Advanced Operating Systems: Three Easy Pieces

Introduction to Operating Systems

Course Content

- Cover the following advanced topics including:
  - Virtualization
  - Memory Management
  - Concurrency Control and Deadlock
  - Persistence
  - Security
  - Distributed Operating System
- Cover briefly few advanced case studies
- Cover briefly few advanced research topics in Operating Systems
- In addition, students (divided in groups) will work on a set of hands-on projects.

Textbook

- “**Operating Systems: Three Easy Pieces**,”by Remzi H. Arpaci-Dusseau and Andrea C. Arpaci-Dusseau.
  Arpaci –Dusseau Books
  March, 2015 (version 0.90)
  http://pages.cs.wisc.edu/~remzi/OSTEP/

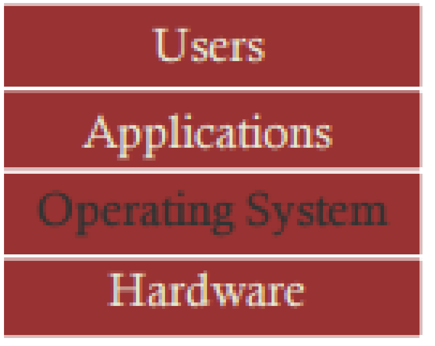
  Three Pieces are: Virtualization, Concurrency, and Persistence

What Does Operating System Provide?

Operating System Roles?

- **Role #1: Abstraction to applications that is hardware independent of the physical hardware resources**
- **What is a resource and its abstraction?**

Physical Resource	Abstraction
CPU	Process / Thread
Memory	Address Space
Disk	Files



Operating System Roles?

- **Role #2: Resource Management**
  1. Protect applications from each other
  2. Provide efficient access to resources
  3. Provide fair access to resources

Operating System Organization

OS Organization: Three Pieces?

- **First Piece: Virtualization**
  - Make each application believe it has each resources to itself
- **Second Piece: Concurrency**
  - Correct behavior while events are occurring simultaneously and may interact with one another
- **Third Piece: Persistence**
  - Access information permanently – lifetime of data is longer and independent of lifetime of any one process / application even in the presence of failure/reboot

OS Organization: Three Pieces?

- **Advanced Topics:**
  - Multiprocessor (tightly coupled)
  - Distributed Systems (loosely coupled)
  - Virtual Machine
  - NUMA and RDMA
  - Data Center OS (DC OS)

First Piece: Virtualization

What a happens when a program runs?

- A running program executes instructions:
  1. The processor **fetches** an instruction from memory.
  2. **Decode**: Figure out which instruction this is
  3. **Execute**: i.e., add two numbers, access memory, check a condition, jump to function, and so forth.
  4. The processor moves on to the **next instruction** and so on.

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.

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.
  - Sometimes, we refer to the OS as a **virtual machine**.

System call

- System call allows user **to ask the OS for what to do or what services is needed**:
  - The OS provides some interface (APIs, standard library) to provide system-level services.
  - A typical OS exports a few hundreds system calls.
    - Run programs
    - Access memory
    - Access devices

The OS is a resource manager.

- The OS **manages resources** such as *CPU*, *memory* and *disk*.
- The OS allows:
  - Many programs to run → Sharing the <u>CPU</u>
  - Many programs to *concurrently* access their own instructions and data → Sharing <u>memory</u>
  - Many programs to access devices → Sharing <u>disks</u>

Virtualizing the 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 the 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];  // str = 1st cmd line arg
        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 1**:

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

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

Virtualizing the CPU (Cont.)

- **Execution result 2**:

```
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

Virtualizing Memory (Cont.)

```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: allocate some memory
                                          to be used as counter
        assert(p != NULL);
        printf("(%d) address of p: %08x\n",
                getpid(), (unsigned) p);  // a2: print out the pid
                                          and address of the memory
        *p = 0;  // a3: put zero into the first slot of the allocated memory
        while (1) {
                Spin(1);
                *p = *p + 1;
                printf("(%d) p: %d\n", getpid(), *p); // a4: print
                                 pid and the content of memory counter
        }
        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    // Heap address
(24114) memory address of p: 00200000    // Heap address
(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 <u>the same address</u>.
  - 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.

Second Piece: Concurrency

The 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;                              /* user supplied value */

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.)

```
                    loops = atoi(argv[1]);
                    pthread_t  p1, p2;
                    printf("Initial value : %d\n", counter);  // counter = 0

/* pthread_create(thread_t t, pthread_attr_t *attr,
                       void *(*start_routine)(void *), void *arg); */
                    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: 1,000.

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

  - loops: 100,000.

```
prompt> ./thread 100000
Initial value : 0
Final value : 143012        // huh?? Not 200,000
prompt> ./thread 100000
Initial value : 0
Final value : 137298        // what is this – different value?
```

  - The issue is “loops” is global variable and it is being accessed without synchronization by 2-threads (read-increment-write) is not atomic.

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.

Third Piece: Persistence

Persistence

- Devices such as DRAM store values/data in a volatile medium.
- *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 called the file system, which handles the requests

Persistence (Cont.)

- **What OS does in order to write to disk?**
  - 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 ordering writes to disk

Operating System Design Goals

OS Design Goals

- Build up **abstraction:**
  - Make the system convenient and easy to use.
  - User program to hardware independent APIs.

- 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

END