The Process Abstraction

CMPU 334 – Operating Systems
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How to Provide the Illusion of Many CPUs?

- Goal: run N processes at once even though there are M CPUs
  - N >> M
- CPU virtualizing
  - The OS can promote the **illusion** that many virtual CPUs exist
  - One **isolated machine** for each program
- Timesharing
  - Running one program, then stopping it and running another
  - The potential cost is **performance**
- What are the benefits?
  - Ease of use for the programmer
  - Protection – program runs on a restricted machine

A Process

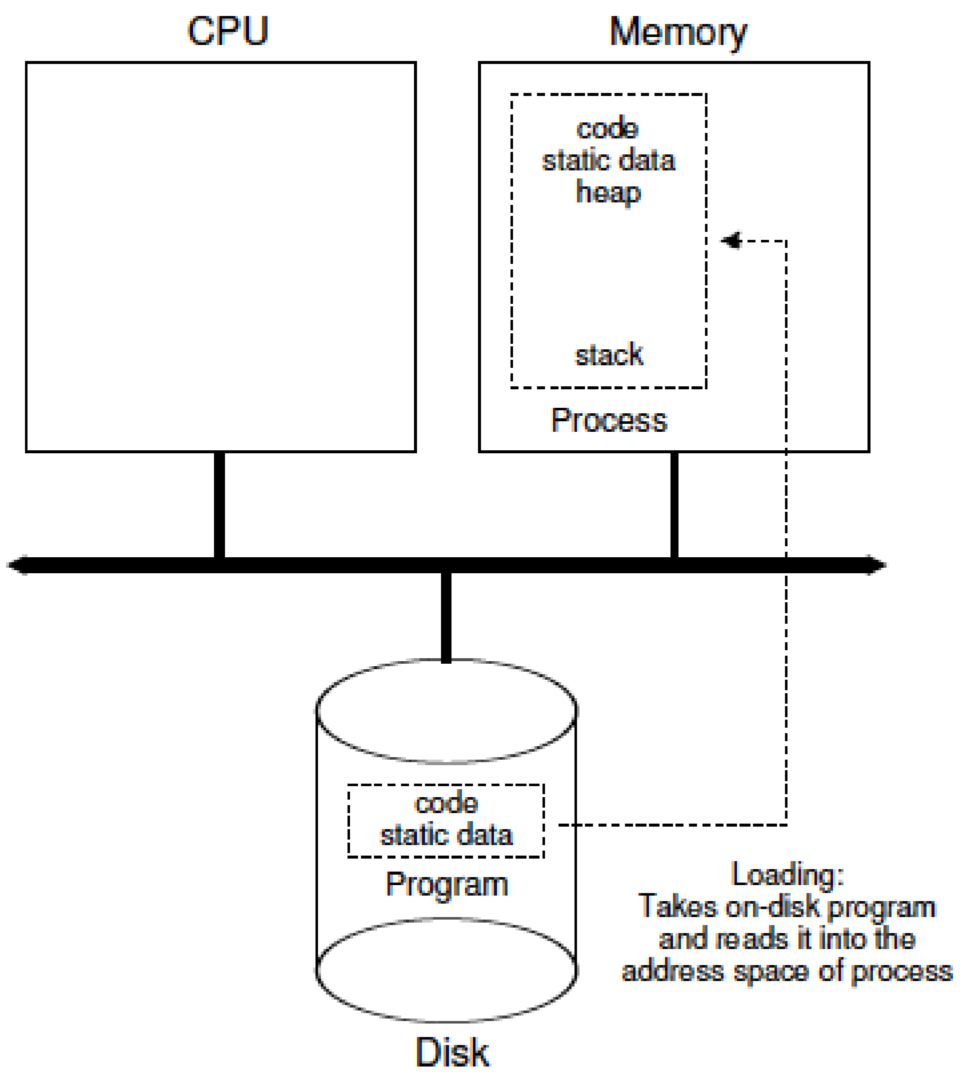
- A process is OS's abstraction of a **running program**
- What constitutes a process?
  - Memory (address space)
    - Instructions
    - Data
  - Registers (state of the processor)
    - General purpose registers
    - Program counter (PC)
    - Stack pointer (SP)
  - I/O Information
    - List of files a process currently has open

Process API

- These APIs are available on any modern OS
  - Create
    - Create a new process to run a program
  - Destroy
    - Halt a runaway process
  - Wait
    - Wait for a process to stop running
  - Miscellaneous Control
    - Suspend
    - Resume
  - Status
    - Get some status information about a process
    - How long it has been running
    - What state is it in

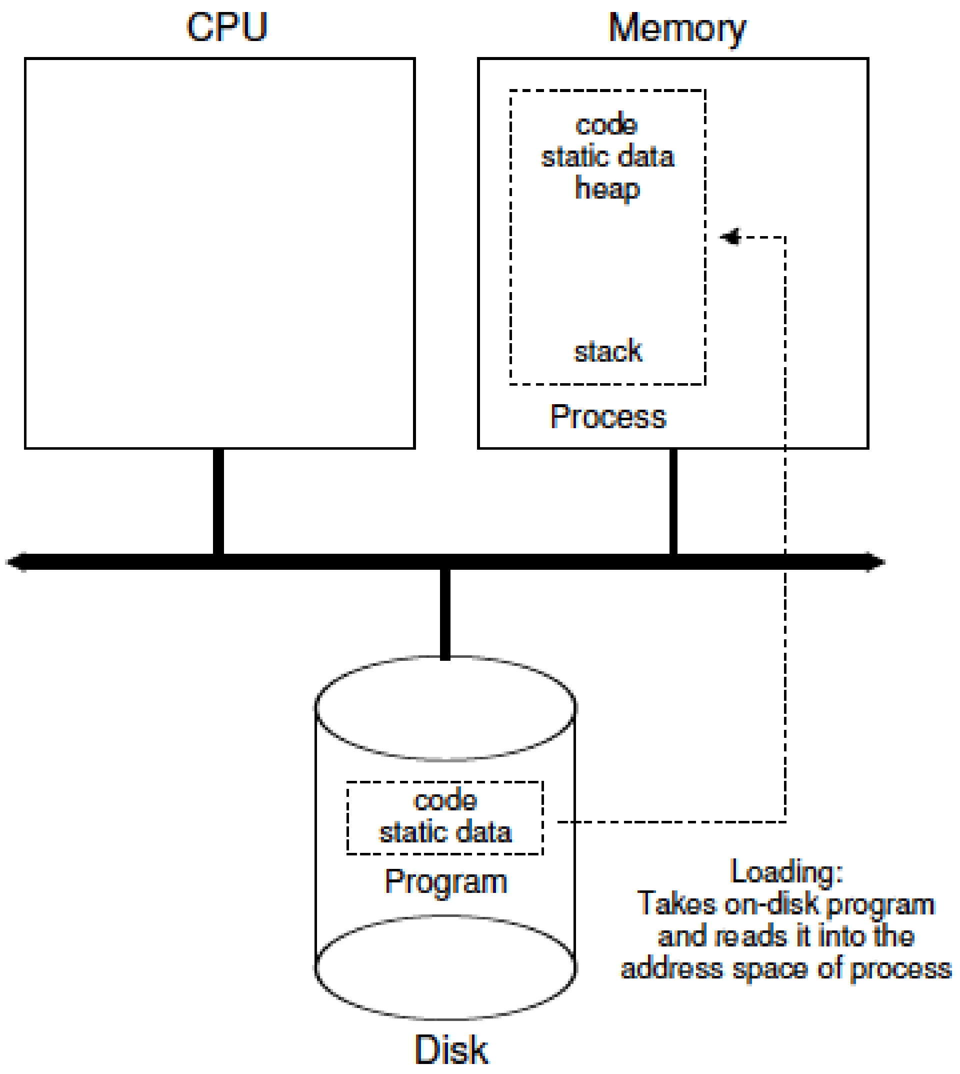
Process Creation

1. Load a program code into **memory**, the address space of the process
   - Programs reside on a disk in an **executable format** (e.g., ELF)
2. The program's **run-time stack** is allocated
   - Stack is used for local variables, function parameters, return address
   - Initialize the stack with arguments
     - `argc` and `argv` array of `main()` function



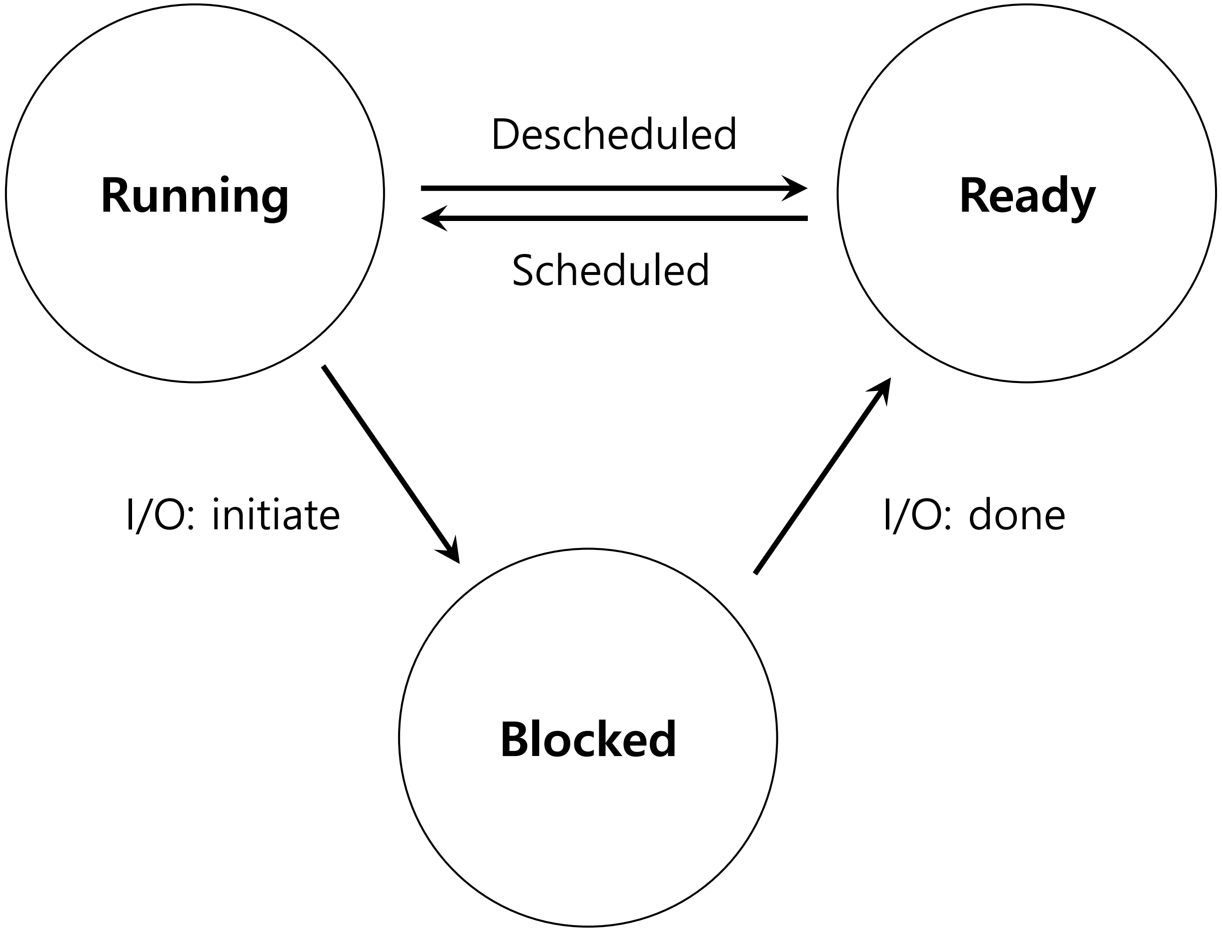
Process Creation (Cont.)

3. The program's **heap** is created
   - Used for explicitly requested dynamically allocated data
   - `malloc(); free()`
4. The OS does some other **initialization**
   - I/O setup (stdin, stdout, stderr)
5. **Start** the program running at the entry point `main()`
   - The OS transfers control of the CPU to the newly-created process



Process States (simplified)

- A process can be in one of three states
  - **Running**
    - A process is running on the CPU
  - **Ready**
    - A process is ready to run but for some reason the OS has chosen not to run it at this given moment
  - **Blocked**
    - A process has performed some kind of operation that it is waiting on
    - E.g., an disk request



Process Data Structures

- The OS has some key data structures that track various pieces of information
  - Process list
    - Ready processes
    - Blocked processes
    - Current running process
  - Register context
    - A copy of all the registers for a process
- The Process Control Block (PCB)
  - A structure that contains information about each process

Process Creation

- We talked about process creation in general terms
- Now let's discuss process creation in UNIX systems
  - `fork()` – Makes a copy of the currently running process
  - `exec()` – Replaces a process with a different program
  - `wait()` – Wait for a child process to finish
- Questions to think about
  - What interfaces should the OS present for process creation and control?
  - How should these interfaces be designed to enable ease of use as well as utility?

The `fork()` System Call

- Create a new process
  - The newly-created process has its own copy of the **address space**, **registers**, and **PC**

p1.c

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

int main(int argc, char *argv[]){
    printf("hello world (pid:%d)\n", (int) getpid());
    int rc = fork();
    if (rc < 0) {         // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) { // child (new process)
        printf("hello, I am child (pid:%d)\n", (int) getpid());
    } else {              // parent goes down this path (main)
        printf("hello, I am parent of %d (pid:%d)\n",
        rc, (int) getpid());
    }
    return 0;
}
```

Calling `fork()` example (Cont.)

Result (Not deterministic)

```
prompt> ./p1
hello world (pid:29146)
hello, I am parent of 29147 (pid:29146)
hello, I am child (pid:29147)
prompt>
```

or

```
prompt> ./p1
hello world (pid:29146)
hello, I am child (pid:29147)
hello, I am parent of 29147 (pid:29146)
prompt>
```

The `wait()` System Call

- This system call won't return until the child has run and exited

p2.c

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/wait.h>

int main(int argc, char *argv[]){
    printf("hello world (pid:%d)\n", (int) getpid());
    int rc = fork();
    if (rc < 0) {          // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) { // child (new process)
        printf("hello, I am child (pid:%d)\n", (int) getpid());
    } else {               // parent goes down this path (main)
        int wc = wait(NULL);
        printf("hello, I am parent of %d (wc:%d) (pid:%d)\n",
        rc, wc, (int) getpid());
    }
    return 0;
}
```

The `wait()` System Call (Cont.)

Result (Deterministic)

```
prompt> ./p2
hello world (pid:29266)
hello, I am child (pid:29267)
hello, I am parent of 29267 (wc:29267) (pid:29266)
prompt>
```

The `exec()` System Call

- Run a program that is different from the calling program

p3.c

```
int main(int argc, char *argv[]){
    printf("hello world (pid:%d)\n", (int) getpid());
    int rc = fork();
    if (rc < 0) {                       // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) {               // child (new process)
        printf("hello, I am child (pid:%d)\n", (int) getpid());
        char *myargs[3];
        myargs[0] = strdup("wc");           // program: "wc" (word count)
        myargs[1] = strdup("p3.c");         // argument: file to count
        myargs[2] = NULL;                   // marks end of array
        execvp(myargs[0], myargs); // runs word count
        printf("this shouldn't print out");
    } else {                            // parent goes down this path (main)
        int wc = wait(NULL);
        printf("hello, I am parent of %d (wc:%d) (pid:%d)\n",
            rc, wc, (int) getpid());
    }
    return 0;
}
```

Result

```
prompt> ./p3
hello world (pid:29383)
hello, I am child (pid:29384)
29 107 1030 p3.c
hello, I am parent of 29384 (wc:29384) (pid:29383)
prompt>
```

Motivating the API

- Why the odd interface for the simple act of creating a new process?
- Why are `fork()` and `exec()` separate functions?
- Necessary for building a UNIX shell
  - It lets the shell run code *after* the call to `fork()` but *before* the call to `exec()`
  - Can alter the environment of the about to be run program
  - Can easily support things like redirection and pipes

All of the above with redirection

p4.c

```
int
main(int argc, char *argv[]){
    int rc = fork();
    if (rc < 0) {          // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) { // child: redirect standard output to a file
        close(STDOUT_FILENO);
        open("./p4.output", O_CREAT|O_WRONLY|O_TRUNC, S_IRWXU);

        // now exec "wc"...
        char *myargs[3];
        myargs[0] = strdup("wc");        // program: "wc" (word count)
        myargs[1] = strdup("p4.c");      // argument: file to count
        myargs[2] = NULL;                // marks end of array
        execvp(myargs[0], myargs);       // runs word count
    } else {                          // parent goes down this path (main)
        int wc = wait(NULL);
    }
    return 0;
}
```

Result

```
prompt> ./p4
prompt> cat p4.output
32 109 846 p4.c
prompt>
```

How to Efficiently Virtualize the CPU with Control?

- The OS needs to share the physical CPU by **time sharing**
- Issues
  - **Performance**: How can we implement virtualization without adding excessive overhead to the system?
  - **Control**: How can we run processes efficiently while retaining control over the CPU?

Direct Execution

Just run the program directly on the CPU

OS	**Program**
1. Create entry for process list 2. Allocate memory for program 3. Load program into memory 4. Set up stack with `argc` / `argv` 5. Clear registers 6. Execute call `main()`	
	7. Run `main()` 8. Execute `return` from `main()`
9. Free memory of process 10. Remove from process list	

Without *limits* on running programs,
the OS wouldn't be in control of anything and
thus would be "just a library"

Problem 1: Restricted Operation

- What if a process wishes to perform some kind of restricted operation such as …
  - Issuing an I/O request to a disk
  - Gaining access to more system resources such as CPU or memory

- **Solution**: Using protected control transfer
  - User mode: Applications do not have full access to hardware resources
  - Kernel mode: The OS has access to the full resources of the machine

System Call

- Allow the kernel to carefully expose certain key pieces of functionality to user program, such as …
  - Accessing the file system
  - Creating and destroying processes
  - Communicating with other processes
  - Allocating more memory
- **Trap** instruction
  - Jump into the kernel
  - Raise the privilege level to kernel mode
- **Return-from-trap** instruction
  - Return into the calling user program
  - Reduce the privilege level back to user mode

Limited Direction Execution Protocol @Boot

OS @ boot (kernel mode)	Hardware
initialize trap table	
	remember address of … syscall handler

Limited Direction Execution Protocol @Run

OS @ run (kernel mode)	Hardware	Program (user mode)
Create entry for process list Allocate memory for program Load program into memory Setup user stack with argv Fill kernel stack with reg/PC **return-from-trap**		
	restore regs from kernel stack move to user mode jump to main	
		Run main() … Call system call **trap** into OS
	save regs to kernel stack move to kernel mode jump to trap handler	
Handle trap Do work of syscall **return-from-trap**		
	restore regs from kernel stack move to user mode jump to PC after trap	
		… return from main trap (via `exit()`)
Free memory of process Remove from process list		

Problem 2: Switching Between Processes

- How can the OS regain control of the CPU so that it can switch between *processes*?
  - A cooperative Approach: **Wait for system calls**
  - A Non-Cooperative Approach: **The OS takes control**

A cooperative Approach: Wait for system calls

- Processes periodically give up the CPU by making **system calls** such as `yield`
  - The OS decides to run some other task
  - Application also transfer control to the OS when they do something illegal
    - Divide by zero
    - Try to access memory that it shouldn't be able to access

  - Examples: early versions of the Macintosh OS, the old Xerox Alto system

A process gets stuck in an infinite loop
→ Reboot the machine

A Non-Cooperative Approach: OS Takes Control

- **A timer interrupt**
  - During the boot sequence, the OS start the timer
  - The timer raise an interrupt every so many milliseconds
  - When the interrupt is raised:
    - The currently running process is halted
    - Save enough of the state of the program
    - A pre-configured interrupt handler in the OS runs

A timer interrupt gives OS the ability to run again on a CPU

Saving and Restoring Context

- Scheduler makes a decision:
  - Whether to continue running the **current process**, or switch to a **different one**
  - If the decision is made to switch, the OS executes a context switch

Context Switch

- A low-level piece of assembly code
  - **Save a few register values** for the current process onto its kernel stack
    - General purpose registers
    - PC
    - Kernel stack pointer
  - **Restore a few register values** for the soon-to-be-executing process from its kernel stack
  - **Switch to the kernel stack** for the soon-to-be-executing process

Limited Direction Execution Protocol (Timer interrupt) @Boot

OS @ boot (kernel mode)	Hardware
initialize trap table	

	remember address of …
	  syscall handler
	  timer handler

start interrupt timer	
	start timer interrupt CPU in X ms

Limited Direction Execution Protocol (Timer interrupt) @Run

OS @ run (kernel mode)	Hardware	Program (user mode)
		Process A …
	timer interrupt save regs(A) to k-stack(A) move to kernel mode jump to trap handler for timer	

Handle the trap
Call switch() routine
  save regs(A) to proc-struct(A)
  restore regs(B) from proc-struct(B)
  switch to k-stack(B)
return-from-trap (into B)		

	restore regs(B) from k-stack(B) move to user mode jump to B's PC	
		Process B …

Worried About Concurrency?

- What happens if, during interrupt or trap handling, another interrupt occurs?
- OS handles these situations:
  - **Disable interrupts** during interrupt processing
  - Use a number of sophisticated **locking** schemes to protect concurrent access to internal data structures

Separating Policy and Mechanism

- Design paradigm
  - Separate high-level policies from their low-level mechanisms
- Mechanism
  - Answers the “how” question about a system
  - How does the OS perform a context switch?
- Policy
  - Answers the “which” question about a system
  - Which process should the OS run right now?
- Allows for policies to change without having to rethink the underlying mechanism
  - Gives the system good modularity