TCSS 422: OPERATING SYSTEMS

Operating Systems – Three Easy Pieces & Processes

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School of Engineering and Technology, University of Washington - Tacoma

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OBJECTIVES – 10/5

- Questions from 9/30
- C Review Survey
- 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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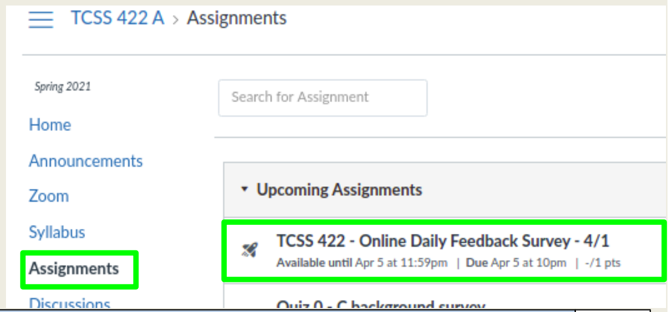
ONLINE DAILY FEEDBACK SURVEY

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



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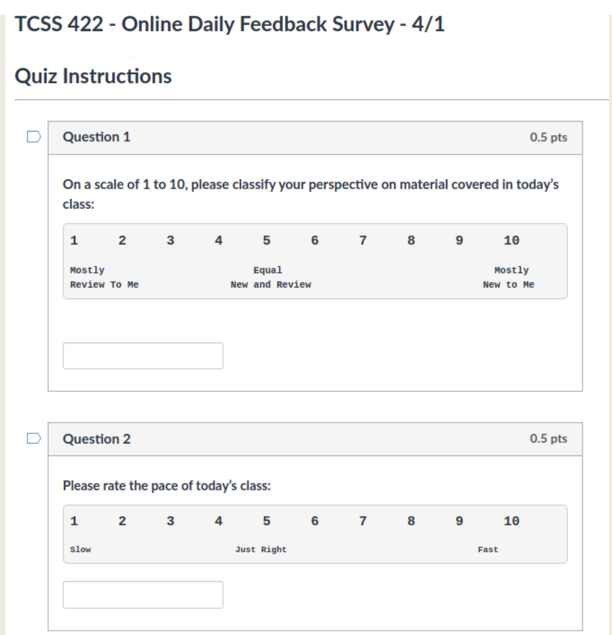

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (28 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 5.64 (*spring 2021, 5.59*)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.38 (*spring 2021, 5.33*)**

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FEEDBACK

- ***How does virtualization work?***
  - Two types of virtualization:
  - **Virtualization (1)**: as in abstraction to hide low-level details and restrict access through interface(s) provided by the operating system
  - **Virtualization (2)**: as it virtual machine technology which emulates a computer using a software program known as a hypervisor
    - Oracle Virtual Box is a software hypervisor for running virtual machines (VMs)
  - In this course, we are primarily focused on the first type

- ***How the CPU transitions from one program to another?***
  - This is known as a "**context switch**"
  - This generally requires swapping out program state data with another programming and transferring control to the other program
  - We will discuss further..

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FEEDBACK - 2

- ***I don't understand the point of virtual addresses and why the OS translates virtual addresses into physical addresses***
  - There are several motivations for virtualizing access to memory
  - **Security:** another user or program should never obtain a physical address to your program's data. If they have a pointer to this memory, then they could read and change it
  - **Flexibility:** because all addresses are virtual, the operating system can physically change the location of your data or entire program in memory without any issues. Your program only works with virtual addresses. Things can change behind the scenes without your program knowing. This allows the OS to swap program out of memory, rearrange memory, or do what ever is needed to keep things running efficiently.

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FEEDBACK - 3

- ***Ubuntu is really slow, I had to download it for a prior class and it made programming in C almost impossible, is there anything else I can do?***

- Natively, Ubuntu is often faster, requiring less memory and disk space than MS Windows
- If Virtual Box VM is running slow, consider increasing configured resources (CPU cores, memory)
- Consider upgrading laptop memory
  - Investigate if laptop is upgradable
  - Investigate proper type of memory
  - For example, upgrading from 12MB to 32MB was $129 Aug 2021 *(now $114)* for HP Pavilion laptop and only took a few minutes using small screwdriver
  - Youtube videos may be available describing how to perform upgrades
- As instructor for further help

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C REVIEW SURVEY

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STUDENT BACKGROUND SURVEY

- Please complete the Student Background Survey
- **https://forms.gle/BuJwXPwZpqf6cnTQ9**

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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/V2sg4iW1awvhFx4W8**
- **Will close Thursday 10/7…**
- **VM requests will be sent to Stephen Rondeau for set up**

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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

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

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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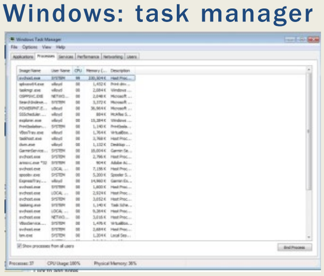
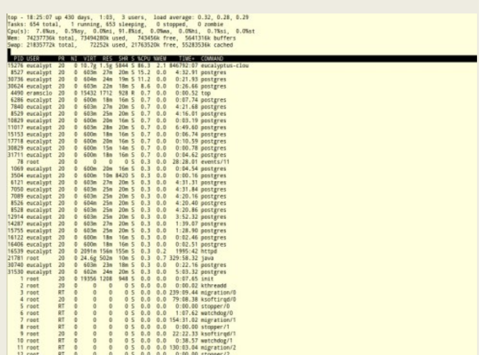
VIRTUALIZING THE CPU

- 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





VIRTUALIZING THE CPU - 2

- Simple Looping C Program

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/time.h>
#include <assert.h>
#include "common.h"

int
main(int argc, char *argv[])
{
        if (argc != 2) {
                fprintf(stderr, "usage: cpu <string>\n");
                exit(1);
        }
        char *str = argv[1];
        while (1) {
                Spin(1); // Repeatedly checks the time and
                returns once it has run for a second
                printf("%s\n", str);
        }
        return 0;
}
```


VIRTUALIZING THE CPU - 3

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

VIRTUALIZING MEMORY - 2

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

```
#include <unistd.h>
#include <stdio.h>
#include <stdlib.h>
#include "common.h"

int
main(int argc, char *argv[])
{
        int *p = malloc(sizeof(int));  // a1: allocate some
                                          memory
        assert(p != NULL);
        printf("(%d) address of p: %08x\n",
                getpid(), (unsigned) p);  // a2: print out the
                                          address of the memmory
        *p = 0;  // a3: put zero into the first slot of the memory
        while (1) {
                Spin(1);
                *p = *p + 1;
                printf("(%d) p: %d\n", getpid(), *p); // a4
        }
        return 0;
}
```


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**

This example no longer works as advertised !

Ubuntu has been updated.

The ptr location is no longer identical. This was 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
...
```

- IN THE BOOK: (int*)p appears to have the same memory location 00200000
- 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

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PERSISTENCE

- DRAM: Dynamic Random Access Memory: DIMMs/SIMMs
  - Stores data while power is present
  - When power is lost, data is lost (*volatile*)
- 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

PERSISTENCE - 2

```
#include <stdio.h>
#include <unistd.h>
#include <assert.h>
#include <fcntl.h>
#include <sys/types.h>

int
main(int argc, char *argv[])
{
        int fd = open("/tmp/file", O_WRONLY | O_CREAT
                       | O_TRUNC, S_IRWXU);
        assert(fd > -1);
        int rc = write(fd, "hello world\n", 13);
        assert(rc == 13);
        close(fd);
        return 0;
}
```

- 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"`

PERSISTENCE - 3

- To write to disk, OS must:
  - Determine where on disk data should reside
  - Perform sys calls to perform I/O:
    - Read/write to file system (*inode record*)
    - Read/write data to file
- OS provides fault tolerance for system crashes
  - 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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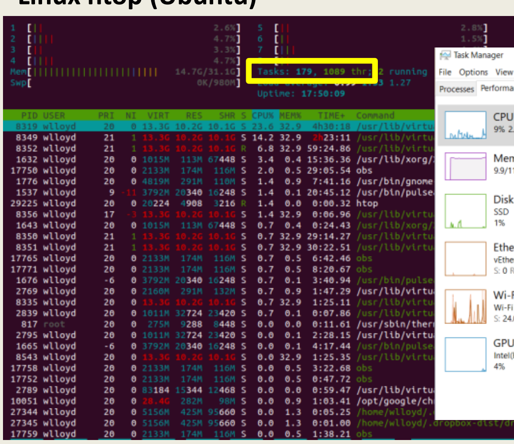
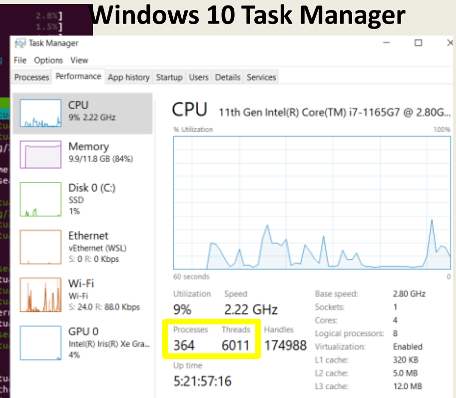
CONCURRENCY

Linux htop (Ubuntu)



Windows 10 Task Manager



CONCURRENCY

- Linux: 179 processes, 1089 threads (**htop**)
- Windows 10: 364 processes, 6011 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?***

CONCURRENCY - 2

```
#include <stdio.h>
#include <stdlib.h>
#include "common.h"

volatile int counter = 0;
int loops;

void *worker(void *arg) {
        int i;
        for (i = 0; i < loops; i++) {
                counter++;
        }
        return NULL;
}
...
```

pthread.c

Listing continues …

CONCURRENCY - 2

```
#include <stdio.h>
#include <stdlib.h>
#include "common.h"

volatile int counter = 0;
int loops;

void
...
}
...
```

Not the same as Java volatile:
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 …

CONCURRENCY - 3

pthread.c

```
int
main(int argc, char *argv[])
{
        if (argc != 2) {
                fprintf(stderr, "usage: threads <value>\n");
                exit(1);
        }
        loops = atoi(argv[1]);
        pthread_t p1, p2;
        printf("Initial value : %d\n", counter);

        Pthread_create(&p1, NULL, worker, NULL);
        Pthread_create(&p2, NULL, worker, NULL);
        Pthread_join(p1, NULL);
        Pthread_join(p2, NULL);
        printf("Final value : %d\n", counter);
        return 0;
}
```

- 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.
```

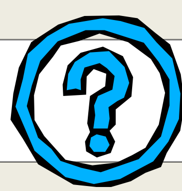

CONCURRENCY - 4

- 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 ???
```



CONCURRENCY - 5

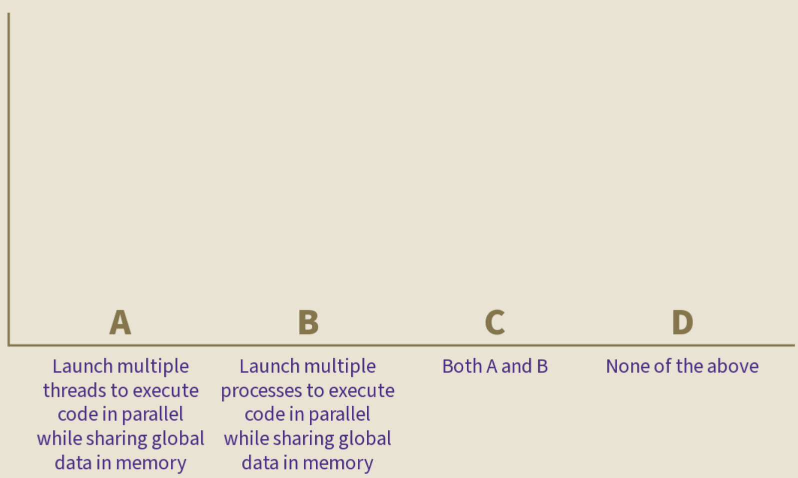
- When loop value is large why do we not achieve 200,000 ?

- 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*

To perform parallel work, a single process may:



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

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

WE WILL RETURN AT 2:40PM

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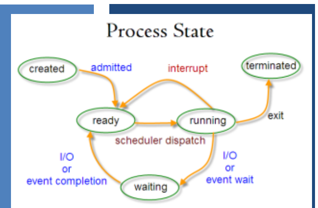

CHAPTER 4: PROCESSES

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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

PROCESS API

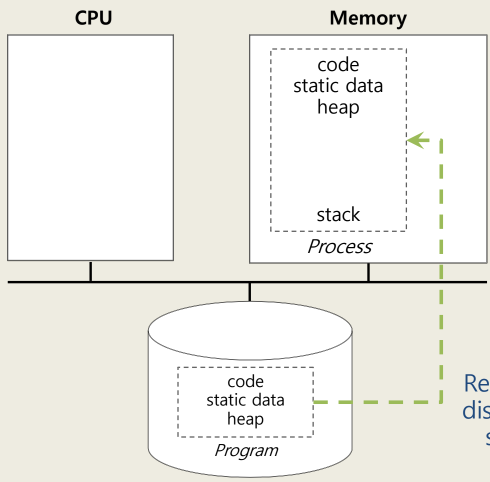
- Modern OSes provide a Process API for process support
- Create
  - Create a new process
- Destroy
  - Terminate a process (ctrl-c)
- Wait
  - Wait for a process to complete/stop
- Miscellaneous Control
  - Suspend process (ctrl-z)
  - Resume process (fg, bg)
- Status
  - Obtain process statistics: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

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)

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



Loading:
Reads program from disk into the address space of process

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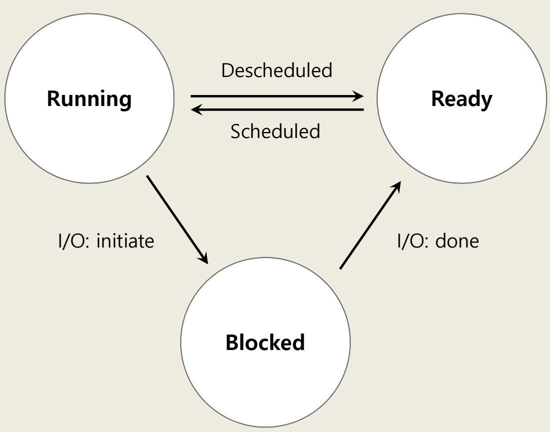
PROCESS STATES

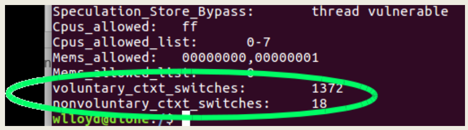
- **RUNNING**
  - Currently executing instructions
- **READY**
  - Process is ready to run, but has been preempted
  - CPU is presently allocated for other tasks
- **BLOCKED**
  - Process is **not** ready to run. It is waiting for another event to complete:
    - Process has already been initialized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

PROCESS STATE TRANSITIONS



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



- 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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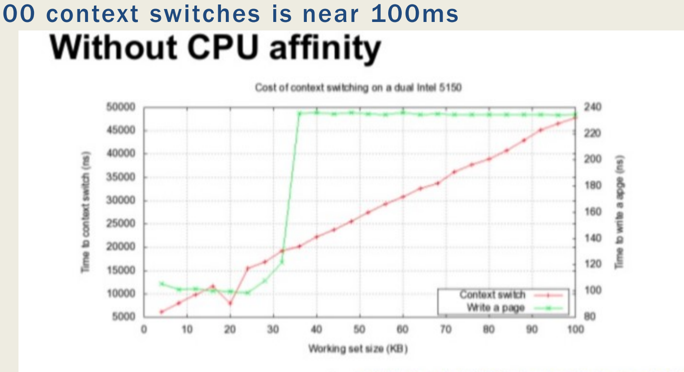
CONTEXT SWITCH

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



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

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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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OBJECTIVES – 10/5

- Questions from 9/30
- C Review Survey
- 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 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

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 };
```

XV6 KERNEL DATA STRUCTURES - 2

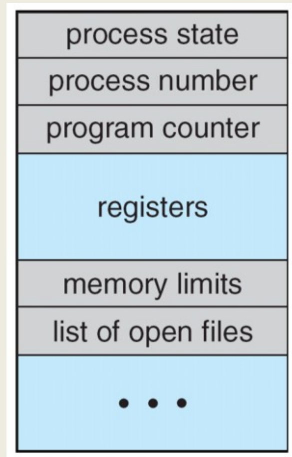
```
// the information xv6 tracks about each process
// including its register context and state
struct proc {
    char *mem;                  // Start of process memory
    uint sz;                    // Size of process memory
    char *kstack;               // Bottom of kernel stack
              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



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

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

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

QUESTIONS

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