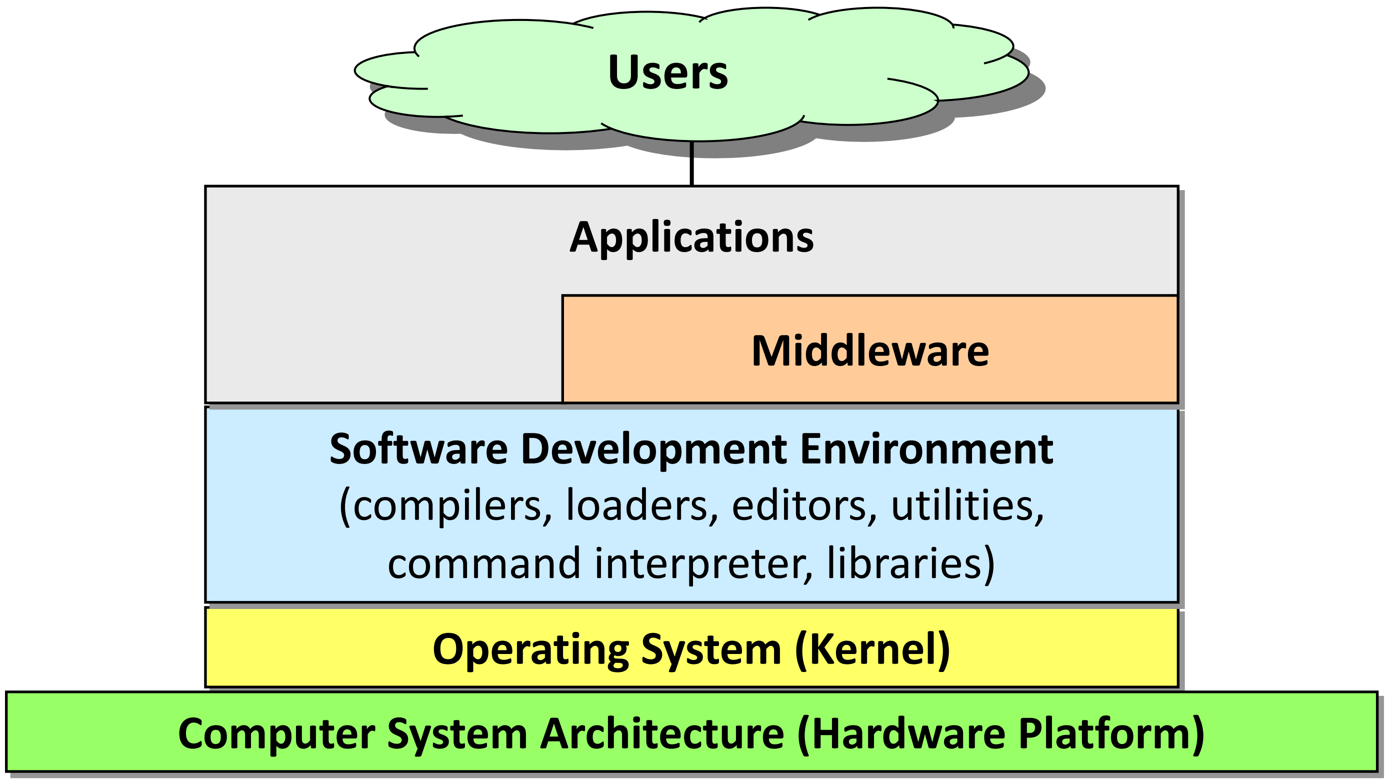
What is
an Operating System?

Software Stack

- An OS is software that converts hardware into a useful form for applications



What a happens when a program runs?

- A running program executes instructions
  - The processor fetches an instruction from memory
  - Decode: Figure out which instruction this is
  - Execute: i.e., add two numbers, access memory, check a condition, jump to function, and so forth
  - The processor moves on to the next instruction and so on
- Who did load this program into memory?
- Who does remove this program when this program acts abnormally?

What happens when many programs run together?

- Two programs share a single main memory
  - Program A may corrupt data of program B
  - How can I tell where my data are located at?
- Two programs share a small set of processors
  - When the number of cores is smaller than the number of running programs, who controls which program uses a processor?
  - Who decides which program runs on which core?
  - You have only one mouse and one keyboard, how can multiple programs share the resources?
- If a program tries to steal your information, which is stored by Chrome web browser, who protects your information from it?

Operating System (OS)

- Responsible for
  - Making it easy to **run** programs
  - Allowing programs to **share** memory
  - Enabling programs to **interact** with devices

OS is in charge of making sure the system operates correctly and efficiently

Three Pieces

- Virtualization
  - Make each application believe it has each resource to itself
    - Processes, CPU scheduling, virtual memory

- Concurrency
  - Handle concurrent events correctly
    - Threads, synchronization

- Persistence
  - Access information permanently while preserving correctness upon unexpected failures
    - Storage, file systems

Virtualization

- The OS takes a physical resource and transforms it into a virtual form of itself
  - **Physical resource**: Processor, Memory, Disk …
  - The virtual form is more general, powerful and easy-to-use

- An application cannot directly access (or see) the underlying hardware
  - An application sees and uses virtualized hardware
  - An OS is located in between an application and hardware, and acts like an intermediary

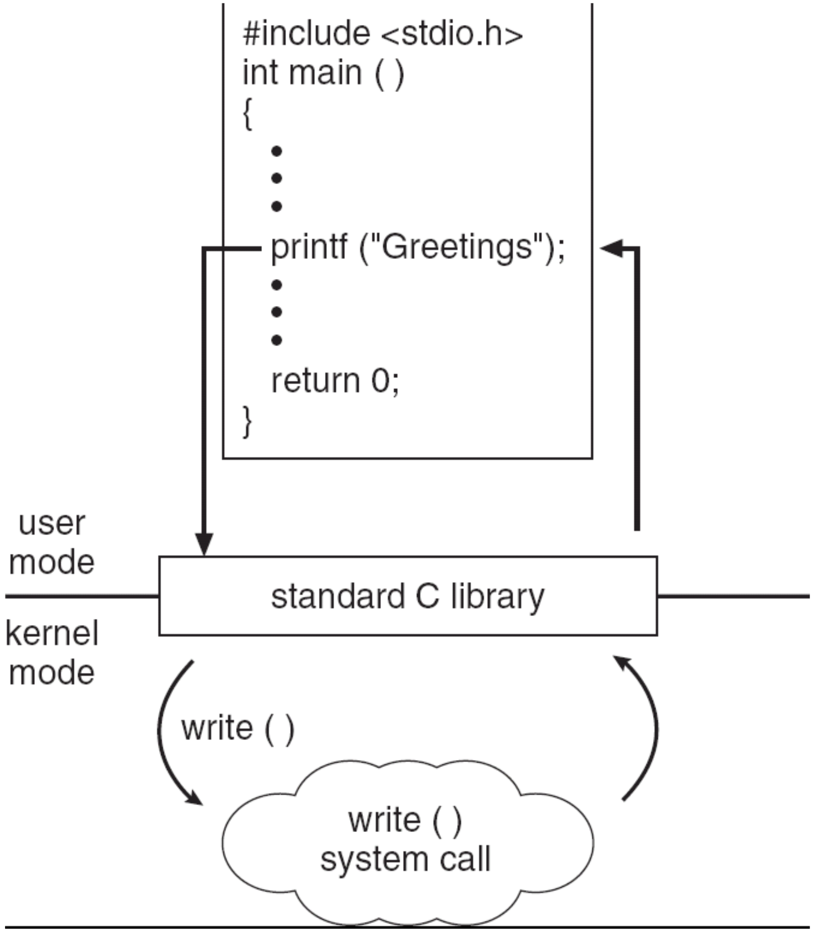
Roles of Operating System

- OS is a resource allocator
  - Manages all resources
  - Decides between conflicting requests for efficient and fair resource use
- OS is a control program
  - Controls execution of programs to prevent errors and improper use of the computer

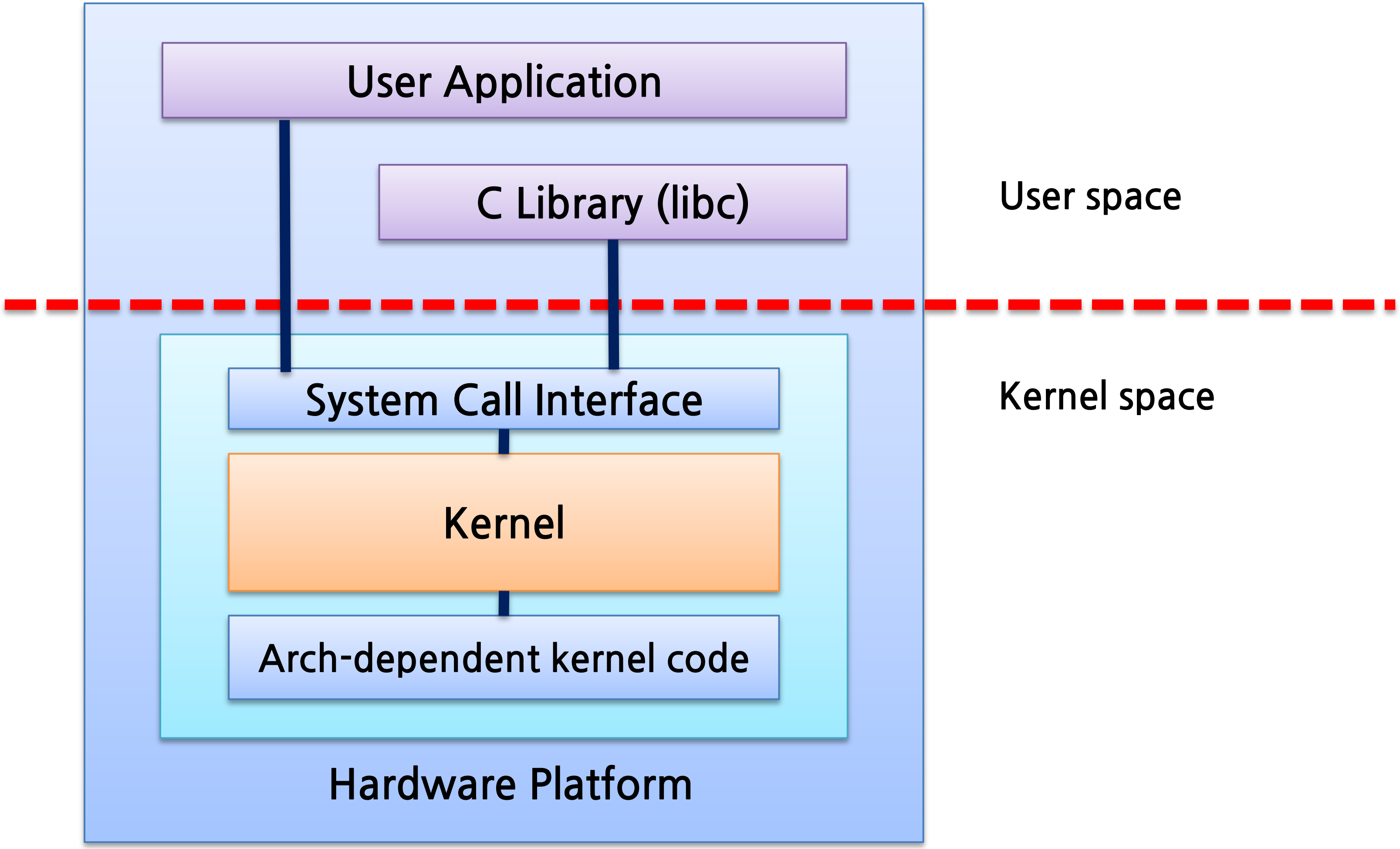
System calls

- A system call allows a program **to request OS what it wants to do**
  - Systems are interface between OS and applications
  - A typical OS exports a few hundred system calls.
    - Run programs
    - Access memory
    - Access devices

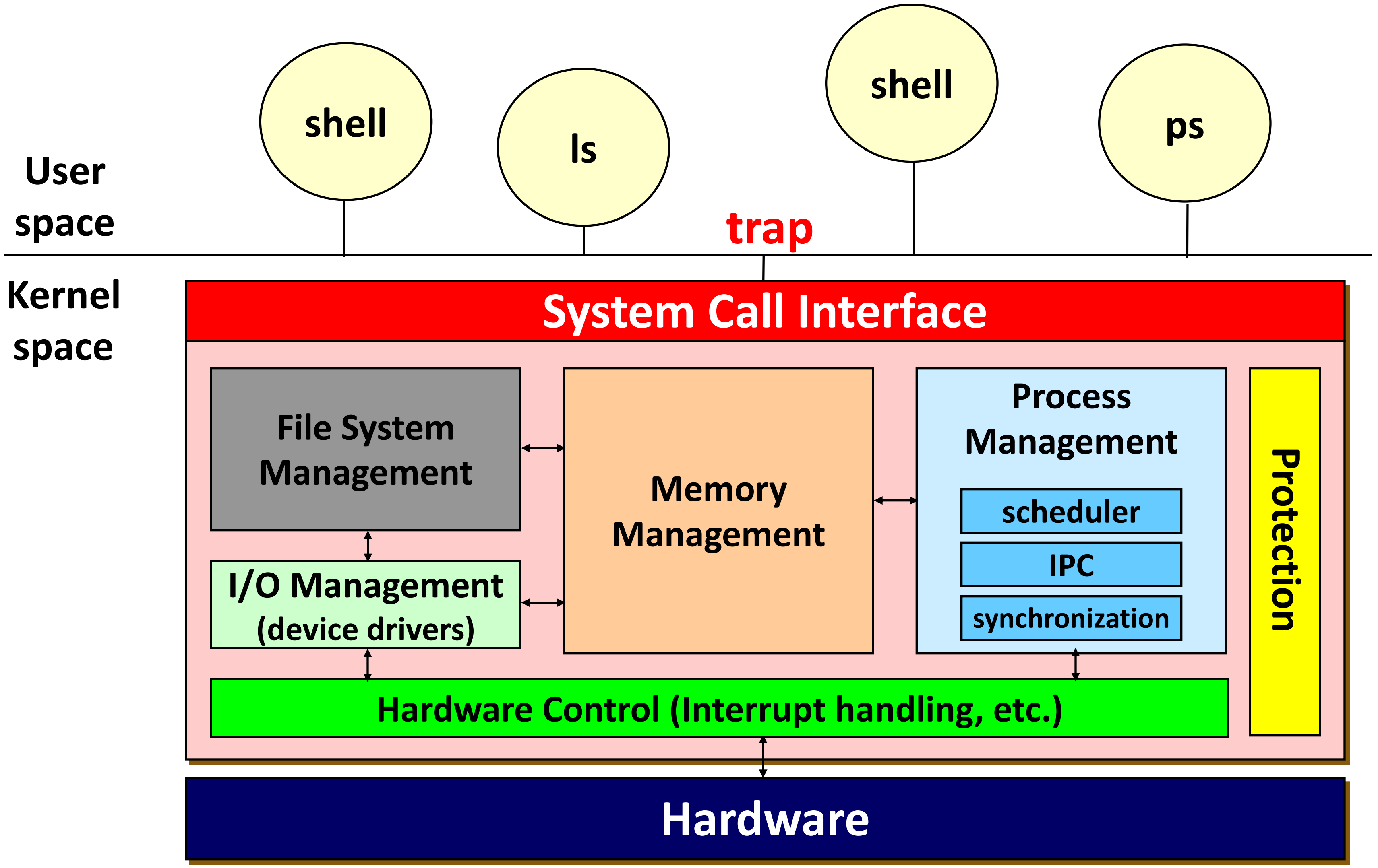
System Call Interface



Interactions Between OS and Apps



Interactions Between OS and Apps



Virtualizing CPU

- The system has a very large number of virtual CPUs
  - Turning a single CPU into a seemingly infinite number of CPUs
  - Allowing many programs to seemingly run at once
    → **Virtualizing the CPU**

Virtualizing CPU (Cont.)

```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); // Repeatedly checks the time and returns once it has run for a second
                printf("%s\n", str);
        }
        return 0;
}
```

Simple Example(`cpu.c`): Code That Loops and Prints

Virtualizing the CPU (Cont.)

- Execution result

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

Run forever; Only by pressing "Control-c" can we halt the program

Virtualizing the CPU (Cont.)

- Execution result

```
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
C
B
D
...
```

Even though we have only one processor, all four of programs seem to be running at the same time!

Virtualizing Memory

- The physical memory is *an array of bytes*
- A program keeps all of its data structures in memory
  - **Read memory** (load):
    - Specify an address to be able to access the data
  - **Write memory** (store):
    - Specify the data to be written to the given address
- Let's read a program that accesses memory (`mem.c`)

Virtualizing Memory (Cont.)

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

int
main(int argc, char *argv[])
{
        int *p = malloc(sizeof(int));  // a1: allocate memory
        assert(p != NULL);
        printf("(%d) address of p: %08x\n",
                getpid(), (unsigned) p);  // a2: print out the
                                             address of the memmory
        *p = 0;  // a3: put zero into the first slot of the memory
        while (1) {
                Spin(1);
                *p = *p + 1;
                printf("(%d) p: %d\n", getpid(), *p); // a4
        }
        return 0;
}
```

Virtualizing Memory (Cont.)

- The output of the program `mem.c`

```
prompt> ./mem
(2134) memory address of p: 00200000
(2134) p: 1
(2134) p: 2
(2134) p: 3
(2134) p: 4
(2134) p: 5
^C
```

  - The newly allocated memory is at address `00200000`.
  - It updates the value and prints out the result.

Virtualizing Memory (Cont.)

- Running `mem.c` multiple times

```
prompt> ./mem &; ./mem &
[1] 24113
[2] 24114
(24113) memory address of p: 00200000
(24114) memory address of p: 00200000
(24113) p: 1
(24114) p: 1
(24114) p: 2
(24113) p: 2
(24113) p: 3
(24114) p: 3
...
```

- It is as if each running program has its **own private memory**.
  - Each running program has allocated memory at the same address.
  - Each seems to be updating the value at `00200000` independently.

Virtualizing Memory (Cont.)

- Each process accesses its own private **virtual address space**
  - The OS maps address space onto the physical memory
  - A memory reference within one running program does not affect the address space of other processes
  - Physical memory is a shared resource, managed by the OS

Problem of Concurrency

- The OS is juggling many things at once, first running one process, then another, and so forth

- Modern multi-threaded programs also exhibit the concurrency problem

Concurrency Example

- A Multi-threaded Program (`thread.c`)

```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);
        }
```

Concurrency Example (Cont.)

```
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;
}
```

- The main program creates **two threads**.
  - Thread: a function running within the same memory space. Each thread start running in a routine called `worker()`
  - `worker()`: increments a counter

Concurrency Example (Cont.)

- `loops` determines how many times each of the two workers will **increment the shared counter** in a loop
  - `loops`: 1000

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

  - `loops`: 100000

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

Why is this happening?

- Increment a shared counter → take three instructions.
  1. Load the value of the counter from memory into register.
  2. Increment it
  3. Store it back into memory

- These three instructions do not execute atomically → Problem of **concurrency** happen

Persistence

- Devices such as DRAM store values in a volatile
- *Hardware* and *software* are needed to store data persistently
  - **Hardware**: I/O device such as a hard drive, solid-state drives(SSDs)
  - **Software**:
    - File system manages the disk
    - File system is responsible for storing any files the user creates

Persistence (Cont.)

- Create a file (`/tmp/file`) that contains the string "hello world"

```
#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;
}
```

`open()`, `write()`, and `close()` system calls are routed to the part of OS and called the file system, which handles the requests

Persistence (Cont.)

- A disk, like main memory, is just a large array of bytes

- What OS does in order to write data to disk and manage them?
  - Figure out **where** on disk this new data will reside
  - **Issue I/O** requests to the underlying storage device

- File system handles system crashes during write
  - **Journaling** or **copy-on-write**
  - Carefully <u>ordering</u> writes to disk

Design Goals

- Build up **abstraction**
  - Make the system convenient and easy to use

- Provide high **performance**
  - Minimize the overhead of the OS
  - OS must strive to provide virtualization without excessive overhead

- **Protection** between applications
  - Isolation: Bad behavior of one does not harm other and the OS itself

Design Goals (Cont.)

- High degree of **reliability**
  - The OS must also run non-stop

- Other issues
  - Energy-efficiency
  - Security
  - Mobility