TCSS 422: OPERATING SYSTEMS

Processes & The Process API

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OBJECTIVES – 4/8

- **Questions from 4/3**
- C Review Survey – Late After Apr 9, Closes Apr 11
- Student Background Survey
- Virtual Machine Survey: VM to be sent to S. Miasishchev
- Assignment 0
- Chapter 4: Processes
  - Process states, context switches
  - Kernel data structures for processes and threads
- Chapter 5: Process API
  - fork(), wait(), exec()

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VIRTUAL MACHINE SUPPORT ON APPLE M1

- Installing a Ubuntu Virtual Machine on Apple M1 MacBooks:
- FREE
- https://mac.getutm.app/
- MACs have switched to using ARM-based CPUs
  - Motivation: faster, less expensive than Intel-based CPUs

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TEXT BOOK COUPON

- 15% off textbook code: **PUBLISHPAGES15** (*through Fri Apr 11*)
- https://www.lulu.com/shop/andrea-arpaci-dusseau-and-remzi-arpaci-dusseau/operating-systems-three-easy-pieces-hardcover-version-110/hardcover/product-15gjeeky.html?q=three+easy+pieces+operating+systems&page=1&pageSize=4
- With coupon textbook is only ~ $33.79 + tax & shipping

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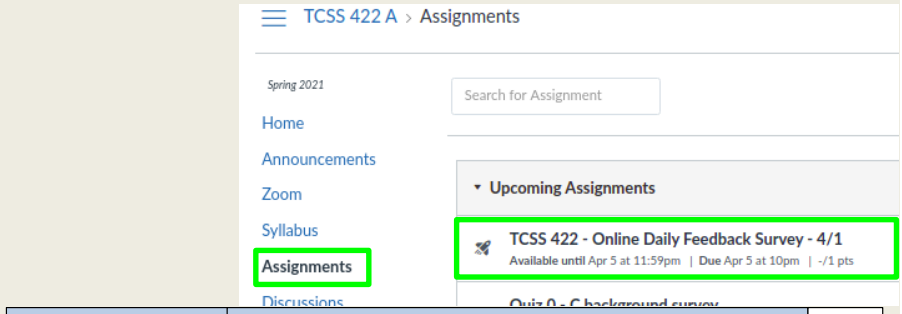
ONLINE DAILY FEEDBACK SURVEY

- Daily Feedback Quiz in Canvas – Available After Each Class
- Extra credit available for completing surveys ***ON TIME***
- Tuesday surveys: due by ~ Wed @ 9p, closes 11:59p
- Thursday surveys: due ~ Mon @ 9p, closes 11:59p



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TCSS 422 - Online Daily Feedback Survey - 4/1

Quiz Instructions

Question 1 0.5 pts

On a scale of 1 to 10, please classify your perspective on material covered in today's class:

1	2	3	4	5	6	7	8	9	10
Mostly Review To Me				Equal New and Review					Mostly New to Me

Question 2 0.5 pts

Please rate the pace of today's class:

1	2	3	4	5	6	7	8	9	10
Slow				Just Right					Fast

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (57 of 63 respondents – 90.48% !!):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 5.86 (↓ - previous 5.92)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.11 (↓ - previous 5.26)**

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FEEDBACK FROM 4/3

- I do not understand how a virtual address space can be the same size as the physical address space. If the entire 4GB virtual address space is full for a single program, won't the entire 4GB physical address space be full with no space left for the other programs?

- Oses use lazy loading. Code pages are only read into memory when they are needed. In the rare event that a single program consumes all of the physical memory, Linux augments RAM with Swap space
- Swap space is a disk volume used as extended memory
- Commands to check your swap space:

```
free
cat /proc/swaps
lsblk | grep -C 5 -i swap
swapon -s
vmstat 1
```


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FEEDBACK - 2

- ***Are we using ubuntu as our main OS to work from? or are we allowed to use windows/MacOS?***
- The OS directly installed on your computer which boots the computer is called the **host operating system.**
- This can be Windows, MacOS, Linux, etc.
- Ubuntu will be installed on a virtual machine (VM)
- The OS installed on a VM is called a **guest operating system**.

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FEEDBACK - 3

- ***What exactly is the difference between processes and threads in regards to OS' virtualization of memory?***
- ***If my understanding is correct, then I know that many threads can share the same physical address space via virtualization, but does the same apply to processes?***
- Threads share the same virtual memory space as the parent process.
- This sharing of memory is what causes synchronization errors when two threads try to modify shared memory at the same time without proper coordination
- Every process has its own distinct virtual memory space

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FEEDBACK - 4

- ***What counts as a process?***
  Does a running program constitute a single process?
  Or are there many processes in a single program?
- As we see when inspecting running processes using tools like 'top', 'htop', and 'ps aux', programs like Zoom and Chrome have multiple processes
- Not every program uses multiple processes
- The issue with multiple processes is they * don't * share memory, so it is hard to coordinate multiple processes

- Linux features IPC – Inter Process Communication
- This is the notion of use "I/O streams" similar to files called pipes to allow programs to open various streams between each other

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FEEDBACK - 5

- ***Why does the shared counter work at smaller loop lengths but not at larger loops?***
- ***I would expect it to be unstable at all scales.***

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MOTIVATION FOR LINUX

- It is worth noting the importance of Linux for today's developers and computer scientists.
- The CLOUD runs many virtual machines, recently in 2019 a key milestone was reached.
- Even on Microsoft Azure (the Microsoft Cloud), there were more Linux Virtual Machines (> 50%) than Windows.
- https://www.zdnet.com/article/microsoft-developer-reveals-linux-is-now-more-used-on-azure-than-windows-server/
- https://www.zdnet.com/article/it-runs-on-the-cloud-and-the-cloud-runs-on-linux-any-questions/
- The majority of application back-ends (server-side), cloud or not, run on Linux.
- This is due to licensing costs, example:

MOTIVATION FOR LINUX - 2

- Consider an example where you're asked to develop a web services backend that requires 10 x 8-CPU-core virtual servers
- Your organization investigates hosting costs on Amazon cloud
- 8-core VM is "c5d.2xlarge"

Name	Instance type	Memory	vCPUs	Linux On Demand cost	Windows On Demand cost
C5 High-CPU Extra Large	c5d.xlarge	8.0 GiB	4 vCPUs	$0.192000 hourly	$0.376000 hourly
C5 High-CPU 18xlarge	c5d.18xlarge	144.0 GiB	72 vCPUs	$3.456000 hourly	$6.768000 hourly
C5 High-CPU Large	c5d.large	4.0 GiB	2 vCPUs	$0.096000 hourly	$0.188000 hourly
C5 High-CPU 24xlarge	c5d.24xlarge	192.0 GiB	96 vCPUs	$4.608000 hourly	$9.024000 hourly
C5 High-CPU Quadruple Extra Large	c5d.4xlarge	32.0 GiB	16 vCPUs	$0.768000 hourly	$1.504000 hourly
C5 High-CPU Metal	c5d.metal	192.0 GiB	96 vCPUs	$4.608000 hourly	$9.024000 hourly
C5 High-CPU Double Extra Large	c5d.2xlarge	16.0 GiB	8 vCPUs	$0.384000 hourly	$0.752000 hourly
C5 High-CPU 12xlarge	c5d.12xlarge	96.0 GiB	48 vCPUs	$2.304000 hourly	$4.512000 hourly
C5 High-CPU 9xlarge	c5d.9xlarge	72.0 GiB	36 vCPUs	$1.728000 hourly	$3.384000 hourly

- Windows hourly price 75.2¢
- Linux hourly price 38.4¢
- See: https://instances.vantage.sh/

MOTIVATION FOR LINUX - 2

- C… s… …ers
- Y… …ud
- 8…

	…and cost
C5 High-C…	…urly
C5 High-C…	…urly
C5 High-C…	…urly
C5 High-C…	…urly
C5 High-C…	…urly
C5 High-C…	…urly
C5 High-C…	…urly
C5 High-C…	…urly

One year cloud hosting cost:

WINDOWS
10 VMs x 8,760 hours x $.752 = $65,875.20

Linux
10 VMs x 8,760 hours x $.384 = $33,638.40

Windows comes at a 95.8% price premium

- W…
- L…
- See: **https://www.ec2instances.info/**

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C REVIEW SURVEY - AVAILABLE THRU 4/5

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STUDENT BACKGROUND SURVEY

- **46 of 63 Responses** as of 4/8 @ ~12am
- Current Standings:
  - Best Office Hours times so far:
    - Rank #1: Wednesday morning (before noon) √ **(47.7%)**
    - Rank #2: Friday early afternoon √ (12-2p) **(45.5%)**
  - Format:
    - Rank #1: Prefer online (Zoom) √ **(54.5%)**

TCSS 422 – OFFICE HRS – SPRING 2025

- **Session 1. Wednesday 11am to noon**
  - This session will be held by zoom.
- **Session 2. Fridays noon to 1pm (Zoom)**
  - This session will mostly be held on zoom.
  - Some Fridays will be canceled due to instructor scheduling conflicts
    - Known conflicts on 4/11, 4/18, 5/16 (?)
- Zoom links for Office Hours will be shared via Canvas
- Also available after class on Tuesdays and Thursdays in CP 229 at 6pm

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VIRTUAL MACHINE SURVEY

- Please complete the Virtual Machine Survey to request a "School of Engineering and Technology" remote hosted Ubuntu VM
- **https://forms.gle/jSwcL1qeKDy2W9498**
- **VM requests have been sent to SET sys admin Slava Miasishchev for set up**
- **If you missed the survey, and need a VM, please complete it**

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CHAPTER 2 SUMMARY : OPERATING SYSTEM DESIGN GOALS

- **ABSTRACTING THE HARDWARE**
  - Makes programming code easier to write
  - Automate sharing resources – save programmer burden
- **PROVIDE HIGH PERFORMANCE**
  - Minimize overhead from OS abstraction (Virtualization of CPU, RAM, I/O)
  - Share resources fairly
  - Attempt to tradeoff performance vs. fairness → consider priority
- **PROVIDE ISOLATION**
  - User programs can't interfere with each other's virtual machines, the underlying OS, or the sharing of resources

CHAPTER 2 SUMMARY : OPERATING SYSTEM DESIGN GOALS - 2

- **RELIABILITY**
  - OS must not crash, 24/7 Up-time
  - Poor user programs must not bring down the system:

    Blue Screen

- ***Other Issues:***
  - Energy-efficiency
  - Security (of data)
  - Cloud: Virtual Machines

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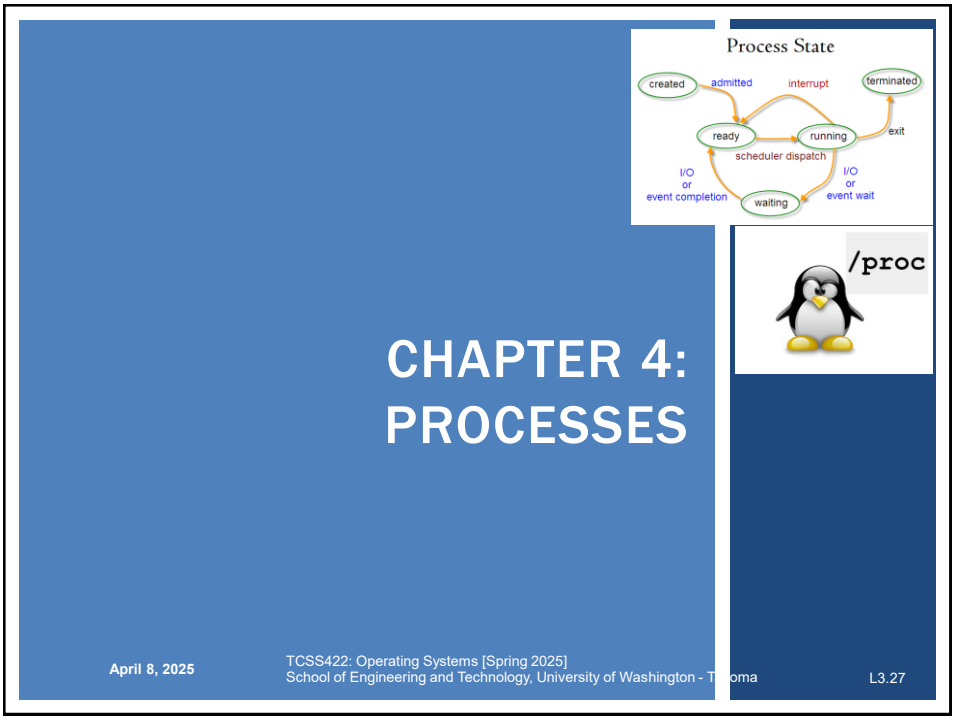

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VIRTUALIZING THE CPU

- How should the CPU be shared?
- Time Sharing:
  Run one process, pause it, run another
- The act of swapping process A out of the CPU to run process B is called a:
  - **CONTEXT SWITCH**
- How do we SWAP processes in and out of the CPU efficiently?
  - Goal is to minimize **overhead** of the swap
- **OVERHEAD** is time spent performing OS management activities that don't help accomplish real work

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PROCESS

A process is a running program.

- Process comprises of:
  - Memory
    - Instructions (“the code”)
    - Data (heap)
  - Registers
    - PC: Program counter
    - Stack pointer

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PROCESS API

- Modern OSes provide a Process API for process support
- Create
  - Create a new process
- Destroy
  - Terminate a process (ctrl-c)
- Wait
  - Wait for a process to complete/stop
- Miscellaneous Control
  - Suspend process (ctrl-z)
  - Resume process (fg, bg)
- Status
  - Obtain process statistics: (top)

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PROCESS API: CREATE

1. Load program code (and static data) into memory
   - Program executable code (binary): loaded from disk
   - Static data: also loaded/created in address space
   - **Eager loading**: Load entire program before running
   - **Lazy loading**: Only load what is immediately needed
     - Modern OSes: Supports paging & swapping
2. Run-time stack creation
   - Stack: local variables, function params, return address(es)

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PROCESS API: CREATE

3. Create program's heap memory
   - For dynamically allocated data
4. Other initialization
   - I/O Setup
     - Each process has three open file descriptors: Standard Input, Standard Output, Standard Error
5. Start program running at the entry point: `main()`
   - OS transfers CPU control to the new process

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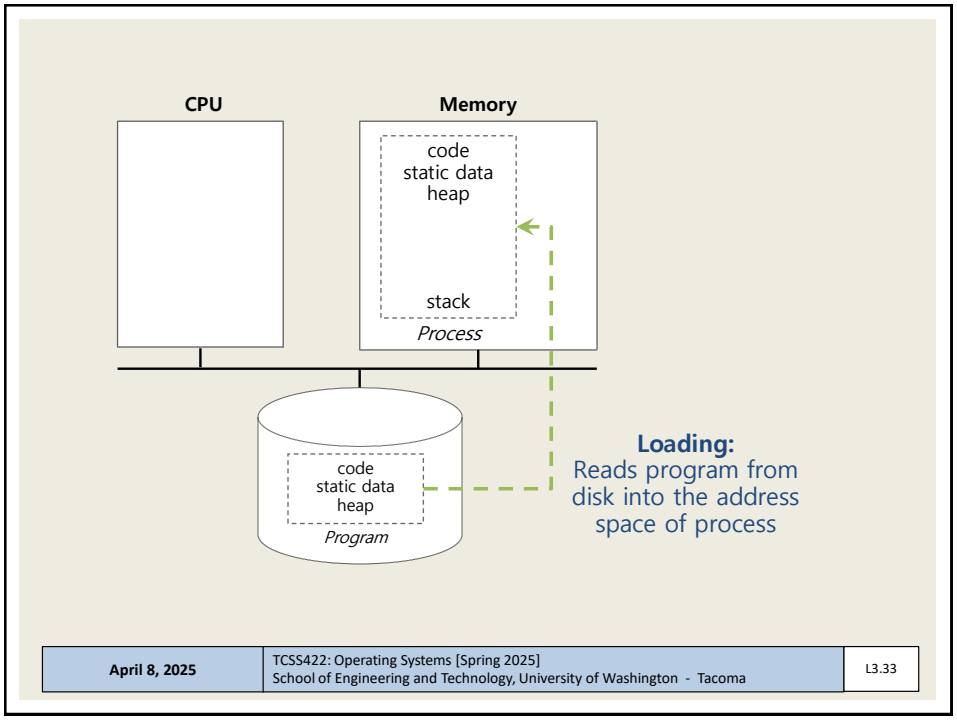
CPU
Memory
code
static data
heap
stack
Process
code
static data
heap
Program
Loading:
Reads program from disk into the address space of process
April 8, 2025
TCSS422: Operating Systems [Spring 2025]
School of Engineering and Technology, University of Washington - Tacoma
L3.33

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WE WILL RETURN AT 5:00PM
April 8, 2025
TCSS422: Operating Systems [Spring 2025]
School of Engineering and Technology, University of Washington -
coma
L3.34

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PROCESS STATES

- **RUNNING**
  - Currently executing instructions
- **READY**
  - Process is ready to run, but has been preempted
  - CPU is presently allocated for other tasks
- **BLOCKED**
  - Process is **not** ready to run. It is waiting for another event to complete:
    - Process has already been initialized and run for awhile
    - Is now waiting on I/O from disk(s) or other devices

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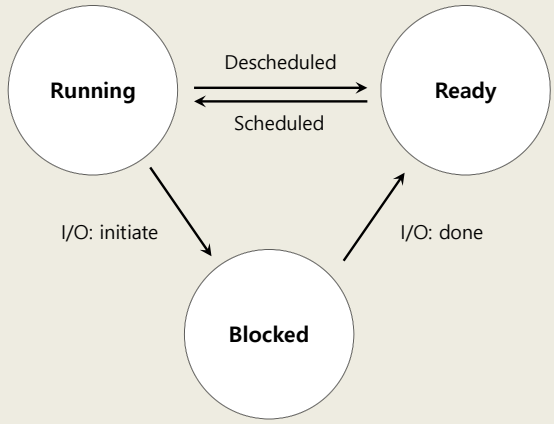
PROCESS STATE TRANSITIONS



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OBSERVING PROCESS META-DATA

- Can inspect the number of **CONTEXT SWITCHES** made by a process
- Let's run mem.c (from chapter 2)
- cat /proc/{process-id}/status

```
Speculation_Store_Bypass:       thread vulnerable
Cpus_allowed:   ff
Cpus_allowed_list:      0-7
Mems_allowed:   00000000,00000001
Mems_allowed_list:      0
voluntary_ctxt_switches:        1372
nonvoluntary_ctxt_switches:     18
```

- proc "status" is a virtual file generated by Linux
- Provides a report with process related meta-data
- **What appears to happen to the number of context switches the longer a process runs? (mem.c)**

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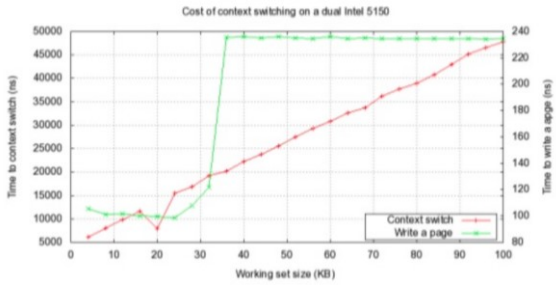
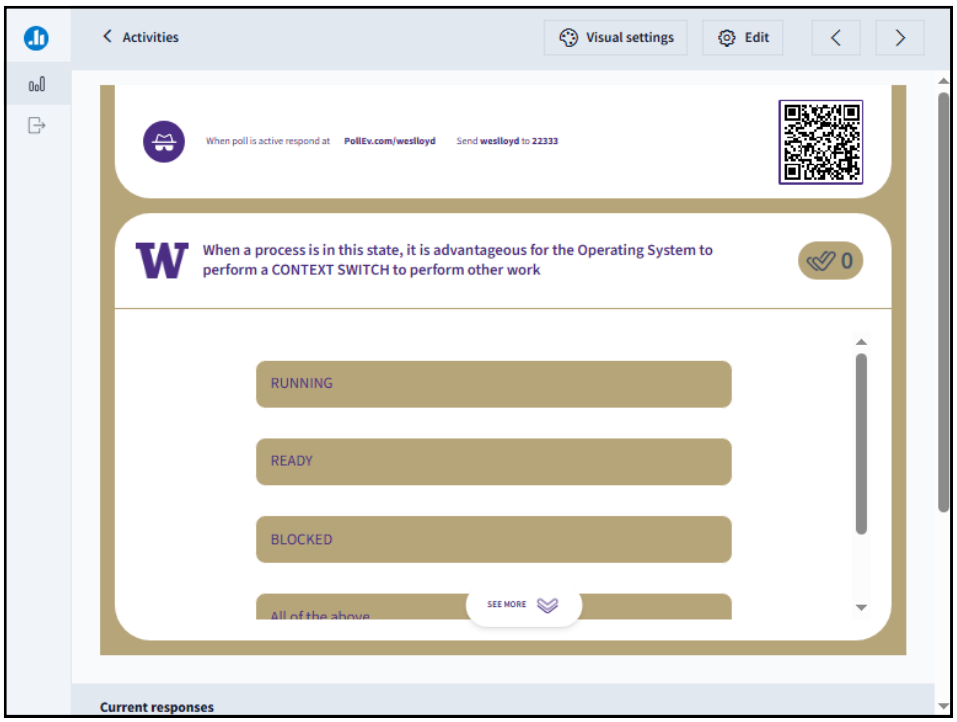
CONTEXT SWITCH

- ***How long does a context switch take?***
- 10,000 to 50,000 ns (.01 to .05 ms)
- 2,000 context switches is near 100ms

Without CPU affinity



(source: http://blog.tsunanet.net/2010/11/how-long-does-it-take-to-make-context.html)



QUESTION: WHEN TO CONTEXT SWITCH

- When a process is about to go into this state, it is advantageous for the Operating System to perform a CONTEXT SWITCH to perform other work:

- (a) RUNNING
- (b) READY
- (c) BLOCKED
- (d) All of the above
- (e) None of the above

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PROCESS DATA STRUCTURES

- OS provides data structures to track process information
  - Process list
    - Process Data
    - State of process: Ready, Blocked, Running
  - Register context
- PCB (Process Control Block)
  - A C-structure that contains information about each process

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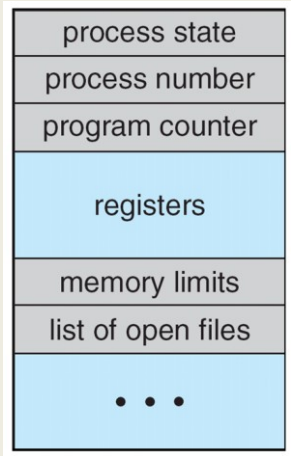
STRUCT TASK_STRUCT PROCESS CONTROL BLOCK

- Process Control Block (PCB)
- Key data regarding a process



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XV6 KERNEL DATA STRUCTURES

- xv6: pedagogical implementation of Linux
- Simplified structures shown in book

```
// the registers xv6 will save and restore
// to stop and subsequently restart a process
struct context {
    int eip;    // Index pointer register
    int esp;    // Stack pointer register
    int ebx;    // Called the base register
    int ecx;    // Called the counter register
    int edx;    // Called the data register
    int esi;    // Source index register
    int edi;    // Destination index register
    int ebp;    // Stack base pointer register
};

// the different states a process can be in
enum proc_state { UNUSED, EMBRYO, SLEEPING,
                  RUNNABLE, RUNNING, ZOMBIE };
```


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XV6 KERNEL DATA STRUCTURES - 2

```
// the information xv6 tracks about each process
// including its register context and state
struct proc {
    char *mem;                  // Start of process memory
    uint sz;                    // Size of process memory
    char *kstack;               // Bottom of kernel stack
                                // for this process
    enum proc_state state;      // Process state
    int pid;                    // Process ID
    struct proc *parent;        // Parent 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
    struct context context;     // Switch here to run process
    struct trapframe *tf;       // Trap frame for the
                                // current interrupt
};
```


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LINUX: STRUCTURES

- `struct task_struct`, equivalent to **struct proc**
  - The Linux process data structure
  - Kernel data type (i.e. record) that describes individual Linux processes
  - Structure is VERY LARGE: **10,000+ bytes**
  - Defined in:
    /usr/src/linux-headers-{kernel version}/include/linux/sched.h
    - Ubuntu kernel version 6.11, **LOC 758 – 1588**
    - Ubuntu kernel version 5.15, **LOC: 721 - 1507**
    - Ubuntu kernel version 5.11, **LOC: 657 – 1394**
    - Ubuntu kernel version 4.4, **LOC: 1391 – 1852**

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STRUCT TASK_STRUCT

- Key elements (e.g. PCB) in Linux are captured in struct task_struct: (LOC from Linux kernel v 6.11)
- **Process ID**
- `pid_t pid;` LOC #995
- **Process State**
- `/* -1 unrunnable, 0 runnable, >0 stopped: */`
- `unsigned int __state;` LOC #766
- **Process time slice**
  how long the process will run before context switching
- Struct sched_rt_entity used in task_struct contains timeslice:
  - `struct sched_rt_entity rt;` LOC #812
  - `unsigned int time_slice;` LOC #583

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STRUCT TASK_STRUCT - 2

- **Address space of the process:**
- "mm" is short for "memory map"
- `struct mm_struct *mm;` LOC #898

- **Parent process**, that launched this one
- `struct task_struct __rcu *parent;` LOC #1009

- **Child processes** (as a list)
- `struct list_head children;` LOC #1017

- **Open files**
- `struct files_struct *files;` LOC #1121

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LINUX STRUCTURES - 2

- List of Linux data structures:
  http://www.tldp.org/LDP/tlk/ds/ds.html

- Description of process data structures:
  https://learning.oreilly.com/library/view/linux-kernel-development/9780768696974/cover.html
  3rd edition is online (dated from 2010):
  See chapter 3 on Process Management

  Safari online – accessible using UW ID SSO login
  Linux Kernel Development, 3rd edition
  Robert Love
  Addison-Wesley

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CHAPTER 5: C PROCESS API

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fork()

- Creates a new process - think of "a fork in the road"
- "Parent" process is the original
- Creates "child" process of the program from the **current execution point**
- Book says "pretty odd"
- Creates a **duplicate** program instance (these are **processes!**)
- **Copy** of
  - Address space (memory)
  - Register
  - Program Counter (PC)
- Fork returns
  - child PID to parent
  - 0 to child

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FORK EXAMPLE

- p1.c

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.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());
    } else {               // parent goes down this path (main)
        printf("hello, I am parent of %d (pid:%d)\n",
        rc, (int) getpid());
    }
    return 0;
}
```


FORK EXAMPLE - 2

- Non deterministic ordering of execution

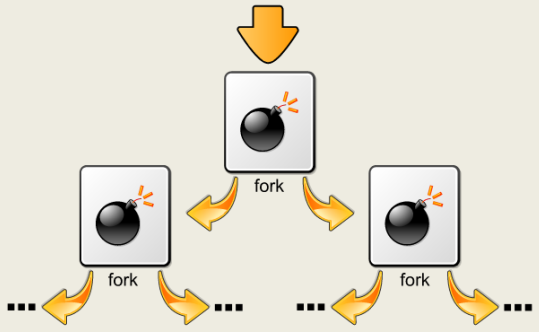
```
prompt> ./p1
hello world (pid:29146)
hello, I am parent of 29147 (pid:29146)
hello, I am child (pid:29147)
prompt>
```

or

```
prompt> ./p1
hello world (pid:29146)
hello, I am child (pid:29147)
hello, I am parent of 29147 (pid:29146)
prompt>
```

- CPU scheduler determines which to run first

:(){ :|: & };:



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wait()

- wait(), waitpid()
- Called by parent process
- Waits for a child process to finish executing
- Not a sleep() function
- Provides some ordering to multi-process execution

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FORK WITH WAIT

```
#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());
    } else {               // parent goes down this path (main)
        int wc = wait(NULL);
        printf("hello, I am parent of %d (wc:%d) (pid:%d)\n",
        rc, wc, (int) getpid());
    }
    return 0;
}
```


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FORK WITH WAIT - 2

- Deterministic ordering of execution

```
prompt> ./p2
hello world (pid:29266)
hello, I am child (pid:29267)
hello, I am parent of 29267 (wc:29267) (pid:29266)
prompt>
```


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FORK EXAMPLE

- Linux example

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OBJECTIVES – 4/8

- Questions from 4/3
- C Review Survey – Late After Apr 9, Closes Apr 11
- Student Background Survey
- Virtual Machine Survey: VM to be sent to S. Miasishchev
- Assignment 0
- Chapter 4: Processes
  - Process states, context switches
  - Kernel data structures for processes and threads
- **Chapter 5: Process API**
  - fork(), wait(), **exec()**

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exec()

- Supports running an external program **by "transferring control"**
- 6 types: execl(), execlp(), execle(), execv(), execvp(), execvpe()
- execl(), execlp(), execle(): const char *arg ***(example: execl.c)***

  Provide cmd and args as individual params to the function
  Each arg is a pointer to a null-terminated string
  ODD: pass a variable number of args: (arg0, arg1, .. argn)
- Execv(), execvp(), execvpe() ***(example: exec.c)***

  Provide cmd and args as an Array of pointers to strings

  Strings are null-terminated
  First argument is name of command being executed
  Fixed number of args passed in

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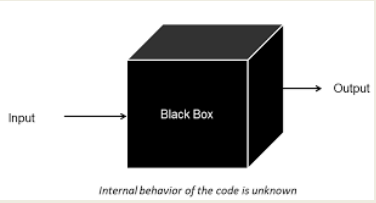
EXEC() - 2

- Common use case:
- Write a new program which wraps a legacy one
- Provide a new interface to an old system: Web services
- Legacy program thought of as a "black box"

- We don't want to know what is inside…



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EXEC EXAMPLE

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <string.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());
        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
        …
```


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EXEC EXAMPLE - 2

```
…
        execvp(myargs[0], myargs); // runs word count
        printf("this shouldn't print out");
    } else {                      // parent goes down this path (main)
        int wc = wait(NULL);
        printf("hello, I am parent of %d (wc:%d) (pid:%d)\n",
            rc, wc, (int) getpid());
    }
    return 0;
}
```

```
prompt> ./p3
hello world (pid:29383)
hello, I am child (pid:29384)
29 107 1030 p3.c
hello, I am parent of 29384 (wc:29384) (pid:29383)
prompt>
```


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EXEC WITH FILE REDIRECTION (OUTPUT)

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <string.h>
#include <fcntl.h>
#include <sys/wait.h>

int
main(int argc, char *argv[]){
    int rc = fork();
    if (rc < 0) {          // fork failed; exit
        fprintf(stderr, "fork failed\n");
        exit(1);
    } else if (rc == 0) { // child: redirect standard output to a file
        close(STDOUT_FILENO);
        open("./p4.output", O_CREAT|O_WRONLY|O_TRUNC, S_IRWXU);
        …
```


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FILE MODE BITS

```
S_IRWXU
read, write, execute/search by owner
S_IRUSR
read permission, owner
S_IWUSR
write permission, owner
S_IXUSR
execute/search permission, owner
S_IRWXG
read, write, execute/search by group
S_IRGRP
read permission, group
S_IWGRP
write permission, group
S_IXGRP
execute/search permission, group
S_IRWXO
read, write, execute/search by others
S_IROTH
read permission, others
S_IWOTH
write permission, others
```


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EXEC W/ FILE REDIRECTION (OUTPUT) - 2

```
        …
        // now exec "wc"...
        char *myargs[3];
        myargs[0] = strdup("wc");          // program: "wc" (word count)
        myargs[1] = strdup("p4.c");        // argument: file to count
        myargs[2] = NULL;                  // marks end of array
        execvp(myargs[0], myargs);         // runs word count
    } else {                        // parent goes down this path (main)
        int wc = wait(NULL);
    }
    return 0;
}
```

```
prompt> ./p4
prompt> cat p4.output
32 109 846 p4.c
prompt>
```


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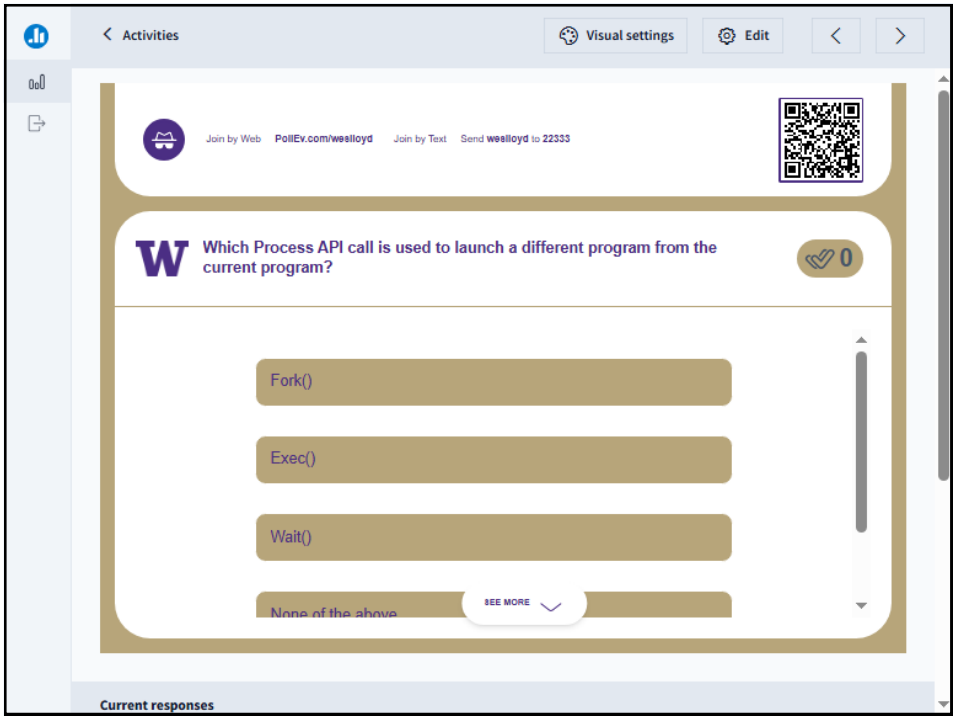

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QUESTION: PROCESS API

- Which Process API call is used to launch a different program from the current program?

- (a) Fork()
- (b) Exec()
- (c) Wait()
- (d) None of the above
- (e) All of the above

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QUESTIONS

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