Operating System Principles: Processes, Execution, and State

CS 111

Summer 2022

Operating System Principles

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Outline

- What are processes?
- How does an operating system handle processes?
- How do we manage the state of processes?

What Is a Process?

- A type of interpreter
- An executing instance of a program
- A virtual private computer
- A process is an *object*
  - Characterized by its properties (*state*)
  - Characterized by its *operations*
  - Of course, not all OS objects are processes
  - But processes are a central and vital OS object type

What is "State"?

- One dictionary definition of "state" is
  - "A mode or condition of being"
  - An object may have a wide range of possible states
- All persistent objects have "state"
  - Distinguishing them from other objects
  - Characterizing object's current condition
- Contents of state depends on object
  - Complex operations often mean complex state
  - But representable as a set of bits
  - We can save/restore the bits of the aggregate/total state
  - We can talk of a state subset (e.g., scheduling state)

Examples Of OS Object State

- Scheduling priority of a process
- Current pointer into a file

- Completion condition of an I/O operation

- List of memory pages allocated to a process

- OS objects' state is mostly managed by the OS itself
  - Not (directly) by user code
  - It must ask the OS to access or alter state of OS objects

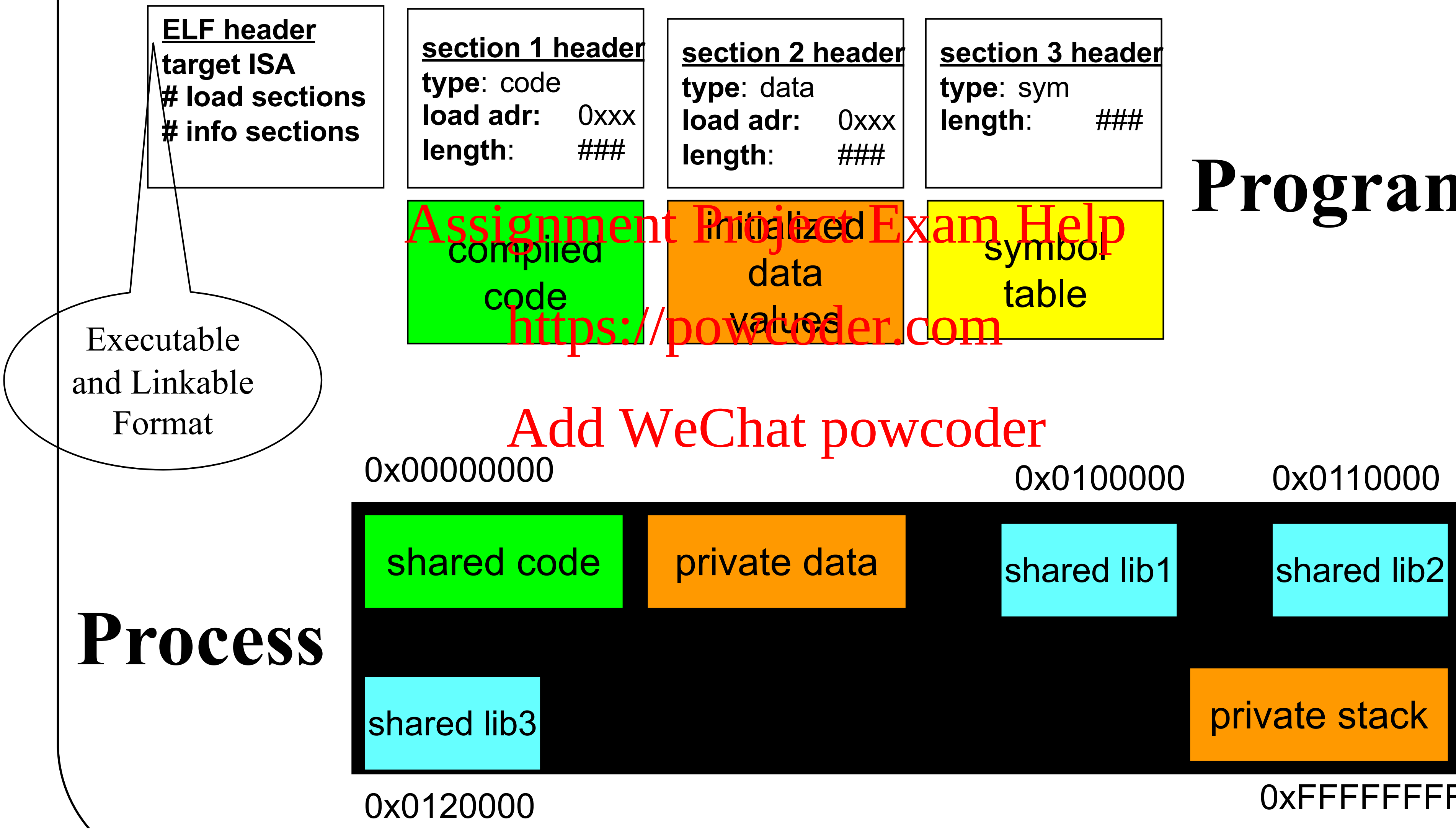
Process Address Spaces

- Each process has some memory addresses reserved for its private use
- That set of addresses is called its *address space*

- A process' address space is made up of all memory locations that the process can address

  – If an address isn't in its address space, the process can't request access to it
- Modern OSes pretend that every process' address space can include all of memory
  – But that's not true, under the covers

Program vs. Process Address Space



Process Address Space Layout

- All required memory elements for a process must be put somewhere in its address space
- Different types of memory elements have different requirements
  - E.g., code is not writable but must be executable
  - And stacks are readable and writable but not executable
- Each operating system has some strategy for where to put these process memory segments

Layout of Unix Processes in Memory

- In Unix systems[1],
  - Code segments are statically sized
  - Data segment grows up
  - Stack segment grows down
- They aren't allowed to meet

[1] Linux is one type of Unix system

Address Space: Code Segments

- We start with a load module
  - The output of a linkage editor
  - All external references have been resolved
  - All modules combined into a few segments
    - Text, data, BSS, etc.
- Code must be loaded into memory
  - Instructions can only be run from RAM
  - A code segment must be created
  - Code must be read in from the load module
  - Map segment into process' address space
- Code segments are read/execute only and sharable
  - Many processes can use the same code segments

Address Space: Data Segments

- Data too must be initialized in address space
  - Process data segment must be created and mapped into the process' address space
  - Initial contents must be copied from load module
  - BSS[1] segments must be initialized to all zeroes
- Data segments:
  - Are read/write, and process private
  - Program can grow or shrink it (using the `sbrk` system call)

[1] Block Started by Symbol – a legacy phrase whose name is of no importance

Processes and Stack Frames

- Modern programming languages are stack-based
- Each procedure call allocates a new stack frame
  - Storage for procedure local (vs. global) variables
  - Storage for invocation parameters
  - Save and restore registers
    - Popped off stack when call returns
- Most modern CPUs also have stack support
  - Stack too must be preserved as part of process state

Address Space: Stack Segment

- Size of stack depends on program activities
  - E.g., amount of local storage used by each routine
  - Grows larger as calls nest more deeply
  - After calls return, their stack frames can be recycled
- OS manages the process' stack segment
  - Stack segment created at same time as data segment
  - Some OSes allocate fixed sized stack at program load time
  - Some dynamically extend stack as program needs it
- Stack segments are read/write and process private
  - Usually not executable

Address Space: Libraries

- Static libraries are added to load module
  - Each load module has its own copy of each library
  - Program must be re-linked to get new version
- Shared libraries use less space
  - One in-memory copy, shared by all processes
  - Keep the library separate from the load modules
  - Operating system loads library along with program
- Reduced memory use, faster program loads
- Easier and better library upgrades

Other Process State

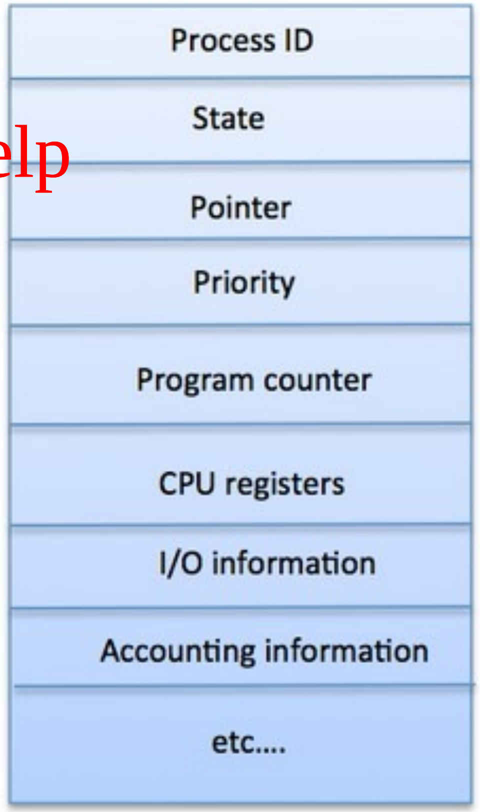
- Registers
  - General registers
  - Program counter, processor status, stack pointer, frame pointer
- Process' own OS resources
  - Open files, current working directory, locks
- But also OS-related state information
- The OS needs some data structure to keep track of all this information

Process Descriptors

- Basic OS data structure for dealing with processes
- Stores all information relevant to the process
  - State to restore when process is dispatched
  - References to allocated resources
  - Information to support process operations
- Managed by the OS
- Used for scheduling, security decisions, allocation issues

Linux Process Control Block

- The data structure Linux (and other Unix systems) use to handle processe
  - AKA *PCB*
- An example of a process descriptor
- Keeps track of:
  - Unique process ID
  - State of the process (e.g., running)
  - Address space information
  - And various other things



Other Process State

- Not all process state is stored directly in the process descriptor
- Other process state is in several other places
  - Application execution state is on the stack and in registers
  - Linux processes also have a supervisor-mode stack
    - To retain the state of in-progress system calls
    - To save the state of an interrupt-preempted process
- A lot of process state is stored in the other memory areas

Handling Processes

- Creating processes
- Destroying processes
- Running processes

Where Do Processes Come From?

- Created by the operating system
  - Using some method to initialize their state
  - In particular, to set up a particular program to run
- At the request of other processes
  - Which specify the program to run
  - And other aspects of their initial state
- Parent processes
  - The process that created your process
- Child processes
  - The processes your process created

Creating a Process Descriptor

- The process descriptor is the OS' basic per-process data structure

- So a new process needs a new descriptor

- What does the OS do with the descriptor?

- Typically puts it into a *process table*
  - The data structure the OS uses to organize all currently active processes
  - Process table contains one entry (e.g., a PCB) for each process in the system

What Else Does a New Process Need?

- An address space
- To hold all of the segments it will need
- So the OS needs to create one
  - And allocate memory for code, data and stack
- OS then loads program code and data into new segments
- Initializes a stack segment
- Sets up initial registers (PC, PS, SP)

Choices for Process Creation

1. Start with a “blank” process
   – No initial state or resources
   – Have some way of filling in the vital stuff
      - Code
      - Program counter, etc.
   – This is the basic Windows approach
2. Use the calling process as a template
   – Give new process the same stuff as the old one
   – Including code, PC, etc.
   – This is the basic Unix/Linux approach

Starting With a Blank Process

- Basically, create a brand new process
- The system call that creates it obviously needs to provide some information
  - Everything needed to set up the process properly
  - At the minimum, what code is to be run
  - Generally a lot more than that
- Other than bootstrapping, the new process is created by command of an existing process

Windows Process Creation

- The `CreateProcess()` system call
- A very flexible way to create a new process
  - Many parameters with many possible values
- Generally, the system call includes the name of the program to run
  - In one of a couple of parameter locations
- Different parameters fill out other critical information for the new process
  - Environment information, priorities, etc.

Process Forking

- The way Unix/Linux creates processes
- Essentially clones the existing parent process
- On assumption that the new child process is a lot like the old one
  - Most likely to be true for some kinds of parallel programming
  - Not so likely for more typical user computing
  - But the approach has advantages, like easing creation of pipelines

What Happens After a Fork?

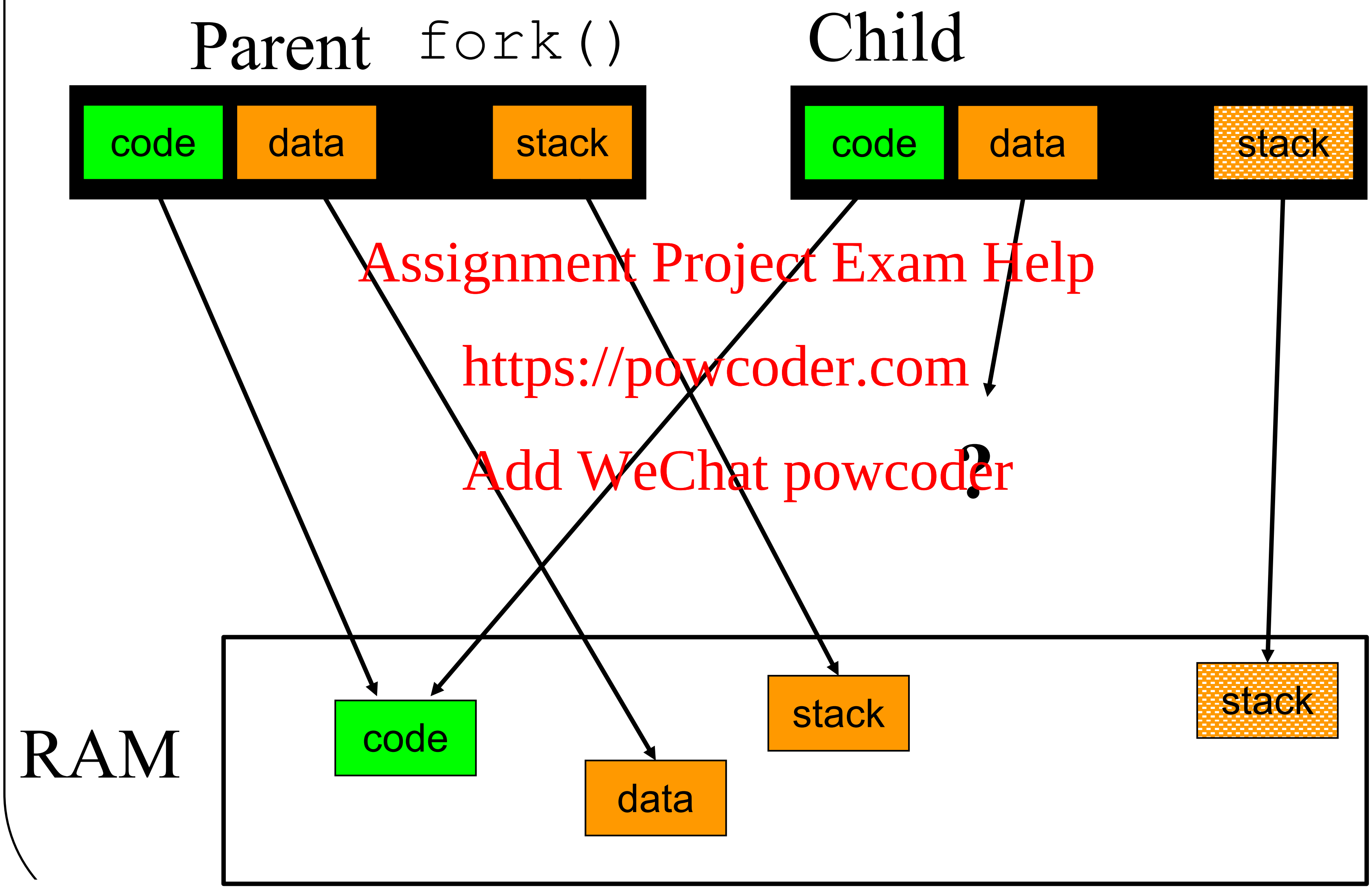
- There are now two processes
  - With different IDs
  - But otherwise mostly exactly the same

- How do I profitably use that?

- Program executes a fork

- Now there are two programs
  - With the same code and program counter
- Write code to figure out which is which
  - Usually, parent goes "one way" and child goes "the other"

Forking and Memory



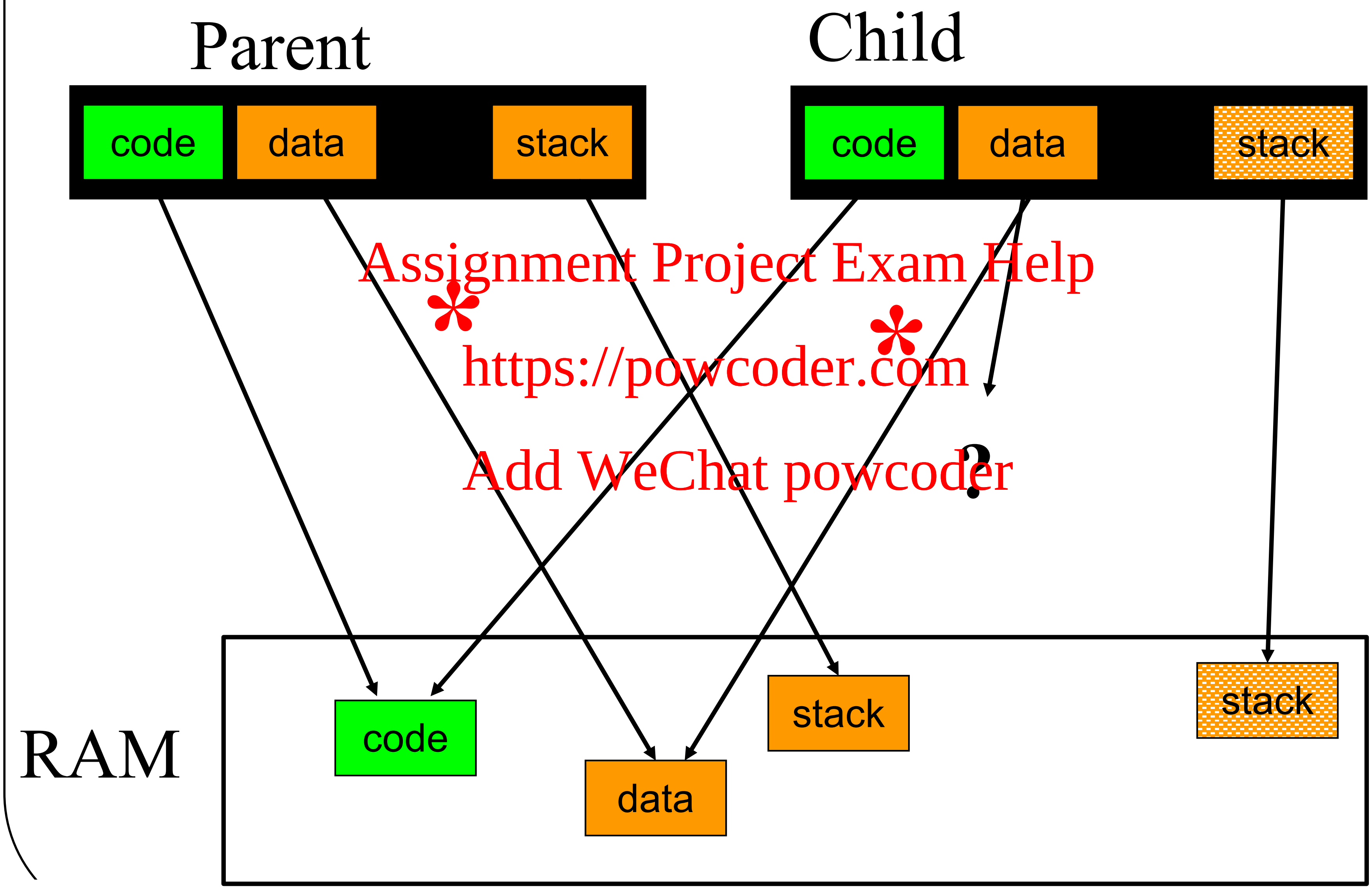
Forking and the Data Segments

- Forked child shares the parent's code
- But not its stack
  - It has its own stack, initialized to match the parent's
  - Just as if a second process running the same program had reached the same point in its run
- Child should also have its own data segment
  - Forked processes do not share their data segments
  - But . . .

Forking and Copy on Write

- If the parent had a big data area, setting up a separate copy for the child is expensive
  - And fork was supposed to be cheap
- If neither parent nor child write the parent's data area, though, no copy necessary
- So set it up as *copy-on-write*
- If one of them writes it, then make a copy and let the process write the copy
  - The other process keeps the original

Forking and Copy on Write



But Fork Isn't What I Usually Want!

- Indeed, you usually don't want another copy of the same process
- You want a process to do something entirely different
- Handled with `exec()`
  - A Unix system call to "remake" a process
  - Changes the code associated with a process
  - Resets much of the rest of its state, too
    - Like open files

The `exec` Call

- A Linux/Unix system call to handle the common case
- Replaces a process' existing program with a different one
  - New code
  - Different set of other resources
  - Different PC and stack
- Essentially, called after you do a fork
  - Though you could call it without forking

How Does the OS Handle Exec?

- Must get rid of the child's old code
  - More precisely, don't point to it any more
- And its stack and data areas
  - Latter is easy if you are using copy-on-write
- Must load a brand new set of code for that process
- Must initialize child's stack, PC, and other relevant control structure
  - To start a fresh program run for the child process

Destroying Processes

- Most processes terminate
  - All do, of course, when the machine goes down
  - But most do some work and then exit before that
  - Others are killed by the OS or another process
- When a process terminates, the OS needs to clean it up
  - Essentially, getting rid of all of its resources
  - In a way that allows simple reclamation

What Must the OS Do to Terminate a Process?

- Reclaim any resources it may be holding
  - Memory
  - Locks
  - Access to hardware devices
- Inform any other process that needs to know
  - Those waiting for interprocess communications
  - Parent (and maybe child) processes
- Remove process descriptor from process table
  - And reclaim its memory

Running Processes

- Processes must execute code to do their job
- Which means the OS must give them access to a processor core
- But usually more processes than cores
  - Easily 200-300 on a typical modern machine
- So processes will need to share the cores
  - So they can't all execute instructions at once
- Sooner or later, a process not running on a core needs to be put onto one

Loading a Process

- To run a process on a core, the core's hardware must be initialized
  - Either to an initial state or whatever state the process was in the last time it ran
- Must load the core's registers
- Must initialize the stack and set the stack pointer
- Must set up any memory control structures
- Must set the program counter
- Then what?

How a Process Runs on an OS

- It uses an execution model called *limited direct execution*
- Most instructions are executed directly by the process on the core
  - Without any OS intervention
- Some instructions instead cause a *trap* to the operating system
  - Privileged instructions that can only execute in supervisor mode
  - The OS takes care of things from there

Limited Direct Execution

- CPU directly executes most application code
  - Punctuated by occasi… …l traps (for system calls)
  - With occasional tim… …rrupts (for time sharing)
- Maximizing di… …s always the goal
  - For Linux and… …ode processes
  - For OS emu… …on Linux)
  - For virtual machines
- Enter the OS as seldom as possible
  - Get back to the application as quickly as possible

The key to good system performance!

Exceptions

- The technical term for what happens when the process can't (or shouldn't) run an instruction
- Some exceptions are routine
  - End-of-file, arithmetic overflow, conversion error
  - We should check for these after each operation
- Some exceptions occur unpredictably
  - Segmentation fault (e.g., dereferencing NULL)
  - User abort (^C), hang-up, power-failure
  - These are *asynchronous exceptions*

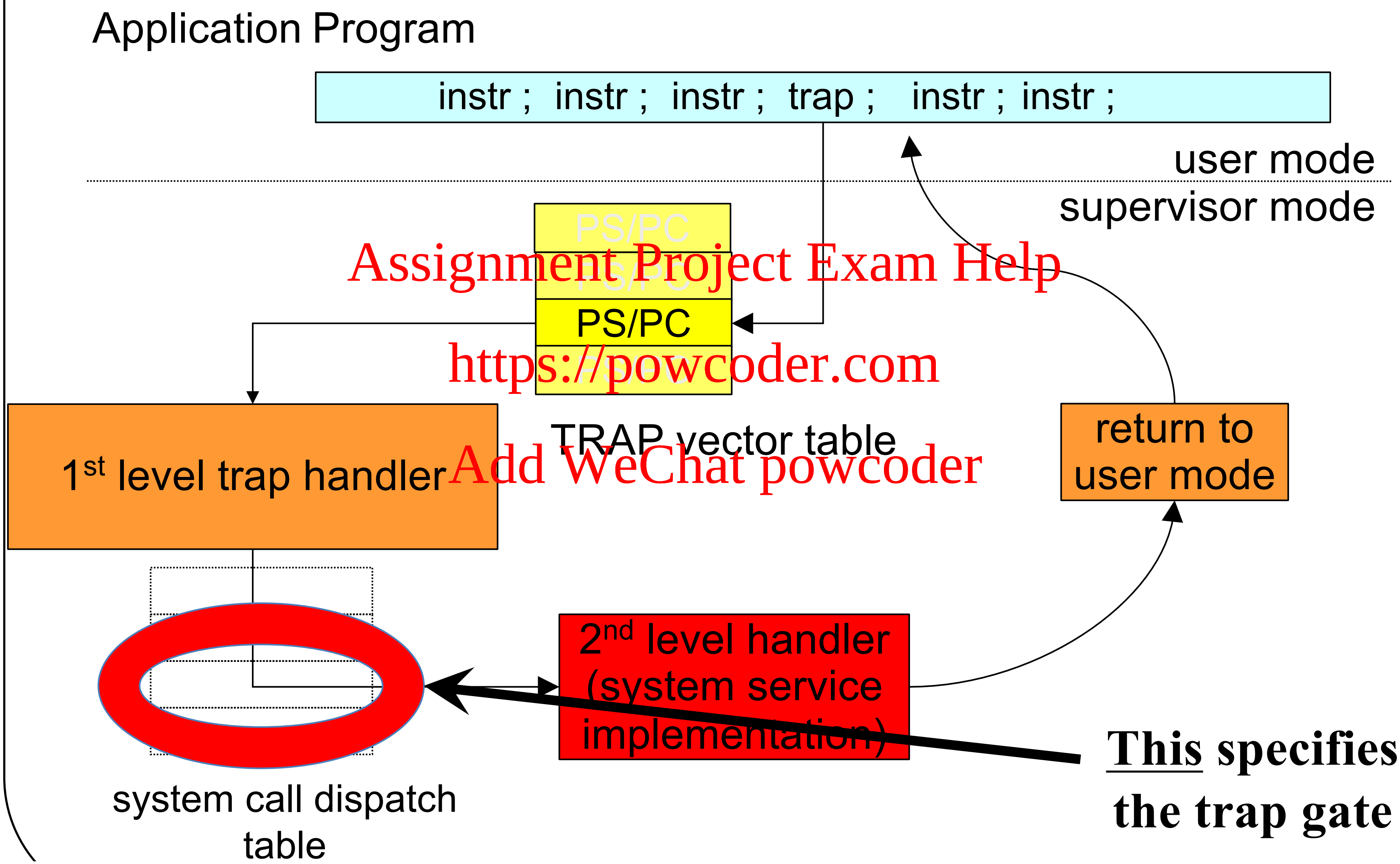
Asynchronous Exceptions

- Inherently unpredictable
- Programs can't check for them, since no way of knowing when and if they happen
- Some languages support try/catch operations
- Hardware and OS support traps
  – Which catch these exceptions and transfer control to the OS
- Operating systems also use these for *system calls*
  – Requests from a program for OS services

Using Traps for System Calls

- Made possible at processor design time, not OS design time
- Reserve one or more privileged instruction for system calls
  – Most ISAs specifically define such instructions
- Define system call linkage conventions
  – Call: r0 = system call number, r1 points to arguments
  – Return: r0 = return code, condition code indicates success/failure
- Prepare arguments for the desired system call
- Execute the designated system call instruction
- Which causes an exception that traps to the OS
- OS recognizes & performs the requested operation
  – Entering the OS through a point called a *gate*
- Returns to instruction after the system call

System Call Trap Gates



Trap Handling

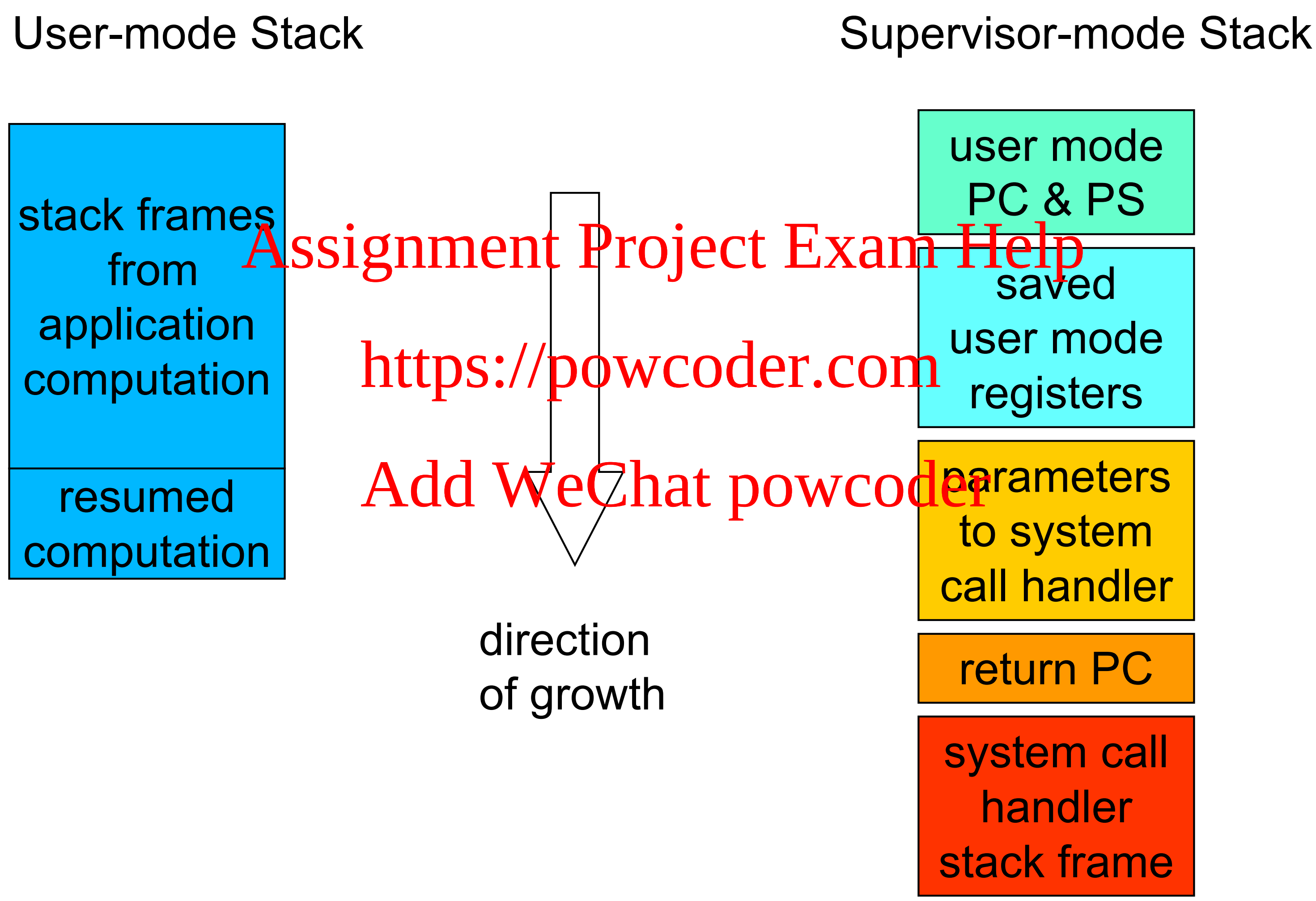
Where do you think this table came from?

- Partially hardware, partially software
- Hardware portion of trap handling
  - Trap cause an index into trap vector table for PC/PS
  - Load new processor status word, switch to supervisor mode
  - Push PC/PS of program that caused trap onto stack
  - Load PC (with address of 1st level handler)
- Software portion of trap handling
  - 1st level handler pushes all other registers
  - 1st level handler gathers info, selects 2nd level handler
  - 2nd level handler actually deals with the problem
    - Handle the event, kill the process, return ...

Traps and the Stack

- The code to handle a trap is just code
  - Although run in privileged mode
- It requires a stack to run
  - Since it might call many routines
- How does the OS provide it with the necessary stack?
- While not losing track of what the user process was doing?
- Or leaving sensitive data in the user's stack area?

Stacking and Unstacking a System Call



Returning to User-Mode

- Return is opposite of interrupt/trap entry
  - 2nd level handler returns to 1st level handler
  - 1st level handler restores all registers from stack
  - Use privileged return instruction to restore PC/PS
  - Resume user-mode execution at next instruction
- Saved registers can be changed before return
  - Change stacked user r0 to reflect return code
  - Change stacked user PS to reflect success/failure

Asynchronous Events

- Some things are worth waiting for
  - When I `read()`, I want to wait for the data
- Other time waiting doesn't make sense
  - I want to do something else while waiting
  - I have multiple operations outstanding
  - Some events demand very prompt attention
- We need *event completion call-backs*
  - This is a common programming paradigm
  - Computers support interrupts (similar to traps)
  - Commonly associated with I/O devices and timers

User-Mode Signal Handling

- OS defines numerous types of signals
  - Exceptions, operator actions, communication
- Processes can control their handling
  - Ignore this signal (pretend it never happened)
  - Designate a handler for this signal
  - Default action (typically kill or coredump process)
- Analogous to hardware traps/interrupts
  - But implemented by the operating system
  - Delivered to user mode processes

Managing Process State

- A shared responsibility
- The process itself takes care of its own stack

- And the contents of its memory

- The OS keeps track of resources that have been allocated to the process

  - Which memory segments
  - Open files and devices
  - Supervisor stack
  - And many other things

Which implies that they can screw these up if they aren't careful

Blocked Processes

- One important process state element is whether a process is ready to run
  - No point in trying to run it if it isn't ready to run
  - Processes not ready to run are *blocked*
- Why might it not be ready to run?
- Perhaps it's waiting for I/O
- Or for some resource request to be satisfied
- The OS keeps track of whether a process is blocked

Blocking and Unblocking Processes

- Why do we block processes?
  - Blocked/unblocked are notes to scheduler
  - So the scheduler knows not to choose them
  - And so other parts of OS know if they later need to unblock
- Any part of OS can set blocks, any part can remove them
  - And a process can ask to be blocked itself
    - Through a system call

Better be sure someone will unblock you . . .

Who Handles Blocking?

- Usually happens in a resource manager
  - When process needs an unavailable resource
    - Change process' scheduling state to "blocked"
    - Call the scheduler and yield the CPU
  - When the required resource becomes available
    - Change process' scheduling state to "ready"
    - Notify scheduler that a change has occurred

Conclusion

- Processes are the fundamental OS interpreter abstraction
- They are created by the OS at application request and managed via process descriptors
- There are different methods for creating processes
- Processes use system calls to transfer control to the OS to obtain system services