The Process Abstraction

CMPU 334 – Operating Systems
Jason Waterman
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

• Time sharing
  • 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 run 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 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
   • OS performs the loading process lazily
     • Loads pieces of code or data only as they are needed during program execution (demand paging)

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
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

• 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 C-structure that contains information about each process
The xv6 Kernel Process Structures

// the registers xv6 will save and restore
// to stop and subsequently restart a process

struct context {
    int eip; // Index pointer register
    int esp; // Stack pointer register
    int ebx; // Called the base register
    int ecx; // Called the counter register
    int edx; // Called the data register
    int esi; // Source index register
    int edi; // Destination index register
    int ebp; // Stack base pointer register
};

// the different states a process can be in
enum procstate { UNUSED, EMBRYO, SLEEPING,
                 Runnable, Running, Zombie };
// Per-process state
struct proc {
    uint sz; // Size of process memory (bytes)
pde_t* pgdir; // Page table
char *kstack; // Bottom of kernel stack for this process
enum procstate state; // Process state
int pid; // Process ID
struct proc *parent; // Parent process
struct trapframe *tf; // Trap frame for current syscall
struct context *context; // swtch() here to run process
void *chan; // If non-zero, sleeping on chan
int killed; // If non-zero, have been killed
struct file *ofile[NOFILE]; // Open files
struct inode *cwd; // Current directory
char name[16]; // Process name (debugging)
};
Process Creation

• We talked about process creation in general terms

• Now 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**.

```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)

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

or

```bash
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

```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.)

<table>
<thead>
<tr>
<th>Result (Deterministic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>prompt&gt; ./p2</td>
</tr>
<tr>
<td>hello world (pid:29266)</td>
</tr>
<tr>
<td>hello, I am child (pid:29267)</td>
</tr>
<tr>
<td>hello, I am parent of 29267 (wc:29267) (pid:29266)</td>
</tr>
<tr>
<td>prompt&gt;</td>
</tr>
</tbody>
</table>
The exec() System Call

- Run a program that is different from the calling program

```
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>

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Motivating the API

• Why the odd interface for the simple act of creating a new process?
• Why is fork() and exec() a separate functions?
• Necessary for building a UNIX shell
  • Let’s 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

```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

<table>
<thead>
<tr>
<th>OS</th>
<th>Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Create entry for process list</td>
<td>7. Run main()</td>
</tr>
<tr>
<td>2. Allocate memory for program</td>
<td>8. Execute return from main()</td>
</tr>
<tr>
<td>3. Load program into memory</td>
<td></td>
</tr>
<tr>
<td>4. Set up stack with <code>argc</code> / <code>argv</code></td>
<td></td>
</tr>
<tr>
<td>5. Clear registers</td>
<td></td>
</tr>
<tr>
<td>6. Execute call <code>main()</code></td>
<td></td>
</tr>
<tr>
<td>9. Free memory of process</td>
<td></td>
</tr>
<tr>
<td>10. Remove from process list</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>OS @ boot (kernel mode)</th>
<th>Hardware</th>
</tr>
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<tbody>
<tr>
<td>initialize trap table</td>
<td>remember address of … syscall handler</td>
</tr>
</tbody>
</table>

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**Limited Direction Execution Protocol @Run**

<table>
<thead>
<tr>
<th>OS @ run (kernel mode)</th>
<th>Hardware</th>
<th>Program (user mode)</th>
</tr>
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<tbody>
<tr>
<td>Create entry for process list</td>
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<td>Run main()</td>
</tr>
<tr>
<td>Allocate memory for program</td>
<td></td>
<td>...</td>
</tr>
<tr>
<td>Load program into memory</td>
<td></td>
<td>Call system call</td>
</tr>
<tr>
<td>Setup user stack with argv</td>
<td></td>
<td>trap into OS</td>
</tr>
<tr>
<td>Fill kernel stack with reg/PC</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>return-from-trap</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Handle trap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Do work of syscall</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>return-from-trap</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free memory of process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remove from process list</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Limited Direction Execution Protocol @Run**

- **OS @ run (kernel 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**

- **Hardware**
  - Restore regs from kernel stack
  - Move to user mode
  - Jump to main

- **Program (user mode)**
  - Run main()
  - ... Call system call
  - trap into OS

- **Handle trap**
  - Do work of syscall
  - **return-from-trap**

- **Hardware**
  - Save regs to kernel stack
  - Move to kernel mode
  - Jump to trap handler

- **Program (user mode)**
  - Restore regs from kernel stack
  - Move to user mode
  - Jump to PC after trap

- **Hardware**
  - Return from main
  - Trap (via exit())
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 starts the timer
  - The timer raises 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 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

<table>
<thead>
<tr>
<th>OS @ boot (kernel mode)</th>
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<tbody>
<tr>
<td>initialize trap table</td>
<td>remember address of ...</td>
</tr>
<tr>
<td></td>
<td>syscall handler</td>
</tr>
<tr>
<td></td>
<td>timer handler</td>
</tr>
<tr>
<td>start interrupt timer</td>
<td>start timer</td>
</tr>
<tr>
<td></td>
<td>interrupt CPU in X ms</td>
</tr>
</tbody>
</table>
Limited Direction Execution Protocol (Timer interrupt) @Run

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<tr>
<th>OS @ run (kernel mode)</th>
<th>Hardware</th>
<th>Program (user mode)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Process A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>...</td>
</tr>
<tr>
<td>timer interrupt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>save regs(A) to k-stack(A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>move to kernel mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>jump to trap handler for timer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Handle the trap</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Call switch() routine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>save regs(A) to proc-struct(A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>restore regs(B) from proc-struct(B)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>switch to k-stack(B)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>return-from-trap (into B)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>return to kernel mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>return from trap (into B)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>move regs(B) from k-stack(B)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>move to user mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>jump to B’s PC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process B</td>
<td></td>
<td>...</td>
</tr>
</tbody>
</table>

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