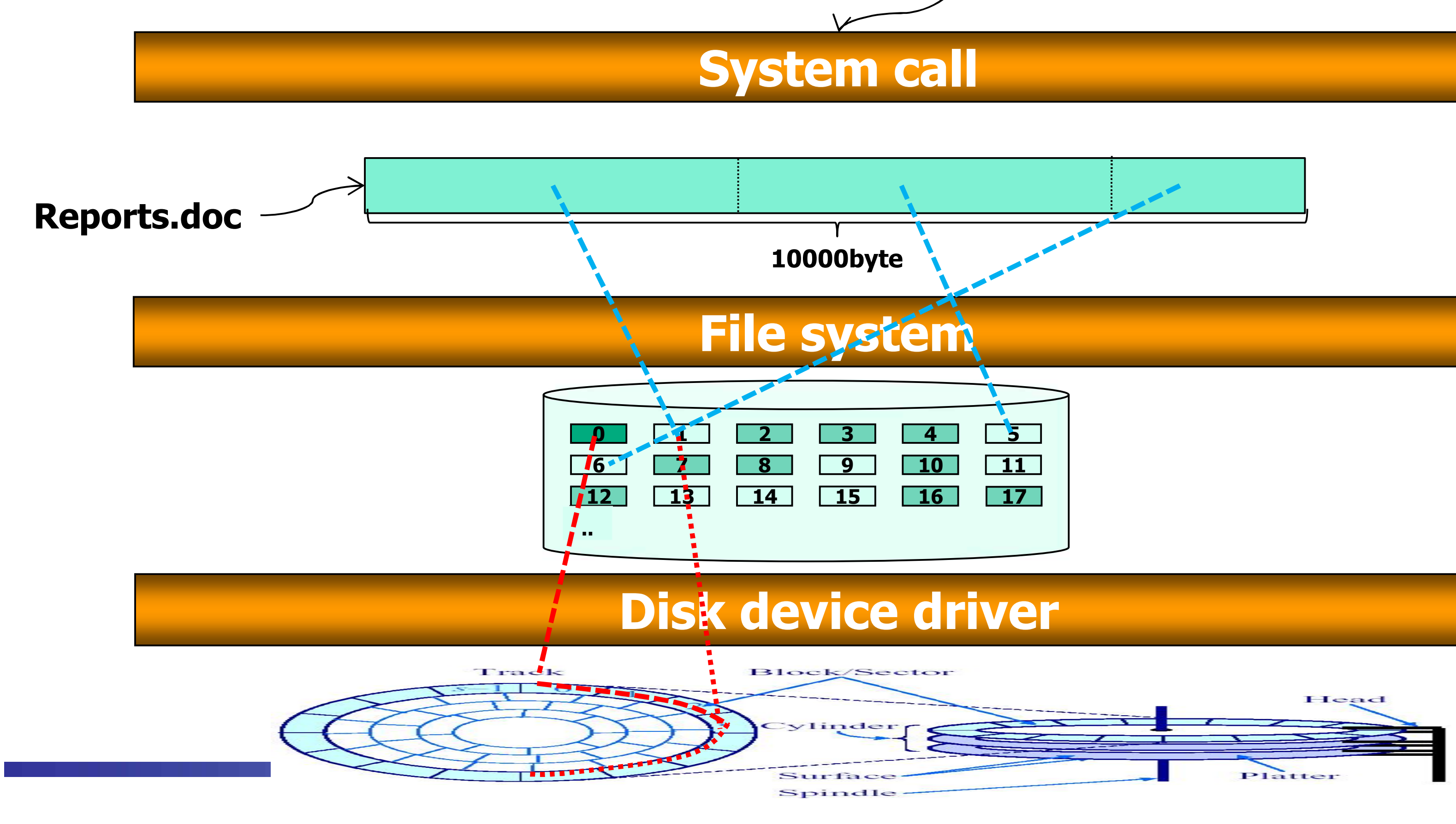
- Quiz
  - ✓ 1) What are the merits and demerit of the sequential allocation? (see 9 page)
  - ✓ 2) How large size can an inode support using direct block pointer? How about single, double, and triple indirect pointer?
  - ✓ Due: until 6 PM Friday of this week (25th, September)



System programs for Disk (6/7)

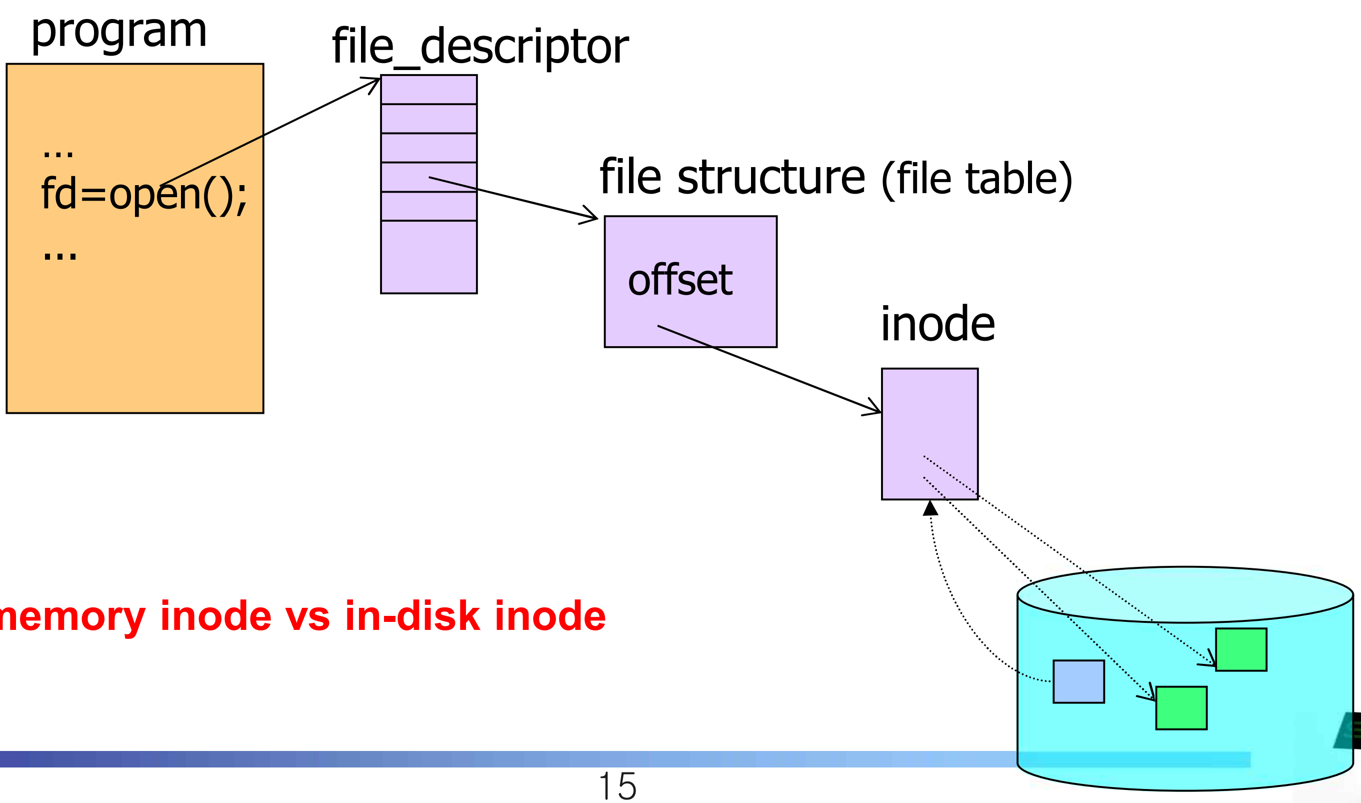
- System call
  - ✓ Support interfaces such as open(), read(), write(), close(), …

```
fd=open("Reports.doc", ...)
read(fd, buf, size) or write(fd, buf, size)
close(fd)
```



System programs for Disk (7/7)

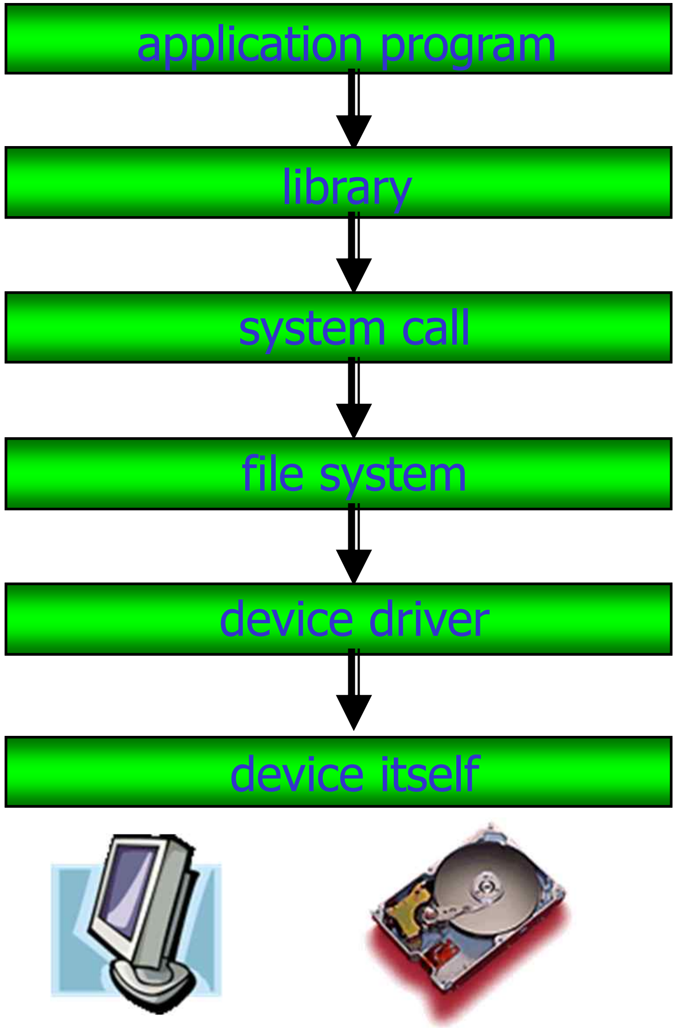
- System call
  - ✓ Use fd (file descriptor) instead of file name (for efficiency)
    - fd: object to point out a file in kernel
    - return value of the open() system call
    - used by the following read(), write(), …, close() system calls
    - fd is connected into inode through various kernel objects (file table)



☞ **in-memory inode vs in-disk inode**

Layered Architecture for Abstraction

- Revisit LN1



application program

library

system call

file system

device driver

device itself

File Programming: Basic (1/11)

- Practice 1: read data from an existing file

```
/* file_test1.c: read data from a file, by choijm. choijm@dku.edu*/
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF    16
char fname[] = “alphabet.txt";

int main()
{
    int fd, size;
    char buf[MAX_BUF];

    fd = open(fname, O_RDONLY);
    if (fd < 0) {
            printf(“Can’t open %s file with errno %d₩n”, fname, errno);
            exit(-1);
    }
    size = read(fd, buf, MAX_BUF);
    if (size < 0) {
            printf(“Can’t read from file %s, size = %d₩n”, fname, size);
            exit(-1);
    }
    else
            printf(“size of read data is %d₩n”, size);
    close(fd);
}
```

Refer to next slide (Syntax)

Inform the cause when an error occurs
cf) Error handling is quite important!!

File Programming: Basic (2/11)

- Syntax of the open() and read() system call

int open(const char *pathname, int flags, [mode_t mode])

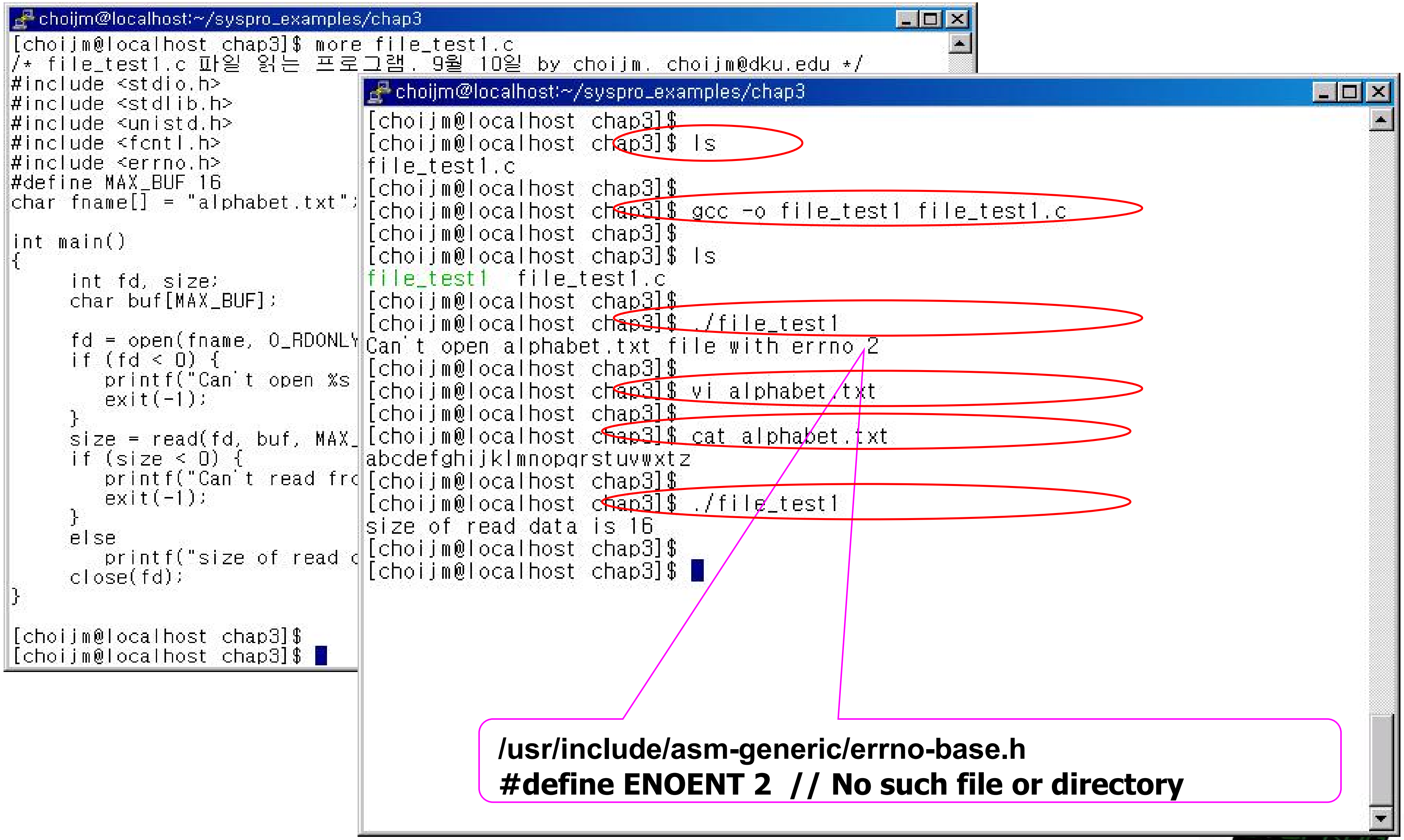
- ✓ pathname : absolute path or relative path
- ✓ flags (see: /usr/include/asm/fcntl.h or Chapter 4.3 in the LPI)
  - O_RDONLY, O_WRONLY, O_RDWR
  - O_CREAT, O_EXCL
  - O_TRUNC, O_APPEND
  - O_NONBLOCK, O_SYNC
  - …
- ✓ mode
  - meaningful with the O_CREAT flag
  - file access mode (S_IRUSR, S_IWUSR, S_IXUSR, S_IRGRP, …, S_IROTH, …)
- ✓ return value
  - file descriptor if success
  - -1 if fail

int read(int fd, char *buf, int size) // same as the write(fd, buf, size)

- ✓ fd: file descriptor (return value of open())
- ✓ buf: memory space for keeping data
- ✓ size: request size
- ✓ return value
  - read size
  - -1 if fail

File Programming: Basic (3/11)

- Practice 1: execution results



```
[choijm@localhost chap3]$ more file_test1.c
/* file_test1.c 파일 읽는 프로그램. 9월 10일 by choijm. choijm@dku.edu */
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF 16
char fname[] = "alphabet.txt";

int main()
{
      int fd, size;
      char buf[MAX_BUF];

      fd = open(fname, O_RDONLY
      if (fd < 0) {
         printf("Can't open %s
         exit(-1);
      }
      size = read(fd, buf, MAX_
      if (size < 0) {
         printf("Can't read fro
         exit(-1);
      }
      else
         printf("size of read c
      close(fd);
}

[choijm@localhost chap3]$
[choijm@localhost chap3]$
```

```
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ls
file_test1.c
[choijm@localhost chap3]$
[choijm@localhost chap3]$ gcc -o file_test1 file_test1.c
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ls
file_test1  file_test1.c
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ./file_test1
Can't open alphabet.txt file with errno 2
[choijm@localhost chap3]$
[choijm@localhost chap3]$ vi alphabet.txt
[choijm@localhost chap3]$
[choijm@localhost chap3]$ cat alphabet.txt
abcdefghijklmnopqrstuvwxtz
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ./file_test1
size of read data is 16
[choijm@localhost chap3]$
[choijm@localhost chap3]$
```

/usr/include/asm-generic/errno-base.h
#define ENOENT 2 // No such file or directory

File Programming: Basic (4/11)

- Practice 2: extend the practice 1 so that it displays the read data on terminal

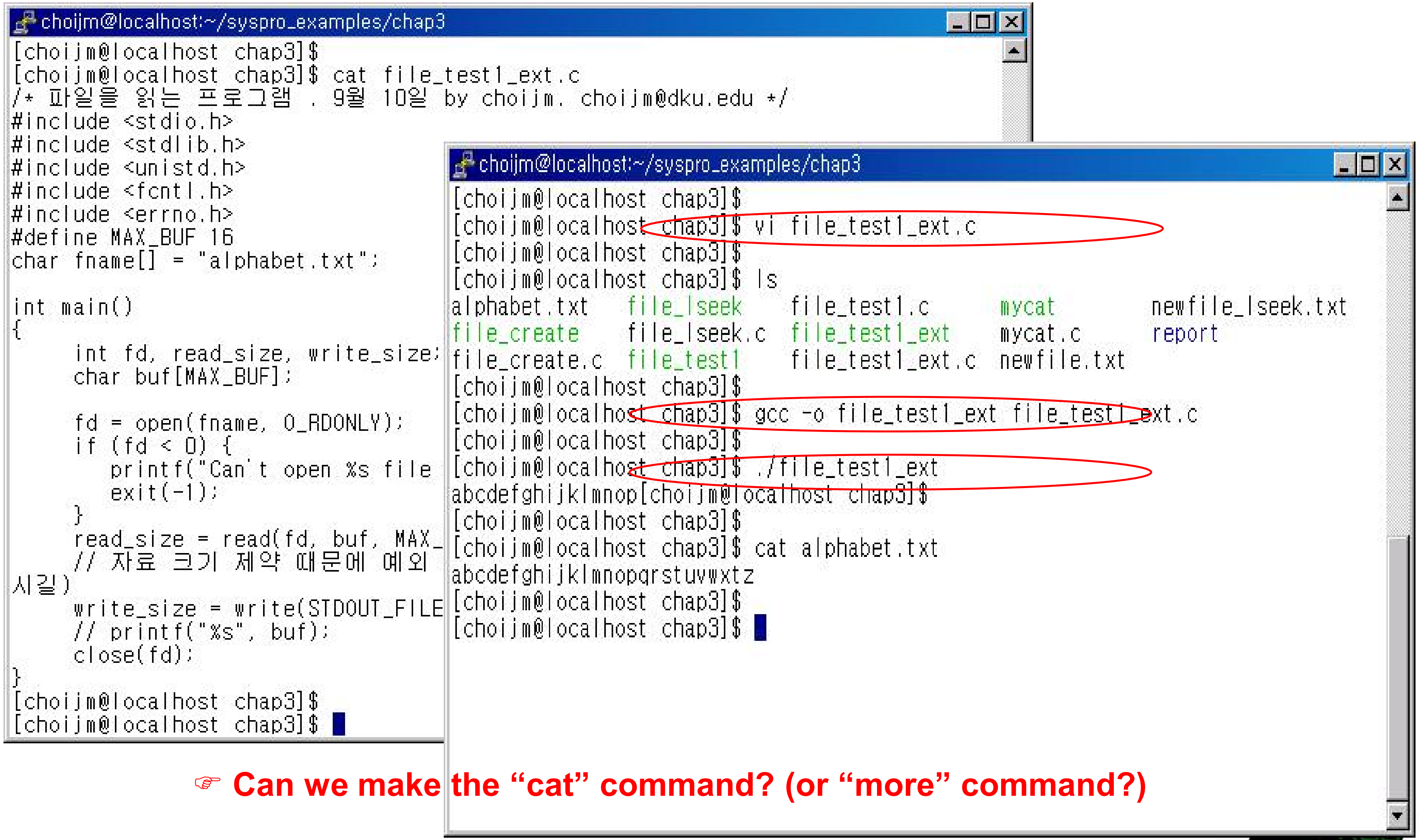
```
/* file_test1_ext.c: read data from a file and display them, by choijm. choijm@dku.edu*/
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF    16
char fname[] = “alphabet.txt";

int main()
{
    int fd, read_size, write_size;
    char buf[MAX_BUF];

    fd = open(fname, O_RDONLY);
    if (fd < 0) {
            printf(“Can’t open %s file with errno %d₩n”, fname, errno);
            exit(-1);
    }
    read_size = read(fd, buf, MAX_BUF);
    // Due to the slide limit, I omit the error handling code (But, students must implement it)
    write_size = write(STDOUT_FILENO, buf, read_size);
    close(fd);
}
```

/usr/include/unistd.h 참조

```
#define STDIN_FILENO     0   // Standard input
#define STDOUT_FILENO    1   // Standard output
#define STDERR_FILENO    2   // Standard error
```

File Programming: Basic (5/11)

- Practice 2: execution results



```
[choijm@localhost chap3]$
[choijm@localhost chap3]$ cat file_test1_ext.c
/* 파일을 읽는 프로그램 . 9월 10일 by choijm. choijm@dku.edu */
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF 16
char fname[] = "alphabet.txt";

int main()
{
     int fd, read_size, write_size;
     char buf[MAX_BUF];

     fd = open(fname, O_RDONLY);
     if (fd < 0) {
        printf("Can't open %s file
        exit(-1);
     }
     read_size = read(fd, buf, MAX_
     // 자료 크기 제약 때문에 예외
시길)
     write_size = write(STDOUT_FILE
     // printf("%s", buf);
     close(fd);
}
[choijm@localhost chap3]$
[choijm@localhost chap3]$
```

```
[choijm@localhost chap3]$
[choijm@localhost chap3]$ vi file_test1_ext.c
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ls
alphabet.txt   file_lseek    file_test1.c      mycat        newfile_lseek.txt
file_create    file_lseek.c  file_test1_ext    mycat.c      report
file_create.c  file_test1    file_test1_ext.c  newfile.txt
[choijm@localhost chap3]$
[choijm@localhost chap3]$ gcc -o file_test1_ext file_test1_ext.c
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ./file_test1_ext
abcdefghijklmnop[choijm@localhost chap3]$
[choijm@localhost chap3]$
[choijm@localhost chap3]$ cat alphabet.txt
abcdefghijklmnopqrstuvwxtz
[choijm@localhost chap3]$
[choijm@localhost chap3]$
```

☞ **Can we make the "cat" command? (or "more" command?)**

File Programming: Basic (6/11)

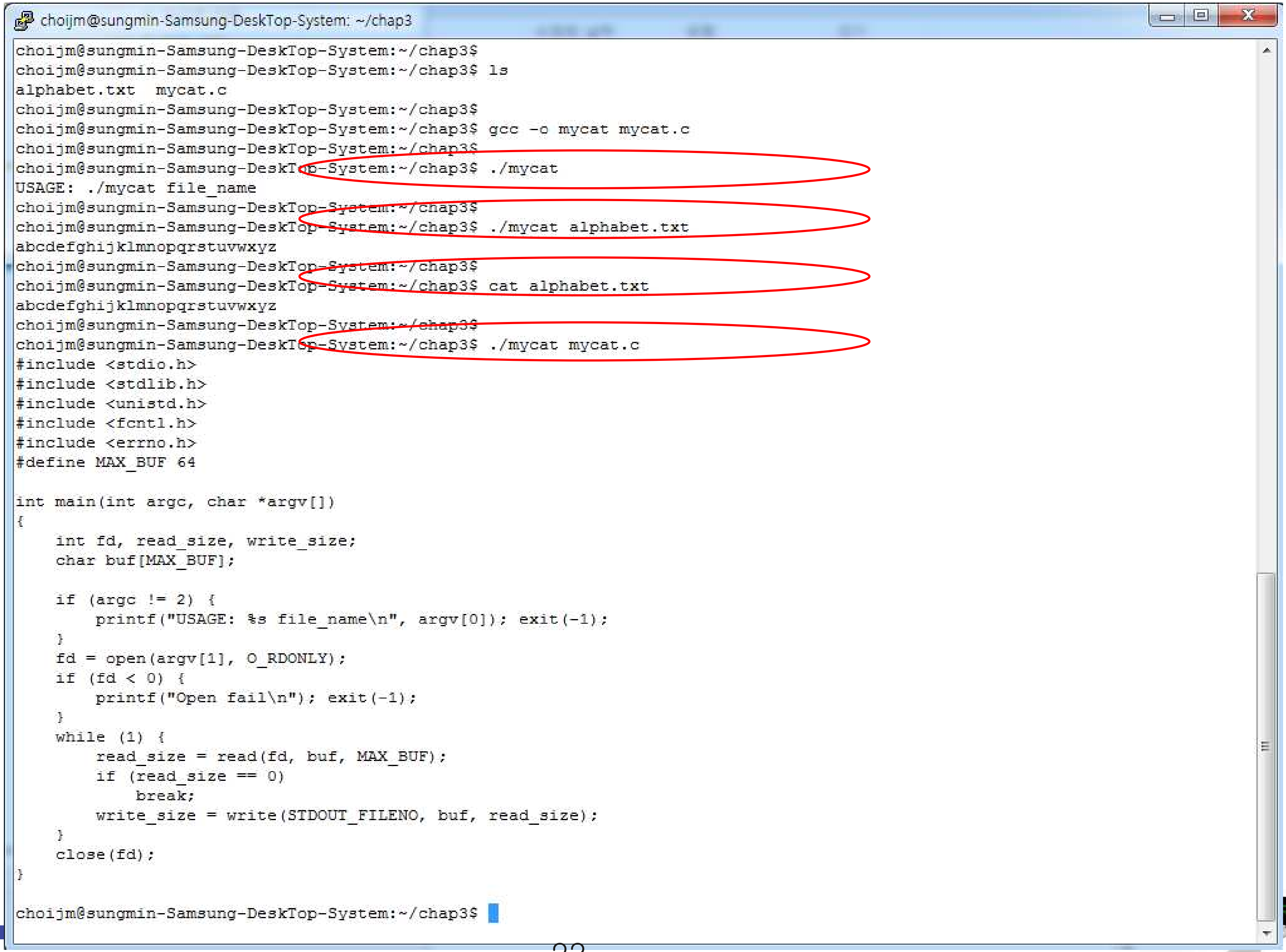
- Practice 3: make a “mycat” command (with argc, argv)

```
/* mycat program, by choijm. choijm@dku.edu */
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF 64

int main(int argc, char *argv[])
{
    int fd, read_size, write_size;
    char buf[MAX_BUF];

    if (argc != 2) {
        printf("USAGE: %s file_name₩n", argv[0]);  exit(-1);
    }
    fd = open(argv[1], O_RDONLY);
    if (fd < 0) {
        // open error handling
    }
    while (1) {
        read_size = read(fd, buf, MAX_BUF);
         if (read_size == 0)
                break;
        write_size = write(STDOUT_FILENO, buf, read_size);
    }
    close(fd);
}
```

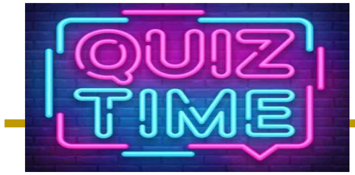
Command Convention

File Programming: Basic (7/11)

- Practice 3: execution results



```
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ ls
alphabet.txt  mycat.c
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ gcc -o mycat mycat.c
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ ./mycat
USAGE: ./mycat file_name
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ ./mycat alphabet.txt
abcdefghijklmnopqrstuvwxyz
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ cat alphabet.txt
abcdefghijklmnopqrstuvwxyz
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ ./mycat mycat.c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF 64

int main(int argc, char *argv[])
{
    int fd, read_size, write_size;
    char buf[MAX_BUF];

    if (argc != 2) {
        printf("USAGE: %s file_name\n", argv[0]); exit(-1);
    }
    fd = open(argv[1], O_RDONLY);
    if (fd < 0) {
        printf("Open fail\n"); exit(-1);
    }
    while (1) {
        read_size = read(fd, buf, MAX_BUF);
        if (read_size == 0)
            break;
        write_size = write(STDOUT_FILENO, buf, read_size);
    }
    close(fd);
}

choijm@sungmin-Samsung-DeskTop-System:~/chap3$ 
```



Quiz for 5th-Week 1st-Lesson

- Quiz
  - ✓ 1) Describe the roles of three system programs for disk.
  - ✓ 2) What is the function of O_SYNC of the flags in the open() system call? What is the merit and demerit?
  - ✓ Due: until 6 PM Friday of the next week (9th, October)

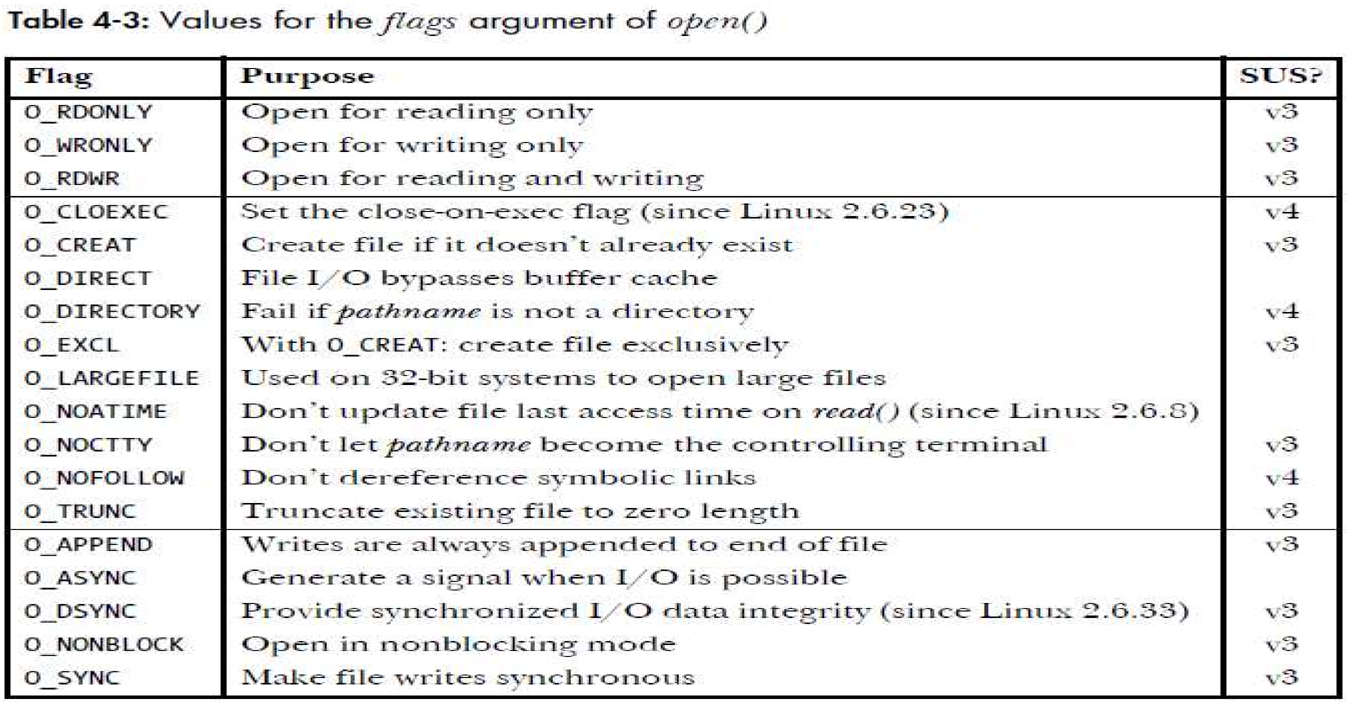


Table 4-3: Values for the *flags* argument of *open()*

Flag	Purpose	SUS?
O_RDONLY	Open for reading only	v3
O_WRONLY	Open for writing only	v3
O_RDWR	Open for reading and writing	v3
O_CLOEXEC	Set the close-on-exec flag (since Linux 2.6.23)	v4
O_CREAT	Create file if it doesn't already exist	v3
O_DIRECT	File I/O bypasses buffer cache	
O_DIRECTORY	Fail if *pathname* is not a directory	v4
O_EXCL	With O_CREAT: create file exclusively	v3
O_LARGEFILE	Used on 32-bit systems to open large files	
O_NOATIME	Don't update file last access time on *read()* (since Linux 2.6.8)	
O_NOCTTY	Don't let *pathname* become the controlling terminal	v3
O_NOFOLLOW	Don't dereference symbolic links	v4
O_TRUNC	Truncate existing file to zero length	v3
O_APPEND	Writes are always appended to end of file	v3
O_ASYNC	Generate a signal when I/O is possible	
O_DSYNC	Provide synchronized I/O data integrity (since Linux 2.6.33)	v3
O_NONBLOCK	Open in nonblocking mode	v3
O_SYNC	Make file writes synchronous	v3

(Source: LPI)

File Programming: Basic (8/11)

- Practice 4: create a new file

```
/* file_create.c: create a new file, by choijm. choijm@dku.edu */
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF 64
char fname[] = "newfile.txt";
char dummy_data[]="abcdefg₩n";

int main() {
    int fd, write_size, read_size;
    char buf[MAX_BUF];

    fd = open(fname, O_RDWR | O_CREAT | O_EXCL, 0664);
    if (fd < 0) {
        printf("Can't create %s file with errno %d₩n", fname, errno); exit(1);
    }
    write_size = write(fd, dummy_data, sizeof(dummy_data));
    printf("write_size = %d₩n", write_size);
    close(fd);

    fd = open(fname, O_RDONLY);
    read_size = read(fd, buf, MAX_BUF);
    printf("read_size = %d₩n", read_size);
    write_size = write(STDOUT_FILENO, buf, read_size);
    close(fd);
}
```

If we rerun this program?

If we rerun without the O_EXCL flag?

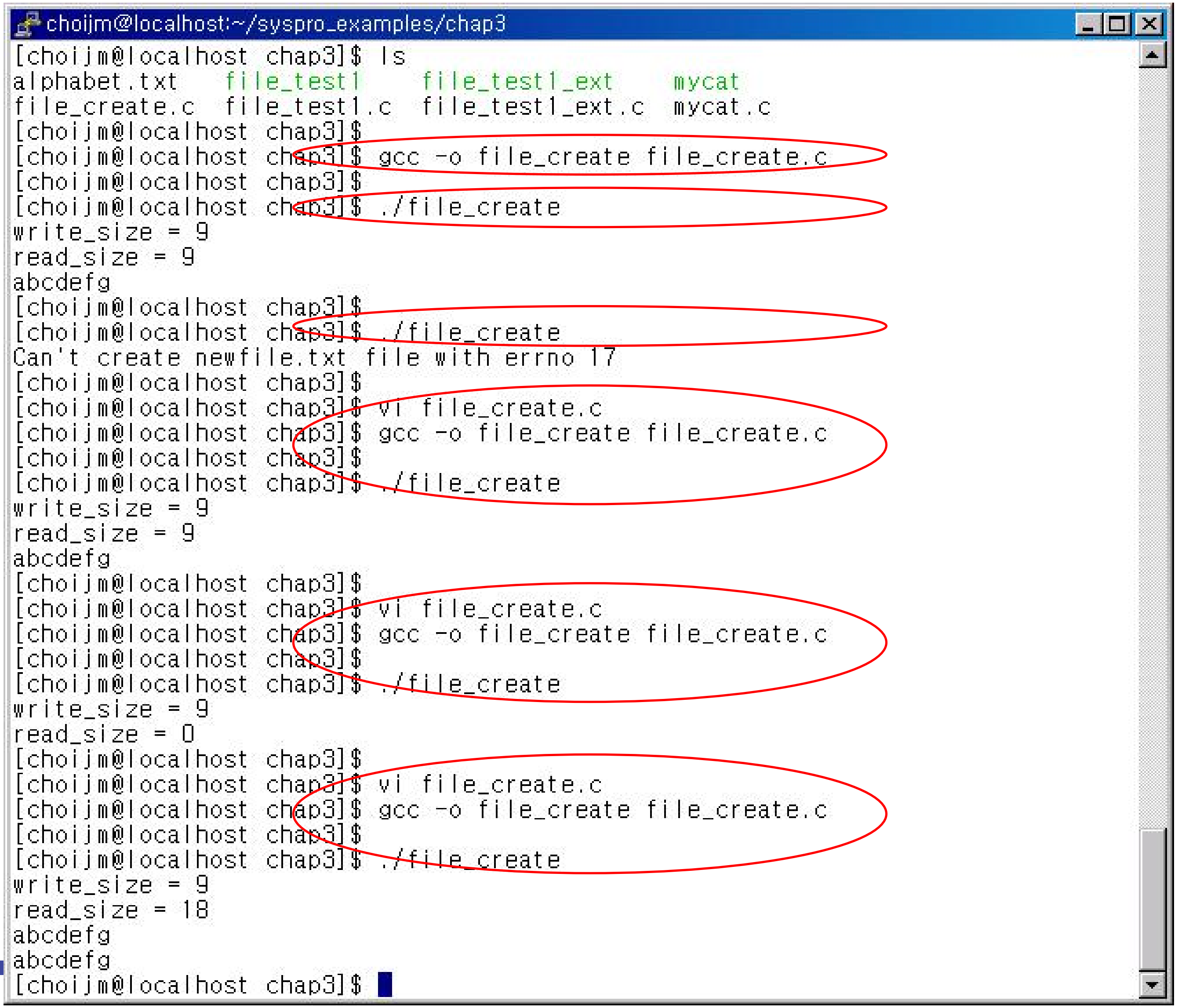
O_CREAT or creat()

If we want to write data at the end of this file?

If we comment out these close() and open() statements?

File Programming: Basic (9/11)

- Practice 4: execution results



choijm@localhost:~/syspro_examples/chap3

```
[choijm@localhost chap3]$ ls
alphabet.txt   file_test1    file_test1_ext    mycat
file_create.c  file_test1.c  file_test1_ext.c  mycat.c
[choijm@localhost chap3]$
[choijm@localhost chap3]$ gcc -o file_create file_create.c
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ./file_create
write_size = 9
read_size = 9
abcdefg
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ./file_create
Can't create newfile.txt file with errno 17
[choijm@localhost chap3]$
[choijm@localhost chap3]$ vi file_create.c
[choijm@localhost chap3]$ gcc -o file_create file_create.c
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ./file_create
write_size = 9
read_size = 9
abcdefg
[choijm@localhost chap3]$
[choijm@localhost chap3]$ vi file_create.c
[choijm@localhost chap3]$ gcc -o file_create file_create.c
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ./file_create
write_size = 9
read_size = 0
[choijm@localhost chap3]$
[choijm@localhost chap3]$ vi file_create.c
[choijm@localhost chap3]$ gcc -o file_create file_create.c
[choijm@localhost chap3]$
[choijm@localhost chap3]$ ./file_create
write_size = 9
read_size = 18
abcdefg
abcdefg
[choijm@localhost chap3]$
```

File Programming: Basic (10/11)

- Practice 5: want to read “d” from a file whose contents are “abcdefg”
  - ✓ Using lseek()

off_t lseek(int fd, off_t offset, int whence)

- ✓ fd : file descriptor
- ✓ offset : offset position
- ✓ whence (/usr/include/unistd.h)
  - SEEK_SET : New offset is set to offset bytes.
  - SEEK_CUR: New offset is set to its current location plus offset bytes.
  - SEEK_END: New offset is set to the size of the file plus offset bytes
- ✓ return value
  - new offset if success
  - -1 if fail

Negative value is allowed

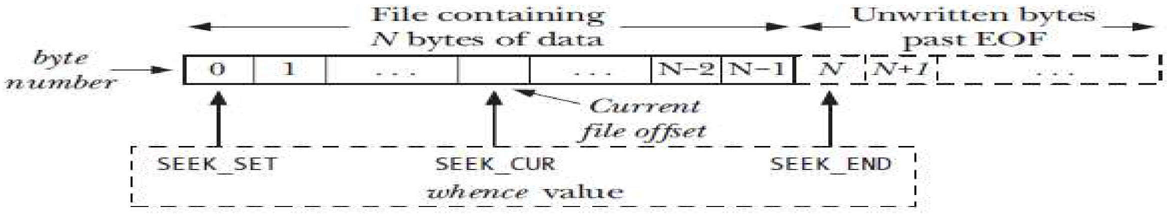


Figure 4-1: Interpreting the *whence* argument of *lseek()*

☞ **sequential access vs. random access**

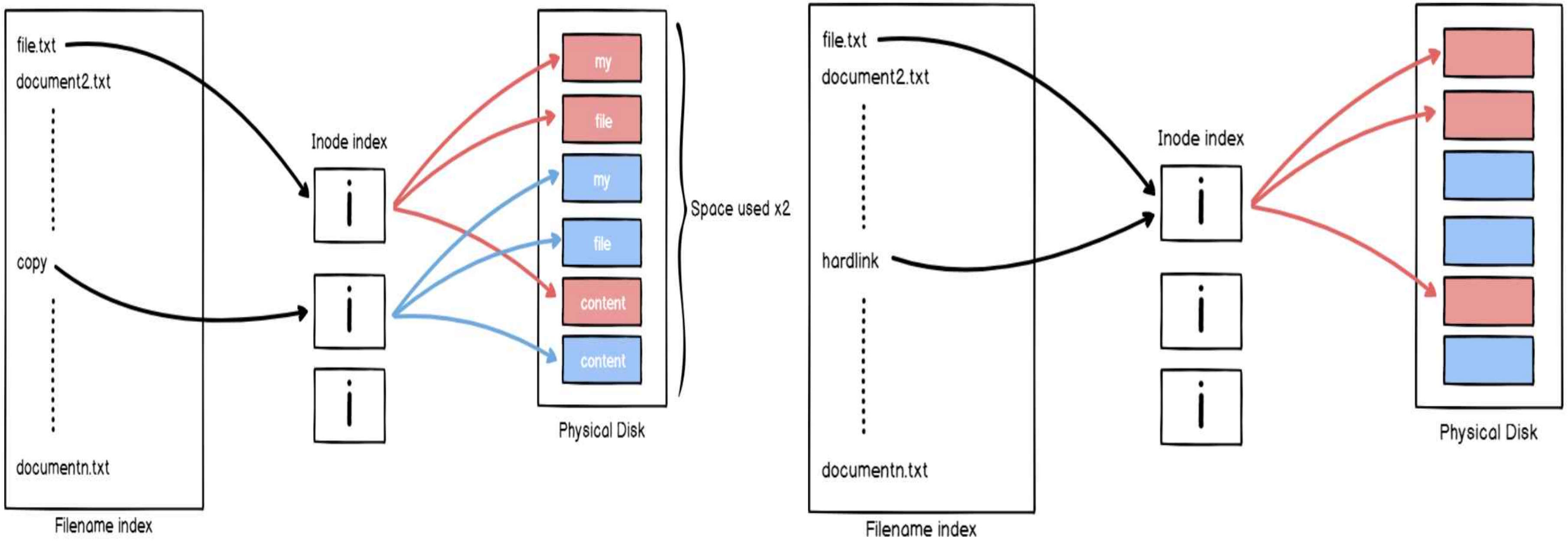
File Programming: Basic (11/11)

- Practice 5: want to read “d” from a file whose contents are “abcdefg”

```
/* file_lseek.c: lseek example, by choijm. choijm@dku.edu */
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF 64
char fname[] = "newfile_lseek.txt";
char dummy_data[]="abcdefg₩n";

int main()
{
   int fd, write_size, read_size, new_offset;
   char buf[MAX_BUF];

   fd = open(fname, O_RDWR | O_CREAT | O_EXCL, 0664);
   write_size = write(fd, dummy_data, sizeof(dummy_data)); printf("write_size = %d₩n", write_size);
   close(fd);

   fd = open(fname, O_RDONLY);
   new_offset = lseek(fd, 3, SEEK_SET);
   read_size = read(fd, buf, MAX_BUF); printf("read_size = %d₩n", read_size);
   write_size = write(STDOUT_FILENO, buf, read_size);
   close(fd);
}
```

File Programming: Advanced (1/6)

- Other system calls related to file
  - ✓ creat() // same as open() with flag **O_WRONLY | O_CREAT | O_TRUNC**
  - ✓ mkdir(), readdir(), rmdir()
  - ✓ pipe()
  - ✓ mknod()
  - ✓ link(), unlink()



(Source: https://devconnected.com/understanding-hard-and-soft-links-on-linux/)

File Programming: Advanced (2/6)

- Other system calls related to file
  - ✓ dup(), dup2()
  - ✓ stat(), fstat()
  - ✓ chmod(), fchmod()
  - ✓ ioctl(), fcntl()
  - ✓ sync(), fsync()

Figure 10.11
Typical kernel data structures for open files. In this example, two descriptors reference distinct files. There is no sharing.

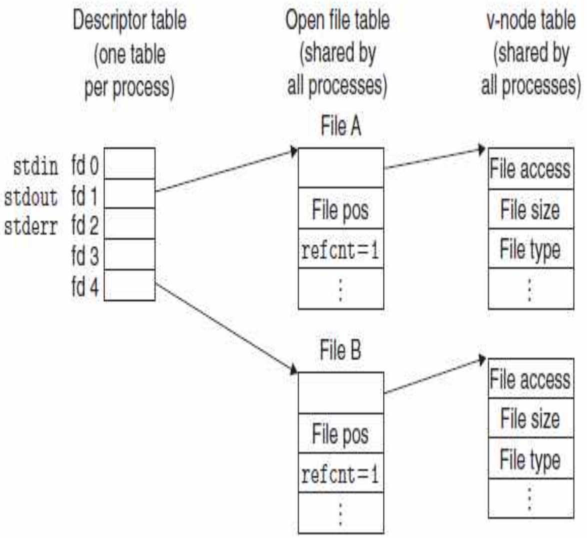
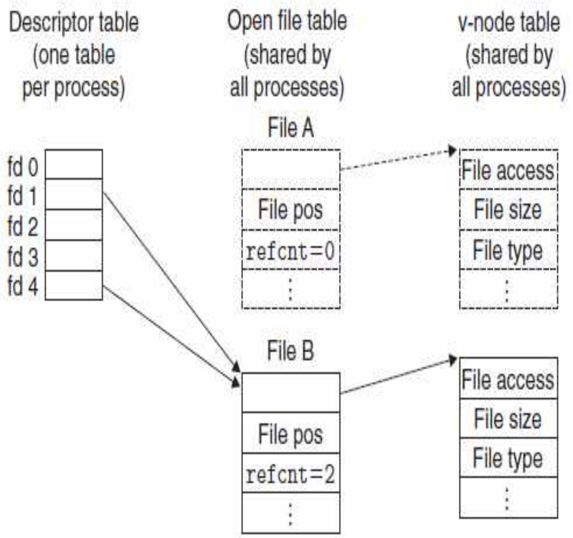


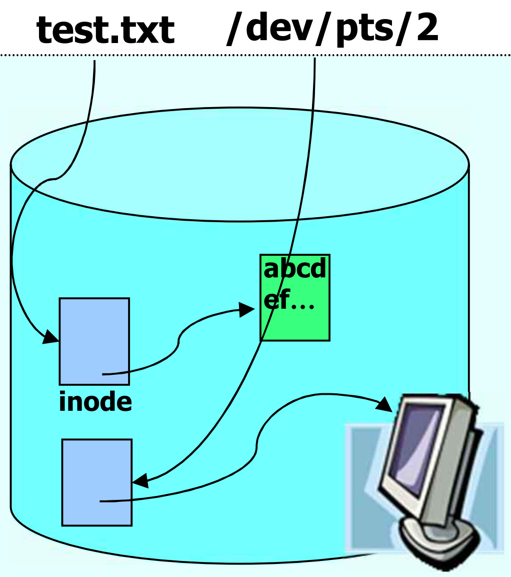
Figure 10.14
Kernel data structures after redirecting standard output by calling dup2(4,1). The initial situation is shown in Figure 10.11.



(Source: CSAPP)

File Programming: Advanced (3/6)

- Practice 6: device file



```
/* file_device.c, by choijm. choijm@dku.edu */
#include <unistd.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>

#define MAX_BUF 4
char fname[] = "test.txt";
char tmp_data[] = "abcdefghijklmn";

int main()
{
        int fd, size;
        char buf[MAX_BUF];

        fd = open(fname, O_RDWR | O_CREAT, S_IRUSR | S_IWUSR);
        write(fd, tmp_data, sizeof(tmp_data));
        close(fd);

        fd = open(fname, O_RDONLY);
        lseek(fd, 5, SEEK_SET);
        size = read(fd, buf, MAX_BUF);
        close(fd);

        fd=open("/dev/pts/2", O_WRONLY);
        write(fd, buf, MAX_BUF);
        close(fd);
}
```

Devices such as terminal can be accessed using file interfaces

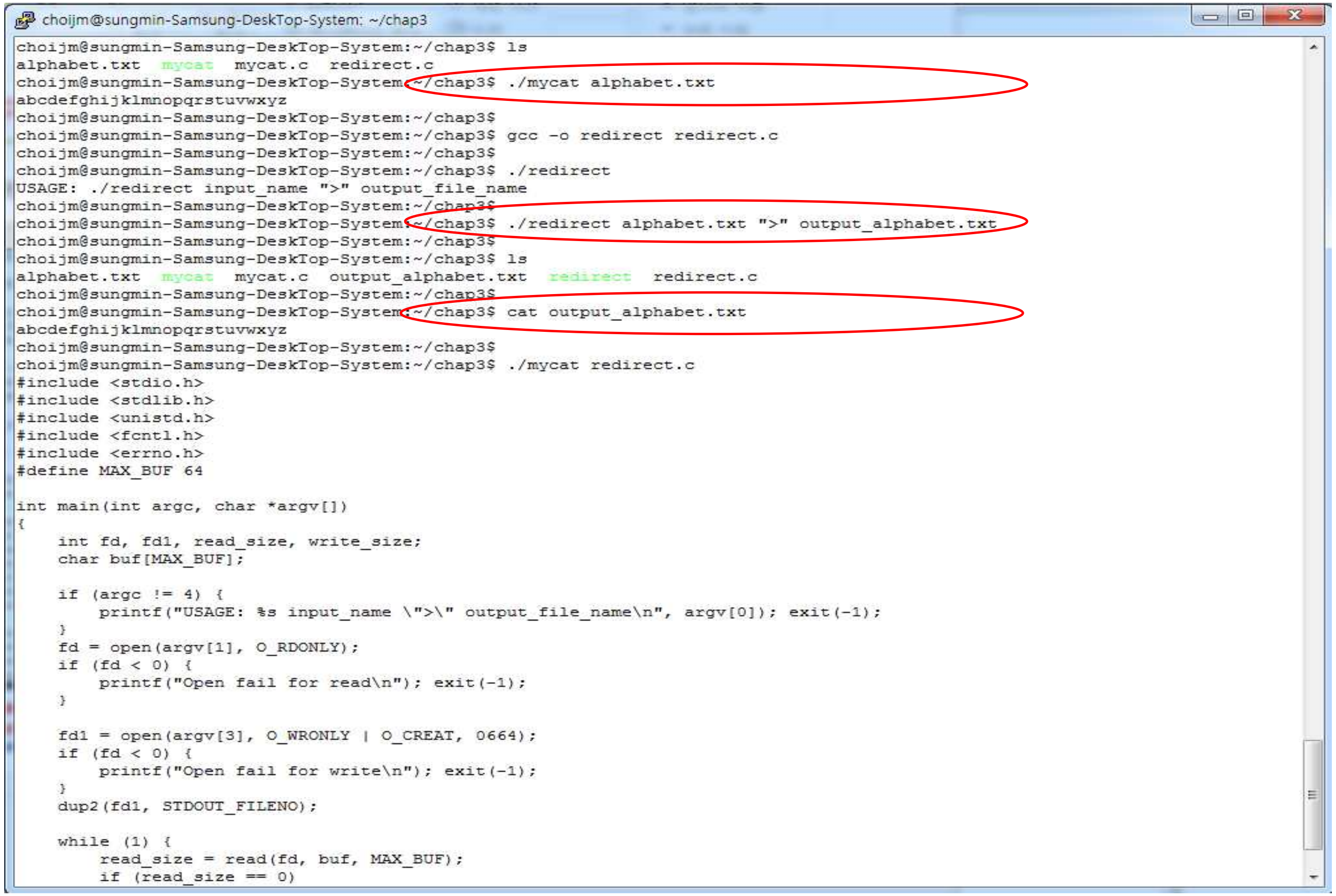
File Programming: Advanced (4/6)

- Practice 7: redirection (derived from “mycat” program)
  - ✓ Same fd but different objects

```
/* file_redirection.c, by choijm. choijm@dku.edu */
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF 64

int main(int argc, char *argv[])
{
   int fd, fd1, read_size, write_size;
   char buf[MAX_BUF];

   if (argc != 4) {
      printf("USAGE: %s input_file_name ₩”>₩” output_file_name₩n", argv[0]);  exit(-1);
   }
   fd = open(argv[1], O_RDONLY);

   // for redirection. (eg. "mycat inputfile.txt > outputfile.txt“)
   // close(STDOUT_FILENO);
    fd1 = open(argv[3], O_RDWR | O_CREAT, 0641);
    dup2(fd1, STDOUT_FILENO);
    // redirection end

  while (1) {
      read_size = read(fd, buf, MAX_BUF);
      if (read_size == 0)
            break;
      write_size = write(STDOUT_FILENO, buf, read_size);
   }
   close(fd);
}
```

File Programming: Advanced (5/6)

- Practice 7: execution results



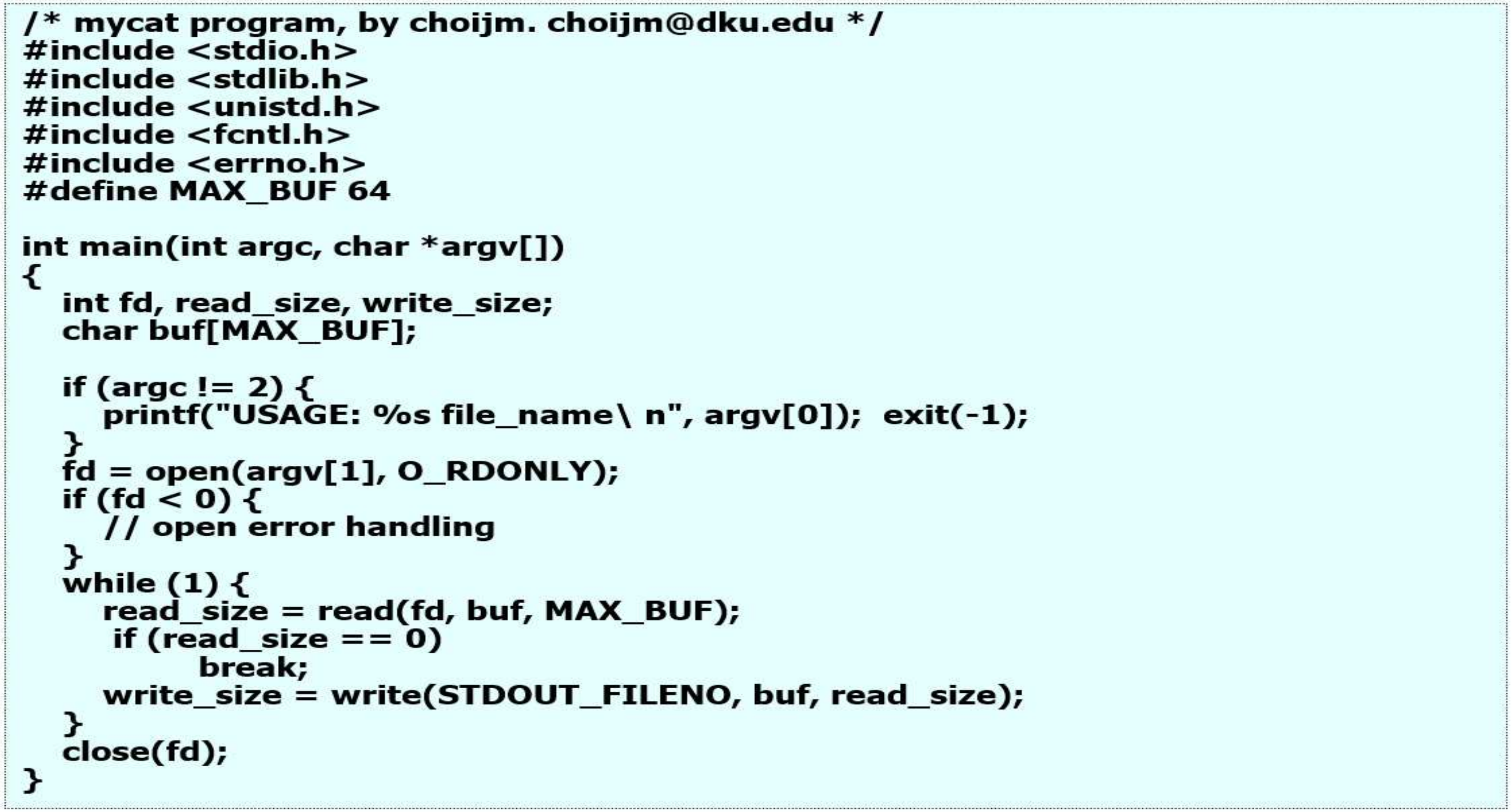
choijm@sungmin-Samsung-DeskTop-System: ~/chap3

```
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ ls
alphabet.txt  mycat  mycat.c  redirect.c
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ ./mycat alphabet.txt
abcdefghijklmnopqrstuvwxyz
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ gcc -o redirect redirect.c
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ ./redirect
USAGE: ./redirect input_name ">" output_file_name
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ ./redirect alphabet.txt ">" output_alphabet.txt
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ ls
alphabet.txt  mycat  mycat.c  output_alphabet.txt  redirect  redirect.c
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ cat output_alphabet.txt
abcdefghijklmnopqrstuvwxyz
choijm@sungmin-Samsung-DeskTop-System:~/chap3$
choijm@sungmin-Samsung-DeskTop-System:~/chap3$ ./mycat redirect.c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF 64

int main(int argc, char *argv[])
{
    int fd, fd1, read_size, write_size;
    char buf[MAX_BUF];

    if (argc != 4) {
        printf("USAGE: %s input_name \">\" output_file_name\n", argv[0]); exit(-1);
    }
    fd = open(argv[1], O_RDONLY);
    if (fd < 0) {
        printf("Open fail for read\n"); exit(-1);
    }

    fd1 = open(argv[3], O_WRONLY | O_CREAT, 0664);
    if (fd < 0) {
        printf("Open fail for write\n"); exit(-1);
    }
    dup2(fd1, STDOUT_FILENO);

    while (1) {
        read_size = read(fd, buf, MAX_BUF);
        if (read_size == 0)
```

☞ **This is just an example. In general, redirection is in the form of "./redirection sourcefile.txt > outputfile.txt" (shell actually handle the redirection code)**

File Programming: Advanced (6/6)

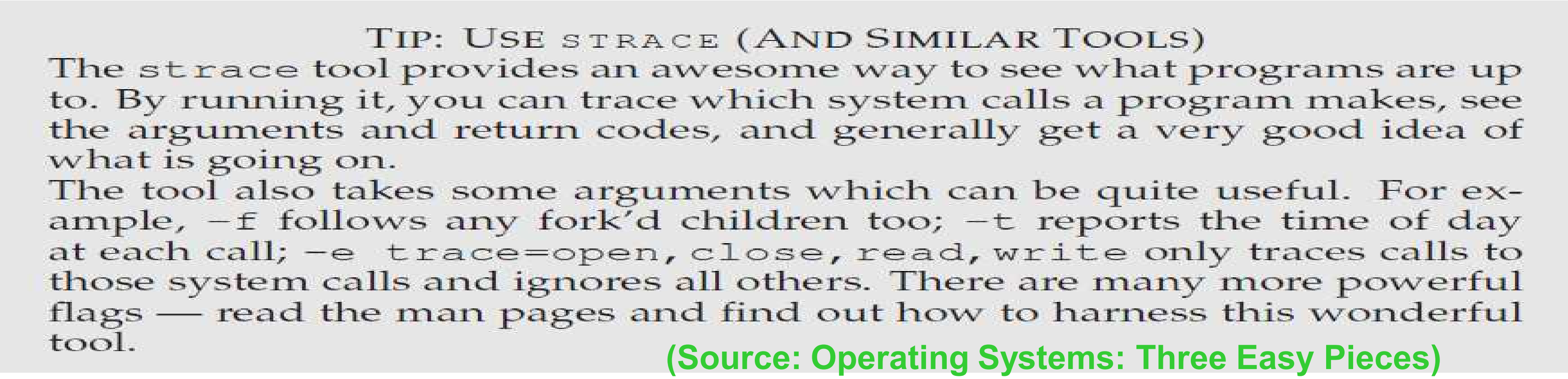
- Discuss the tradeoff about the buffer size in read() and write()
    - ✓ Revisit mycat again: what if we change the MAX_BUF as 32 or 128



```
/* mycat program, by choijm. choijm@dku.edu */
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <fcntl.h>
#include <errno.h>
#define MAX_BUF 64

int main(int argc, char *argv[])
{
   int fd, read_size, write_size;
   char buf[MAX_BUF];

   if (argc != 2) {
      printf("USAGE: %s file_name\ n", argv[0]);  exit(-1);
   }
   fd = open(argv[1], O_RDONLY);
   if (fd < 0) {
      // open error handling
   }
   while (1) {
      read_size = read(fd, buf, MAX_BUF);
       if (read_size == 0)
              break;
      write_size = write(STDOUT_FILENO, buf, read_size);
   }
   close(fd);
}
```

Tracing system call

- Using “strace”

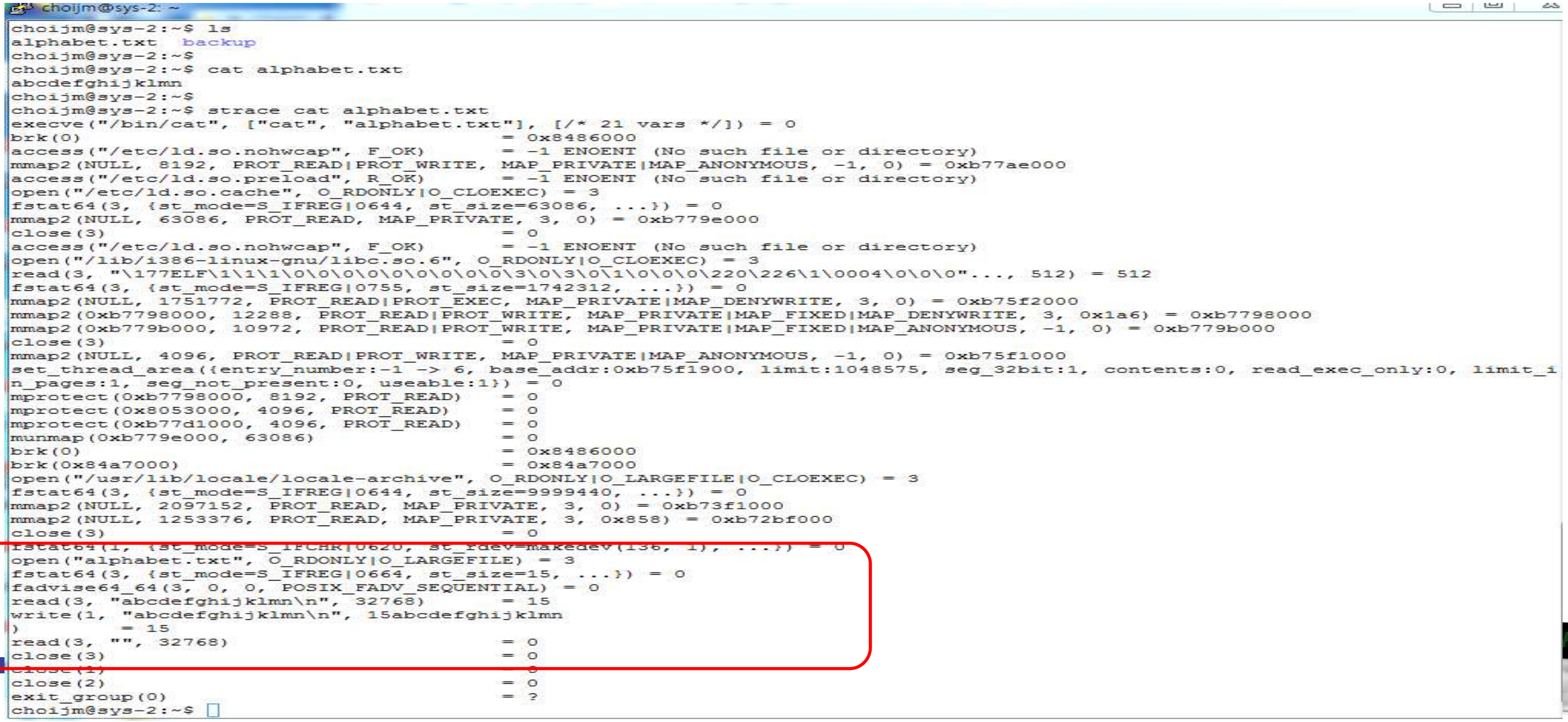


TIP: USE strace (AND SIMILAR TOOLS)

The strace tool provides an awesome way to see what programs are up to. By running it, you can trace which system calls a program makes, see the arguments and return codes, and generally get a very good idea of what is going on.

The tool also takes some arguments which can be quite useful. For example, -f follows any fork’d children too; -t reports the time of day at each call; -e trace=open,close,read,write only traces calls to those system calls and ignores all others. There are many more powerful flags — read the man pages and find out how to harness this wonderful tool.

(Source: Operating Systems: Three Easy Pieces)



```
choijm@sys-2:~$ ls
alphabet.txt  backup
choijm@sys-2:~$
choijm@sys-2:~$ cat alphabet.txt
abcdefghijklmn
choijm@sys-2:~$
choijm@sys-2:~$ strace cat alphabet.txt
execve("/bin/cat", ["cat", "alphabet.txt"], [/* 21 vars */]) = 0
brk(0)                                  = 0x8486000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
mmap2(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0xb77ae000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat64(3, {st_mode=S_IFREG|0644, st_size=63086, ...}) = 0
mmap2(NULL, 63086, PROT_READ, MAP_PRIVATE, 3, 0) = 0xb779e000
close(3)                                = 0
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file or directory)
open("/lib/i386-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\1\1\1\0\0\0\0\0\0\0\0\0\3\0\3\0\1\0\0\0\220\226\1\0004\0\0\0"..., 512) = 512
fstat64(3, {st_mode=S_IFREG|0755, st_size=1742312, ...}) = 0
mmap2(NULL, 1751772, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0xb75f2000
mmap2(0xb7798000, 12288, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1a6) = 0xb7798000
mmap2(0xb779b000, 10972, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0xb779b000
close(3)                                = 0
mmap2(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0xb75f1000
set_thread_area({entry_number:-1 -> 6, base_addr:0xb75f1900, limit:1048575, seg_32bit:1, contents:0, read_exec_only:0, limit_i
n_pages:1, seg_not_present:0, useable:1}) = 0
mprotect(0xb7798000, 8192, PROT_READ)   = 0
mprotect(0x8053000, 4096, PROT_READ)    = 0
mprotect(0xb77d1000, 4096, PROT_READ)   = 0
munmap(0xb779e000, 63086)               = 0
brk(0)                                  = 0x8486000
brk(0x84a7000)                          = 0x84a7000
open("/usr/lib/locale/locale-archive", O_RDONLY|O_LARGEFILE|O_CLOEXEC) = 3
fstat64(3, {st_mode=S_IFREG|0644, st_size=9999440, ...}) = 0
mmap2(NULL, 2097152, PROT_READ, MAP_PRIVATE, 3, 0) = 0xb73f1000
mmap2(NULL, 1253376, PROT_READ, MAP_PRIVATE, 3, 0x858) = 0xb72bf000
close(3)                                = 0
fstat64(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(136, 1), ...}) = 0
open("alphabet.txt", O_RDONLY|O_LARGEFILE) = 3
fstat64(3, {st_mode=S_IFREG|0664, st_size=15, ...}) = 0
fadvise64_64(3, 0, 0, POSIX_FADV_SEQUENTIAL) = 0
read(3, "abcdefghijklmn\n", 32768)      = 15
write(1, "abcdefghijklmn\n", 15abcdefghijklmn
)       = 15
read(3, "", 32768)                      = 0
close(3)                                = 0
close(1)                                = 0
close(2)                                = 0
exit_group(0)                           = ?
choijm@sys-2:~$
```

Summary

- Understand the internal structure of disk
- Find out the relation between system programs for disk
  - ✓ Driver, file system, system call
- Grasp the role of the inode
- Make a program with file interfaces
  - ✓ open, read, write, close
  - ✓ lseek
  - ✓ device file and redirection

☞ **Homework 3: Make a command called "mycp"**

✓ Requirements

- use argc and argv[ ]

- do not create a file if the same name already exists in current directory

- shows student's ID and date (using whoami and date)

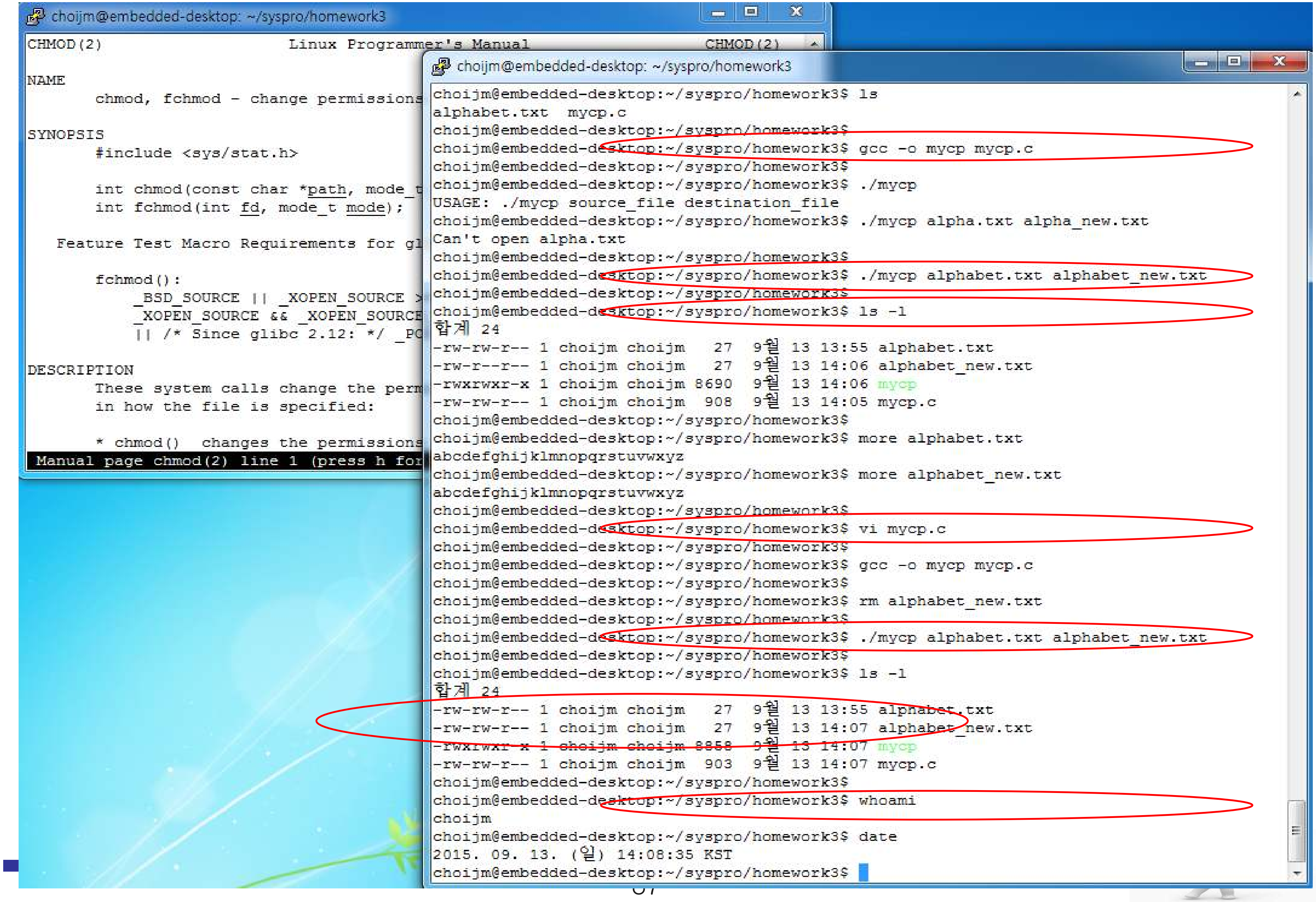
- Make a report that includes a snapshot and discussion.

1) Upload the report to the e-Campus (pdf format!!, 9th October)

2) Send the report and source code to TA (이성현: wwbabaww@gmail.com)

✓ Bonus: copy not only the contents but also the attributes

Homework 3: Snapshot example

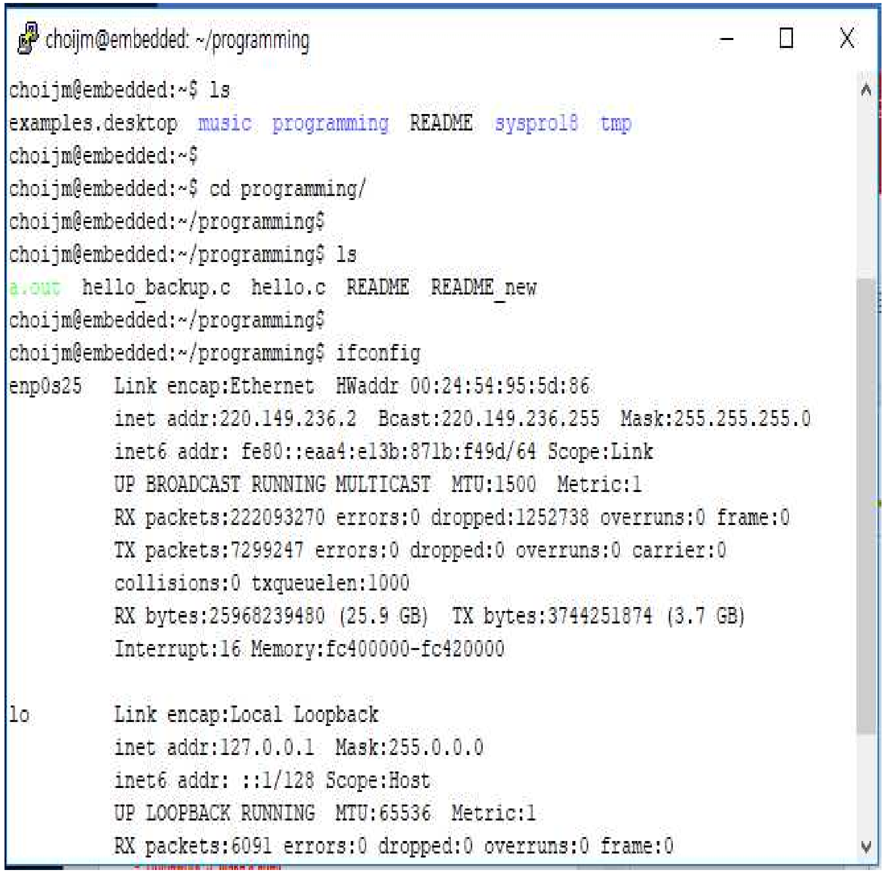


```
CHMOD(2)                  Linux Programmer's Manual                  CHMOD(2)

NAME
       chmod, fchmod - change permissions

SYNOPSIS
       #include <sys/stat.h>

       int chmod(const char *path, mode_t
       int fchmod(int fd, mode_t mode);

   Feature Test Macro Requirements for gl

       fchmod():
           _BSD_SOURCE || _XOPEN_SOURCE >
           _XOPEN_SOURCE && _XOPEN_SOURCE
           || /* Since glibc 2.12: */ _PO

DESCRIPTION
       These system calls change the perm
       in how the file is specified:

       * chmod() changes the permissions
 Manual page chmod(2) line 1 (press h for
```

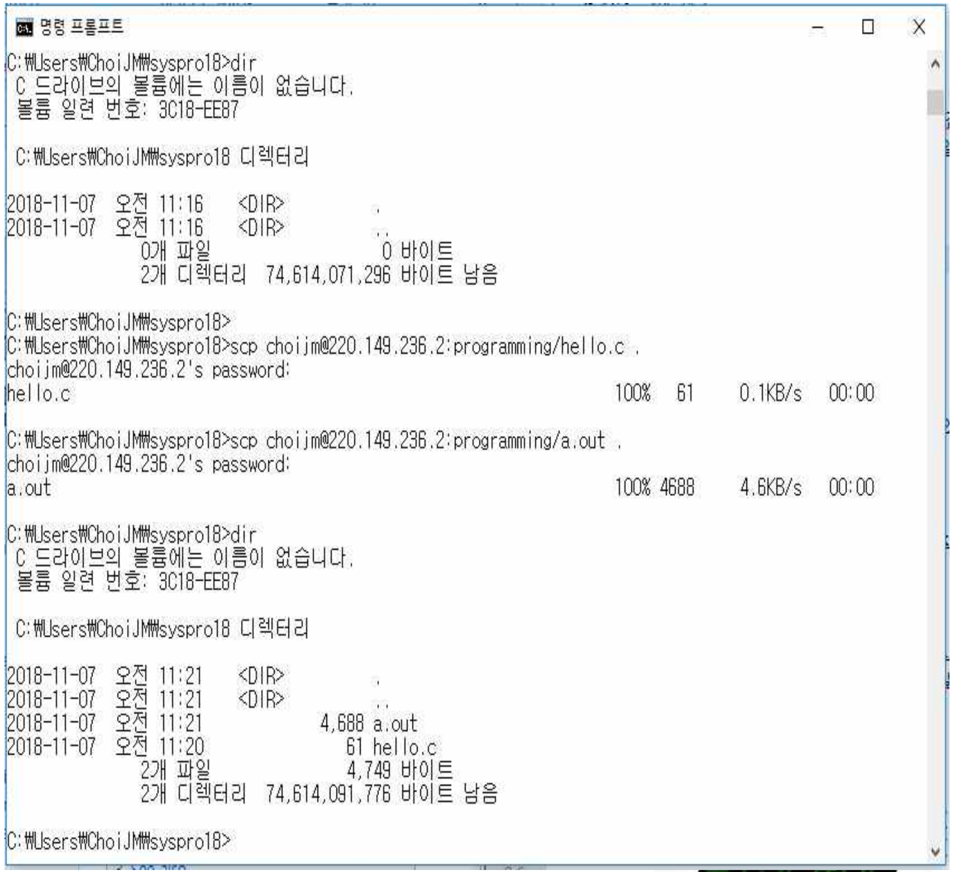
```
choijm@embedded-desktop:~/syspro/homework3$ ls
alphabet.txt  mycp.c
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ gcc -o mycp mycp.c
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ ./mycp
USAGE: ./mycp source_file destination_file
choijm@embedded-desktop:~/syspro/homework3$ ./mycp alpha.txt alpha_new.txt
Can't open alpha.txt
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ ./mycp alphabet.txt alphabet_new.txt
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ ls -l
합계 24
-rw-rw-r-- 1 choijm choijm   27  9월 13 13:55 alphabet.txt
-rw-r--r-- 1 choijm choijm   27  9월 13 14:06 alphabet_new.txt
-rwxrwxr-x 1 choijm choijm 8690  9월 13 14:06 mycp
-rw-rw-r-- 1 choijm choijm  908  9월 13 14:05 mycp.c
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ more alphabet.txt
abcdefghijklmnopqrstuvwxyz
choijm@embedded-desktop:~/syspro/homework3$ more alphabet_new.txt
abcdefghijklmnopqrstuvwxyz
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ vi mycp.c
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ gcc -o mycp mycp.c
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ rm alphabet_new.txt
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ ./mycp alphabet.txt alphabet_new.txt
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ ls -l
합계 24
-rw-rw-r-- 1 choijm choijm   27  9월 13 13:55 alphabet.txt
-rw-rw-r-- 1 choijm choijm   27  9월 13 14:07 alphabet_new.txt
-rwxrwxr-x 1 choijm choijm 8858  9월 13 14:07 mycp
-rw-rw-r-- 1 choijm choijm  903  9월 13 14:07 mycp.c
choijm@embedded-desktop:~/syspro/homework3$
choijm@embedded-desktop:~/syspro/homework3$ whoami
choijm
choijm@embedded-desktop:~/syspro/homework3$ date
2015. 09. 13. (일) 14:08:35 KST
choijm@embedded-desktop:~/syspro/homework3$
```

Appendix 1

- How to download files from Linux server?
  - ✓ scp (secure copy protocol)
    - A means of securely transferring computer files between a local host and a remote host or between two remote hosts



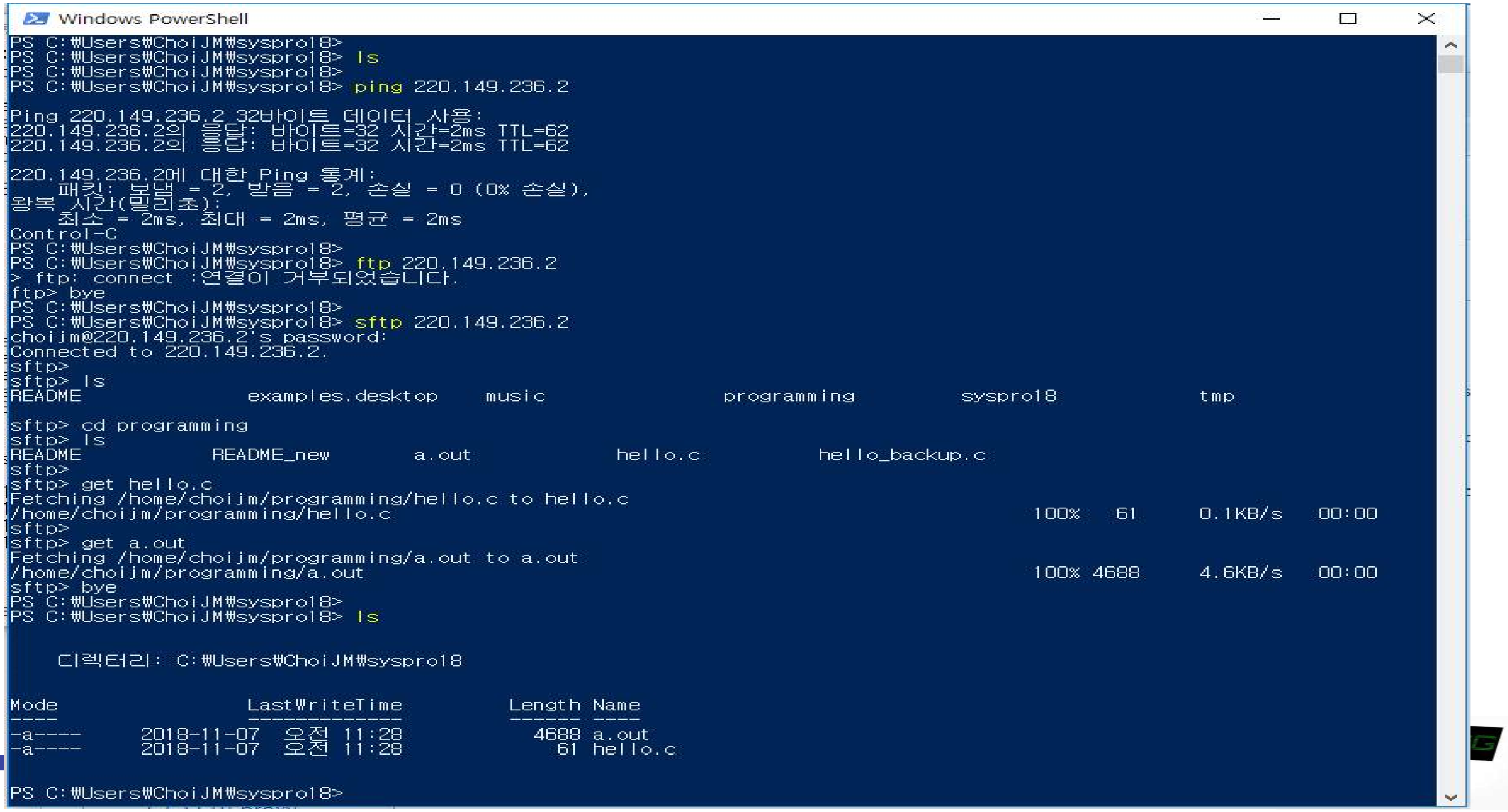
```
choijm@embedded:~$ ls
examples.desktop  music  programming  README  sysprol8  tmp
choijm@embedded:~$
choijm@embedded:~$ cd programming/
choijm@embedded:~/programming$
choijm@embedded:~/programming$ ls
a.out  hello_backup.c  hello.c  README  README_new
choijm@embedded:~/programming$
choijm@embedded:~/programming$ ifconfig
enp0s25   Link encap:Ethernet  HWaddr 00:24:54:95:5d:86
          inet addr:220.149.236.2  Bcast:220.149.236.255  Mask:255.255.255.0
          inet6 addr: fe80::eaa4:e13b:871b:f49d/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:222093270 errors:0 dropped:1252738 overruns:0 frame:0
          TX packets:7299247 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:25968239480 (25.9 GB)  TX bytes:3744251874 (3.7 GB)
          Interrupt:16 Memory:fc400000-fc420000

lo        Link encap:Local Loopback
          inet addr:127.0.0.1  Mask:255.0.0.0
          inet6 addr: ::1/128 Scope:Host
          UP LOOPBACK RUNNING  MTU:65536  Metric:1
          RX packets:6091 errors:0 dropped:0 overruns:0 frame:0
```



```
C:₩Users₩ChoiJM₩syspro18>dir
 C 드라이브의 볼륨에는 이름이 없습니다.
 볼륨 일련 번호: 3C18-EE87

 C:₩Users₩ChoiJM₩syspro18 디렉터리

2018-11-07  오전 11:16    <DIR>          .
2018-11-07  오전 11:16    <DIR>          ..
               0개 파일                   0 바이트
               2개 디렉터리  74,614,071,296 바이트 남음

C:₩Users₩ChoiJM₩syspro18>
C:₩Users₩ChoiJM₩syspro18>scp choijm@220.149.236.2:programming/hello.c .
choijm@220.149.236.2's password:
hello.c                                                  100%   61     0.1KB/s   00:00

C:₩Users₩ChoiJM₩syspro18>scp choijm@220.149.236.2:programming/a.out .
choijm@220.149.236.2's password:
a.out                                                    100% 4688     4.6KB/s   00:00

C:₩Users₩ChoiJM₩syspro18>dir
 C 드라이브의 볼륨에는 이름이 없습니다.
 볼륨 일련 번호: 3C18-EE87

 C:₩Users₩ChoiJM₩syspro18 디렉터리

2018-11-07  오전 11:21    <DIR>          .
2018-11-07  오전 11:21    <DIR>          ..
2018-11-07  오전 11:21             4,688 a.out
2018-11-07  오전 11:20                61 hello.c
               2개 파일               4,749 바이트
               2개 디렉터리  74,614,091,776 바이트 남음

C:₩Users₩ChoiJM₩syspro18>
```

Appendix 1

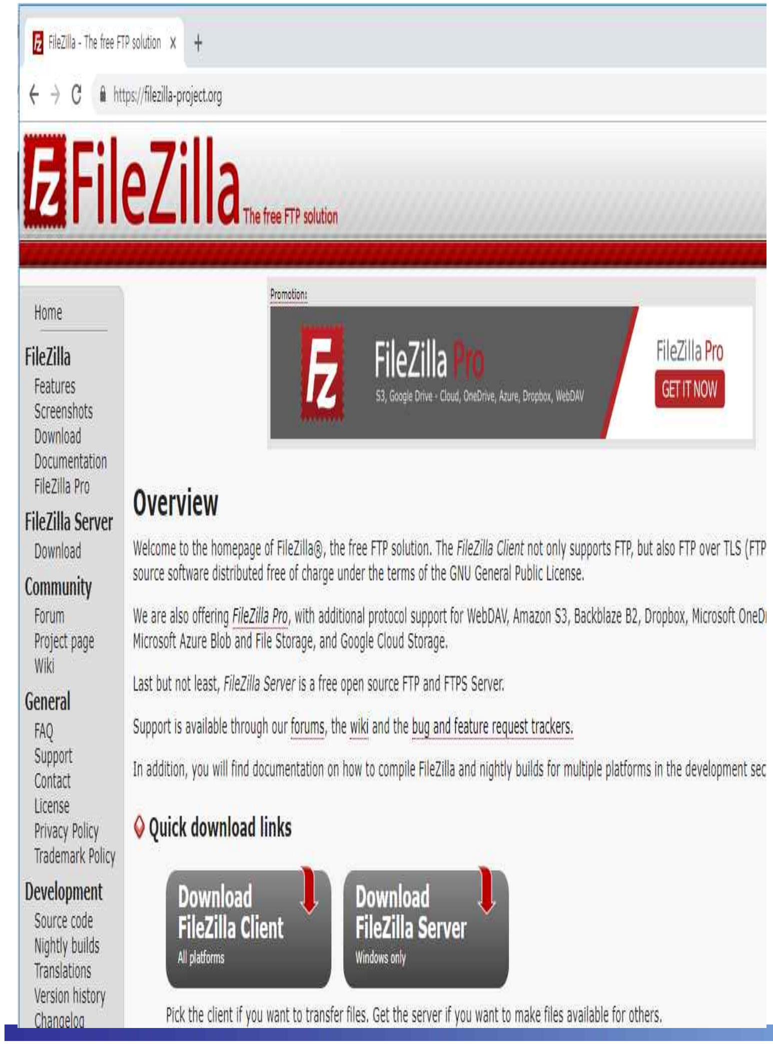
- How to download files from Linux server?
  - ✓ ftp (File Transfer Protocol)
    - a standard network protocol used for the transfer of computer files between a client and server on a computer network
  - ✓ sftp (secure ftp)



```
PS C:₩Users₩ChoiJM₩syspro18>
PS C:₩Users₩ChoiJM₩syspro18> ls
PS C:₩Users₩ChoiJM₩syspro18>
PS C:₩Users₩ChoiJM₩syspro18> ping 220.149.236.2

Ping 220.149.236.2 32바이트 데이터 사용:
220.149.236.2의 응답: 바이트=32 시간=2ms TTL=62
220.149.236.2의 응답: 바이트=32 시간=2ms TTL=62

220.149.236.2에 대한 Ping 통계:
    패킷: 보냄 = 2, 받음 = 2, 손실 = 0 (0% 손실),
왕복 시간(밀리초):
    최소 = 2ms, 최대 = 2ms, 평균 = 2ms
Control-C
PS C:₩Users₩ChoiJM₩syspro18>
PS C:₩Users₩ChoiJM₩syspro18> ftp 220.149.236.2
> ftp: connect :연결이 거부되었습니다.
ftp> bye
PS C:₩Users₩ChoiJM₩syspro18>
PS C:₩Users₩ChoiJM₩syspro18> sftp 220.149.236.2
choijm@220.149.236.2's password:
Connected to 220.149.236.2.
sftp>
sftp> ls
README              examples.desktop    music               programming         syspro18            tmp

sftp> cd programming
sftp> ls
README           README_new       a.out            hello.c          hello_backup.c
sftp>
sftp> get hello.c
Fetching /home/choijm/programming/hello.c to hello.c
/home/choijm/programming/hello.c                                                      100%   61     0.1KB/s   00:00
sftp>
sftp> get a.out
Fetching /home/choijm/programming/a.out to a.out
/home/choijm/programming/a.out                                                        100% 4688     4.6KB/s   00:00
sftp> bye
PS C:₩Users₩ChoiJM₩syspro18>
PS C:₩Users₩ChoiJM₩syspro18> ls


    디렉터리: C:₩Users₩ChoiJM₩syspro18


Mode                LastWriteTime         Length Name
----                -------------         ------ ----
-a----       2018-11-07   오전 11:28           4688 a.out
-a----       2018-11-07   오전 11:28             61 hello.c


PS C:₩Users₩ChoiJM₩syspro18>
```

Appendix 1

- How to download files from Linux server?
  - ✓ Using free ftp application with GUI



Overview

Welcome to the homepage of FileZilla®, the free FTP solution. The *FileZilla Client* not only supports FTP, but also FTP over TLS (FTP
source software distributed free of charge under the terms of the GNU General Public License.

We are also offering *FileZilla Pro*, with additional protocol support for WebDAV, Amazon S3, Backblaze B2, Dropbox, Microsoft OneDr
Microsoft Azure Blob and File Storage, and Google Cloud Storage.

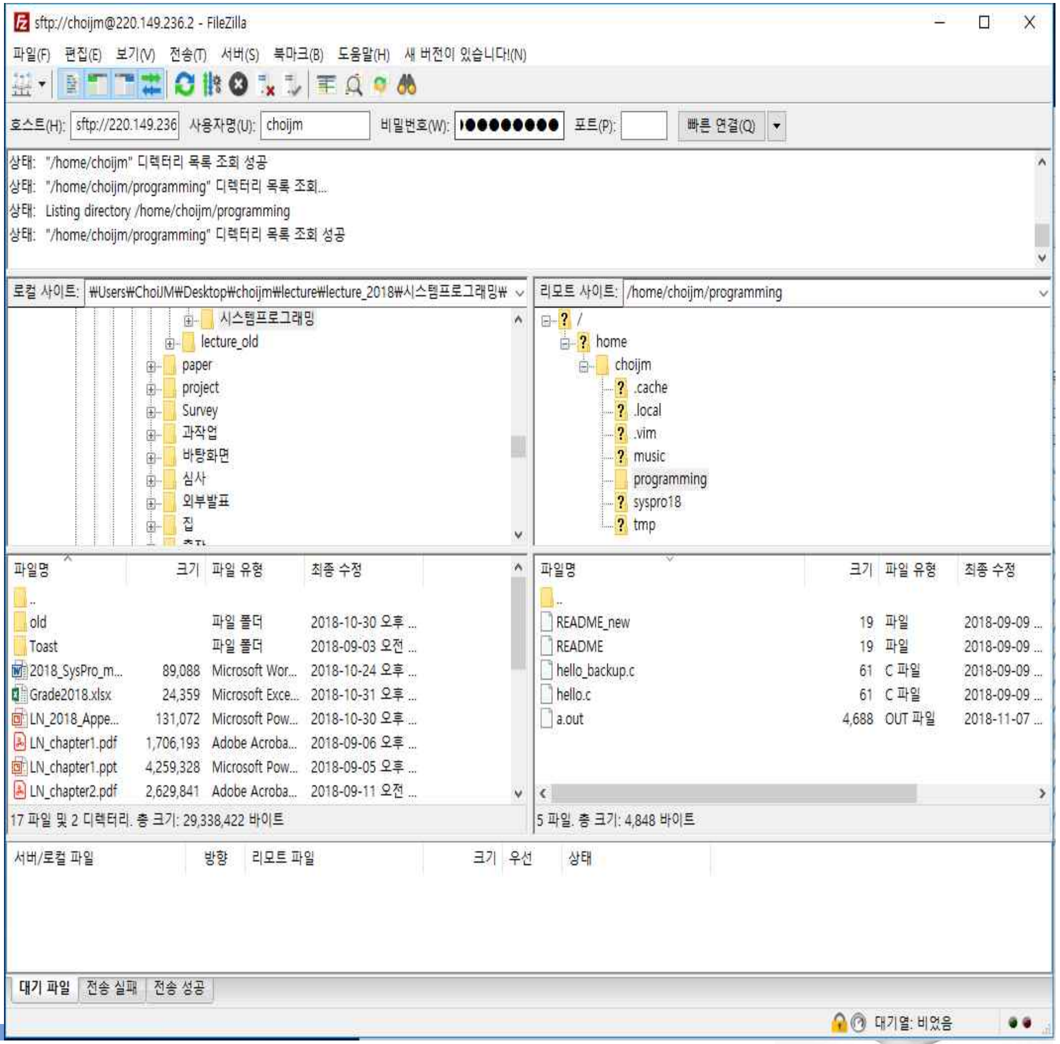
Last but not least, *FileZilla Server* is a free open source FTP and FTPS Server.

Support is available through our forums, the wiki and the bug and feature request trackers.

In addition, you will find documentation on how to compile FileZilla and nightly builds for multiple platforms in the development sec

Quick download links

Pick the client if you want to transfer files. Get the server if you want to make files available for others.



호스트(H): sftp://220.149.236 사용자명(U): choijm 비밀번호(W): ●●●●●●●●● 포트(P):

```
상태:  "/home/choijm" 디렉터리 목록 조회 성공
상태:  "/home/choijm/programming" 디렉터리 목록 조회...
상태:  Listing directory /home/choijm/programming
상태:  "/home/choijm/programming" 디렉터리 목록 조회 성공
```

로컬 사이트: ₩Users₩ChoiJM₩Desktop₩choijm₩lecture₩lecture_2018₩시스템프로그래밍₩

리모트 사이트: /home/choijm/programming

파일명	크기	파일 유형	최종 수정
..			
old		파일 폴더	2018-10-30 오후 ...
Toast		파일 폴더	2018-09-03 오전 ...
2018_SysPro_m...	89,088	Microsoft Wor...	2018-10-24 오후 ...
Grade2018.xlsx	24,359	Microsoft Exce...	2018-10-31 오후 ...
LN_2018_Appe...	131,072	Microsoft Pow...	2018-10-30 오후 ...
LN_chapter1.pdf	1,706,193	Adobe Acroba...	2018-09-06 오후 ...
LN_chapter1.ppt	4,259,328	Microsoft Pow...	2018-09-05 오후 ...
LN_chapter2.pdf	2,629,841	Adobe Acroba...	2018-09-11 오전 ...

17 파일 및 2 디렉터리. 총 크기: 29,338,422 바이트

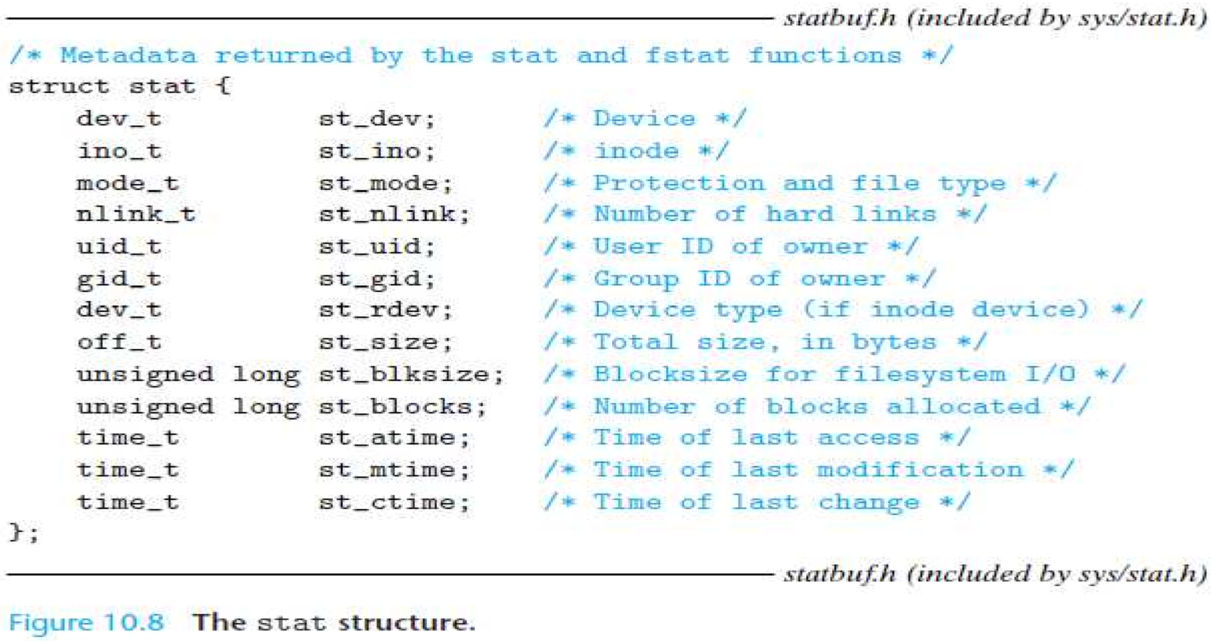
파일명	크기	파일 유형	최종 수정
..			
README_new	19	파일	2018-09-09 ...
README	19	파일	2018-09-09 ...
hello_backup.c	61	C 파일	2018-09-09 ...
hello.c	61	C 파일	2018-09-09 ...
a.out	4,688	OUT 파일	2018-11-07 ...

5 파일. 총 크기: 4,848 바이트

대기열: 비었음

Quiz for 5th-Week 2nd-Lesson

- Quiz
  - ✓ 1) Explain the difference between “cp” and “link” using inode.
  - ✓ 2) How can we figure out the size of a file using file interfaces that we learnt in this LN3? (Hint: 3 ways, NOT “ls –l”)
  - ✓ Due: until 6 PM Friday of the next week (9th, October)



statbuf.h (included by sys/stat.h)

```
/* Metadata returned by the stat and fstat functions */
struct stat {
    dev_t          st_dev;      /* Device */
    ino_t          st_ino;      /* inode */
    mode_t         st_mode;     /* Protection and file type */
    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 type (if inode device) */
    off_t          st_size;     /* Total size, in bytes */
    unsigned long  st_blksize;  /* Blocksize for filesystem I/O */
    unsigned long  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 change */
};
```

statbuf.h (included by sys/stat.h)

Figure 10.8 The stat structure.

(Source: CSAPP)