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Processes

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Portions courtesy Emmett Witchel

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What is a process?

Intuitively, one of these

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What is a process?

- A process is a program during execution.
 - Program = static file (image)
 - Process = executing program = program + execution state.
- A process is the basic unit of execution in an operating system
 - Each process has a number, its process identifier (pid).
- Different processes may run different instances of the same program
 - E.g., my javac and your javac process both run the Java compiler
- At a minimum, process execution requires following resources:
 - Memory to contain the program code and data
 - A set of CPU registers to support execution

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Program to process

- We write a program in e.g., Java.
- A compiler turns that program into an instruction list.
- The CPU interprets the instruction list (which is more a graph of basic blocks).

```
void X (int b) {
    if (b == 1) {
        ...
    }
    int main() {
        int a = 2;
        X(a);
    }
}
```

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Process in memory

What you wrote:

```
void X (int b) {
    if (b == 1) {
        ...
    }
    int main() {
        int a = 2;
        X(a);
    }
}
```

What is in memory:

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Where do processes come from?

- When I type './a.out', the binary runs, right?
 - Really only true for static binaries (more on this later)
- In reality a **loader** sets up the program
 - Usually a user-level program
 - Can also be in-kernel, or split between both

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Where do processes come from?

- In order to run a program, the loader:
 - reads and interprets the executable file
 - sets up the process's memory to contain the code & data from executable
 - pushes "argc", "argv" on the stack
 - sets the CPU registers properly & calls "_start()"
- Program starts running at _start()


```

_start(args) {
    initialize_java();
    ret = main(args);
    exit(ret);
}
      
```

"process" is now running; no longer think of "program"
- When main() returns, OS calls "exit()" which destroys the process and returns all resources

What bookkeeping does the OS need for processes?

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Keeping track of a process

- A process has code.
 - OS must track program counter (code location).
- A process has a stack.
 - OS must track stack pointer.
- OS stores state of processes' computation in a process control block (PCB).
 - E.g., each process has an identifier (process identifier, or PID)
- Data (program instructions, stack & heap) resides in memory, metadata is in PCB (which is a kernel data structure in memory)

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Context Switching

- The OS periodically switches execution from one process to another
- Called a **context switch**, because the OS saves one execution context and loads another

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What causes context switches?

- Waiting for I/O (disk, network, etc.)
 - Might as well use the CPU for something useful
 - Called a blocked state
- Timer interrupt (preemptive multitasking)
 - Even if a process is busy, we need to be fair to other programs
- Voluntary yielding (cooperative multitasking)
- A few others
 - Synchronization, IPC, etc.

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Process life cycle

- Processes are always either:
 - Executing
 - Waiting to execute, or
 - Blocked waiting for an event to occur

```

graph TD
    Start([Start]) --> Ready([Ready])
    Ready --> Running([Running])
    Running --> Ready
    Running --> Blocked([Blocked])
    Blocked --> Ready
    Running --> Done([Done])
  
```

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Process contexts

Memory layout (bottom to top): Operating System, "System Software", User Process 1, User Process 2, User Process n.

Execution flow:

- Process 1: `main{` → `k: read()` → `read{` → `startio()` → `schedule()` → `}`
- Process 2: `main{` → `schedule()` → `}`
- Interrupt: `interrupt` → `save state` → `endio{` → `schedule()` → `}` → `k+1:`
- State transitions: `save state` (from Process 1) → `restore state` (to Process 1)

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When a process is waiting for I/O, what is its state?

1. Ready
2. Running
3. Blocked 😊
4. Zombie
5. Exited

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CPU Scheduling

- Problem of choosing which process to run next
 - And for how long until the next process runs
- Why bother?
 - Improve performance: amortize context switching costs
 - Improve user experience: e.g., low latency keystrokes
 - Priorities: favor “important” work over background work
 - Fairness

We will cover techniques later

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When does scheduling happen?

- When a process blocks
- When a device interrupts the CPU to indicate an event occurred (possibly un-blocking a process)
- When a process yields the CPU
- **Preemptive scheduling:** Setting a timer to interrupt the CPU after some time
 - Places an upper bound on how long a CPU-bound process can run without giving another process a turn
- **Non-preemptive scheduling:** Processes must explicitly yield the CPU

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Scheduling processes

- OS uses PCBs to represent a process
- Every resource is represented with a queue
- OS puts PCB on an appropriate queue.
 - Ready to run queue.
 - Blocked for IO queue (Queue per device).
 - Zombie queue.
- When CPU becomes available, choose from ready to run queue
- When an event occurs, remove waiting process from blocked queue, move to ready queue.

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Why use multiple processes in one app?

Consider a Web server:

```

get network message (URL) from client
fetch URL data from disk
compose response
send response
  
```

How well does this web server perform?
With many incoming requests?
That access data all over the disk?

A single process cannot overlap CPU and I/O

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Why use multiple processes in one app?

Consider a Web server

```

get network message (URL) from client
create child process, send it URL
                                Child
                                fetch URL data from disk
                                compose response
                                send response
  
```

- ◆ Now the child can block on I/O, parent keeps working
- ◆ Different children can block on reading different files
- ◆ How does server know if child succeeded or failed?

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Orderly termination: exit()

- After the program finishes execution, it calls `exit()`
- This system call:
 - takes the “result” of the program as an argument
 - closes all open files, connections, etc.
 - deallocates memory
 - deallocates most of the OS structures supporting the process
 - checks if parent is alive:
 - ✦ If so, it holds the result value until parent requests it; in this case, process does not really die, but it enters the zombie/defunct state
 - ✦ If not, it deallocates all data structures, the process is dead
- Process termination is the ultimate garbage collection

Web server ex: Child uses exit code for success/failure

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The wait() system call


- Child returns a value to parent via `exit()`
- The parent receives this value with `wait()`
- Specifically, `wait()`:
 - Blocks the parent until child finishes (need a wait queue)
 - When a child calls `exit()`, the OS unblocks the parent and returns the value passed by `exit()` as a result of the `wait()` call (along with the pid of the child)
 - If there are no children alive, `wait()` returns immediately

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Zombies!!!

- A parent can wait indefinitely to call `wait()`
- The OS to store the exit code for a finished child until the parent calls `wait()`
- Hack: Keep PCB for dead processes around until:
 - Parent calls `wait()`, or
 - Parent `exit()`s (don't need to `wait()` on grandkids)
- And that is a zombie (done state)
 - Will not be scheduled again



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Where do processes come from? (redux)

- Parent/child model
- An existing program has to spawn a new one
 - Most OSes have a special ‘init’ program that launches system services, logon daemons, etc.
 - When you log in (via a terminal or ssh), the login program spawns your shell

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Approach 1: Windows CreateProcess

- In Windows, when you create a new process, you specify the program
 - And can optionally allow the child to inherit some resources (e.g., an open file handle)

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Approach 2: Unix fork/exec()

- In Unix, a parent makes a copy of itself using `fork()`
 - Child inherits everything, runs same program
 - Only difference is the return value from `fork()`
 - Child gets 0; parent gets child pid
- A separate `exec()` system call loads a new program
 - Like getting a brain transplant
- Some programs, like our web server example, `fork()` clones (without calling `exec()`).
 - Common case is probably `fork+exec`

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Program loading: exec()

- The `exec()` call allows a process to “load” a different program and start execution at main (actually `_start`).
- It allows a process to specify the number of arguments (`argc`) and the string argument array (`argv`).
- If the call is successful
 - it is the same process ...
 - but it runs a different program !!
- Code, stack & heap is overwritten
 - Sometimes memory mapped files are preserved.

• **Exec does not return!**

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fork() + exec() example

In the parent process:

```
main()
...
int rv = fork();           // create a child
if(0 == rv) {              // child continues here
    exec_status = exec("calc", argc, argv0, argv1, ...);
    printf("Something is horribly wrong\n");
    exit(exec_status);
} else {                   // parent continues here
    printf("Who's your daddy?");
    ...
    child_status = wait(rv);
}
```

Exec should not return

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A shell forks and execs a calculator

USER	OS
<pre>int rv = fork(); if(rv == 0) { close(".history"); exec("/bin/calc"); } else { wait(rv); }</pre>	<pre>int rv = fork(); if(rv == 0) { close(".history"); exec("/bin/calc"); } else { wait(rv); }</pre>
	<p>pid = 128 open files = ".history" last_cpu = 0</p> <p>pid = 128 open files = last_cpu = 0</p>

Process Control Blocks (PCBs)

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A shell forks and then execs a calculator

USER	OS
<p>main; a = 2</p> <p>0xFC0933CA</p> <pre>int shell_main() { int a = 2; ... }</pre>	<p>Stack</p> <p>Heap</p> <p>0x43178050</p> <pre>int calc_main() { int q = 7; ... }</pre>
	<p>pid = 128 open files = ".history" last_cpu = 0</p> <p>pid = 128 open files = last_cpu = 0</p>

Process Control Blocks (PCBs)

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Why separate fork & exec?

- Key issue: **Inheritance** of file descriptors, environment, etc.
 - Or, making the shell work
- Remember how the shell can do redirection?
 - `./warmup < testinput.txt`
 - File handle 0 (stdin) is opened to read `testinput.txt`
- The parent (shell) opens `testinput.txt` before `fork()`
 - The child (warmup) inherits this open file handle
 - Even after `exec()`

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The convenience of separate fork/exec

- Decoupling `fork` and `exec` lets you do anything to the child's process environment without adding it to the `CreateProcess` API.


```
int rv = fork();           // create a child
if(0 == rv) {              // child continues here
    // Do anything (unmap memory, close net connections...)
    exec("program", argc, argv0, argv1, ...);
}
```
- `fork()` creates a child process that inherits:
 - identical copy of all parent's variables & memory
 - identical copy of all parent's CPU registers (except one)
- Parent and child execute at the same point after `fork()` returns:
 - by convention, for the child, `fork()` returns 0
 - by convention, for the parent, `fork()` returns the pid of the child

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The CreateProcess alternative

- Windows does allow you to create a process that is initially suspended
 - You can also change memory and handles of another process
 - And then unblock it
- Somewhat isomorphic
 - But a bit cumbersome
 - And prone to security issues (loading threads and libraries in another app!)

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At what cost, fork()?

- Simple implementation of fork():
 - allocate memory for the child process
 - copy parent's memory and CPU registers to child's
 - Expensive !!
- In 99% of the time, we call exec() after calling fork()
 - the memory copying during fork() operation is useless
 - the child process will likely close the open files & connections
 - overhead is therefore high

Any ideas to improve this?

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Pro tool: vfork

- If you know you are going to call exec() almost immediately:
 - Create a new PCB, stack, register state
 - But not a new copy of the full memory
- You can change OS state and call exec safely
- You cannot:
 - Return from the function that called fork()
 - Touch the heap
 - Probably other stuff
- Why does it improve performance? Avoids copies
- Unfortunate example of implementation influence on interface
 - Current Linux & BSD 4.4 have it for backwards compatibility

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Copy-on-write fork (preview)

- Idea: write protect everything in memory after a fork()
 - Detect and copy only what you touch, until the exec()
 - After exec(), remove write protection from child memory
- Common case: exec quickly
 - Some overhead to setting copy-on-write, but cheaper than copying everything
- Uncommon case: fork never execs
 - Eventually copy everything
- We will see more about this later...

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Process control

OS must include calls to enable special control of a process:

- Priority manipulation:
 - nice(), which specifies base process priority (initial priority)
 - In UNIX, process priority decays as the process consumes CPU
- Debugging support:
 - ptrace(), allows a process to be put under control of another process
 - The other process can set breakpoints, examine registers, etc.
- Alarms and time:
 - Sleep puts a process on a timer queue waiting for some number of seconds, supporting an alarm functionality


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Tying it all together: The Unix shell

```
while(! EOF){
    read input
    handle regular expressions
    int rv = fork();           // create a child
    if(rv == 0){               // child continues here
        exec("program", argc, argv0, argv1, ...);
    }
    else {                     // parent continues here
        ...
    }
}
```

- Translates <CTRL-C> to the kill() system call with SIGKILL
- Translates <CTRL-Z> to the kill() system call with SIGSTOP
- Allows input-output redirections, pipes, and a lot of other stuff that we will see later

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<div data-bbox="396 279 544 323">Summary</div> <ul data-bbox="224 323 673 520" style="list-style-type: none">• Understand what a process is• The high-level idea of context switching and process states• How a process is created• Pros and cons of different creation APIs<ul data-bbox="256 489 613 520" style="list-style-type: none">– Intuition of copy-on-write fork and vfork		