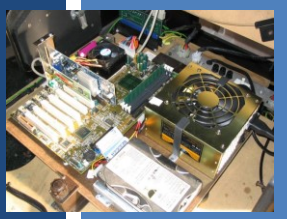
TCSS 422: OPERATING SYSTEMS



Operating Systems – Three Easy Pieces & Processes

Wes J. Lloyd
School of Engineering and Technology
University of Washington - Tacoma

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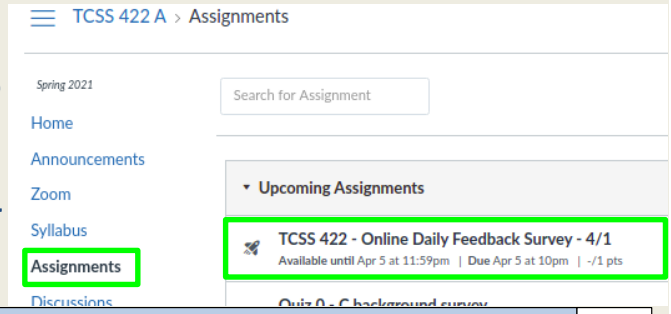
OBJECTIVES – 1/13

- Questions from 1/13
- C Review Survey - available thru 1/17 AOE
- Student Background Survey
- Virtual Machine Survey
- Chapter 2: Operating Systems – Three Easy Pieces
  - Concepts of virtualization/abstraction
  - Three Easy Pieces: CPU, Memory, I/O
  - Concurrency
  - Operating system design goals
- Chapter 4: Processes
  - Process states, context switches
  - Kernel data structures for processes and threads

2

FEEDBACK SURVEYS

- Feedback Survey in Class and on Canvas
- **All Quarter: 1-point Extra Credit** for completing online
- **Weeks 1-6: 2-points Extra Credit** completing in class
- **Weeks 7-9: 3-points Extra Credit**, 4-points (week 10)
- 46 points possible
- 2.5% added to final course grade for (46/46)
- **There will be other opportunities (seminars, etc.) to earn survey pts**



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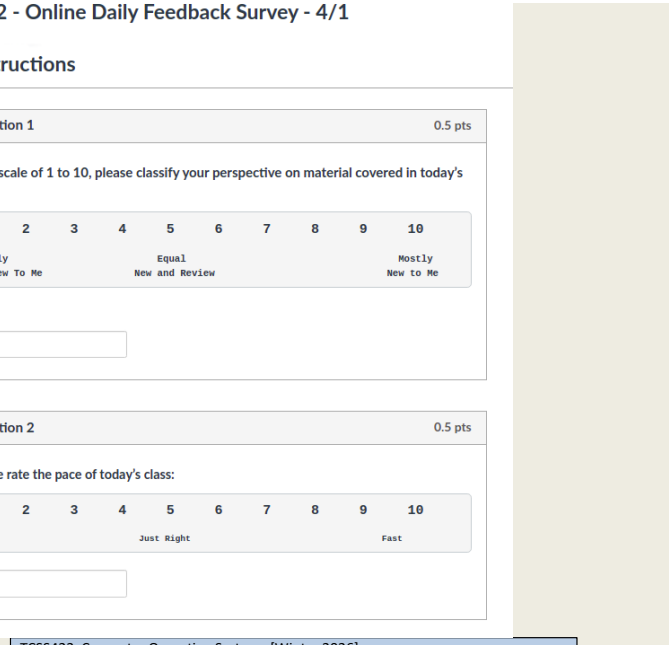

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (47 of 46 respondents – 102%):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 5.83** (*Spring 2025, 5.92*)

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.21** (*Spring 2025, 5.26*)

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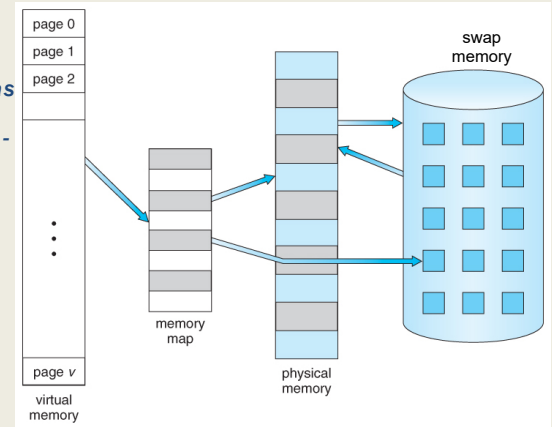
FEEDBACK FROM 1/6

- ***Where is virtual memory stored? (I thought it was through the cloud)***
- *Virtual memory is a memory-management model where each process behaves as if it has its own large, private, contiguous memory space - even when the machine's physical RAM is limited.*
- *In practice, Linux achieves this by mapping virtual addresses used by programs to physical memory (RAM) or to disk (swap), transparently and efficiently.*



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FEEDBACK - 2

- Virtual memory (core idea)
  - Programs don't access RAM directly.
  - They use virtual addresses.
  - The kernel and CPU translate virtual memory page addresses to physical RAM page addresses or, if needed, they retrieve memory pages from disk (swap).
  - This allows the OS to run programs larger than RAM, isolate processes, and use/share memory more efficiently.

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Another common feedback question, was how the operating system virtualizes (abstracts) the Three Easy Pieces…

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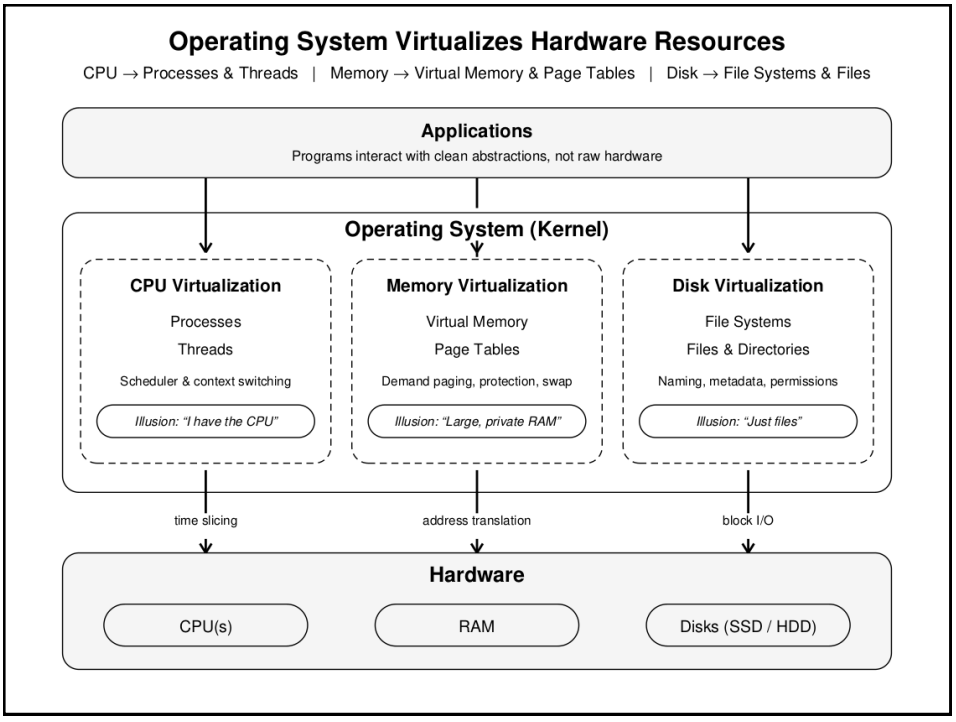

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RESOURCES

- **Textbook coupon 15% off "AAC72SAVE15"**
- **Hardcover edition (version 1.1) from lulu.com:**
- 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+softcover&page=1&pageSize=4
- With coupon textbook is only $33.79 + tax & shipping

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C REVIEW SURVEY - AVAILABLE THRU 1/17 AOE

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STUDENT BACKGROUND SURVEY

- Please complete the Student Background Survey
- **https://forms.gle/TBZMRUavzhihdUdb8**
- **31 of 46 Responses** as of 1/13 @ ~8am
- Will consider survey results through Mon Jan 19 for office hours…

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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/G679XUXXxXcHAffi6
- 30 of 46 Responses as of 1/13 @ ~8am
- Will close Thursday Jan 15…
- VM requests will be sent to SET for creation
- Survey response not required if no VM desired

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OBJECTIVES – 1/13

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ABSTRACTIONS

- What form of abstraction does the OS provide?
  - CPU
    - Process and/or thread
  - Memory
    - Address space
    - → large array of bytes
    - All programs see the same "size" of RAM
  - Disk
    - Files, File System(s)

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WHY ABSTRACTION?

- Allow applications to reuse common facilities
- Make different devices look the same
  - Easier to write common code to use devices
    - Linux/Unix Block Devices
- Provide higher level abstractions
- More useful functionality

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ABSTRACTION CHALLENGES

- What level of abstraction?
  - How much of the underlying hardware should be exposed?
    - What if **too much**?
    - What if **too little**?
- What are the correct abstractions?
  - Security concerns

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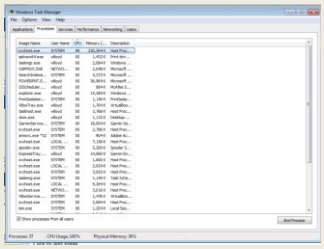
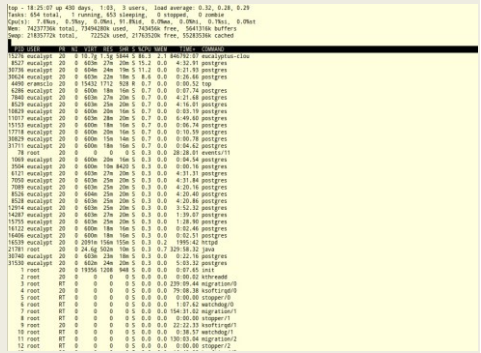
VIRTUALIZING THE CPU

- Each running program gets its own "virtual" representation of the CPU
- Many programs seem to run at once
- Linux: "top" command shows process list
- Windows: task manager





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VIRTUALIZING THE CPU - 2

- Simple Looping C Program

```
1       #include <stdio.h>
2       #include <stdlib.h>
3       #include <sys/time.h>
4       #include <assert.h>
5       #include "common.h"
6
7       int
8       main(int argc, char *argv[])
9       {
10              if (argc != 2) {
11                      fprintf(stderr, "usage: cpu <string>\n");
12                      exit(1);
13              }
14              char *str = argv[1];
15              while (1) {
16                      Spin(1); // Repeatedly checks the time and
                        returns once it has run for a second
17                      printf("%s\n", str);
18              }
19              return 0;
20      }
```


VIRTUALIZING THE CPU - 3

```
prompt> gcc -o cpu cpu.c -Wall
prompt> ./cpu "A"
A
A
A
^C
prompt>
```

- Runs forever, must Ctrl-C to halt…

VIRTUALIZATION THE CPU - 4

```
prompt> ./cpu A & ; ./cpu B & ; ./cpu C & ; ./cpu D &
[1] 7353
[2] 7354
[3] 7355
[4] 7356
A
B
D
C
A
B
D
C
A
C
B
D
...
```

Even though we have only one processor, all four instances of our program seem to be running at the same time!

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MANAGING PROCESSES FROM THE CLI

- & - run a job in the background
- fg – brings a job to the foreground
- bg – sends a job to the background
- CTRL-Z to suspend a job
- CTRL-C to kill a job
- "jobs" command – lists running jobs
- "jobs –p" command – lists running jobs by process ID

top –d .2	top utility shows active running jobs like the Windows task manager
top –H –d .2	display all processes & threads
top –H –p <pid>	display all threads of a process
htop	alternative to top, shows CPU core graphs

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VIRTUALIZING MEMORY

- Computer memory is treated as a large array of bytes
- Programs store all data in this large array
  - **Read memory (load)**
  - Specify an address to read data from
  - **Write memory (store)**
  - Specify data to write to an address

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VIRTUALIZING MEMORY - 2

- Program to read/write memory: (**mem.c**) (from ch. 2 pgs. 5-6)

```
1       #include <unistd.h>
2       #include <stdio.h>
3       #include <stdlib.h>
4       #include "common.h"
5
6       int
7       main(int argc, char *argv[])
8       {
9               int *p = malloc(sizeof(int));  // a1: allocate some
                                                  memory
10              assert(p != NULL);
11              printf("(%d) address of p: %08x\n",
12                      getpid(), (unsigned) p);  // a2: print out the
                                                     address of the memmory
13              *p = 0;  // a3: put zero into the first slot of the memory
14              while (1) {
15                      Spin(1);
16                      *p = *p + 1;
17                      printf("(%d) p: %d\n", getpid(), *p); // a4
18              }
19              return 0;
20      }
```


VIRTUALIZING MEMORY - 3

- Output of **mem.c** (example from ch. 2 pgs. 5-6)

```
prompt> ./mem
(2134) memory address of p: 00200000
(2134) p: 1
(2134) p: 2
(2134) p: 3
(2134) p: 4
(2134) p: 5
^C
```

- int value stored at virtual address 00200000
- program increments int value pointed to by p

VIRTUALIZING MEMORY - 4

- Multiple instances of **mem.c**

By default this example no longer works as advertised !

Ubuntu now applies address space randomization (ASR) by default.

ASR makes the ptr location of program instances not identical. Having identical addresses is considered a security issue.

```
prompt> ./mem &; ./mem &
[1] 24113
[2] 24114
(24113) memory address of p: 00200000
(24114) memory address of p: 00200000
(24113) p: 1
(24114) p: 1
(24114) p: 2
(24113) p: 2
(24113) p: 3
(24114) p: 3
...
```

- BOOK SHOWS:(int*)p with the same memory location **00200000**
- To disable ASR: `'echo 0 | tee /proc/sys/kernel/randomize_va_space'`
- Why does modifying the value of *p in program #1 (PID 24113), not interfere with the value of *p in program #2 (PID 24114) ?
  - The OS has "virtualized" memory, and provides a "virtual" address

VIRTUAL MEMORY

- Key take-aways:
- Each process (program) has its own ***virtual address space***
- The OS maps virtual ***address spaces*** onto ***physical memory***
- A memory reference from one process can not affect the address space of others.
  - ***Isolation***
- Physical memory, a shared resource, is managed by the OS

WE WILL RETURN AT 4:50PM

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WHY PERSISTENCE ?

- DRAM: Dynamic Random Access Memory: DIMMs/SIMMs
  - Store data while power is present
  - When power is lost, data is lost (*i.e. volatile memory*)
- Operating System helps "persist" data more **permanently**
  - I/O device(s): hard disk drive (HDD), solid state drive (SSD)
  - File system(s): "catalog" data for storage and retrieval

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PERSISTENCE - 2

```
1       #include <stdio.h>
2       #include <unistd.h>
3       #include <assert.h>
4       #include <fcntl.h>
5       #include <sys/types.h>
6
7       int
8       main(int argc, char *argv[])
9       {
10              int fd = open("/tmp/file", O_WRONLY | O_CREAT
                                | O_TRUNC, S_IRWXU);
11              assert(fd > -1);
12              int rc = write(fd, "hello world\n", 13);
13              assert(rc == 13);
14              close(fd);
15              return 0;
16      }
```

- open(), write(), close(): OS ***system calls*** for device I/O
- Note: man page for open(), write() requires page number: "man 2 open", "man 2 write", "man close"

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PERSISTENCE - 3

- To write to disk, OS must:
  - Determine where on disk data should reside
  - Instrument system calls to perform I/O:
    - Read/write to file system (*inode record*)
    - Read/write data to file
- OS provides fault tolerance for system crashes via special filesystem features:
  - **Journaling**: Record disk operations in a journal for replay
  - **Copy-on-write**: replicate shared data across multiple disks - *see ZFS filesystem*
  - Carefully order writes on disk (*especially spindle drives*)

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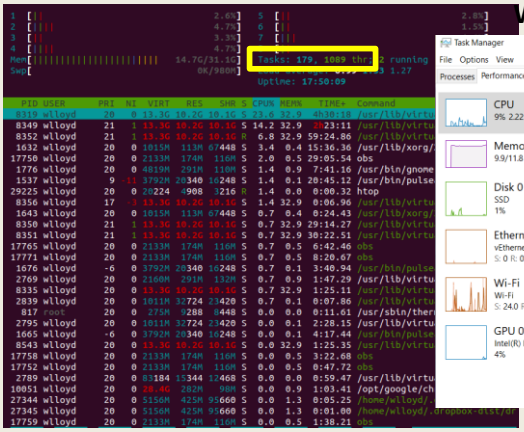
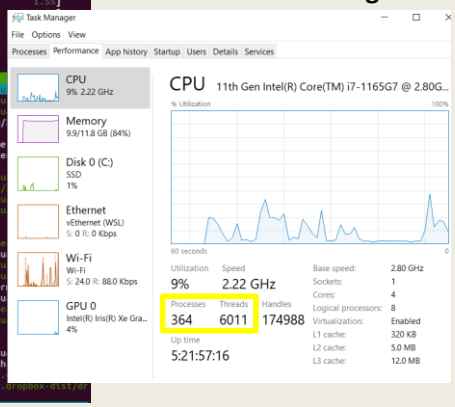
CONCURRENCY

Linux htop (Ubuntu)



Windows 10 Task Manager



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CONCURRENCY

- Linux: 211 processes, 1542 threads (`htop`)
- Windows 10/11: 192 processes, 2371 threads (task mgr)
- OSes appear to run many programs at once, juggling them
- Modern **multi-threaded** programs feature concurrent threads and processes
- ***What is a key difference between a process and a thread?***

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CONCURRENCY - 2

```
1       #include <stdio.h>
2       #include <stdlib.h>
3       #include "common.h"
4
5       volatile int counter = 0;
6       int loops;
7
8       void *worker(void *arg) {
9               int i;
10              for (i = 0; i < loops; i++) {
11                      counter++;
12              }
13              return NULL;
14  }
15  ...
```

pthread.c

Listing continues …

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CONCURRENCY - 2

```
1       #include <stdio.h>
2       #include <stdlib.h>
3       #include "common.h"
4
5       volatile int counter = 0;
6       int loops;
7
8       void
9
10
11
12
13
14  }
15  ...
```

Not the same as Java volatile ***(java guarantees visibility of changes):***
Provides a compiler hint than an object may change value unexpectedly (in this case by a separate thread) so aggressive optimization must be avoided.

pthread.c

Listing continues …

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CONCURRENCY - 3

pthread.c

```
16      int
17      main(int argc, char *argv[])
18      {
19              if (argc != 2) {
20                      fprintf(stderr, "usage: threads <value>\n");
21                      exit(1);
22              }
23              loops = atoi(argv[1]);
24              pthread_t p1, p2;
25              printf("Initial value : %d\n", counter);
26
27              Pthread_create(&p1, NULL, worker, NULL);
28              Pthread_create(&p2, NULL, worker, NULL);
29              Pthread_join(p1, NULL);
30              Pthread_join(p2, NULL);
31              printf("Final value : %d\n", counter);
32              return 0;
33      }
```

- Program creates two threads
- Check documentation: "man pthread_create"
- worker() method counts from 0 to argv[1] (loop)

Linux "man" page

example

PTHREAD_CREATE(3) Linux Programmer's Manual PTHREAD_CREATE(3)

NAME top

pthread_create - create a new thread

SYNOPSIS top

```
#include <pthread.h>

int pthread_create(pthread_t *thread, const pthread_attr_t *attr,
                   void *(*start_routine) (void *), void *arg);

Compile and link with -pthread.
```

DESCRIPTION top

The **pthread_create**() function starts a new thread in the calling process. The new thread starts execution by invoking *start_routine*(); *arg* is passed as the sole argument of *start_routine*().

The new thread terminates in one of the following ways:

* It calls pthread_exit(3), specifying an exit status value that is available to another thread in the same process that calls pthread_join(3).

* It returns from *start_routine*(). This is equivalent to calling pthread_exit(3) with the value supplied in the *return* statement.

* It is canceled (see pthread_cancel(3)).

* Any of the threads in the process calls exit(3), or the main thread performs a return from *main*(). This causes the termination of all threads in the process.

The *attr* argument points to a *pthread_attr_t* structure whose contents are used at thread creation time to determine attributes for the new thread; this structure is initialized using pthread_attr_init(3) and related functions. If *attr* is NULL, then the thread is created with default attributes.

CONCURRENCY - 4

- Command line parameter argv[1] provides loop length
- Defines number of times the shared counter is incremented
- Loops: 1000

```
prompt> gcc -o pthread pthread.c -Wall -pthread
prompt> ./pthread 1000
Initial value : 0
Final value : 2000
```

- Loops 100000

```
prompt> ./pthread 100000
Initial value : 0
Final value : 143012 // huh??
prompt> ./pthread 100000
Initial value : 0
Final value : 137298 // what ???
```

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CONCURRENCY - 5

- When loop value is large why do we not achieve 200,000 ?
- C code is translated to (3) assembly code operations

1. Load counter variable into register
2. Increment it
3. Store the register value back in memory

- These instructions happen concurrently and VERY FAST
- (P1 || P2) write incremented register values back to memory, While (P1 || P2) read same memory
- Memory access here is **unsynchronized** (**non-atomic**)
- *Some of the increments are lost*

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PARALLEL PROGRAMMING

- To perform parallel work, a single process may:
- A. Launch multiple threads to execute code in parallel while sharing global data in memory
- B. Launch multiple processes to execute code in parallel without sharing global data in memory
- C. Both A and B
- D. None of the above

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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

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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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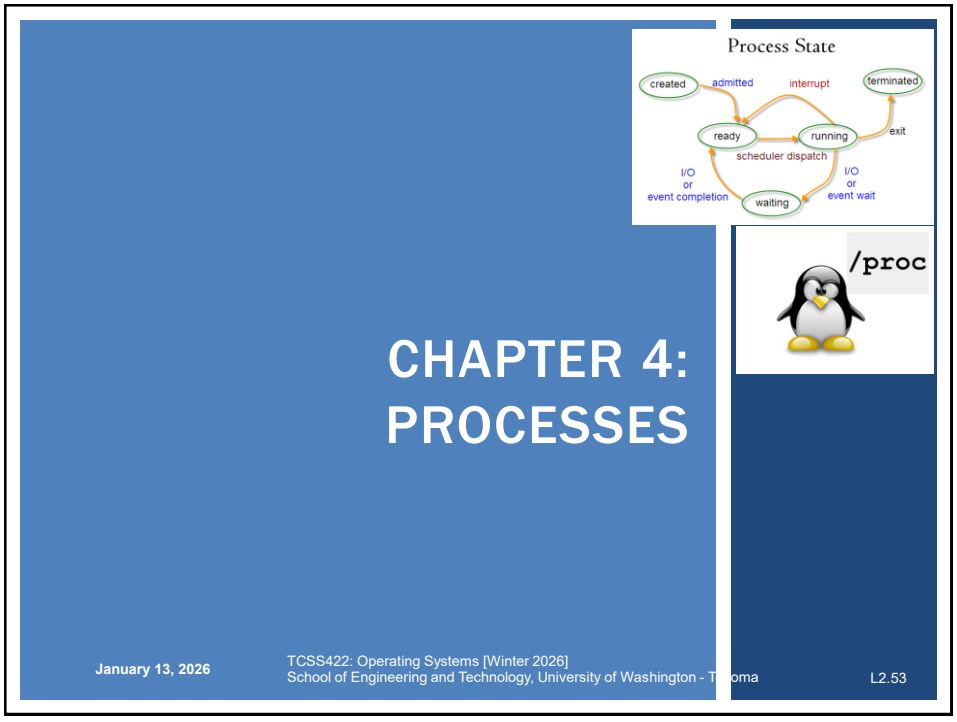
Process State
created
admitted
interrupt
terminated
ready
running
exit
scheduler dispatch
I/O
or
event completion
I/O
or
event wait
waiting
/proc
CHAPTER 4:
PROCESSES
January 13, 2026
TCSS422: Operating Systems [Winter 2026]
School of Engineering and Technology, University of Washington - Tacoma
L2.53

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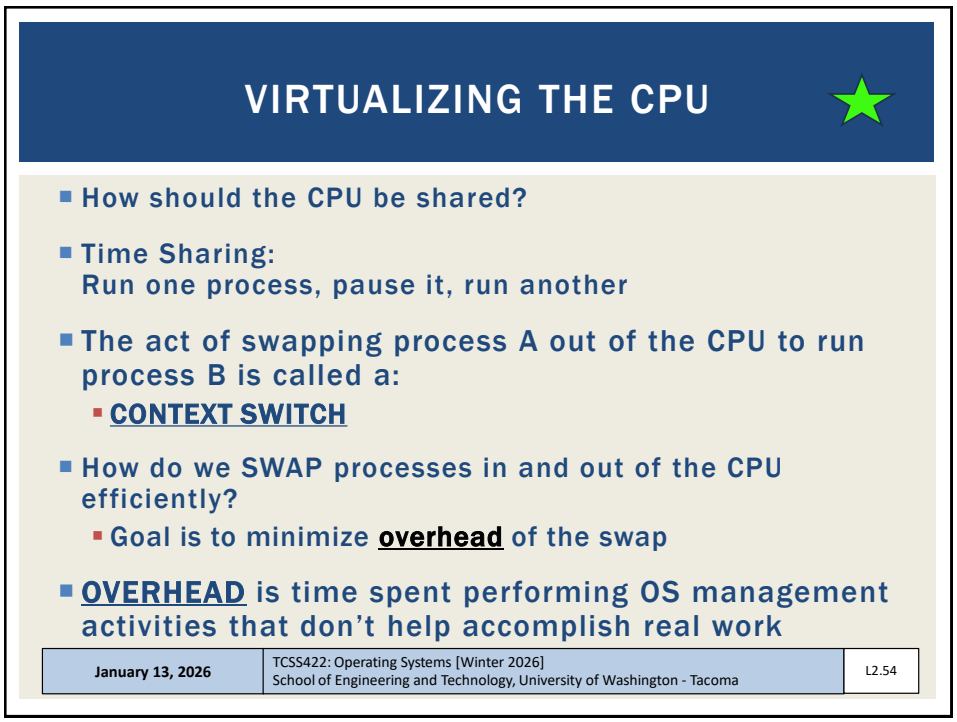
VIRTUALIZING THE CPU
How should the CPU be shared?
Time Sharing:
Run one process, pause it, run another
The act of swapping process A out of the CPU to run process B is called a:
CONTEXT SWITCH
How do we SWAP processes in and out of the CPU efficiently?
Goal is to minimize overhead of the swap
OVERHEAD is time spent performing OS management activities that don't help accomplish real work
January 13, 2026
TCSS422: Operating Systems [Winter 2026]
School of Engineering and Technology, University of Washington - Tacoma
L2.54

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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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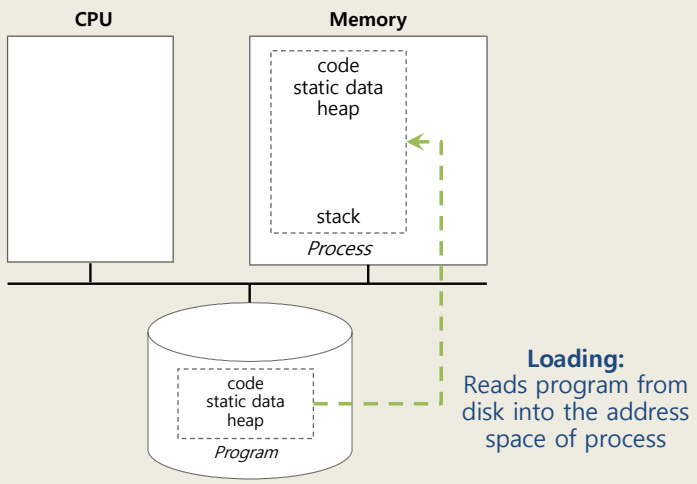

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OBJECTIVES – 1/13

- Questions from 1/13
- C Review Survey - available thru 1/17 AOE
- Student Background Survey
- Virtual Machine Survey
- Chapter 2: Operating Systems – Three Easy Pieces
  - Concepts of virtualization/abstraction
  - Three Easy Pieces: CPU, Memory, I/O
  - Concurrency
  - Operating system design goals
- Chapter 4: Processes
  - **Process states, context switches**
  - Kernel data structures for processes and threads

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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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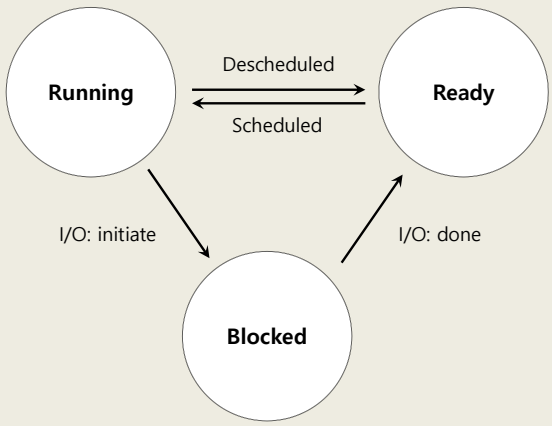
PROCESS STATE TRANSITIONS



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OBSERVING PROCESS META-DATA

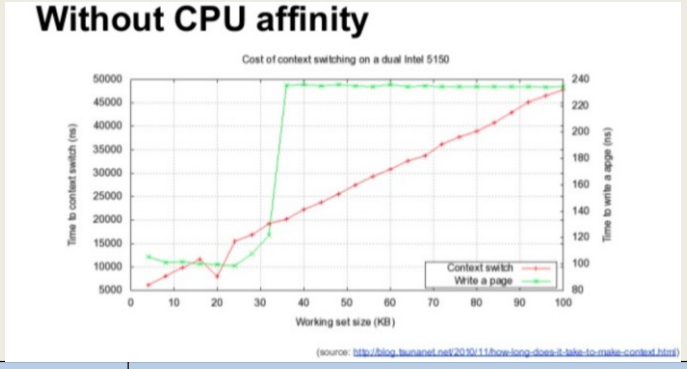
- Can inspect the number of **CONTEXT SWITCHES** made by a process
- Let's run mem.c (from chapter 2)
- cat /proc/{process-id}/status

```
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)**

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



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
- Mileage can vary depending on system conditions, etc.
- See blog: https://blog.tsunanet.net/2010/11/how-long-does-it-take-to-make-context.html

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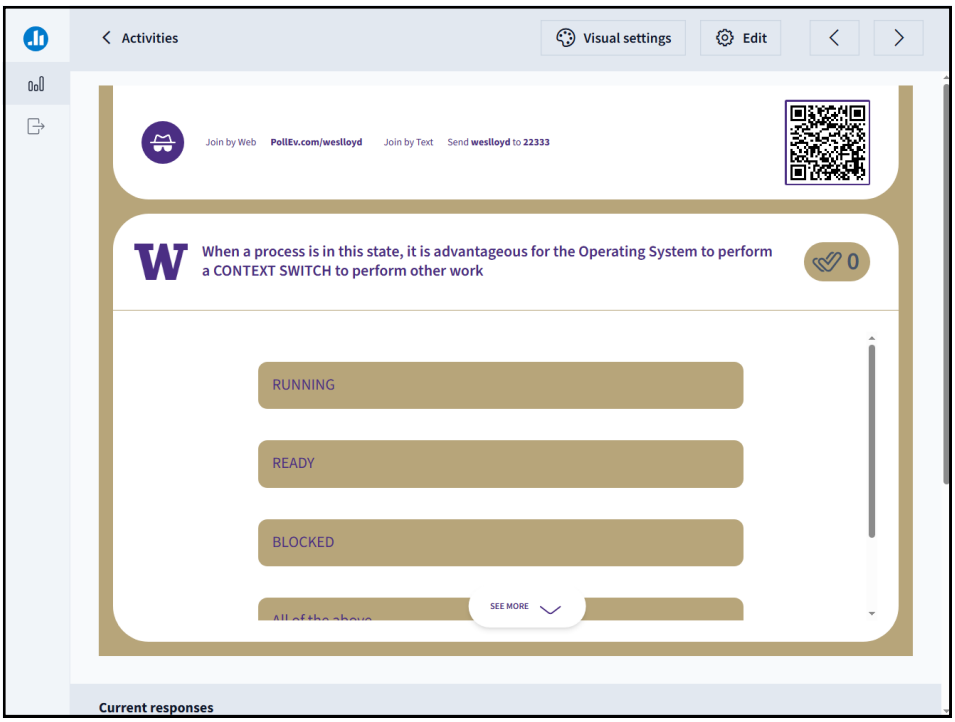

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QUESTION: WHEN TO CONTEXT SWITCH

- When a process is in 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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- Chapter 4: Processes
  - Process states, context switches
  - **Kernel data structures for processes and threads**

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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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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

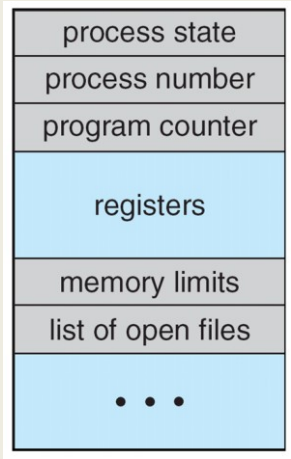
```
// the information xv6 tracks about each process
// including its register context and state
struct proc {
    char *mem;                // Start of process memory
    uint sz;                  // Size of process memory
    char *kstack;             // Bottom of kernel stack
                              // 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
};
```


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 20.04 w/ kernel version 5.11, **LOC: 657 – 1394**
    - Ubuntu 20.04 w/ kernel version 4.4, **LOC: 1391 – 1852**

STRUCT TASK_STRUCT PROCESS CONTROL BLOCK

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



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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 5.11)
- **Process ID**
- `pid_t pid;` LOC #857
- **Process State**
- `/* -1 unrunnable, 0 runnable, >0 stopped: */`
- `volatile long state;` LOC #666
- **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 #710
  - `unsigned int time_slice;` LOC #503

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STRUCT TASK_STRUCT - 2

- **Address space of the process:**
- "mm" is short for "memory map"
- `struct mm_struct *mm;` LOC #779

- **Parent process**, that launched this one
- `struct task_struct __rcu *parent;` LOC #874

- **Child processes** (as a list)
- `struct list_head children;` LOC #879

- **Open files**
- `struct files_struct *files;` LOC #981

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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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QUESTIONS

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