Lecture Note 1: OS Introduction

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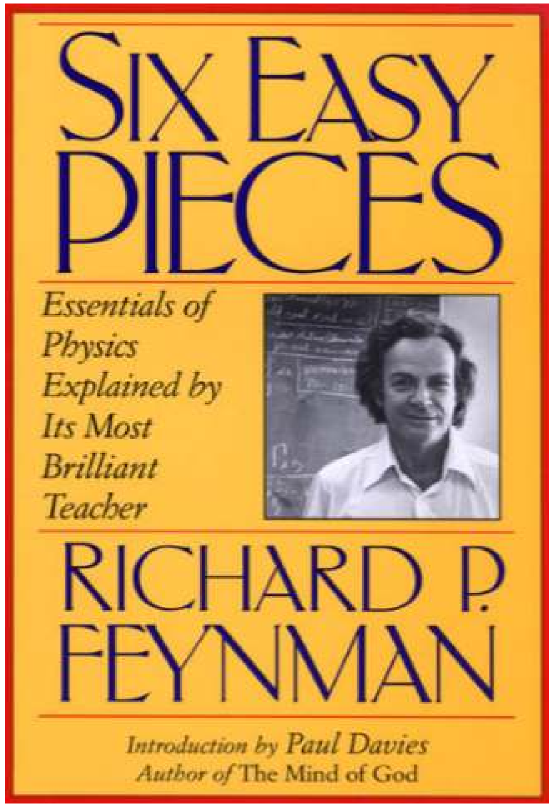
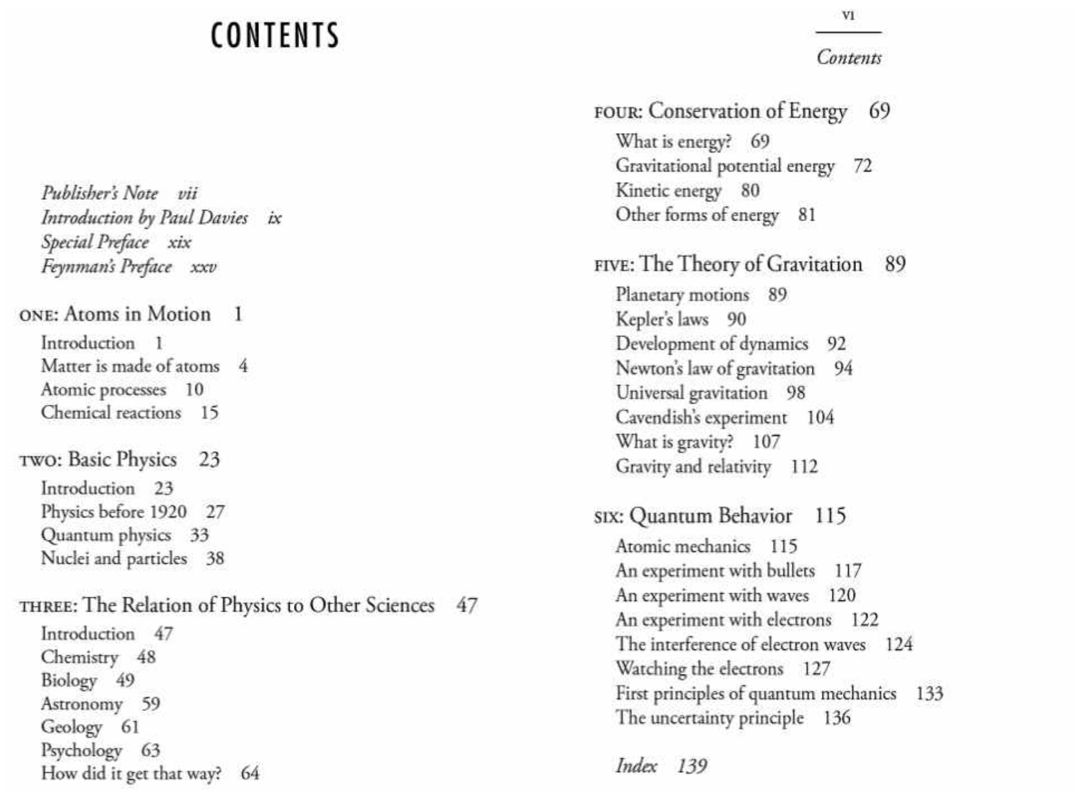
Contents

- From Chap 1~2 of the OSTEP
- Chap 1. A Dialogue on the Book
- Chap 2. Introduction to Operating System
  - ✓ Virtualizing the CPU
  - ✓ Virtualizing Memory
  - ✓ Concurrency
  - ✓ Persistence
  - ✓ Design Goals
  - ✓ Some History
  - ✓ References

Chap 1. A Dialog on the Book

- OSTEP
  - ✓ Operating Systems: Three Easy Pieces
  - ✓ Homage to the Feynman's famous "Six Easy Pieces on Physics"
    - OS is about half as hard as Physics: from Six to Three Pieces


SIX EASY PIECES
Essentials of Physics Explained by Its Most Brilliant Teacher
RICHARD P. FEYNMAN
Introduction by Paul Davies
Author of The Mind of God



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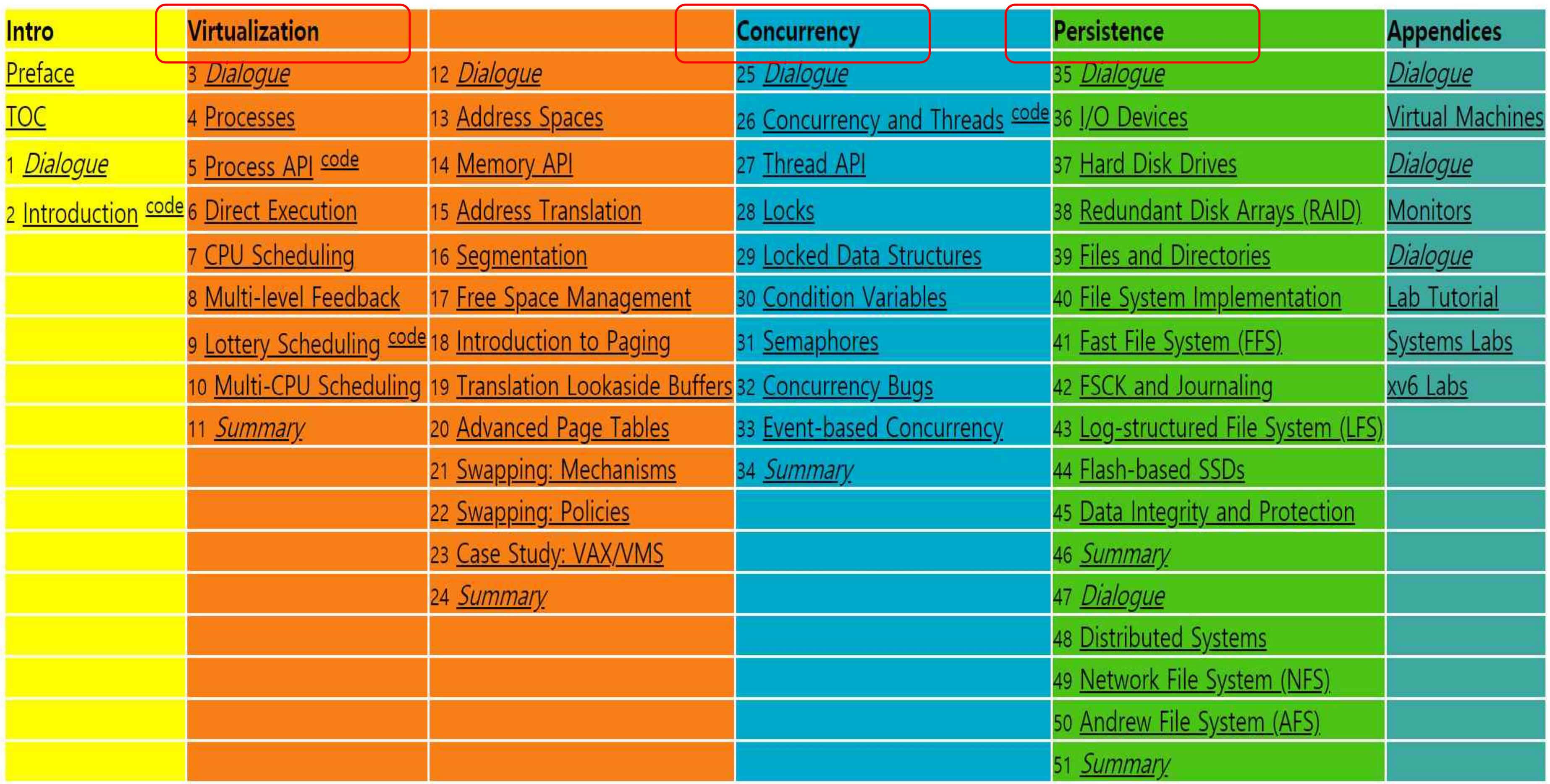
(Source: https://www.amazon.com/Six-Easy-Pieces-Essentials-Explained/dp/0465025277)

Chap 1. A Dialog on the Book

- OSTEP
  - ✓ What are Three Pieces: Virtualization, Concurrency, Persistence

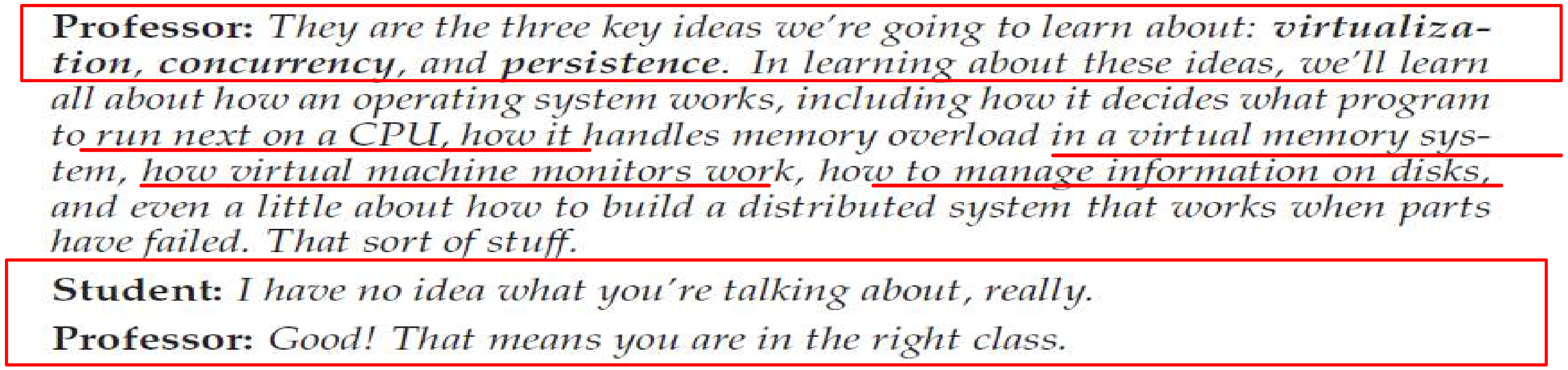


Intro	Virtualization		Concurrency	Persistence	Appendices
Preface	3 *Dialogue*	12 *Dialogue*	25 *Dialogue*	35 *Dialogue*	*Dialogue*
TOC	4 Processes	13 Address Spaces	26 Concurrency and Threads code	36 I/O Devices	Virtual Machines
1 *Dialogue*	5 Process API code	14 Memory API	27 Thread API	37 Hard Disk Drives	*Dialogue*
2 Introduction code	6 Direct Execution	15 Address Translation	28 Locks	38 Redundant Disk Arrays (RAID)	Monitors
	7 CPU Scheduling	16 Segmentation	29 Locked Data Structures	39 Files and Directories	*Dialogue*
	8 Multi-level Feedback	17 Free Space Management	30 Condition Variables	40 File System Implementation	Lab Tutorial
	9 Lottery Scheduling code	18 Introduction to Paging	31 Semaphores	41 Fast File System (FFS)	Systems Labs
	10 Multi-CPU Scheduling	19 Translation Lookaside Buffers	32 Concurrency Bugs	42 FSCK and Journaling	xv6 Labs
	11 *Summary*	20 Advanced Page Tables	33 Event-based Concurrency	43 Log-structured File System (LFS)	
		21 Swapping: Mechanisms	34 *Summary*	44 Flash-based SSDs	
		22 Swapping: Policies		45 Data Integrity and Protection	
		23 Case Study: VAX/VMS		46 *Summary*	
		24 *Summary*		47 *Dialogue*	
				48 Distributed Systems	
				49 Network File System (NFS)	
				50 Andrew File System (AFS)	
				51 *Summary*	

(Source: http://pages.cs.wisc.edu/~remzi/OSTEP/)

Chap 1. A Dialog on the Book

- OSTEP
  - ✓ What to study?

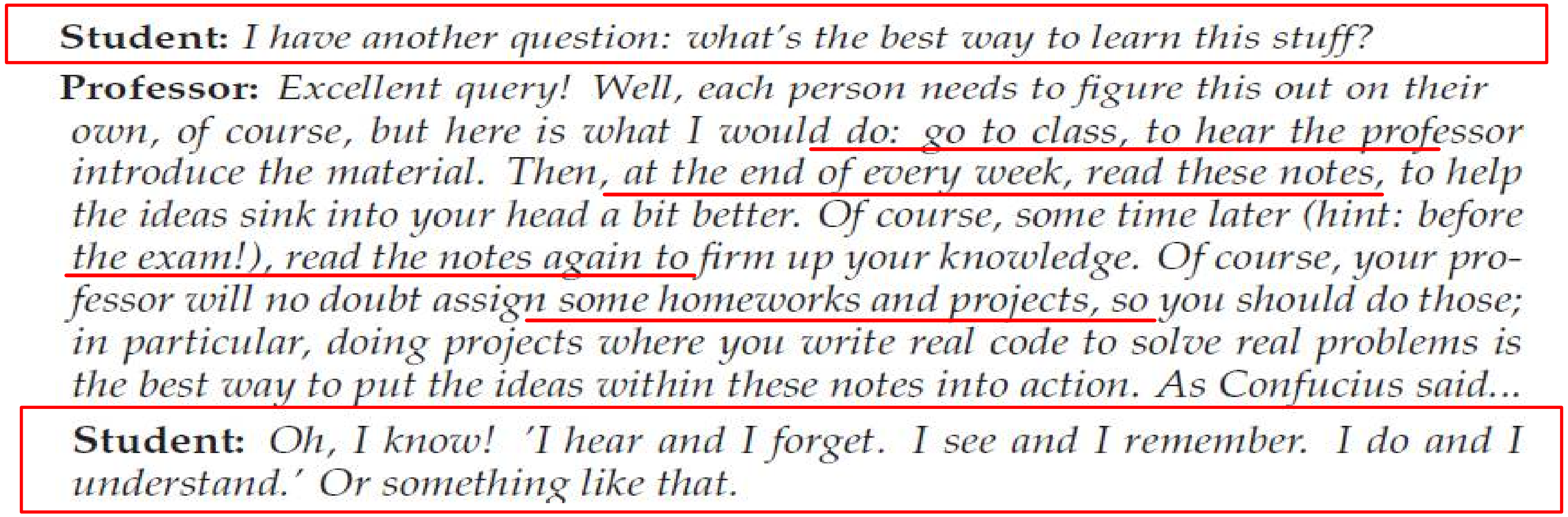


Professor: *They are the three key ideas we're going to learn about:* ***virtualization, concurrency,*** *and* ***persistence****. In learning about these ideas, we'll learn all about how an operating system works, including how it decides what program to run next on a CPU, how it handles memory overload in a virtual memory system, how virtual machine monitors work, how to manage information on disks, and even a little about how to build a distributed system that works when parts have failed. That sort of stuff.*

Student: *I have no idea what you're talking about, really.*

Professor: *Good! That means you are in the right class.*

  - ✓ How to study?



Student: *I have another question: what's the best way to learn this stuff?*

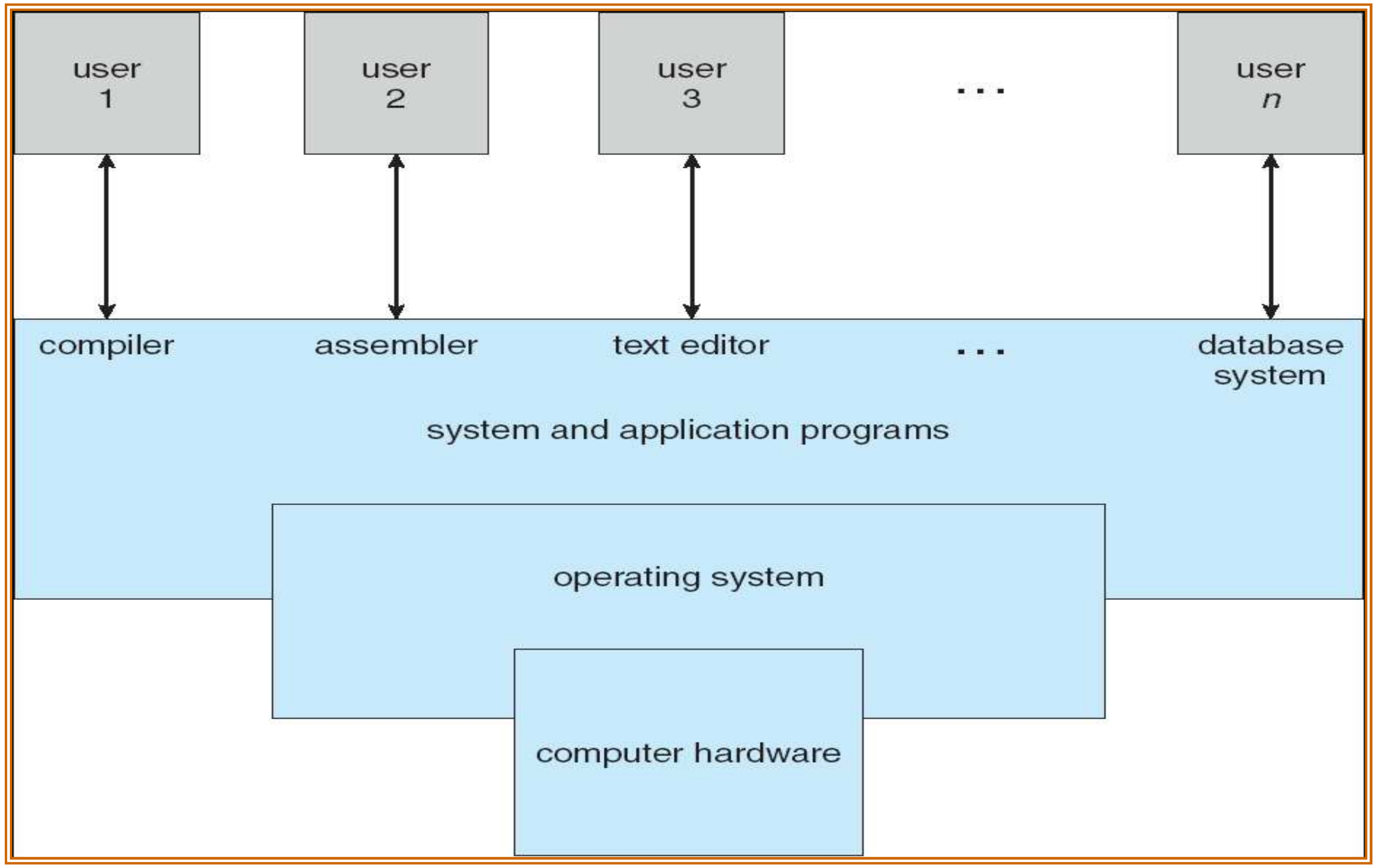
Professor: *Excellent query! Well, each person needs to figure this out on their own, of course, but here is what I would do: go to class, to hear the professor introduce the material. Then, at the end of every week, read these notes, to help the ideas sink into your head a bit better. Of course, some time later (hint: before the exam!), read the notes again to firm up your knowledge. Of course, your professor will no doubt assign some homeworks and projects, so you should do those; in particular, doing projects where you write real code to solve real problems is the best way to put the ideas within these notes into action. As Confucius said...*

Student: *Oh, I know! 'I hear and I forget. I see and I remember. I do and I understand.' Or something like that.*

Chap 2. Introduction to Operating Systems

Introduction

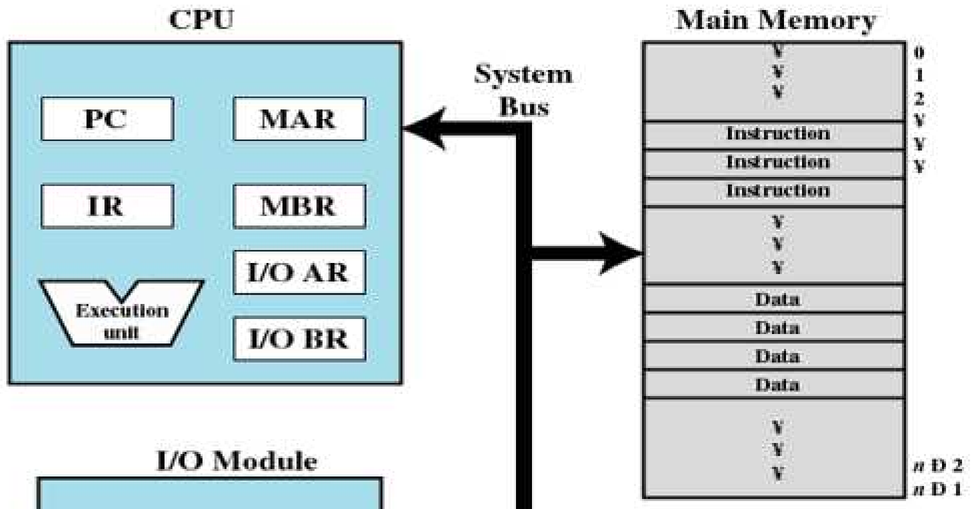
- Layered structure of a computer system



(Source: A. Silberschatz, “Operating system Concept”)

Introduction

- What happens when a program runs?
  - ✓ 1. Simple view about running a program



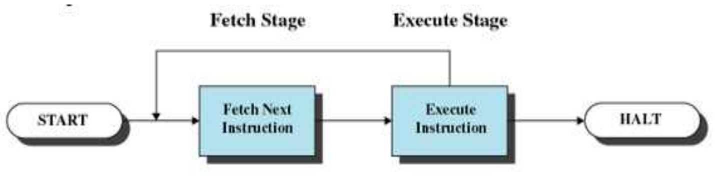
PC	=	Program counter
IR	=	Instruction register
MAR	=	Memory address register
MBR	=	Memory buffer register
I/O AR	=	Input/output address register
I/O BR	=	Input/output buffer register

Figure 1.1 Computer Components: Top-Level View

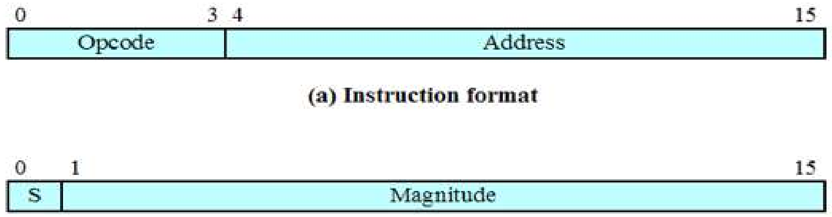
(Source: W. Stalling, "Operating Systems: Internals and Design Principles")

Introduction

- What happens when a program runs?
  - ✓ Details: execute instructions
    - Fetch and Execute



<Instruction cycle>



(a) Instruction format

(b) Integer format

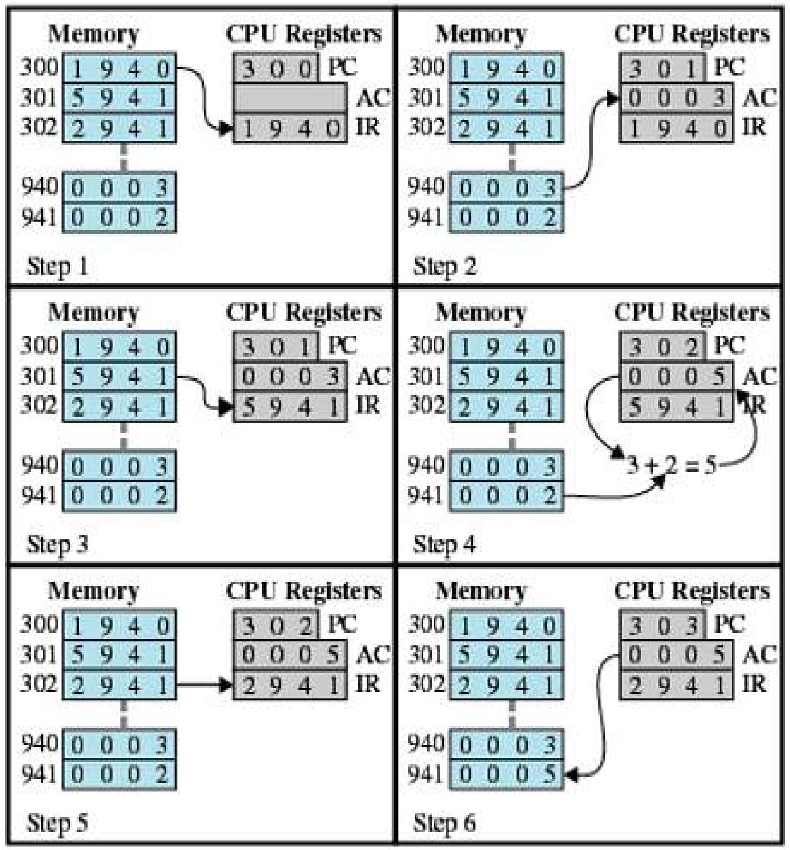
Program Counter (PC) = Address of instruction
Instruction Register (IR) = Instruction being executed
Accumulator (AC) = Temporary storage

(c) Internal CPU registers

0001 = Load AC from Memory
0010 = Store AC to Memory
0101 = Add to AC from Memory

(d) Partial list of opcodes

<Hypothetical machine>



<Run example>

(Source: W. Stalling, "Operating Systems: Internals and Design Principles")

Introduction

- What happens when a program runs?
  - ✓ 2. A lot of stuff for running a program
    - Loading, memory management, scheduling, context switching, I/O processing, file management, IPC, …
    - Operating system: 1) make it easy to run programs, 2) operate a system correctly and efficiently

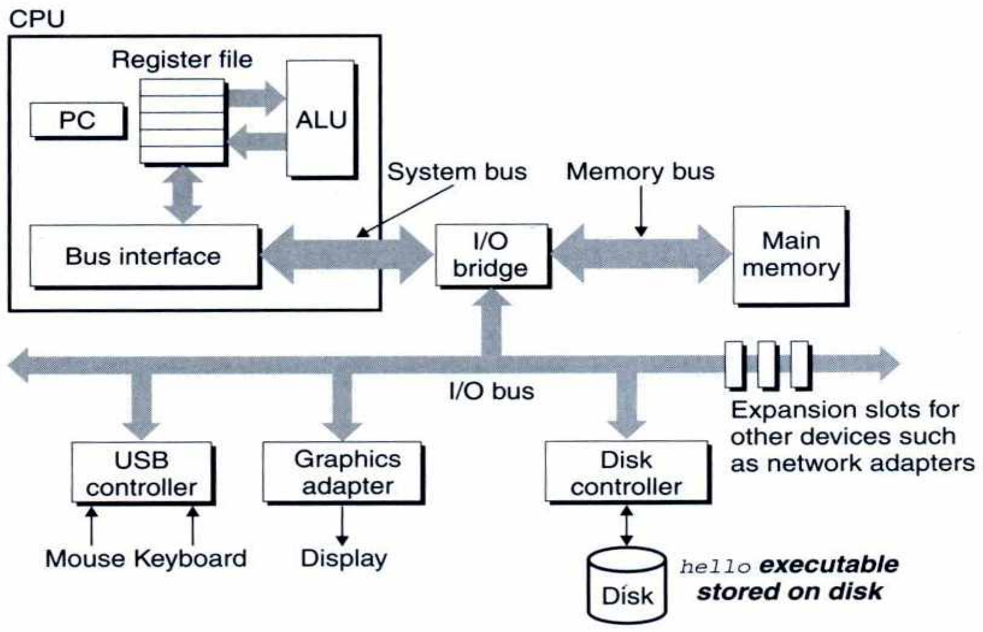
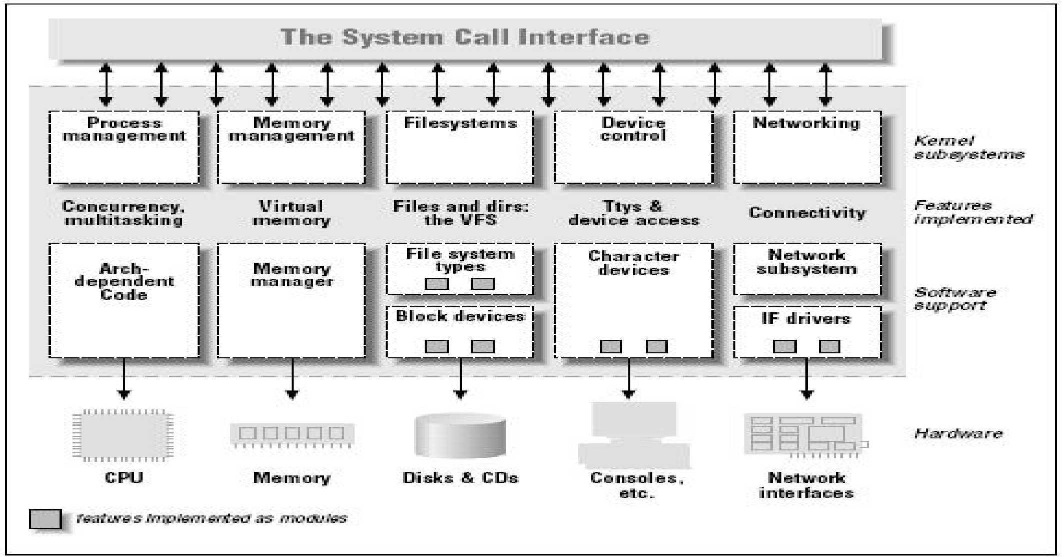


Figure 1.4 **Hardware organization of a typical system.** CPU: Central Processing Unit, ALU: Arithmetic/Logic Unit, PC: Program Counter, USB: Universal Serial Bus.

(Source: computer systems: a programmer perspective)

Introduction

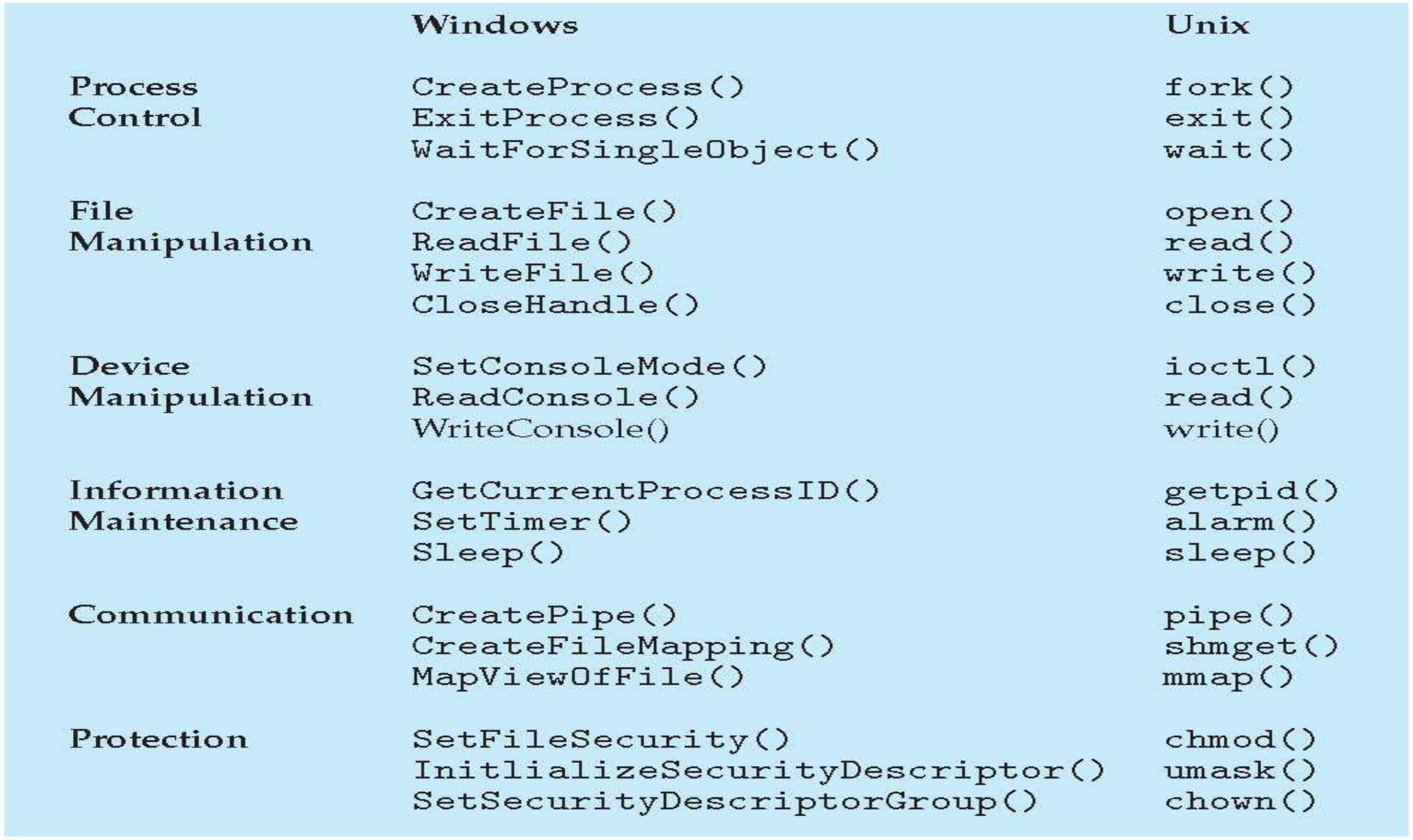
- Definition of operating system
  - ✓ Resource manager
    - Physical resources: CPU (core), DRAM, Disk, Flash, KBD, Network, …
    - Virtual resources: Process, Thread, Virtual memory, Page, File, Directory, Driver, Protocol, Access control, Security, …
  - ✓ Virtualization (Abstraction)
    - Transform a physical resource into a more general, powerful, and easy-to-use virtual form



(Source: Linux Device Driver, O'Reilly)

Introduction

- System call
  - ✓ Interfaces (APIs) provided by OS

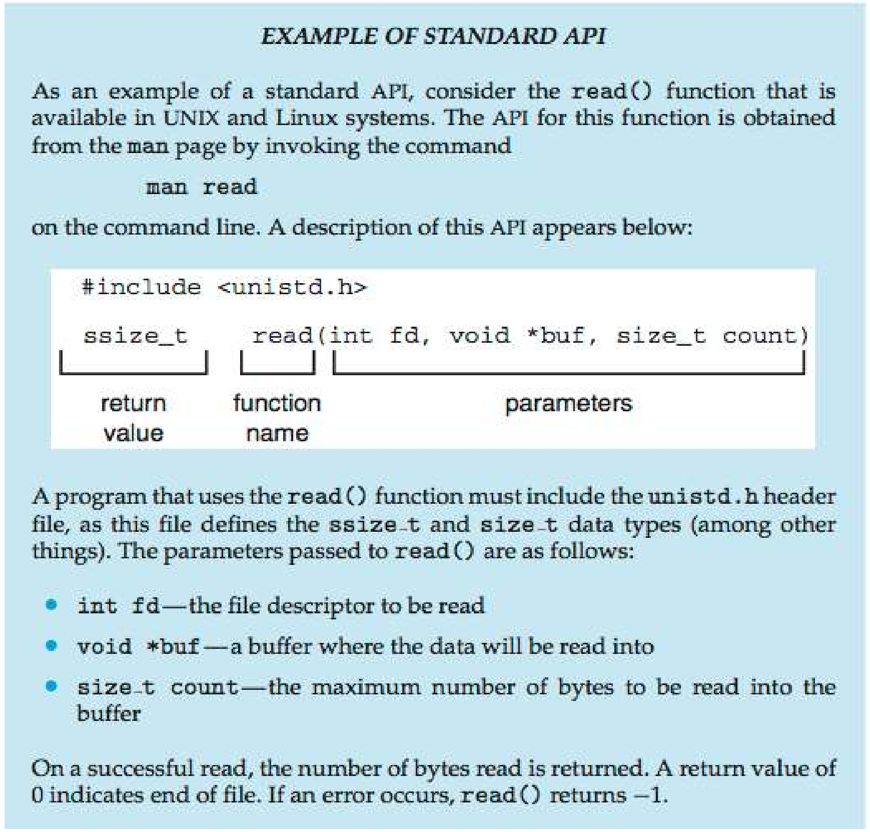


	Windows	Unix
Process Control	CreateProcess()	fork()
	ExitProcess()	exit()
	WaitForSingleObject()	wait()
File Manipulation	CreateFile()	open()
	ReadFile()	read()
	WriteFile()	write()
	CloseHandle()	close()
Device Manipulation	SetConsoleMode()	ioctl()
	ReadConsole()	read()
	WriteConsole()	write()
Information Maintenance	GetCurrentProcessID()	getpid()
	SetTimer()	alarm()
	Sleep()	sleep()
Communication	CreatePipe()	pipe()
	CreateFileMapping()	shmget()
	MapViewOfFile()	mmap()
Protection	SetFileSecurity()	chmod()
	InitlializeSecurityDescriptor()	umask()
	SetSecurityDescriptorGroup()	chown()

(Source: A. Silberschatz, “Operating system Concept”)

Introduction

- System call
  - ✓ Standard (e.g.. POSIX, Win32, …)
  - ✓ Mode switch (user mode, kernel mode)



EXAMPLE OF STANDARD API

As an example of a standard API, consider the `read()` function that is available in UNIX and Linux systems. The API for this function is obtained from the `man` page by invoking the command

```
man read
```

on the command line. A description of this API appears below:

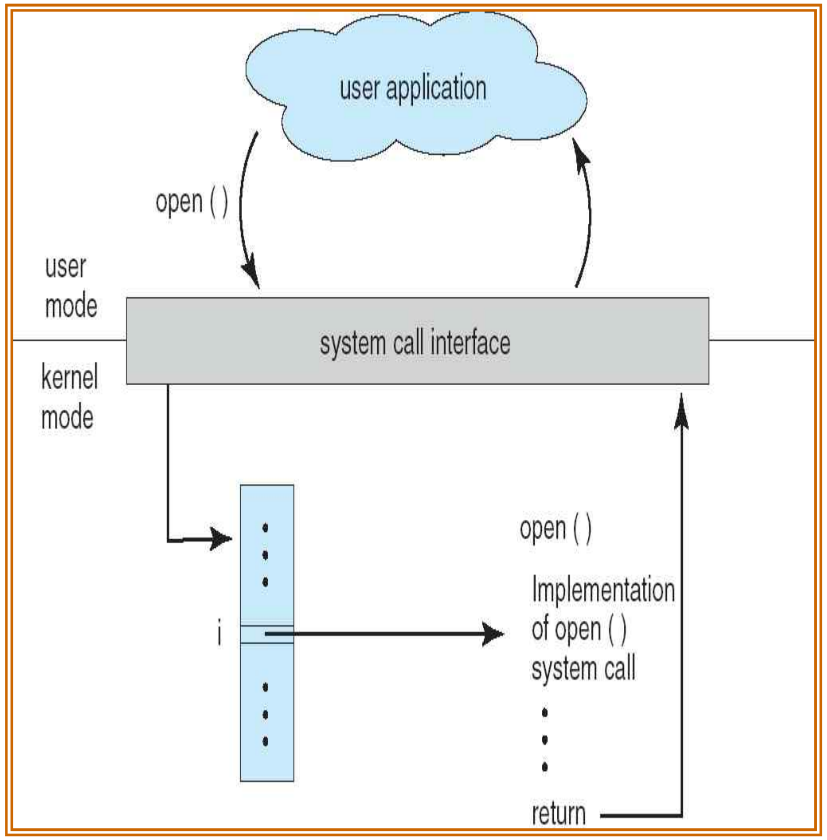
```
#include <unistd.h>

ssize_t    read(int fd, void *buf, size_t count)
```

return value
function name
parameters

A program that uses the `read()` function must include the `unistd.h` header file, as this file defines the `ssize_t` and `size_t` data types (among other things). The parameters passed to `read()` are as follows:

- `int fd`—the file descriptor to be read
- `void *buf`—a buffer where the data will be read into
- `size_t count`—the maximum number of bytes to be read into the buffer

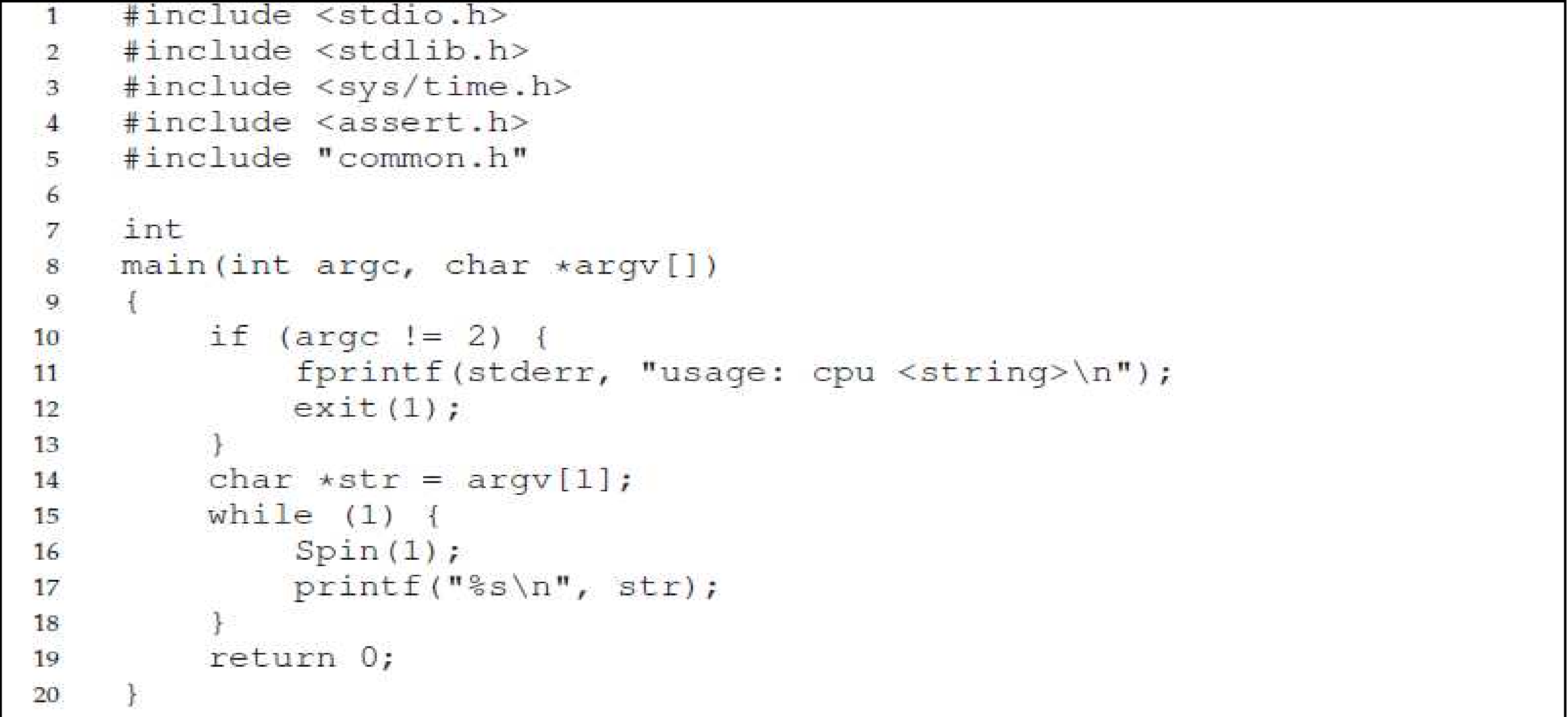
On a successful read, the number of bytes read is returned. A return value of 0 indicates end of file. If an error occurs, `read()` returns −1.



(Source: A. Silberschatz, “Operating system Concept”)

2.1 Virtualizing CPU

- A program for the discussion of virtualizing CPU
  - ✓ call Spin (busy waiting and return when it has run for a second)
  - ✓ print out a string passed in on the command line



```c
#include <stdio.h>
#include <stdlib.h>
#include <sys/time.h>
#include <assert.h>
#include "common.h"

int
main(int argc, char *argv[])
{
    if (argc != 2) {
        fprintf(stderr, "usage: cpu <string>\n");
        exit(1);
    }
    char *str = argv[1];
    while (1) {
        Spin(1);
        printf("%s\n", str);
    }
    return 0;
}
```

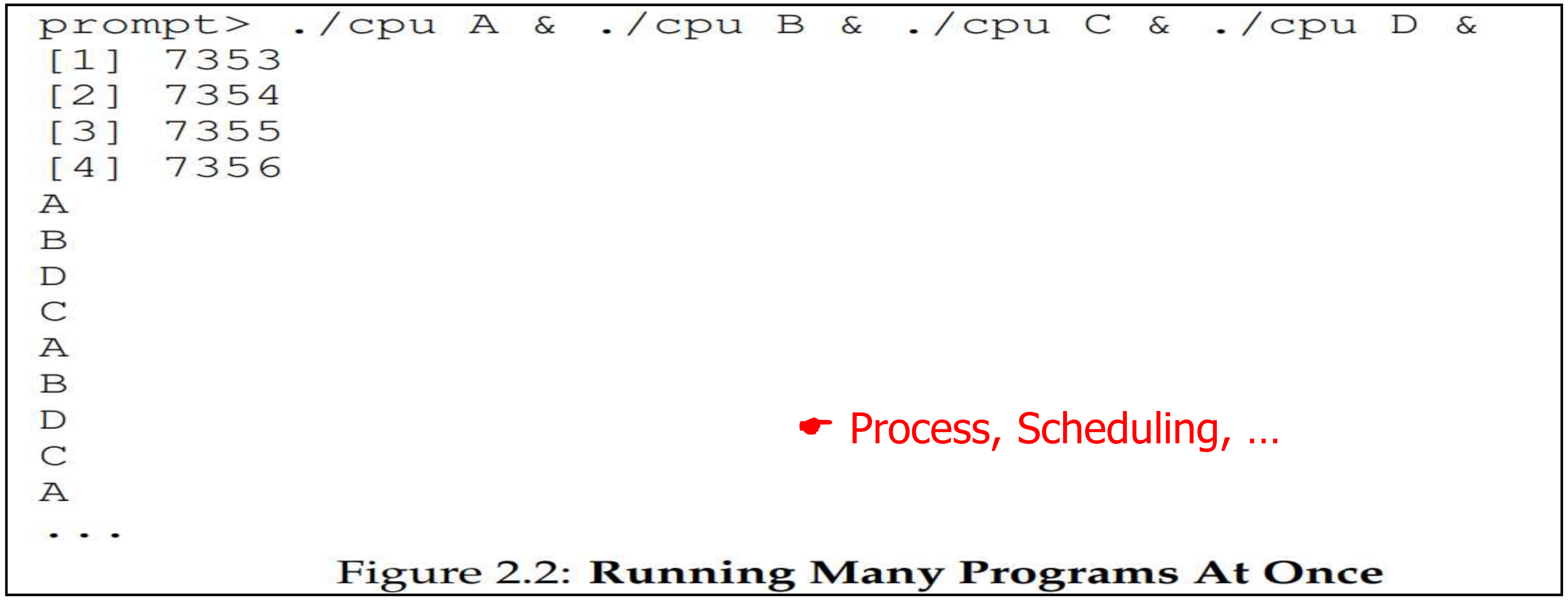
Figure 2.1: **Simple Example: Code That Loops and Prints (cpu.c)**

2.1 Virtualizing CPU

- Execute the CPU program

```
prompt> gcc -o cpu cpu.c -Wall
prompt> ./cpu "A"
A
A
A
A
^C
prompt>
```

- Execute the program in parallel



```
prompt> ./cpu A & ./cpu B & ./cpu C & ./cpu D &
[1] 7353
[2] 7354
[3] 7355
[4] 7356
A
B
D
C
A
B
D
C
A
...
```

☛ Process, Scheduling, …

Figure 2.2: **Running Many Programs At Once**

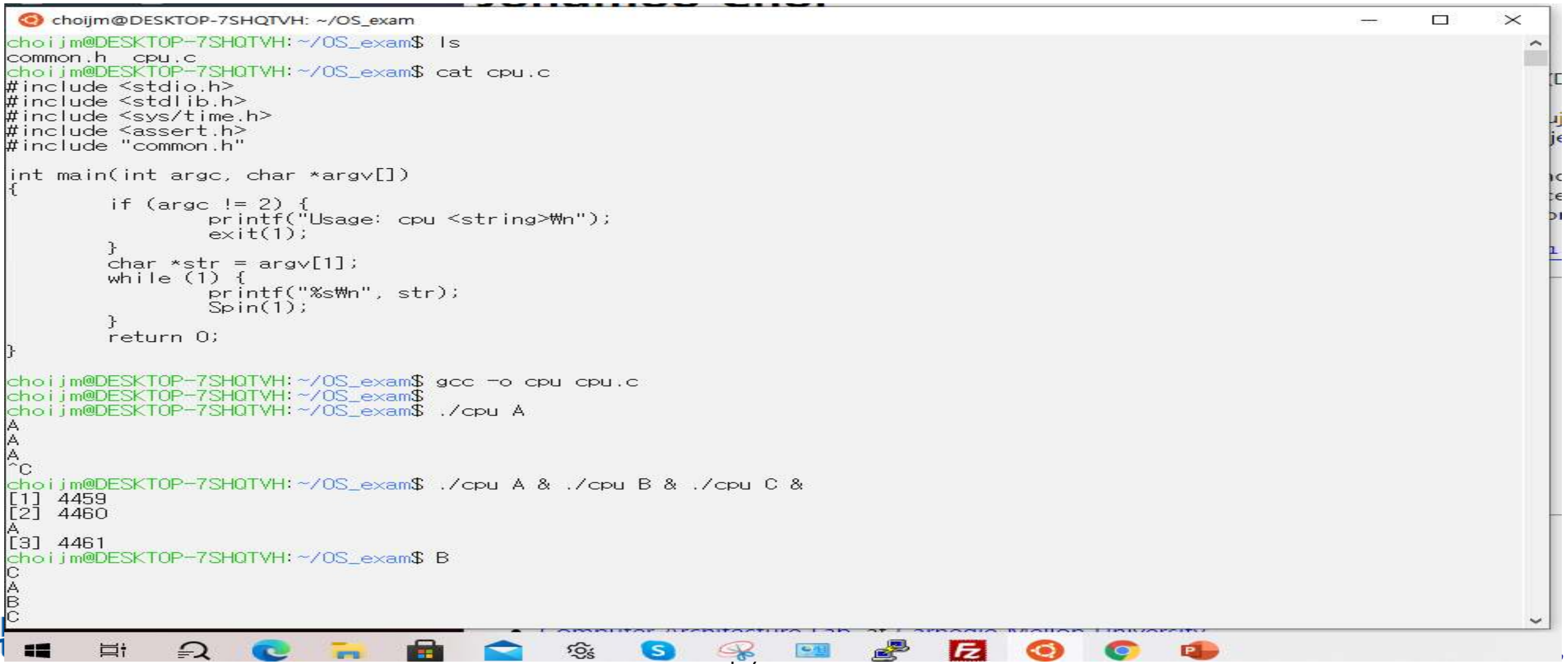
2.1 Virtualizing CPU

- Issues for Virtualizing CPU
  - ✓ How to run a new program? ➔ process
  - ✓ How to make a new process? ➔ fork()
  - ✓ How to stop a process? ➔ exit()
  - ✓ How to execute a new process? ➔ exec()
  - ✓ How to block a process? ➔ sleep(), pause(), lock(), …
  - ✓ How to select a process to run next? ➔ scheduling
  - ✓ How to run multiple processes? ➔ context switch
  - ✓ How to manage multiple cores (CPUs)? ➔ multi-processor scheduling, cache affinity, load balancing
  - ✓ How to communicate among processes? ➔ IPC (Inter-Process Communication), socket
  - ✓ How to notify an event to a process? ➔ signal (e.g. ^C)
  - ✓ …

☛ Illusion: A process has its own CPU even though there are less CPUs than processes

Quiz for 1st-Week 2nd-Lesson

- Quiz
  - ✓ 1. Operating system is defined as a resource manager. What kinds of resources are managed by operating system? Discuss physical and virtual resources separately.
  - ✓ 2. What is the role of “&” in the below example? (I do this experiment using wsl(windows subsystem for Linux) in my laptop.)
  - ✓ Due: until 6 PM Friday of this week (5th, March)



```
choijm@DESKTOP-7SHQTVH: ~/OS_exam
choijm@DESKTOP-7SHQTVH:~/OS_exam$ ls
common.h   cpu.c
choijm@DESKTOP-7SHQTVH:~/OS_exam$ cat cpu.c
#include <stdio.h>
#include <stdlib.h>
#include <sys/time.h>
#include <assert.h>
#include "common.h"

int main(int argc, char *argv[])
{
        if (argc != 2) {
                printf("Usage: cpu <string>₩n");
                exit(1);
        }
        char *str = argv[1];
        while (1) {
                printf("%s₩n", str);
                Spin(1);
        }
        return 0;
}

choijm@DESKTOP-7SHQTVH:~/OS_exam$ gcc -o cpu cpu.c
choijm@DESKTOP-7SHQTVH:~/OS_exam$
choijm@DESKTOP-7SHQTVH:~/OS_exam$ ./cpu A
A
A
A
^C
choijm@DESKTOP-7SHQTVH:~/OS_exam$ ./cpu A & ./cpu B & ./cpu C &
[1] 4459
[2] 4460
A
[3] 4461
choijm@DESKTOP-7SHQTVH:~/OS_exam$ B
C
A
B
C
```

2.2 Virtualizing Memory

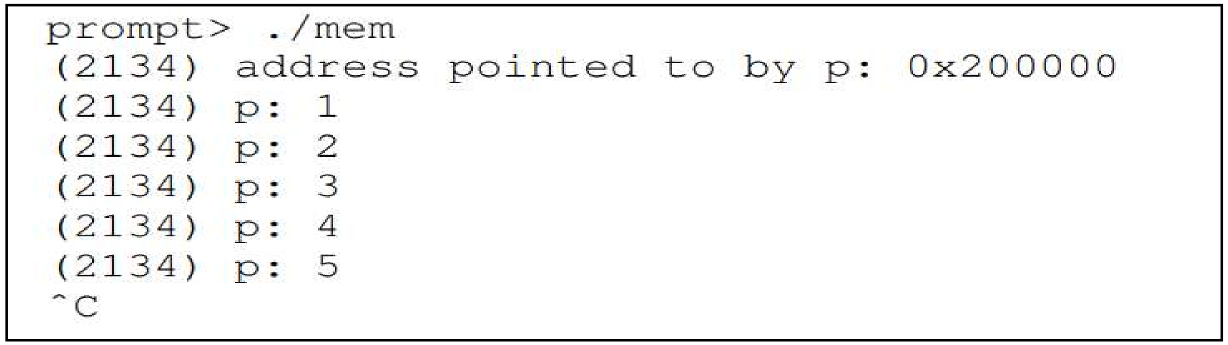
- Memory
  - ✓ Can be considered as an array of bytes
- Another program example
  - ✓ Allocate a portion of memory and access it

```c
#include <unistd.h>
#include <stdio.h>
#include <stdlib.h>
#include "common.h"

int
main(int argc, char *argv[])
{
    int *p = malloc(sizeof(int));                       // a1
    assert(p != NULL);
    printf("(%d) address pointed to by p: %p\n",
           getpid(), p);                                // a2
    *p = 0;                                             // a3
    while (1) {
        Spin(1);
        *p = *p + 1;
        printf("(%d) p: %d\n", getpid(), *p);           // a4
    }
    return 0;
}
```

Figure 2.3: **A Program That Accesses Memory (mem.c)**

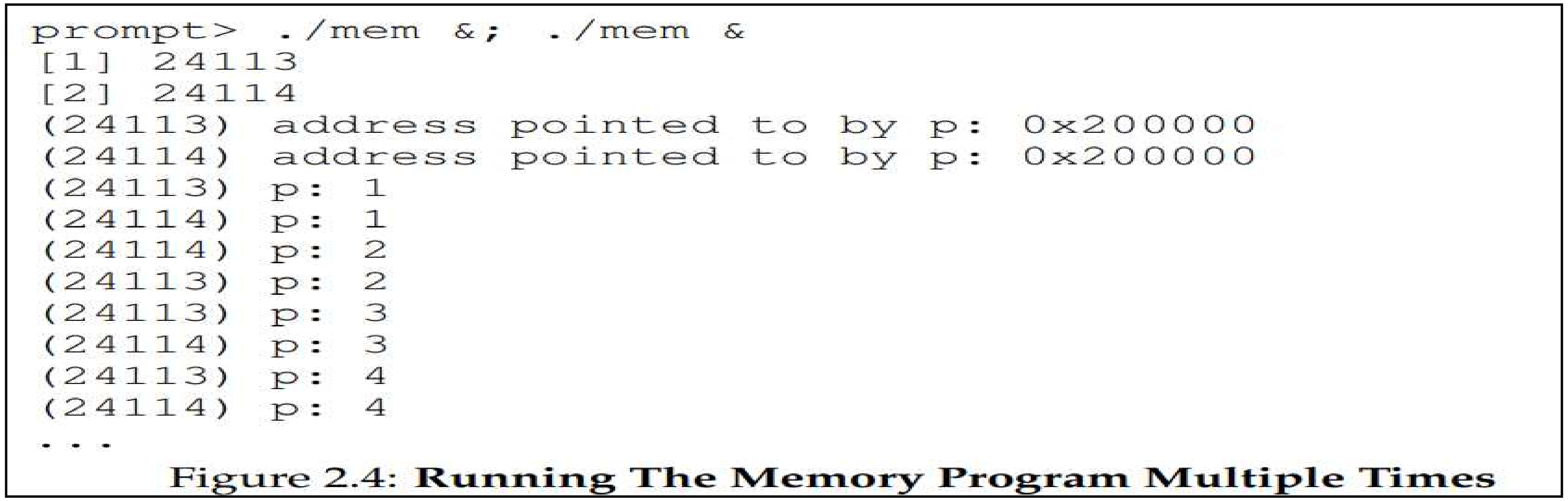
2.2 Virtualizing Memory

- Execute the Mem program



```
prompt> ./mem
(2134) address pointed to by p: 0x200000
(2134) p: 1
(2134) p: 2
(2134) p: 3
(2134) p: 4
(2134) p: 5
^C
```

- Execute the program in parallel



```
prompt> ./mem &; ./mem &
[1] 24113
[2] 24114
(24113) address pointed to by p: 0x200000
(24114) address pointed to by p: 0x200000
(24113) p: 1
(24114) p: 1
(24114) p: 2
(24113) p: 2
(24113) p: 3
(24114) p: 3
(24113) p: 4
(24114) p: 4
...
```

Figure 2.4: Running The Memory Program Multiple Times

☛ Same address but independent

2.2 Virtualizing Memory

- Issues for Virtualizing Memory
  - ✓ How to manage the address space of a process? ➔ text, data, stack, heap, …
  - ✓ How to allocate memory to a process? ➔ malloc(), calloc(), brk(), …
  - ✓ How to deallocate memory from a process? ➔ free()
  - ✓ How to manage free space? ➔ buddy, slab, …
  - ✓ How to protect memory among processes? ➔ virtual memory
  - ✓ How to implement virtual memory? ➔ page, segment
  - ✓ How to reduce the overhead of virtual memory? ➔ TLB
  - ✓ How to share memory among processes? ➔ shared memory
  - ✓ How to exploit memory to hide the storage latency? ➔ page cache, buffer cache, …
  - ✓ How to manage NUMA? ➔ local/remote memory
  - ✓ …

☛ Illusion: A process has its own unlimited and independent memory even though several processes are sharing limited memory in reality

2.3 Concurrency

- Background: how to create a new scheduling entity?
  - ✓ Two programming model: process (task) and thread
  - ✓ Key difference: data sharing

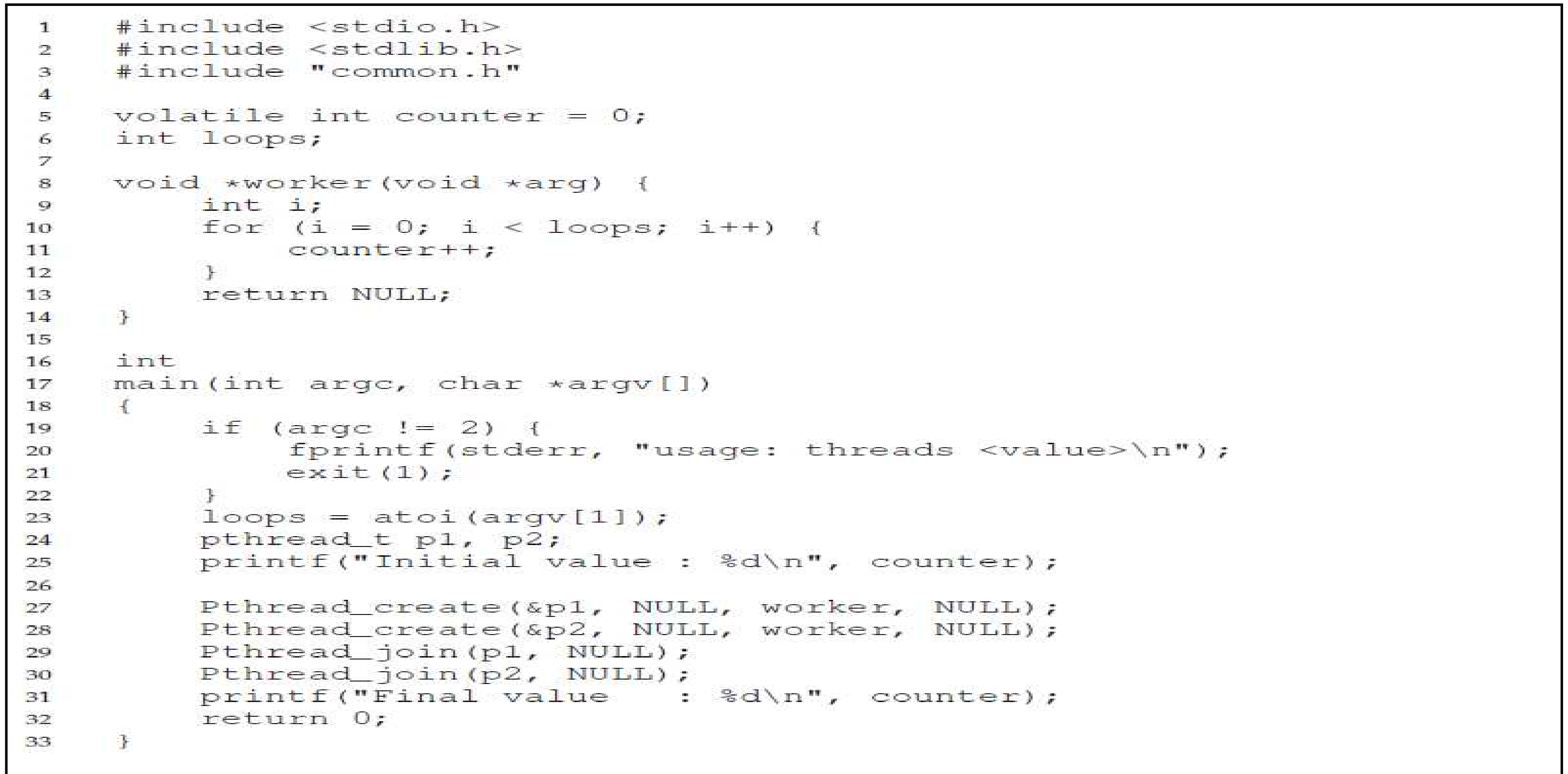
```
// fork example (Refer to the Chapter 5 in OSTEP)
// by J. Choi  (choijm@dku.edu)
#include <stdio.h>
#include <stdlib.h>

int a = 10;

void *func()
{
        a++;
        printf("pid = %d\n", getpid());
}

int main()
{
        int pid;
        if ((pid = fork()) == 0) { //need exception handle
                func();
                exit(0);
        }
        wait();
        printf("a = %d by pid = %d\n", a, getpid());
}
```

```
// thread example (Refer to the Chapter 27 in OSTEP)
// by J. Choi (choijm@dku.edu)
#include <stdio.h>
#include <stdlib.h>

int a = 10;

void *func()
{
        a++;
        printf("pid = %d\n", getpid());
}

int main()
{
        pthread_t p_thread;
        if ((pthread_create(&p_thread, NULL, func, (void *)NULL))
< 0) {
                exit(0);
        }
        pthread_join(p_thread, (void *)NULL);
        printf("a = %d by pid = %d\n", a, getpid());
}
```

(Source: System programming lecture note)

2.3 Concurrency

- Concurrency
  - ✓ Problems arise when working on many things simultaneously on the same data
- A program for discussing concurrency



```c
#include <stdio.h>
#include <stdlib.h>
#include "common.h"

volatile int counter = 0;
int loops;

void *worker(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        counter++;
    }
    return NULL;
}

int
main(int argc, char *argv[])
{
    if (argc != 2) {
        fprintf(stderr, "usage: threads <value>\n");
        exit(1);
    }
    loops = atoi(argv[1]);
    pthread_t p1, p2;
    printf("Initial value : %d\n", counter);

    Pthread_create(&p1, NULL, worker, NULL);
    Pthread_create(&p2, NULL, worker, NULL);
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("Final value   : %d\n", counter);
    return 0;
}
```

Figure 2.5: A Multi-threaded Program (threads.c)

2.3 Concurrency

- Execute the multi-thread program

```
prompt> gcc -o thread thread.c -Wall -pthread
prompt> ./thread 1000
Initial value : 0
Final value   : 2000
```

```
prompt> ./thread 100000
Initial value : 0
Final value   : 143012    // huh??
prompt> ./thread 100000
Initial value : 0
Final value   : 137298    // what the??
```

- ✓ Programing model
  - thread model: share data section (a.k.a data segment)
  - process model: independent, need explicit IPC for sharing
- ✓ Reason for the odd results for the large loop
  - Lack of atomicity, scheduling effect, … ➔ need concurrency control

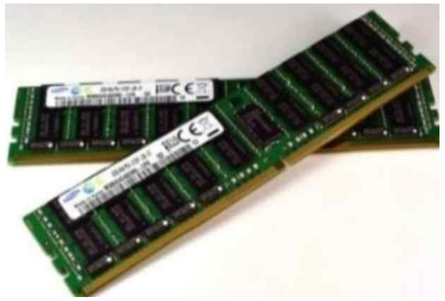
2.3 Concurrency

- Issues for Concurrency
  - ✓ How to support concurrency correctly? ➔ lock(), semaphore()
  - ✓ How to implement atomicity in hardware? ➔ test_and_set(), swap()
  - ✓ What is the semaphore?
  - ✓ What is the monitor?
  - ✓ How to solve the traditional concurrent problems such as producer-consumer, readers-writers and dining philosophers?
  - ✓ What is a deadlock?
  - ✓ How to deal with the deadlock?
  - ✓ How to handle the timing bug?
  - ✓ What is the asynchronous I/Os?
  - ✓ …

☛ Illusion: Multiple processes run in a cooperative manner on shared resources even though they actually race with each other on the resources

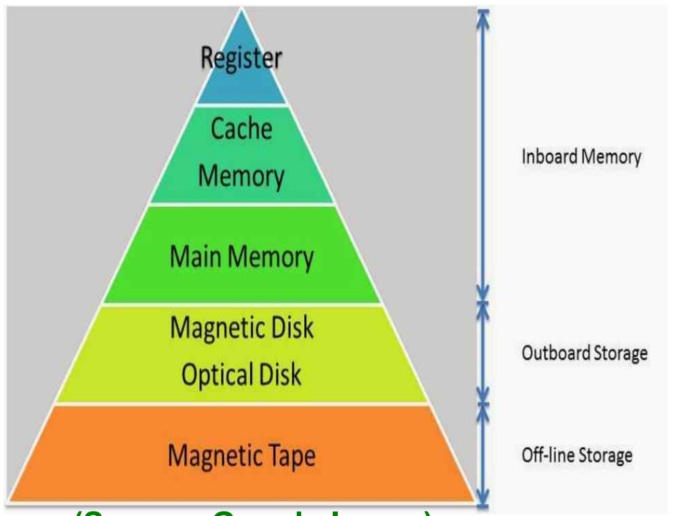
2.4 Persistence

- Background: DRAM vs. Disk



vs

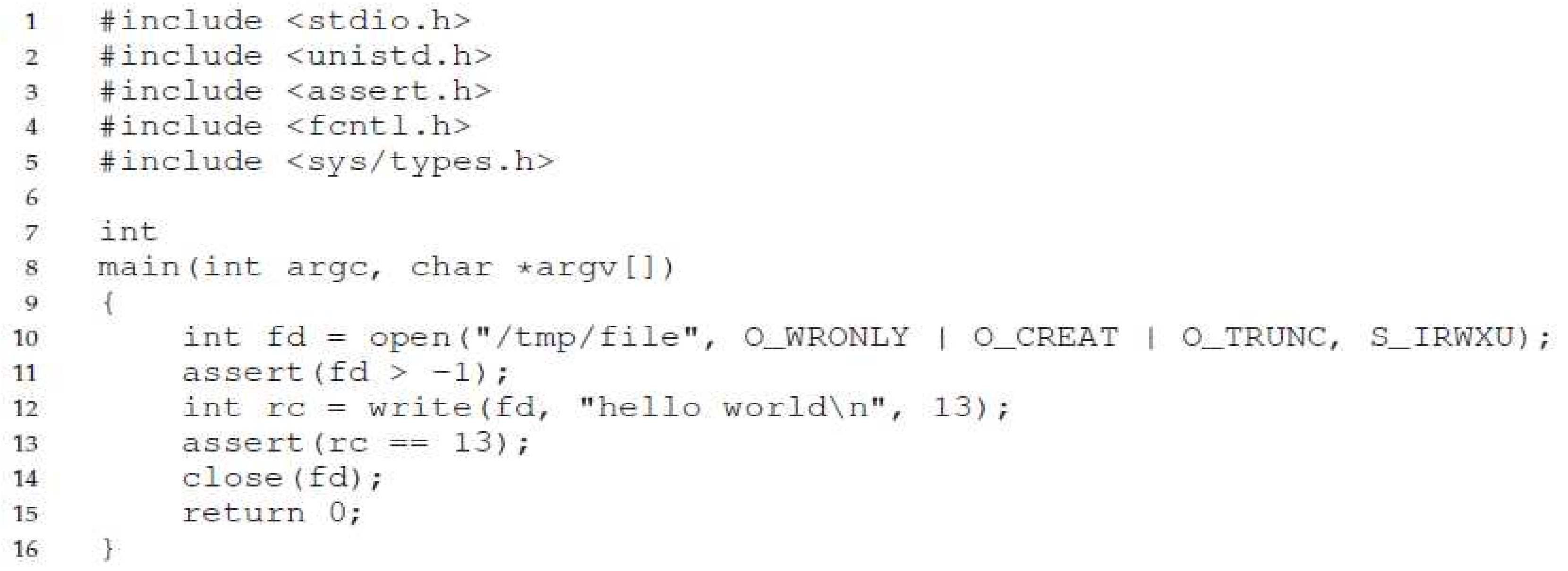
- ✓ Capacity, Speed, Cost, …
- ✓ Access granularity: Byte vs. Sector
- ✓ Durability: Volatile vs. Non-volatile



(Source: Google Image)

2.4 Persistence

- Persistence
  - ✓ Users want to maintain data permanently (durability)
  - ✓ DRAM is volatile, requiring write data into storage (disk, SSD) explicitly
- A program for discussing persistence
  - ✓ Use the notion of a file (not handle disk directly)



```
#include <stdio.h>
#include <unistd.h>
#include <assert.h>
#include <fcntl.h>
#include <sys/types.h>

int
main(int argc, char *argv[])
{
    int fd = open("/tmp/file", O_WRONLY | O_CREAT | O_TRUNC, S_IRWXU);
    assert(fd > -1);
    int rc = write(fd, "hello world\n", 13);
    assert(rc == 13);
    close(fd);
    return 0;
}
```

Figure 2.6: **A Program That Does I/O (`io.c`)**

2.4 Persistence

- Issues for Persistence
  - ✓ How to access a file? ➔ open(), read(), write(), …
  - ✓ How to manage a file? ➔ inode, FAT, …
  - ✓ How to manipulate a directory?
  - ✓ How to design a file system? ➔ UFS, LFS, Ext2/3/4, FAT, F2FS, NFS, AFS, …
  - ✓ How to find a data in a disk?
  - ✓ How to improve performance in a file system? ➔ cache, delayed write, …
  - ✓ How to handle a fault in a file system? ➔ journaling, copy-on-write
  - ✓ What is a role of a disk device driver?
  - ✓ What are the internals of a disk and SSD?
  - ✓ What is the RAID?

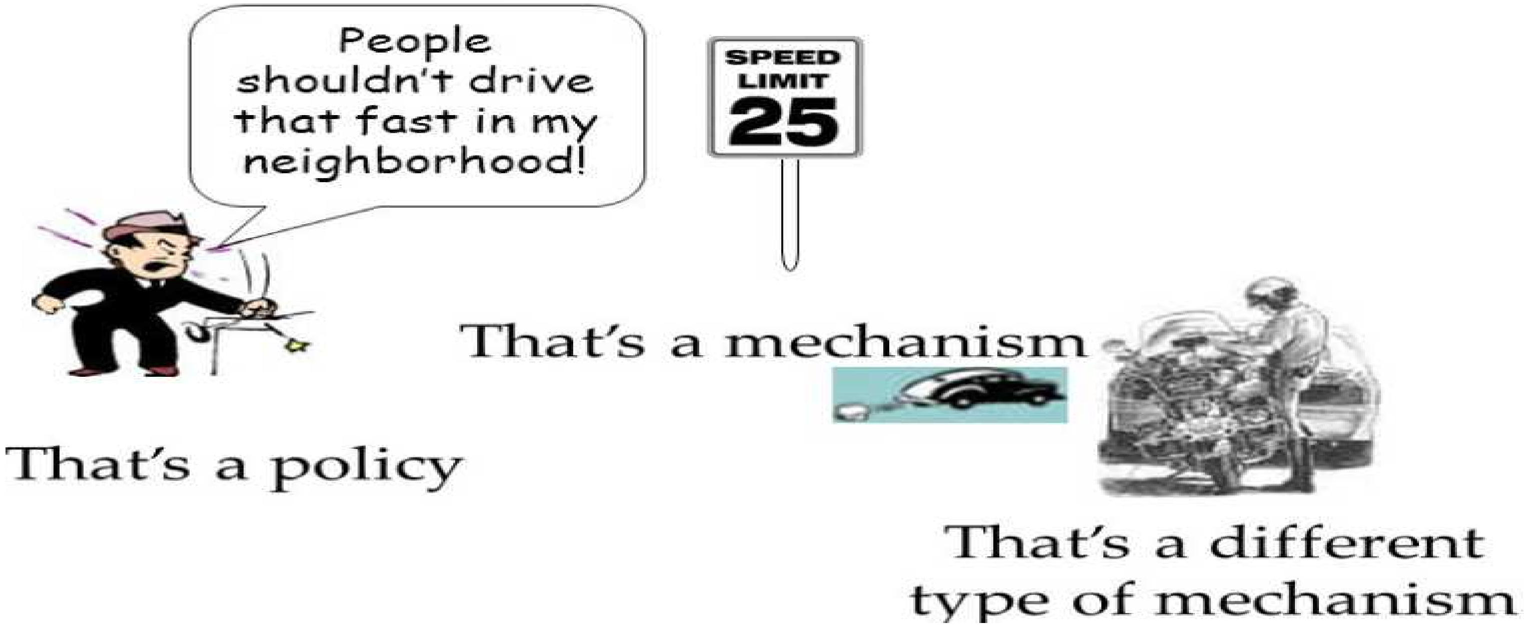
☛ Illusion: Data is always maintained in a reliable non-volatile area while it is often kept in a volatile DRAM (for performance reason) and storage is broken from time to time.

2.5 Design Goals

- Abstraction
  - ✓ Focusing on relevant issues only while hiding details
    - E.g. Car, File system, Make a program without thinking of logic gates
  - ✓ "Abstraction is fundamental to everything we do in computer science" by Remzi
- Performance
  - ✓ Minimize the overhead of the OS (both time and space)
- Protection
  - ✓ Isolate processes from one another
  - ✓ Access control, security, …
- Reliability
  - ✓ Fault-tolerant
- Others
  - ✓ Depend on the area where OS is employed
  - ✓ Real time, Energy-efficiency, Mobility, Load balancing, Autonomous, …

2.5 Design Goals

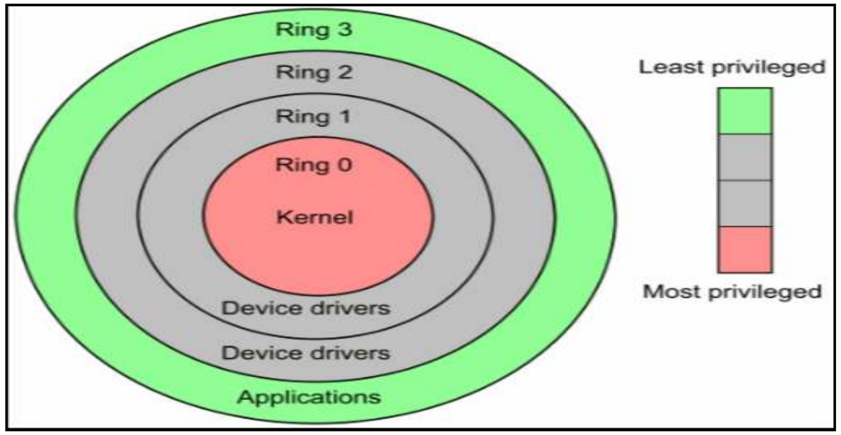
- Separation of Policy and Mechanism
  - ✓ Policy: Which (or What) to do?
    - e.g.) Which process should run next?
  - ✓ Mechanism: How to do?
    - e.g.) Multiple processes are managed by a scheduling queue or RB-tree


People shouldn't drive that fast in my neighborhood!
SPEED LIMIT 25
That's a mechanism
That's a policy
That's a different type of mechanism

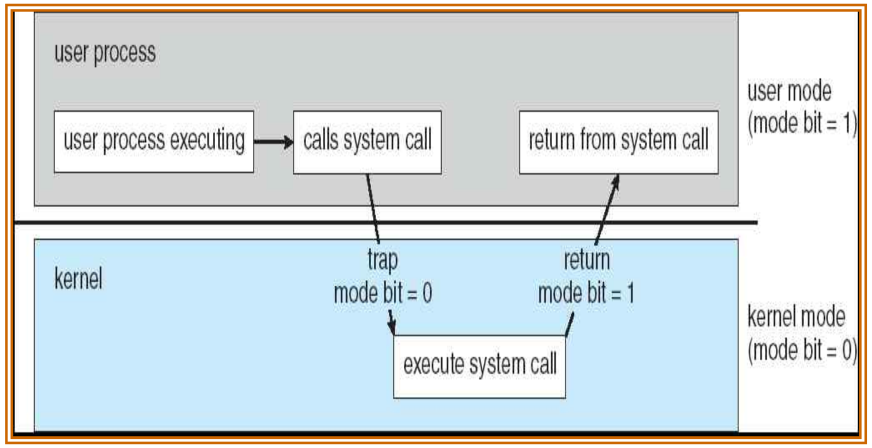
(Source: Security Principles and Policies CS 236 On-Line MS Program Networks and Systems Security, Peter Reiher, Spring, 2008)

2.6 Some History

- Early Operating Systems: Just libraries
  - ✓ Commonly-used functions such as low-level I/Os (e.g. MS-DOS)
  - ✓ Batch processing
    - a number of jobs were set up and then run all together (Not interactive)
- Beyond Libraries: Protection
  - ✓ Require OS to be treated differently than user applications
  - ✓ Separation user/kernel mode, system call
  - ✓ Use trap (special instruction, SW interrupt) to go into the kernel mode
    - Transfer control to a pre-specific trap handler (system_call handler)



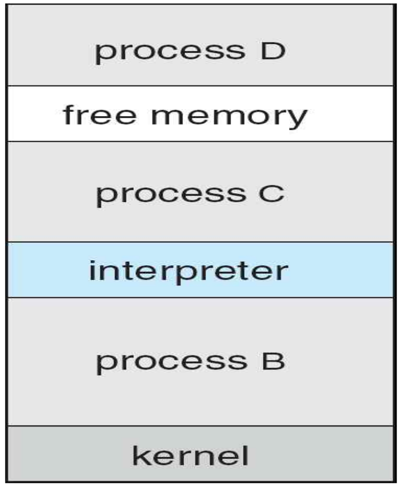
(Source: Google Image)

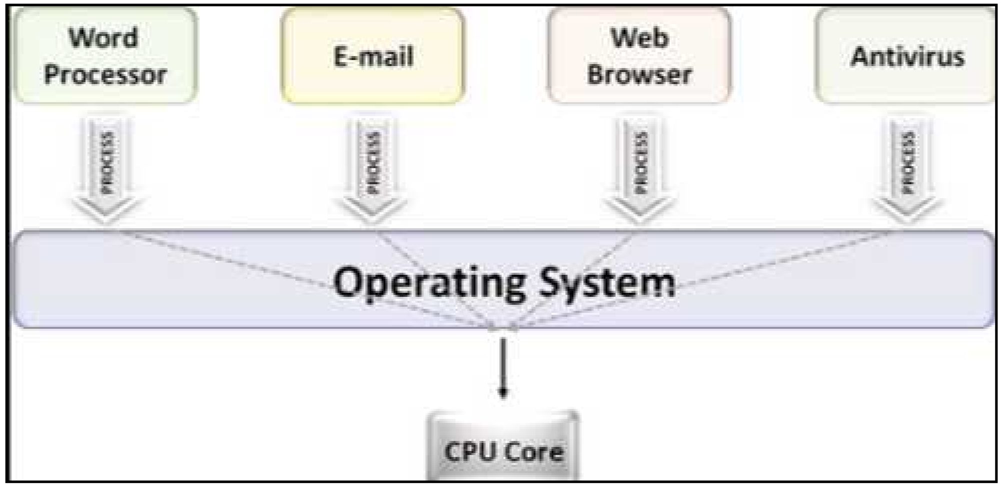


(Source: A. Silberschatz, "Operating system Concept")

2.6 Some History

- The Era of Multiprogramming (c.f. multitasking)
  - ✓ Definition: OS load a number of applications into memory and switch them rapidly
  - ✓ Reason: Advanced hardware ➔ Want to utilize machine resources better ➔ Multiple users share a system (workstation, minicomputer) ➔ multiprogramming (and multitasking)
  - ✓ Especially important due to the slow I/O devices ➔ while doing I/O, switch CPU to another process ➔ enhancing CPU utilization
  - ✓ Memory protection and concurrency become quite important ➔ UNIX

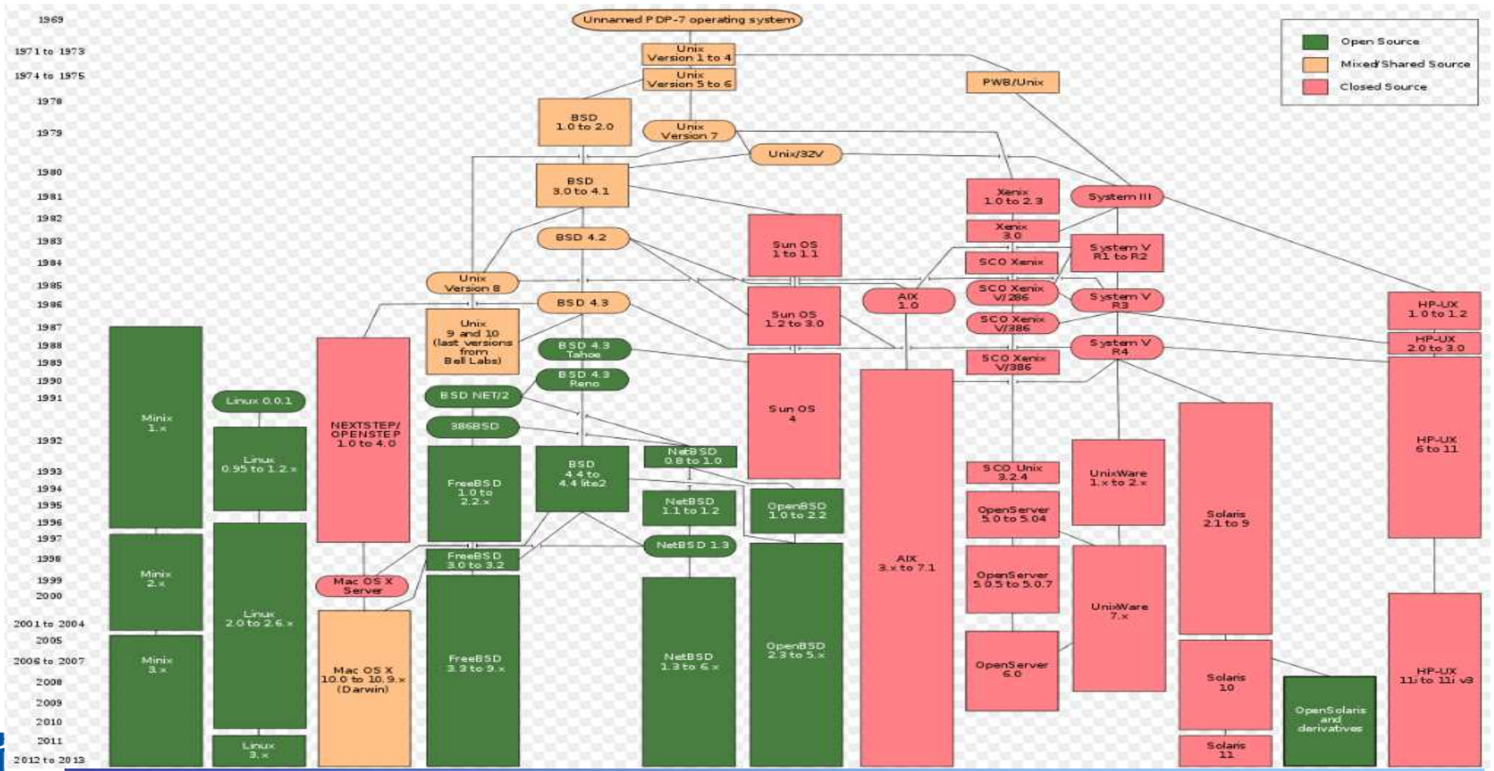




(Source: Google Image)

2.6 Some History

- The Era of Multiprogramming (c.f. multitasking)
  - ✓ UNIX
    - By Ken Thompson and Dennis Ritche (Bell Labs), Influenced by Multics
    - C language based, excellent features such as shell, pipe, inode, small, everything is a file, …
    - Influence OSes such as BSD, SUNOS, AIX, HPUX, Nextstep and Linux



(Source: Wikipedia)

2.6 Some History

- The Modern Era
  - ✓ PC
    - MS Windows, Mac OS X, Linux, …
  - ✓ Smartphone
    - Android, iOS, Windows Mobile, …
  - ✓ IoT
    - What is the next?

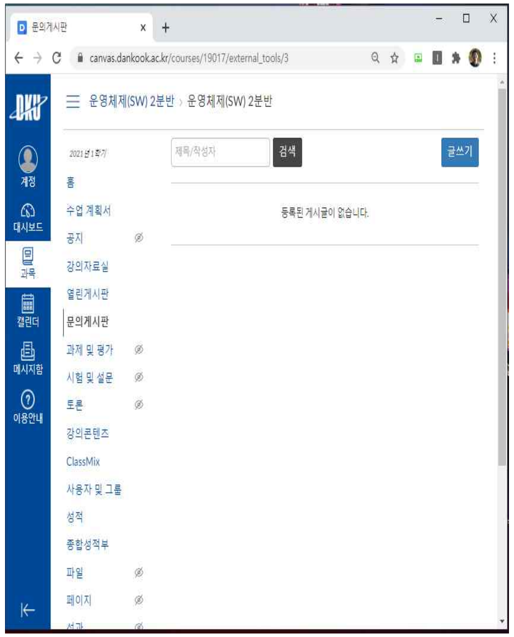
DIY KIT
Linux robots
ARM mbed
TIZEN
The Concept of IoT (Internet of Things)
Google Brillo OS
Operating System for Internet of Things
The Contiki Operating System
Windows 10 IoT Editions
LiteOS
iOS
OS X
watchOS
tvOS

Ubuntu Core on the Internet of Things

Snappy Ubuntu Core delivers bullet-proof security, reliable updates and the enormous Ubuntu ecosystem at your fingertips, bringing the developer's favourite … devices and … and 64-bit ARM and

2.7 Summary

- OS
  - ✓ Resource manager (Efficiency)
  - ✓ Make systems easy to use (Convenience)
- Cover in this book
  - ✓ Virtualization, Concurrency, Persistence
- Not being covered
  - ✓ Network, Security, Graphics
  - ✓ There are several excellent courses for them



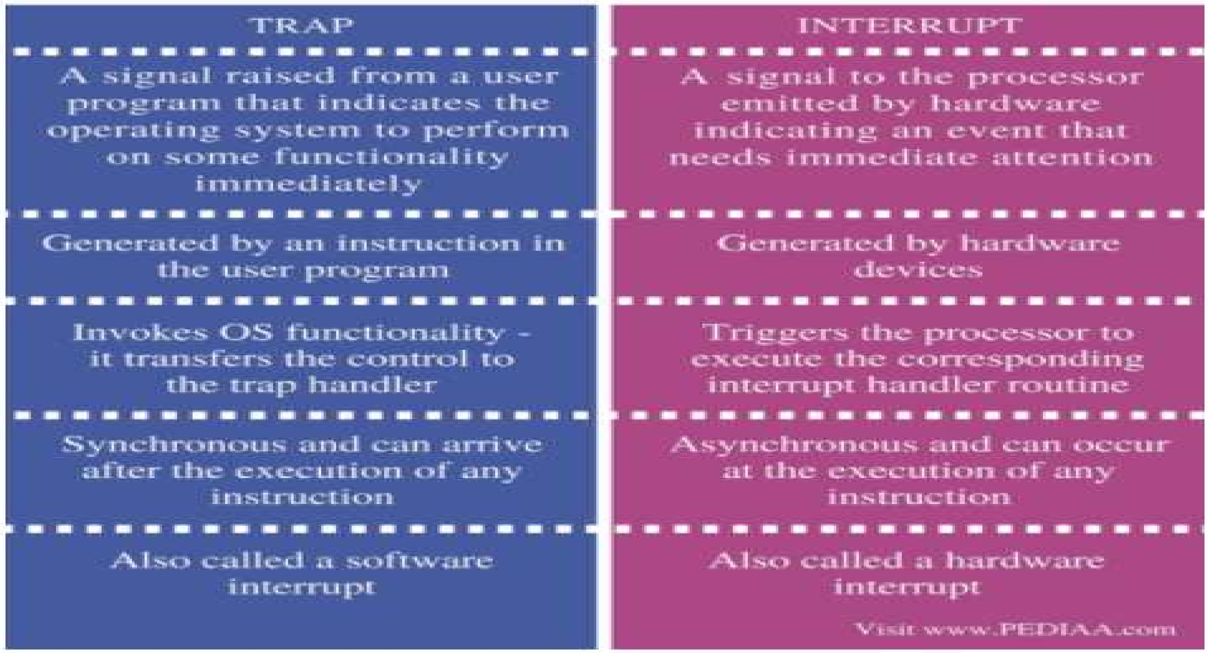
등록된 게시글이 없습니다.

☛ Homework 1: summarize the chap 2 of the OSTEP
- – Requirement: 1) personal, 2) up to 6 pages for summary, 3) 1 page for the goal you want to study
- – Due: until 6 PM, 19th March (Friday)
- – Bonus: Snapshot of the results of example programs in a Linux system (ubuntu on virtual box or wsl or Linux server)

☛ Any questions? Feel free to put your questions at "문의게시판"!!

Quiz for 2nd-Week 1st-Lesson

- Quiz
  - ✓ 1. What are the differences between disks and DRAM? (at least 3 differences). These differences lead operating system to manage them differently (memory object vs. file)
  - ✓ 2. Discuss differences between interrupt and trap which was discussed in page 30.
  - ✓ Due: until 6 PM Friday of this week (12th, March)



TRAP	INTERRUPT
A signal raised from a user program that indicates the operating system to perform on some functionality immediately	A signal to the processor emitted by hardware indicating an event that needs immediate attention
Generated by an instruction in the user program	Generated by hardware devices
Invokes OS functionality - it transfers the control to the trap handler	Triggers the processor to execute the corresponding interrupt handler routine
Synchronous and can arrive after the execution of any instruction	Asynchronous and can occur at the execution of any instruction
Also called a software interrupt	Also called a hardware interrupt

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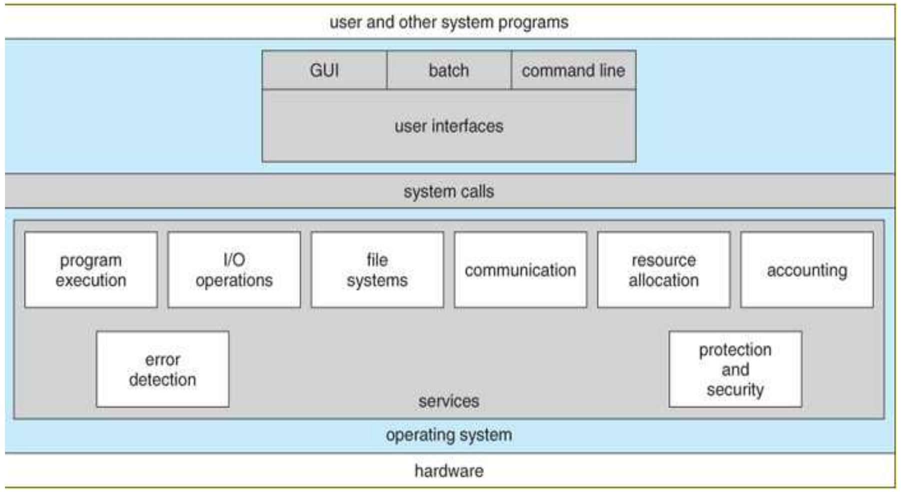
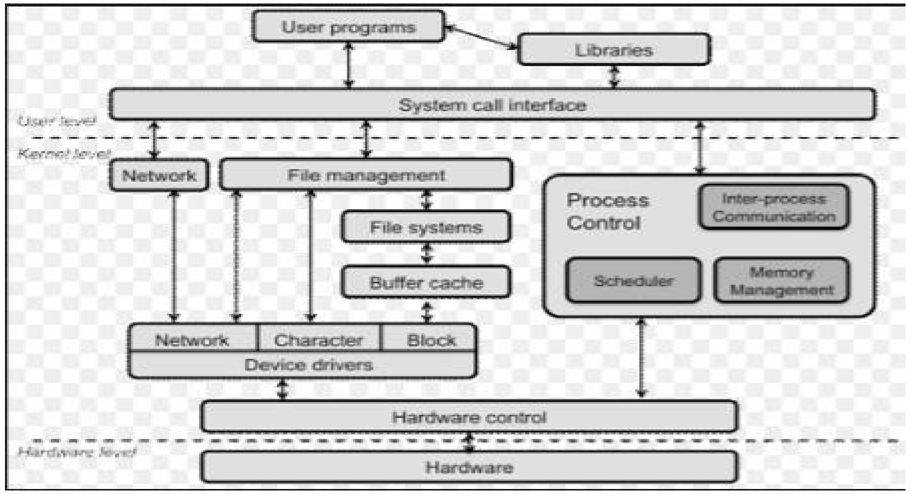
Appendix

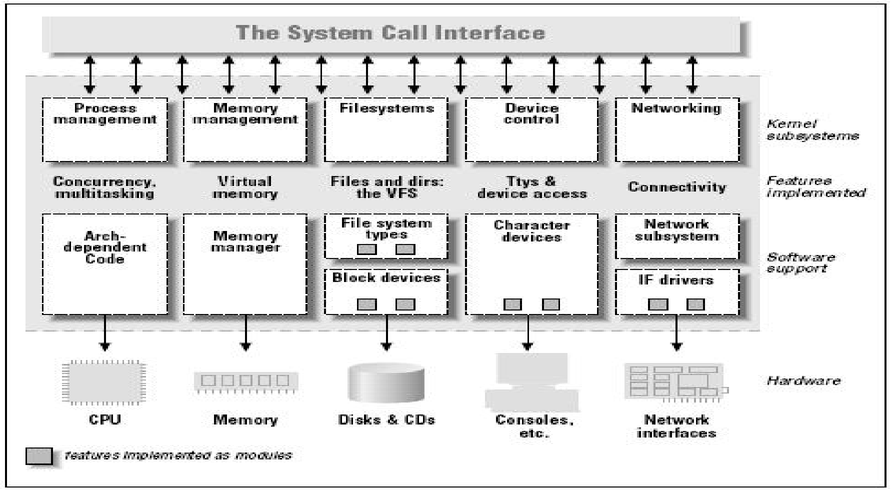
- OS structure in General



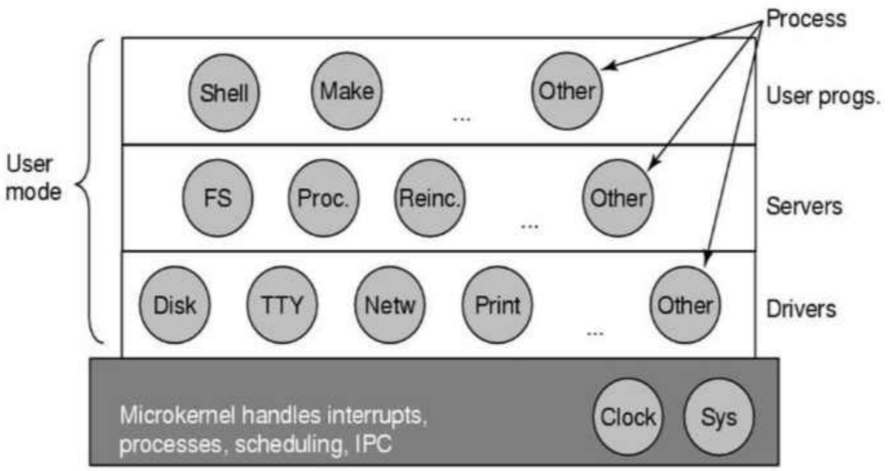
(Source: Operating System Concepts)



(Source: https://www.cs.rutgers.edu/~pxk/416/notes/03-concepts.html)



(Source: Linux Device Driver)



(Source: Modern Operating System)