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Operating Systems

Part 1: Virtualization – 1) Processes

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Outline

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CPU Virtualization

CPU Virtualization

Remember: In the introduction, we provided a few motivations to virtualize the CPU:

- ▶ Enables running multiple programs at the “same” time
- ▶ Provides the illusion of having an infinite number of CPUs
- ▶ Instructions from different programs do not interfere with each other

The interesting question now is: How can such virtualization actually be implemented?

Virtualization: Abstract Idea

The main concept behind virtualization is to provide access to a single resource multiple times “at once” (and probably for different parties).

In the physical world, this is difficult. However, in computing, we can resort to a trick:

- ▶ Each resource is available only once
- ▶ Full access is given for a resource...
- ▶ ...but only during a *restricted* time frame
- ▶ This is known as time sharing
- ▶ Everyone requiring the resource accesses it in turns

How is this possible?



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Introduction to Processes

The Process

Definition

A process ^a is (informally) a *running instance* of a *program*.

- ▶ A program is a set of instructions (and possibly data) stored *on disk*
- ▶ Each program in general exists only once on a computer
- ▶ A process is an instantiation of a program
- ▶ There can be $0 \dots N$ processes (from different programs) running at the same time

^aSometimes also called a task

Process as an Abstraction

A process is an *abstraction* of a running program: A representation of everything relevant being read or written while the program is running (its machine state). Most importantly:

- ▶ The address space : The whole memory belonging to the process
- ▶ CPU registers , especially
 - ▶ The program counter (PC) , also called instruction pointer (IP)
 - ▶ Stack pointer (SP) and corresponding frame pointer (FP)
- ▶ I/O information (e.g. open files)

Process API

In order to work with processes, an OS must provide an API, which supports in some form:

- ▶ The *creation* of processes, as well as their *destruction*
- ▶ Functionality for *waiting* and *controlling*
- ▶ Access process *status* information

All modern operating systems provide such an API, although they all look a bit different.

Process Creation

When creating a process, the OS performs a series of steps. In a nutshell:

- ▶ Load the program into memory:¹ executable *code* and *static data* (i.e. initialized variables)
 - ▶ This includes code from *shared libraries*
- ▶ Allocate the stack ; often initialized with *program arguments* and *environment*
- ▶ Maybe preallocate some heap memory
- ▶ Initialize I/O
 - ▶ E.g. UNIX: open `stdin`, `stdout` and `stderr` file descriptors
- ▶ Run the `main()` function

¹This is often done *lazily*, i.e. only when selected parts are required.

Process Creation Illustrated

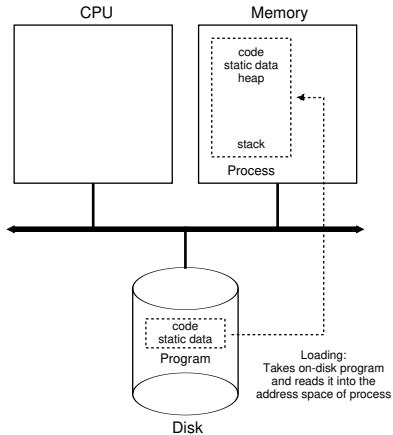


Figure: Loading a Program

Courtesy of [ADAD18]

Process States

A process can be in different states, simplified:

Running The process is running on a CPU, i.e. *it is executing instructions*

Ready The process is *ready to be run*. For some reasons, the OS has chosen not to run it at this given moment

Blocked (waiting) The process has performed some operation which makes it wait for an event to happen. Often, this is caused by an I/O request: reading data from disk or waiting for user input.

We say that a process is being **scheduled** if it moves from ready to running state; **descheduled** if it moves from running to ready.

Process States Illustrated

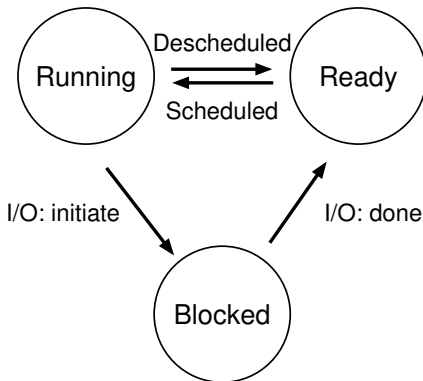


Figure: Process States and Transitions

Courtesy of [ADAD18]

Process State Trace: CPU only

This is an example of two processes running, using only the CPU (no I/O):

Time	Process ₀	Process ₁	Notes
1	Running	Ready	
2	Running	Ready	
3	Running	Ready	
4	Running	Ready	Process ₀ done
5	-	Running	
6	-	Running	
7	-	Running	
8	-	Running	Process ₁ done

Process State Trace: CPU and IO

This is an example with two processes; at some time, one of them is blocked due to an I/O request.

Time	Process ₀	Process ₁	Notes
1	Running	Ready	
2	Running	Ready	
3	Running	Ready	Process ₀ initiates I/O
4	Blocked	Running	
5	Blocked	Running	
6	Blocked	Running	
7	Ready	Running	I/O done
8	Ready	Running	Process ₁ done
9	Running	-	
10	Running	-	Process ₀ done

OS Data Structures

Internally, OSes use a variety of *data structures* to track and manage processes, I/O, users and much more. Typically, a process list (task list) tracks all processes present in a system.

A process structure (sometimes called process control block (PCB) or process descriptor) represents an individual process:²

- ▶ Process ID (PID)
- ▶ Parent process
- ▶ Process state
- ▶ Information about memory, stack, ...
- ▶ Context (register values)
- ▶ ...and more!

²The fields in the process structure are highly dependent of the OS. Different fields may be present and they may have different names!

The xv6 proc Structure

Source: [xv6a]

```
struct context {
    uint edi;
    uint esi;
    uint ebx;
    uint ebp;
    uint eip;
};

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; // switch() 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)
};
```



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Limited Direct Execution

Time Sharing for Virtualization

Now that we have some understanding of processes, let's come back to CPU virtualization:

- ▶ CPU virtualization can be achieved using time sharing
- ▶ *Basic idea*: let a process run for a while, then switch to another
- ▶ Issue No.1: *Control*
 - ▶ How to keep control over the CPU?
 - ▶ Why should a process return? What about endless loops?
 - ▶ How to prevent it from accessing restricted information?
- ▶ Issue No.2: *Performance*

Limited Direct Execution

The model which we will use is called limited direct execution . It consists of two key points:

Direct Execution: Processes run directly on the CPU, i.e. there is no additional abstraction layer between process and CPU (performance!)

Limits: There are some limiting mechanisms in place for

- ▶ Running time (we want to switch back to the OS or other processes. . .)
- ▶ Resource access (e.g. memory of other processes or I/O devices)

For this, some support from the CPU is required: Distinction of user mode and kernel mode .³

³★ Sometimes, these are also referred to as *CPU rings* or *domains*.

Direct Execution

(Without Limits)

OS	Process
Create process list entry	
Allocate memory	
Load program into memory	
Set up stack (<code>argc/argv</code>)	
Clear registers	
Execute call <code>main()</code>	Run <code>main()</code>
	Execute return from <code>main()</code>
Free memory of process	
Remove from proc. list	

Interlude: What is the Kernel?

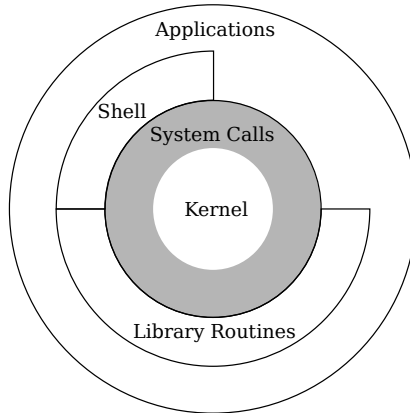


Figure: Architecture of the UNIX Operating System

Courtesy of [SR13]

Switching Between Modes

Having user- and kernel mode enables limiting the capabilities of a process. But two important questions remain open:

1. How can a process do privileged things, e.g. access a file?
2. How does the OS regain control?

Introducing System Calls

Question 1 is generally solved using system calls⁴ (think of a “function call” from the process into the OS):

- ▶ With a special trap CPU instruction (often an interrupt), the process returns control to kernel mode. It's context is saved by the CPU on the kernel stack
- ▶ The CPU knows which kernel code to call due to a trap table (often called interrupt vector table), *initialized at boot time*
- ▶ Using a return-from-trap instruction, the OS returns control to the process, context is restored

⁴👉 On GNU/Linux, you can obtain a list of system calls with “`man 2 syscalls`”. In general, there is also a man page per syscall available with “`man 2 <syscall>`” – use it!

Limited Direct Execution

OS @boot (kernel mode)	Hardware	
Initialize trap table	Store addr. of syscall handler	
OS @run (kernel mode)	Hardware	Process (user mode)
Create process list entry		
Allocate memory		
Load program into memory		
Set up <i>user stack</i> (<i>argc/argv</i>)		
Push regs/PC to <i>kernel stack</i>		
return-from-trap	Restore regs from <i>kernel stack</i> Move to user mode Jump to <code>main()</code>	

Limited Direct Execution (cont.)

OS @run (kernel mode)	Hardware	Process (user mode)
		Run <code>main()</code>
		...
		Perform <code>syscall</code>
		trap into OS
	Save regs to <i>kernel stack</i>	
	Move to kernel mode	
	Jump to trap handler	
Handle trap		
Do <code>syscall</code> work		
return-from-trap		
	Restore regs from <i>kernel stack</i>	
	Move to user mode	
	Jump to PC after trap	
		...
		Return from <code>main()</code>
		trap (via <code>exit()</code>)
Free memory of process		
Remove from proc. list		

Question 2: Regaining Control

The OS wants to switch to another process. . . No problem – except: *It is not running on the CPU anymore!*

Two possible solutions:

Cooperation Provide a special *yield* syscall or simply wait for the next regular one. They happen often.

OS takes control Using a timer interrupt (requires hardware), “automatic” return to the OS at regular intervals is possible.

→ Which one is better, what do you think? What are the pros and cons? What if a timer interrupt occurs during another timer interrupt?

Context Switches

A context switch occurs, when the operating system switches from one process to another. It consists of a few steps:

- ▶ While switching to *kernel mode*, general purpose registers and SP/PC of the currently running process are saved on the kernel stack
- ▶ In kernel mode, they are then saved to the corresponding process structure
- ▶ A *scheduling decision* takes place
- ▶ The registers of the next process to run are restored from its process structure to kernel stack
- ▶ A *return-from-trap* takes place
- ▶ The registers are restored from kernel stack while switching to *user mode*

Limited Direct Execution

(Timer Interrupt)

OS@boot (kernel mode)	Hardware	
Initialize trap table	Store addr. of syscall handler <i>Store addr. of timer handler</i>	
Start interrupt timer	Start timer Interrupt CPU in X ms	
OS @run (kernel mode)	Hardware	Process (user mode)
		Process A
		...
	Timer interrupt Save regs(A) to <i>kernel stack (A)</i> Move to kernel mode Jump to trap handler	

Limited Direct Execution (cont.)

(Timer Interrupt)

OS @run (kernel mode)	Hardware	Process (user mode)
Handle trap Call <code>switch()</code>save regs(A) to struct(A) ...restore regs(B) from struct(B) ...switch to <i>kernel</i> <i>stack (B)</i> return-from-trap (into B)	Restore regs(B) from <i>kernel stack (B)</i> Move to user mode Jump to PC (B)	Process B ...

The xv6 swtch Function

Source: [xv6b]

```
# Context switch
#
# void swtch(struct context **old, struct context *new);
#
# Save the current registers on the stack, creating
# a struct context, and save its address in *old.
# Switch stacks to new and pop previously-saved registers.

.globl swtch
swtch:
    movl 4(%esp), %eax
    movl 8(%esp), %edx

    # Save old callee-saved registers
    pushl %ebp
    pushl %ebx
    pushl %esi
    pushl %edi

    # Switch stacks
    movl %esp, (%eax)
    movl %edx, %esp

    # Load new callee-saved registers
    popl %edi
    popl %esi
    popl %ebx
    popl %ebp
    ret
```



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Creating Processes

The `fork()` and `wait()` Syscalls

On UNIX systems, new processes are *created* using the `fork()` syscall. It has an interesting behavior:

- ▶ It creates an almost exact copy of the calling process
 - ▶ The child gets a *copy* of data, stack and heap; the text section is shared
 - ▶ Open file descriptors are duplicated
 - ▶ Numerous other properties are inherited – see “man 2 fork”
- ▶ It *returns twice*, once in the parent process and once in the child process
 - ▶ In the parent, the return value is the PID of the child; in the child it is 0 (why?)
 - ▶ Which process returns first is *not deterministic*

The `wait()` syscall enables the parent process to wait for child termination (and some other state changes – see “man 2 wait”)

Example for fork() and wait()

Source: [ost], cpu-api/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());
        sleep(1);
    } else {
        // parent goes down this path (original process)
        int wc = wait(NULL);
        printf("hello, I am parent of %d (wc:%d) (pid:%d)\n",
            rc, wc, (int) getpid());
    }
    return 0;
}

// Output:
// hello world (pid:22103)
// hello, I am child (pid:22104)
// hello, I am parent of 22104 (wc:22104) (pid:22103)
```

The `exec()` Functions

To start a *different* program, the child process can use one of the `exec()` functions (which are front-ends to the `execve()` syscall):

- ▶ Different options available for parametrization: `execl()`, `execlp()`, `execle()`, `execv()`, `execvp()` and `execvpe()`
- ▶ Replace the *current* process by loading a new program
 - ▶ Load code and static data
 - ▶ Reinitialize heap, stack and other parts of memory
 - ▶ Run the program with arguments, environment etc.
- ▶ Does *not* return (if no error occurred)
- ▶ The `fork()` and `exec()` pattern allows to *modify the environment* when starting a new program

Example for exec()

Source: [ost], cpu-api/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 (original process)
        int wc = wait(NULL);
        printf("hello, I am parent of %d (wc:%d) (pid:%d)\n",
            rc, wc, (int) getpid());
    }
    return 0;
}

// Output:
// hello world (pid:22615)
// hello, I am child (pid:22616)
// 32 123 966 p3.c
// hello, I am parent of 22616 (wc:22616) (pid:22615)
```

Function or Syscall?

You may have noticed, that functions and syscalls seem to look the same so far. . .

- ▶ If it looks the same, how can the system decide what is is?
- ▶ Actually, these were all *function calls*
 - ▶ A system call is low level: Place arguments in registers, invoke the trap instruction, retrieve returned data. . .
 - ▶ The C library offers functions which perform these steps, as for instance `fork()` and the different variants of `exec()`



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Appendix

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