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

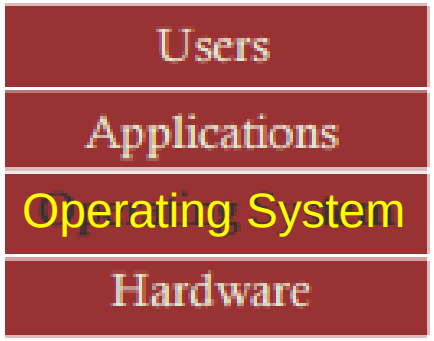
- "**Operating Systems: Three Easy Pieces**,"by Remzi H. Arpaci-Dusseau and Andrea C. Arpaci-Dusseau.
  Arpaci –Dusseau Books
  March, 2015 (version 0.90)
  http://pages.cs.wisc.edu/~remzi/OSTEP/

  Three Pieces are: Virtualization, Concurrency, and Persistence

What Does Operating System Provide?

Operating System Roles?

- **Role #1: Resources' 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 – I own the CPU
- **Second Piece: Concurrency**
  - **Correct behavior** while events are occurring randomly & simultaneously and may interact with one another
- **Third Piece: Persistence**
  - **Information is permanent** – 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 systems)
  - Distributed Systems (loosely coupled systems)
  - 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/application **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 CPU
  - Many programs to *concurrently* access their own instructions and data → Sharing memory
  - Many programs to access devices → Sharing disks

Virtualizing the CPU

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

Virtualizing the CPU (Cont.)

```
1       #include <stdio.h>
2       #include <stdlib.h>
3       #include <sys/time.h>
4       #include <assert.h>
5       #include "common.h"
6
7       int
8       main(int argc, char *argv[])
9       {
10              if (argc != 2) {
11                      fprintf(stderr, "usage: cpu <string>\n");
12                      exit(1);
13              }
14              char *str = argv[1];  // str = 1st cmd line arg
15              while (1) {
16                      Spin(1); // Repeatedly checks the time and
                                 // returns once it has run for a second
17                      printf("%s\n", str);
18              }
19              return 0;         // never executed
20      }
```

% a.out "Hello"

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 read the data from
  - **Write memory** (store):
    - Specify the data to be written to the given target address

Virtualizing Memory (Cont.)

```
1       #include <unistd.h>
2       #include <stdio.h>
3       #include <stdlib.h>
4       #include "common.h"
5
6       int
7       main(int argc, char *argv[])
8       {
9               int *p = malloc(sizeof(int));  // a1: allocate some memory
                                                  to be used as counter
10              assert(p != NULL);
11              printf("(%d) address of p: %08x\n",
12                      getpid(), (unsigned) p);  // a2: print out the pid
                                                  and address of the memory
13              *p = 0;  // a3: put value zero in 1st slot of the allocated memory
14              while (1) {
15                      Spin(1);
16                      *p = *p + 1;
17                      printf("(%d) p: %d\n", getpid(), *p); // a4: print
                                        pid and the content of memory counter
18              }
19              return 0;                   // never executed
20      }
```

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 the same address but at different address space
    - Each seems to be updating the value at VA = 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 as each process address space is mapped into different physical memory segments.
  - **Physical memory** is a shared resource to be assigned to different processes' address spaces, managed by the OS.

Second Piece: Concurrency

The problem of Concurrency

- **The OS is juggling** many things at the same time, 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)

```
1       #include <stdio.h>
2       #include <stdlib.h>
3       #include "common.h"
4
5       volatile int counter = 0;   /* shared counter between threads */
6       int loops;                              /* user supplied value */
7
8       void *worker(void *arg) {
9               int i;
10              for (i = 0; i < loops; i++) {
11                      counter++;          /* This is not an atomic op */
12              }
13              return NULL;
14      }
15
16      int
17      main(int argc, char *argv[])
18      {
19              if (argc != 2) {
20                      fprintf(stderr, "usage: threads <value>\n");
21                      exit(1);
22              }
```

Concurrency Example (Cont.)

```
23                  loops = atoi(argv[1]);
24                  pthread_t  p1, p2;
25                  printf("Initial value : %d\n", counter);  // counter = 0
26
27                  /* pthread_create(thread_t t, pthread_attr_t *attr,
28                            void *(*start_routine)(void *), void *arg); */
29                  Pthread_create(&p1, NULL, worker, NULL);
30                  Pthread_create(&p2, NULL, worker, NULL);
31                  Pthread_join(p1, NULL);
32                  Pthread_join(p2, NULL);
33                  printf("Final value : %d\n", counter);
34                  return 0;
35          }
```

- **The main program creates two threads**:
  - **Thread**: a function running within the same memory address 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 "counter" is a 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”

```
1       #include <stdio.h>
2       #include <unistd.h>
3       #include <assert.h>
4       #include <fcntl.h>
5       #include <sys/types.h>
6
7       int
8       main(int argc, char *argv[])
9       {
10              int fd = open("/tmp/file", O_WRONLY | O_CREAT
                                | O_TRUNC, S_IRWXU);
11              assert(fd > -1);
12              int rc = write(fd, "hello world\n", 13);
13              assert(rc == 13);
14              close(fd);
15              return 0;
16      }
```

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, and provides simple easy to use abstraction to access the data:
  - **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 application does not harm another or the OS itself.

Design Goals (Cont.)

- **High degree of reliability**
  - The OS must also run non-stop.
- **Other issues**
  - Energy-efficiency
  - Security
  - Mobility

END