Processes
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September 9, 2019
Chapter 3: Roadmap

3.1 What is a process?
3.2 Process states
3.3 Process description
3.4 Process control
3.5 Execution of the OS
3.6 Security issues
3.7 Unix process management

Part II

Chapter 3: Processes
Chapter 4: Threads
Chapter 5: Concurrency
Chapter 6: Deadlocks
From the 1960s, jobs were described by a special data structure that allowed the OS to systematically monitor, control, and synchronize them. This became known as a process, which consists of:

- Program in execution
- Data
- Stack
- Process Control Block (PCB)

Note that programs stored on disk do not become processes until they are started.
Processes

- Processes with shared memory
  - If shared memory is created by a process, it can be accessed in other processes in the system
  - This is called *memory mapping*
  - Just like named pipes, shared memory in Windows is addressable using some unique name
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Process States

- **Process trace**
  - **Offsets** (i.e., relative addresses) of instructions executed by a process

- **CPU trace**
  - Sequence of absolute addresses executed by the CPU
  - Suppose OS allows 6 CPU instructions in a slice, needs 3 to perform a process switch
Process States

- This brings us to the issue of how the OS keeps track of processes and what runs next.
- Simple **2-state model**:

![Diagram showing process states and transitions]

- Implementation:
Process States

- Process creation in 2-state model
  - OS creates a PCB, loads necessary code and data in RAM, and moves process to the Not Running state

- Possible reasons for creation
  - Ready for next job in batch mode (old supercomputers)
  - User demand (command-line, login-related)
  - Needed by OS to serve a request
  - Explicitly spawned by a user program (e.g., CC.exe in hw #1)

- Original process is *parent*, spawned process *child*
  - Child may inherit access to certain open handles
  - Parent usually has full access rights to control the child (e.g., set its priority/affinity or terminate it)
Process States

- Process termination
  - Normal completion
  - User request (e.g., Ctrl-C)
  - Request from another process
  - Access violation
  - Arithmetic error (division by zero)
  - Invalid instruction
  - Privileged instruction
  - Not enough RAM (bad_alloc exception)

- Stealthy crashes
  - Severe stack corruption may cause program to quit without any warning or error

- If code crashes in Release mode, will it crash in Debug?
  - Not necessarily
  - Some bugs can be seen only in release mode
  - Reasons?

- What about vice versa?
Process States

- Notice that 2-state model has no simple way of selecting the next ready process
  - Some might be blocked on I/O or events
- Next version, called 5-state model, solves this:

7-state model: suspends blocked processes to disk; medium-term scheduler activates them back to RAM
Process States

• Process creation in 5-state model
  – When the OS creates a PCB, it moves the process to New
  – However, data/code may still be on disk

• Given enough RAM, process is admitted to Ready
  – Code/data is loaded (fully or partially depending on whether virtual memory is available)

• Upon termination
  – Process memory is released, PCB is moved to the Exit state
  – May be beneficial to retain some PCB information (e.g., process exit code, PID, process handle)
  – Queries about a terminated process can be resolved using the PCB in the Exit state
Process States

- Common transitions
  - Ready $\rightarrow$ Running: scheduler decides based on its policy (e.g., round-robin, strict priority, weighted round-robin)
  - Running $\rightarrow$ Ready: either 1) time slice is over or 2) preempted by a higher-priority process in the Ready state
  - Running $\rightarrow$ Blocked: one of three options: process 1) voluntarily sleeping; 2) waiting for other processes (i.e., IPC); 3) waiting for I/O devices
  - Blocked $\rightarrow$ Ready: event signaled
  - Running $\rightarrow$ Exit: quits normally, crashes, or forced to quit

- Rarer cases
  - Ready $\rightarrow$ Exit, New $\rightarrow$ Exit, or Blocked $\rightarrow$ Exit: forced termination by user, OS, or another process
Process States

- Implementing 5-state model
  - Single blocked queue

new → ready queue → dispatch → CPU → exit

pause

event occurs → blocked queue

- Multiple blocked queues

new → ready queue → dispatch → CPU → exit

pause

event occurs → blocked queue₁ → event₁ wait

... → blocked queueₙ → eventₙ wait
Implementation Notes

• By default, I/O requests are **blocking**
  - *Non-blocking (asynchronous)*: APIs return control to the process regardless of whether data is ready or not

• How to know when async requests are finished
  - *Polling*: the process must periodically check on the status of the pending operation (Unix, Windows)
  - *Event-driven*: the API works with a special *event handle* that gets signaled when the operation is finished (Windows)
  - *Callback*: OS calls a specific function in the process upon event (GUI applications such as MFC)
  - *Overlapped*: asynchronous model that allows multiple requests to be pending to the same I/O handle
  - *I/O Completion Ports (IOCP)*: OS send notifications into a shared queue that the process can read (Windows)
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Process Description

- Process Control Block split into 3 general parts

  1) Identification
    - Process ID (PID)
    - PPID sometimes needed to verify inherited rights
    - User/group IDs

  2) CPU state is used during context (process) switches
    - User-modified registers (30-100 depending on the architecture)
    - Control registers (e.g., PC, flags)
    - Various stack pointers

- Context switch entails
  - Storing all CPU/FPU registers into PCB of running process
  - Deciding which process to run next
  - Loading registers from context of that process
3) Process control information

- **Scheduling**
  - Process state (e.g., ready, running, blocked)
  - Priority class
  - Info that helps scheduler (e.g., current wait time, estimated completion time, past CPU usage)
  - Events (if any) currently preventing the process from being ready

- **Queues**
  - Various wait queues the process is part of (e.g., scheduler, device I/O)
Process Description

- Inter-process communication (IPC)
  - Message-passing handles and data (e.g., pipes, mailslots)
  - Shared memory handles/pointers
  - Synchronization objects (e.g., mutex)
- Privileges
  - Various system permissions
- Allocated memory
  - Virtual memory used by process including pages in pagefile
- Resource usage
  - Other open handles and various accounting
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Execution Modes

• CPU provides at least 2 execution modes
  - User mode prohibits all I/O instructions, virtual table manipulation, access to blocks of RAM not owned by process, and modification of certain registers
  - Kernel mode has no restrictions

• Some architectures allow more than 2 modes
  - These are often called protection rings
  - More granularity to allow “intermediate” privileges to certain processes (e.g., printer driver should be able to perform I/O, but not modify virtual-memory tables)

• Intel/AMD CPUs support 4 execution levels
  - Some older supercomputers had 8
Execution Modes

• Consider a hypothetical 4-ring system:
  - Ring 3 always user mode
  - Ring 0 always kernel
  - Rings 1 and 2 depend on the implementation

• Windows and Linux support only rings 0 and 3
  - Partly because other architectures these can run on (e.g., PowerPC and MIPS) traditionally had only 2 modes
  - Partly to reduce complexity

• Main drawback of 2-level systems
  - Any driver crash bluescreens the system and forces a reboot
Execution Modes

- **Microsoft virtualization server (Hyper-V) is an exception**
  - Virtual machines (VM) allow multiple guest OSes to run transparently on the CPU
- **Guest OSes are managed by the virtual machine monitor (VMM) called hypervisor**
  - In contrast to normal kernels that are called supervisors
- **Hypervisor runs in ring 0, guest OS in ring 1**
  - AMD-V was supported starting with Athlon 64 (2006) and Intel VT-x starting with Pentium 4 (2005)
Mode Switch

- CPU support for changing execution mode
  - On some architectures special register called Program Status Word (PSW) tracks current mode

- On Intel, protection is scattered across many registers
  - CPL (current privilege level): 2 bits in CS (code segment) reg
  - DPL (data privilege level): 2 bits in virtual table of the segment
  - IOPL (I/O privilege level): 2 bits in EFLAGS register

- I/O requires CPL \(\leq\) IOPL; data access CPL \(\leq\) DPL
Mode Switch

- Upon interrupt or kernel call (syscall)
  - CPL cleared to 0
  - Old values of registers are stored in stack (and later in PCB if a context switch occurs)
  - Execution passed to kernel address
  - Interrupt return (iret) causes old values to be restored

- Violations of current execution mode must be supported by the CPU
  - Throws a general protection fault if it detects attempts to circumvent kernel defenses (e.g., read/write or execute parts of memory with insufficient CPL, modify certain flags, execute I/O instructions, exceed allocated segment size)
  - OS intercepts these interrupts and terminates the process
Context (Process) Switch

- OS can switch processes whenever it gains control
- When does the OS actually execute?
- Three main instances:
  - External interrupt
  - CPU exception/fault/trap
  - System call
- Interrupts
  - Timer (e.g., slice over)
  - I/O (e.g., device ready)
- CPU Traps
  - Invalid instructions
  - Protection violations
  - Memory faults (e.g., virtual page not in RAM)
  - Arithmetic errors
- System calls
  - Kernel-level APIs invoked by user process
- Kernel may return control to current process, let it continue
Context (Process) Switch

• In fact, most non-timer interrupts do not switch processes
  - Short routines record interrupt conditions, reset the device, and return to user mode quickly
  - Later, other parts of the kernel (e.g., svchost.exe) perform full handling of the interrupt
  - Implemented via Deferred Procedure Calls (DPC) in Windows

• Process switch typically occurs only when either:
  - Time slice expires or process blocks on API

• Note that process switch requires mode switch, but not vice versa!
  - Q: Which of the two is more expensive?
  - A: Process switch
  - Transition to kernel mode, selection of task to run, saving/restoring registers
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Three ways to execute calls to OS:

A. API executes in kernel outside any process
   - 2 user-OS context switches and 2 mode switches
   - old monolithic Unix

B. API executes in kernel mode as part of process
   - 2 mode switches
   - Windows/Linux

C. API executes as separate user process
   - 2 process context switches and 4 mode switches
   - micro-kernels
**Execution of the OS**

- **Method A**
  - Scheduler cannot interrupt the API when its running
  - 2 extra context switches per call compared to method B

- **Method C (micro-kernels)**
  - High switching overhead, but allows rapid user-mode API development
  - Better security as untrusted components (e.g., drivers) run in user mode
  - Certain high-security (e.g., military) applications

- **Method B**
  - Fastest switch to APIs, but less secure and more complex to develop
  - APIs must be *re-entrant*
  - Kernel attaches its own stack to each process image

![Diagram of process image](chart.png)