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

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) {
        ...
    }
}
```

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)

Process in Memory

- Program to process.
- What you wrote
  ```
  void X (int b) {
      if(b == 1) {
          ...
      }
      int main() {
          int a = 2;
          X(a);
      }
  }
  ```
- What must the OS track for a process?
  - What is in memory
    ```
    main: a = 2
    X: b = 2
    ```
  - Heap
    ```
    void X (int b) {
        if(b == 1) {
            ...
        }
        int main() {
            int a = 2;
            X(a);
        }
    }
    ```
  - Stack
  - Code
**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.

**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.

**Process Life Cycle**

- Processes are always either executing, waiting to execute or blocked waiting for an event to occur.
- A preemptive scheduler will force a transition from running to ready. A non-preemptive scheduler waits.

**Process Contexts**

**Example: Multiprogramming**

**Process Contexts**

Example: Multiprogramming

<pre>
User Program 1
User Program 2
User Program 1
System Software
Operating System
Memory

User Program 1
Program 1
main
read()
startIO()
save
state
schedule()
main
endio{
interrupt
main{
read{
save
state
schedule()
interrupt
main{
read{

Program 2
OS
Program 2
I/O Device

OS puts PCB on an appropriate queue.
- Ready to run queue.
- Blocked for IO queue (Queue per device).
- Zombie queue.
- Stopping a process and starting another is called a context switch.
  - 100-10,000 per second, so must be fast.
</pre>
### Why Use Processes?

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?

### Why Use Processes?

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
- If server has configuration file open for writing
  - Prevent child from overwriting configuration
- How does server know child serviced request?
  - Need return code from child process

### Where do new processes come from?

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

### Approach 1: Windows `CreateProcess`

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

### 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()`
- A separate `exec()` system call loads a new program

- Major design trade-off:
  - How easy to inherit
  - Vs. Security (accidentally inheriting something the parent didn’t intend)
  - Note that security is a newer concern, and Windows is a newer design...

### The Convenience of separating `Fork/Exec`

- Life with `CreateProcess(filename);`
  - But I want to close a file in the child.
    - `CreateProcess(filename, list of files);`
    - And I want to change the child’s environment.
    - `CreateProcess(filename, CLOSE_FD, new_envp);`
  - Etc. (and a very ugly etc.)
- `fork()` = split this process into 2 (new PID)
  - Returns 0 in child
- `exec()` = overlay this process with new program (PID does not change)
The Convenience of Separating Fork/Exec

- Decoupling fork and exec lets you do anything to the child’s process environment without adding it to the CreateProcess API.
  
  ```c
  int pid = fork(); // create a child
  if(0 == pid) {  // 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 process identifier of the child
  - fork() return code a convenience, could always use getpid()

  A shell forks and then execs a calculator
  ```

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.

General Purpose Process Creation

- In the parent process:
  ```c
  main()
  ```

- In 99% of the time, we call exec() after calling fork()

A shell forks and then execs a calculator

- 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

At what cost, fork()?

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- vfork():
  - a system call that creates a process “without” creating an identical memory image
  - child process should call exec() almost immediately
  - Unfortunate example of implementation influence on interface
  - Current Linux & BSD 4.4 have it for backwards compatibility
  - Copy-on-write to implement fork avoids need for vfork
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, the process does not really die, but it enters the zombie/defunct state
    - If not, it deallocates all data structures, the process is dead
  - cleans up all waiting zombies
- Process termination is the ultimate garbage collection (resource reclamation).

The wait() System Call

- A child program returns a value to the parent, so the parent must arrange to receive that value.
- The wait() system call serves this purpose:
  - It puts the parent to sleep waiting for a child’s result
  - 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
  - Also, if there are zombies waiting for their parents, wait() returns one of the values immediately (and deallocates the zombie)

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

Tying it All Together: The Unix Shell

```c
while(! EOF) {
    read input
    handle regular expressions
    int pid = fork();
    // create a child
    if (pid == 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

Summary

- 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
  - Intuition of copy-on-write fork and vfork