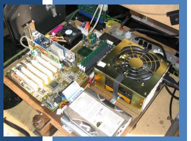
TCSS 422: OPERATING SYSTEMS



Three Easy Pieces
Process API,
Limited Direct Execution,
Scheduling Introduction

Wes J. Lloyd
Institute of Technology
University of Washington - Tacoma

OBJECTIVES

- Assignment 0 – Introduction to Linux
- Active Reading Quiz – Chapter 7
- Feedback from 3/28

- Processes – Ch. 4
- C Linux Process API – Ch. 5
- Limited Direct Execution – Ch. 6
  - Virtualizing the CPU
- Introduction to Scheduling – Ch. 7
- Multi-level Feedback Queue Scheduler – Ch. 8

VIRTUAL MACHINE SURVEY

- Please complete the Virtual Machine Survey is wanting an Institute of Technology hosted Ubuntu 16.04 VM

- https://goo.gl/forms/w9VWqkX756yXBUBt1

- Submitting results today…

SELECTED FEEDBACK FROM 3/28

- What is context switching?
- Most bash scripts I have seen begin with #!/bin/bash
  - You did not include this in your sample, yet it still worked.
  - Why did it work? and/or why is this usually included if it is not needed?
- What is fork used for? Such as in real-world applications?
- What is CPU virtualization?

FEEDBACK - 2

- How do you schedule processes manualy?
  - Check out the “nice” command

  - Does this command, schedule processes?

  - Why? Why not?

- What’s an example of a process state that’s blocked?

CHAPTER 5: C PROCESS API

API

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

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

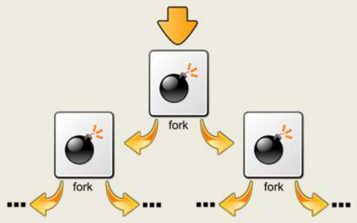
```
prompt> ./p1
hello world (pid:29146)
hello, I am parent of 29147 (pid:29146)
hello, I am child (pid:29147)
prompt>
```

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

:(){ :|: & };:



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

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;
}
```

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>
```

FORK EXAMPLE

- Linux example

exec()

- Supports running an external program
- 6 types: execl(), execlp(), execle(), execv(), execvp(), execvpe()

- execl(), execlp(), execle(): const char *arg

  List of pointers (terminated by null pointer)
  to strings provided as arguments… (arg0, arg1, .. argn)

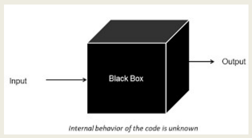
- Execv(), execvp(), execvpe()
  Array of pointers to strings as arguments

  Strings are null-terminated
  First argument is name of file being executed

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… ☺



EXEC EXAMPLE

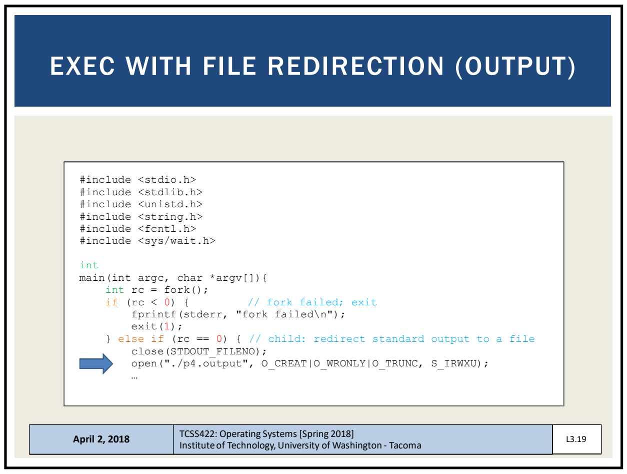
```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <string.h>
#include <sys/wait.h>

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
        …
```

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>
```

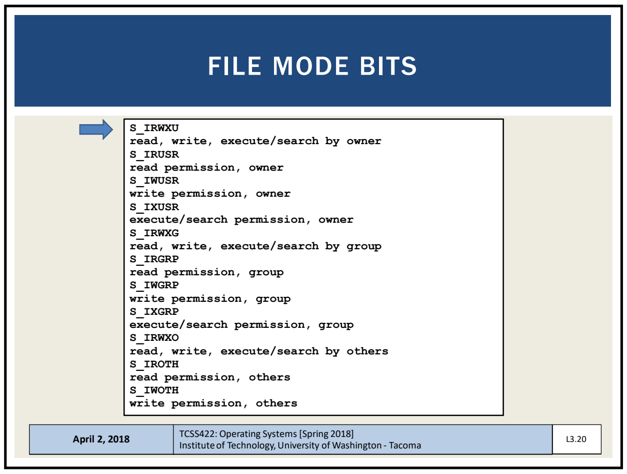


EXEC WITH FILE REDIRECTION (OUTPUT)

```
#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);
        …
```

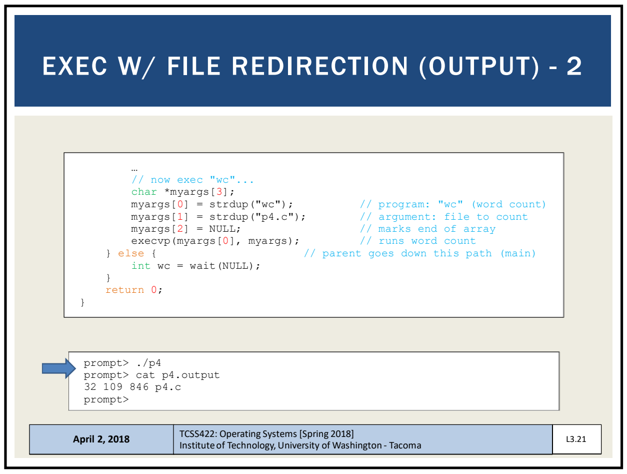
April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.19



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
```

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.20

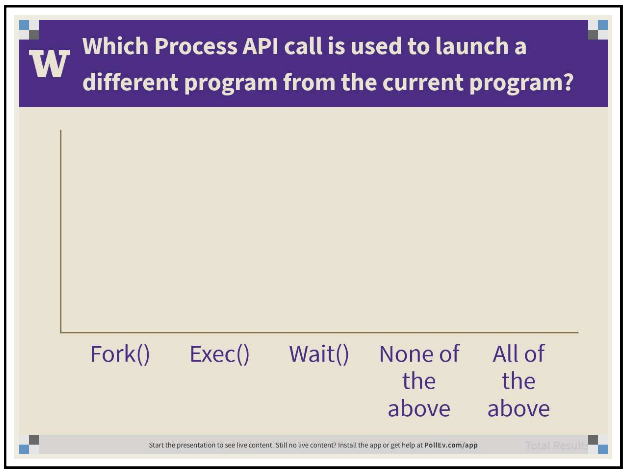


EXEC W/ FILE REDIRECTION (OUTPUT) - 2

```
        …
        // 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;
}
```

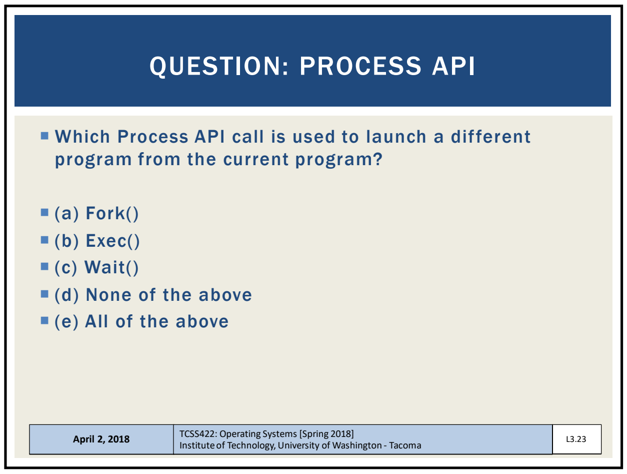
```
prompt> ./p4
prompt> cat p4.output
32 109 846 p4.c
prompt>
```

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.21



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

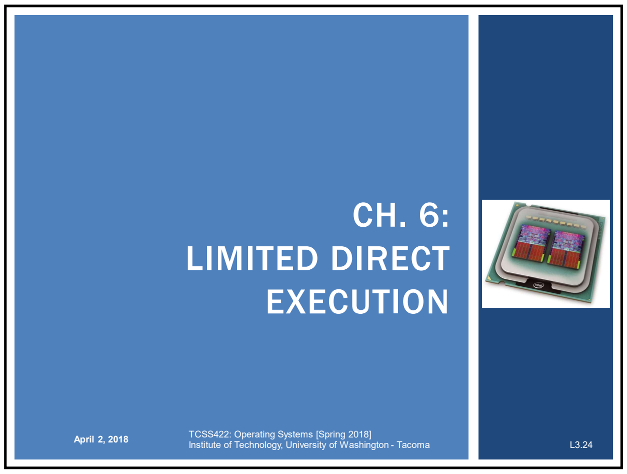
Start the presentation to see live content. Still no live content? Install the app or get help at PollEv.com/app



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

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.23

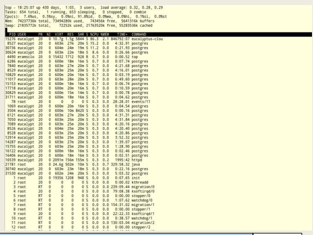


CH. 6: LIMITED DIRECT EXECUTION

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.24

VIRTUALIZING THE CPU

- How does the CPU support running so many jobs simultaneously?
- **Time Sharing**
- Tradeoffs:
  - Performance
    - Excessive overhead
  - Control
    - Fairness
    - Security
- Both HW and OS support is used



COMPUTER BOOT SEQUENCE: OS WITH DIRECT EXECUTION

- What if programs could directly control the CPU / system?

OS	Program
1. Create entry for process list 2. Allocate memory for program 3. Load program into memory 4. Set up stack with `argc` / `argv` 5. Clear registers 6. Execute call `main()`	 7. Run `main()` 8. Execute `return` from `main()`
9. Free memory of process 10. Remove from process list	

COMPUTER BOOT SEQUENCE: OS WITH DIRECT EXECUTION

- What if programs could directly control the CPU / system?

OS	Program
1. Create entry for process list 2. Allocate memory for	
`argv` 5. Clear registers 6. Execute call `main()`	7. Run `main()` 8. Execute `return` from `main()`
9. Free memory of process 10. Remove from process list	

Without *limits* on running programs, the OS wouldn't be in control of anything and would "just be a library"

DIRECT EXECUTION - 2

- **With direct execution:**

  How does the OS stop a program from running, and switch to another to support **time sharing**?

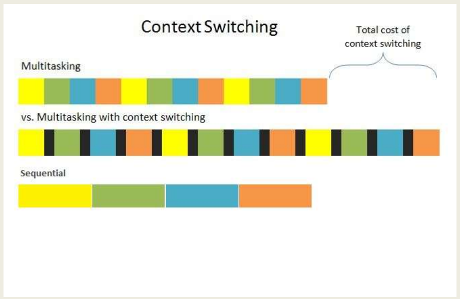
  How do programs share disks and perform I/O if they are given direct control? Do they know about each other?

  With direct execution, how can dynamic memory structures such as linked lists grow over time?

CONTROL TRADEOFF

- **Too little control:**
  - No security
  - No time sharing
- **Too much control:**
  - Too much OS overhead
  - Poor performance for compute & I/O
  - Complex APIs (system calls), difficult to use

CONTEXT SWITCHING OVERHEAD


Context Switching
Total cost of context switching
Multitasking
vs. Multitasking with context switching
Sequential

LIMITED DIRECT EXECUTION

- OS implements LDE to support time/resource sharing
- Limited direct execution means "only limited" processes can execute DIRECTLY on the CPU in ***trusted*** mode
- TRUSTED means the process is trusted, and it can do anything… (e.g. it is a system / kernel level process)
- Enabled by ***protected (safe) control transfer***
- CPU supported context switch
- Provides data isolation

CPU MODES

- Utilize CPU Privilege Rings (Intel x86)
  - rings 0 (kernel), 1 (VM kernel), 2 (unused), 3 (user)

  access ⟵ no access
- **User mode**:
  Application is running, but w/o direct I/O access
- **Kernel mode**:
  OS kernel is running performing restricted operations

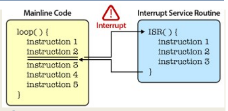
CPU MODES

- **User mode: ring 3 - untrusted**
  - Some instructions and registers are disabled by the CPU
  - Exception registers
  - HALT instruction
  - MMU instructions
  - OS memory access
  - I/O device access
- **Kernel mode: ring 0 – trusted**
  - All instructions and registers enabled

SYSTEM CALLS

- Implement restricted "OS" operations
- Kernel exposes key functions through an API:
  - Device I/O (e.g. file I/O)
  - Task swapping: context switching between processes
  - Memory management/allocation: malloc()
  - Creating/destroying processes

TRAPS: SYSTEM CALLS, EXCEPTIONS, INTERRUPTS



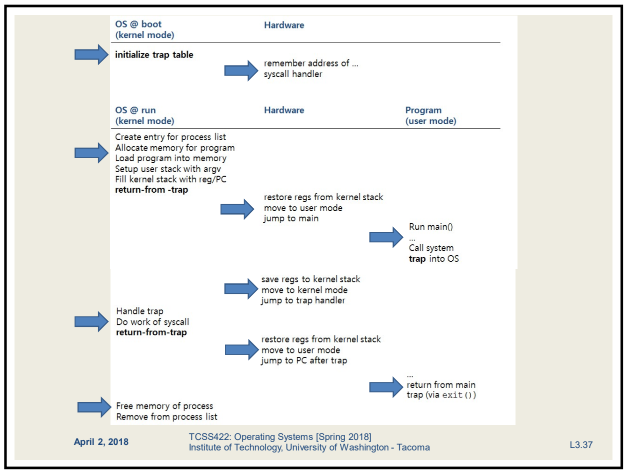
```
loop( ) {
    instruction 1
    instruction 2
    instruction 3
    instruction 4
    instruction 5
}
```

```
ISR( ) {
    instruction 1
    instruction 2
    instruction 3
}
```

- Trap: any transfer to kernel mode
- Three kinds of traps
  - **System call:** (planned) user → kernel
    - SYSCALL for I/O, etc.
  - **Exception:** (error) user → kernel
    - Div by zero, page fault, page protection error
  - **Interrupt:** (event) user → kernel
    - Non-maskable vs. maskable
    - Keyboard event, network packet arrival, timer ticks
    - Memory parity error (ECC), hard drive failure

EXCEPTION TYPES

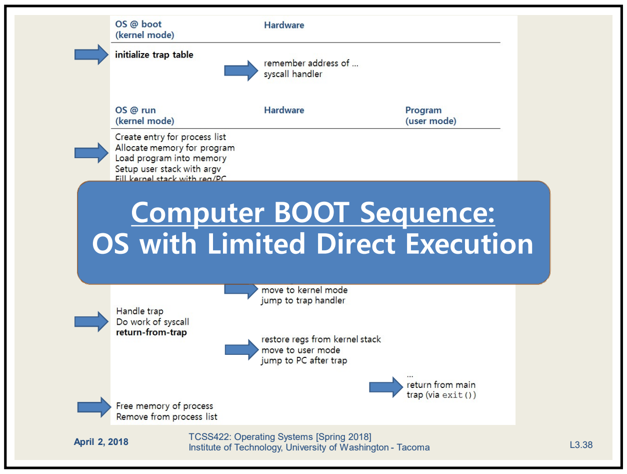
Exception type	Synchronous vs. asynchronous	User request vs. coerced	User maskable vs. nonmaskable	Within vs. between instructions	Resume vs. terminate
I/O device request	Asynchronous	Coerced	Nonmaskable	Between	Resume
Invoke operating system	Synchronous	User request	Nonmaskable	Between	Resume
Tracing instruction execution	Synchronous	User request	User maskable	Between	Resume
Breakpoint	Synchronous	User request	User maskable	Between	Resume
Integer arithmetic overflow	Synchronous	Coerced	User maskable	Within	Resume
Floating-point arithmetic overflow or underflow	Synchronous	Coerced	User maskable	Within	Resume
Page fault	Synchronous	Coerced	Nonmaskable	Within	Resume
Misaligned memory accesses	Synchronous	Coerced	User maskable	Within	Resume
Memory protection violation	Synchronous	Coerced	Nonmaskable	Within	Resume
Using undefined instruction	Synchronous	Coerced	Nonmaskable	Within	Terminate
Hardware malfunction	Asynchronous	Coerced	Nonmaskable	Within	Terminate
Power failure	Asynchronous	Coerced	Nonmaskable	Within	Terminate



OS @ boot (kernel mode)	Hardware	
initialize trap table		
	remember address of … syscall handler	

OS @ run (kernel mode)	Hardware	Program (user mode)
Create entry for process list Allocate memory for program Load program into memory Setup user stack with argv Fill kernel stack with reg/PC **return-from -trap**		
	restore regs from kernel stack move to user mode jump to main	
		Run main() … Call system **trap** into OS
	save regs to kernel stack move to kernel mode jump to trap handler	
Handle trap Do work of syscall **return-from-trap**		
	restore regs from kernel stack move to user mode jump to PC after trap	
		… return from main trap (via `exit()`)
Free memory of process Remove from process list		

April 2, 2018 TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma L3.37

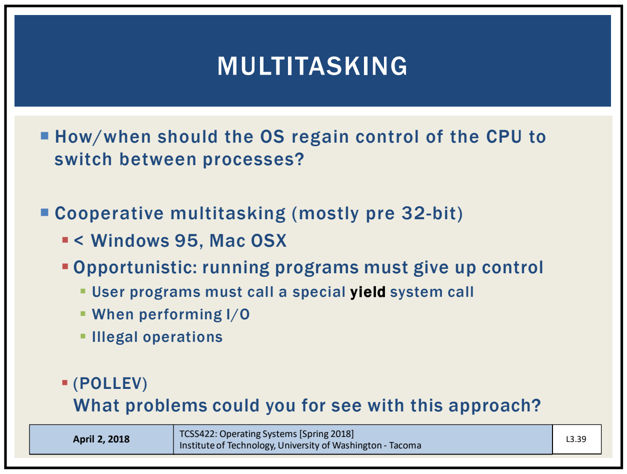


OS @ boot (kernel mode)	Hardware	
initialize trap table		
	remember address of … syscall handler	

OS @ run (kernel mode)	Hardware	Program (user mode)
Create entry for process list Allocate memory for program Load program into memory Setup user stack with argv Fill kernel stack with reg/PC		
	move to kernel mode jump to trap handler	
Handle trap Do work of syscall **return-from-trap**		
	restore regs from kernel stack move to user mode jump to PC after trap	
		… return from main trap (via `exit()`)
Free memory of process Remove from process list		

Computer BOOT Sequence:
OS with Limited Direct Execution

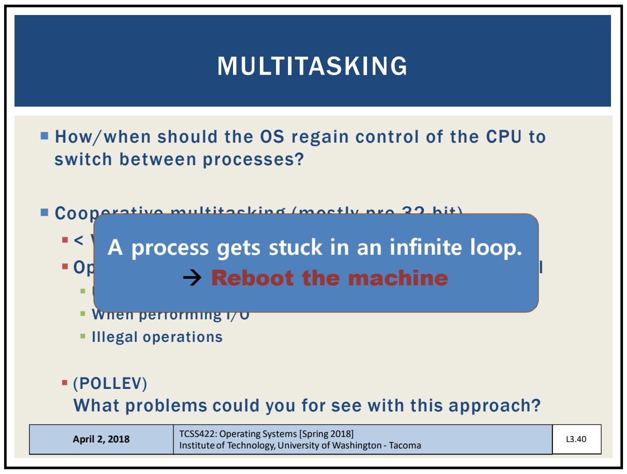
April 2, 2018 TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma L3.38



MULTITASKING

- How/when should the OS regain control of the CPU to switch between processes?
- Cooperative multitasking (mostly pre 32-bit)
  - < Windows 95, Mac OSX
  - Opportunistic: running programs must give up control
    - User programs must call a special **yield** system call
    - When performing I/O
    - Illegal operations
  - (POLLEV)
    What problems could you for see with this approach?

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.39

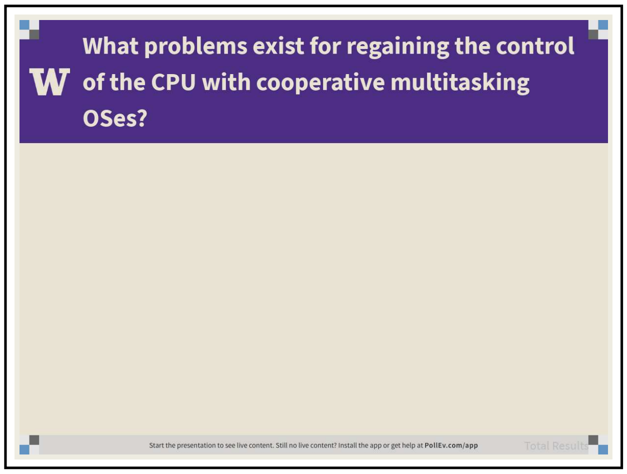


MULTITASKING

- How/when should the OS regain control of the CPU to switch between processes?
- Cooperative multitasking (mostly pre 32-bit)
  - < W
  - Op
    - When performing I/O
    - Illegal operations
  - (POLLEV)
    What problems could you for see with this approach?

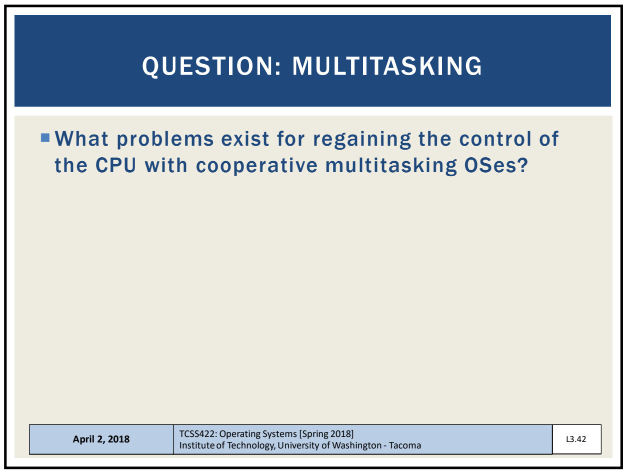
A process gets stuck in an infinite loop.
→ **Reboot the machine**

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.40



W What problems exist for regaining the control of the CPU with cooperative multitasking OSes?

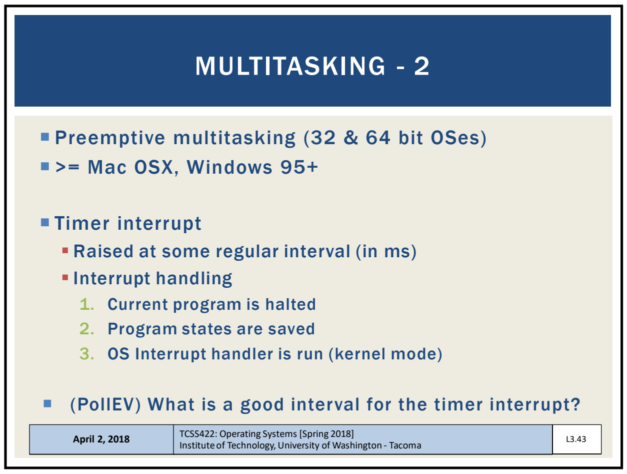
Start the presentation to see live content. Still no live content? Install the app or get help at PollEv.com/app Total Results



QUESTION: MULTITASKING

- What problems exist for regaining the control of the CPU with cooperative multitasking OSes?

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.42



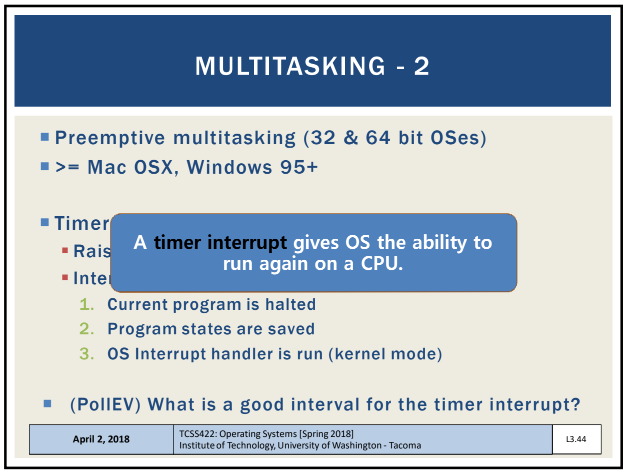
MULTITASKING - 2

- Preemptive multitasking (32 & 64 bit OSes)
- >= Mac OSX, Windows 95+

- Timer interrupt
  - Raised at some regular interval (in ms)
  - Interrupt handling
    1. Current program is halted
    2. Program states are saved
    3. OS Interrupt handler is run (kernel mode)

- (PollEV) What is a good interval for the timer interrupt?

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.43



MULTITASKING - 2

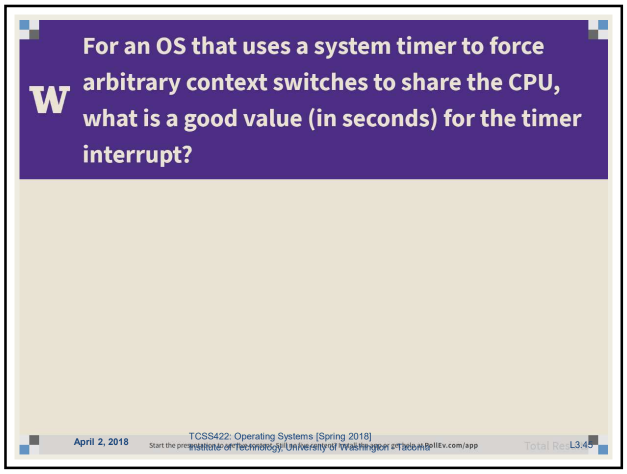
- Preemptive multitasking (32 & 64 bit OSes)
- >= Mac OSX, Windows 95+

- Timer
  - Rais
  - Inte
    1. Current program is halted
    2. Program states are saved
    3. OS Interrupt handler is run (kernel mode)

A **timer interrupt** gives OS the ability to run again on a CPU.

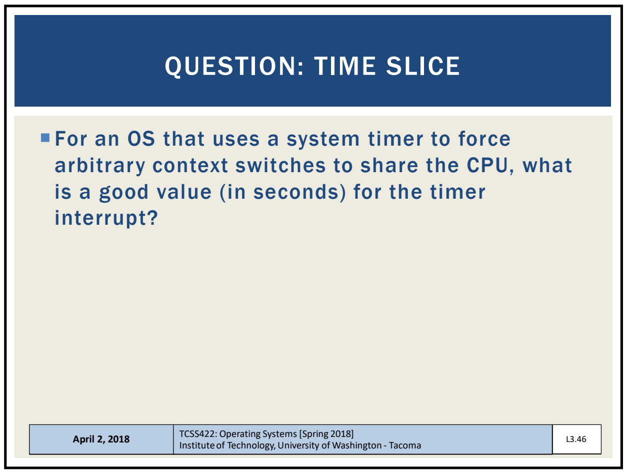
- (PollEV) What is a good interval for the timer interrupt?

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.44



W For an OS that uses a system timer to force arbitrary context switches to share the CPU, what is a good value (in seconds) for the timer interrupt?

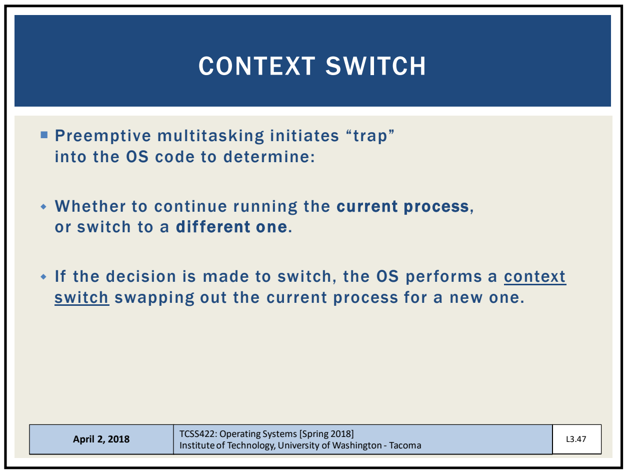
April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | Start the presentation to see live content. Still no live content? Install the app or get help at PollEv.com/app | Total Results | L3.45



QUESTION: TIME SLICE

- For an OS that uses a system timer to force arbitrary context switches to share the CPU, what is a good value (in seconds) for the timer interrupt?

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.46



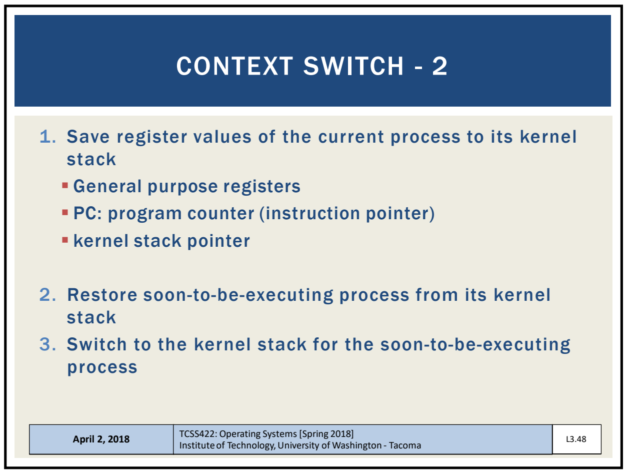
CONTEXT SWITCH

- Preemptive multitasking initiates "trap" into the OS code to determine:

- Whether to continue running the **current process**, or switch to a **different one**.

- If the decision is made to switch, the OS performs a context switch swapping out the current process for a new one.

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.47

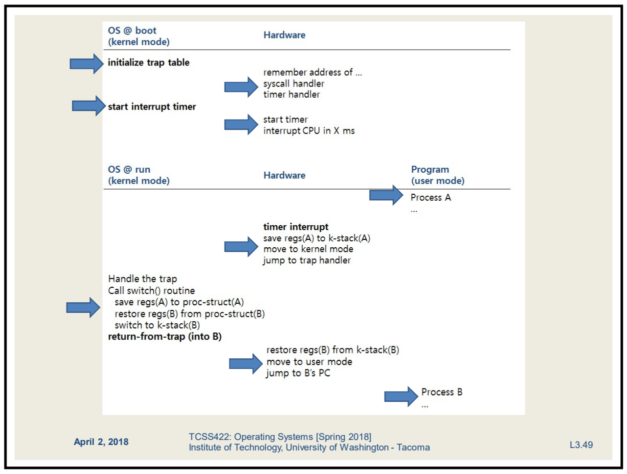


CONTEXT SWITCH - 2

1. Save register values of the current process to its kernel stack
   - General purpose registers
   - PC: program counter (instruction pointer)
   - kernel stack pointer

2. Restore soon-to-be-executing process from its kernel stack
3. Switch to the kernel stack for the soon-to-be-executing process

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.48



OS @ boot (kernel mode) | Hardware

initialize trap table

remember address of …
syscall handler
timer handler

start interrupt timer

start timer
interrupt CPU in X ms

OS @ run (kernel mode) | Hardware | Program (user mode)

Process A
…

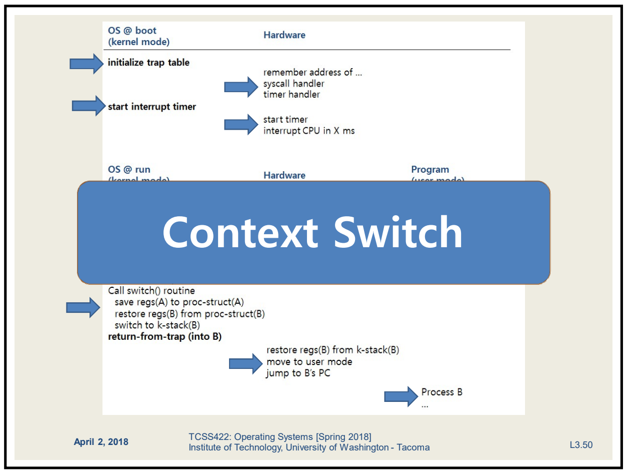
timer interrupt
save regs(A) to k-stack(A)
move to kernel mode
jump to trap handler

Handle the trap
Call switch() routine
  save regs(A) to proc-struct(A)
  restore regs(B) from proc-struct(B)
  switch to k-stack(B)
return-from-trap (into B)

restore regs(B) from k-stack(B)
move to user mode
jump to B's PC

Process B
…

April 2, 2018 TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma L3.49



Context Switch

OS @ boot (kernel mode) | Hardware

initialize trap table

remember address of …
syscall handler
timer handler

start interrupt timer

start timer
interrupt CPU in X ms

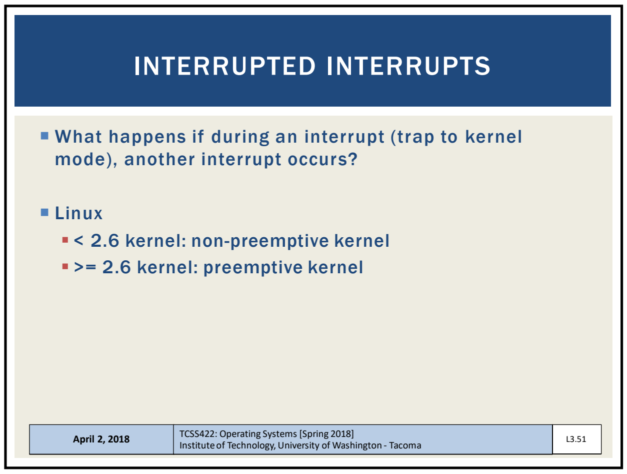
OS @ run | Hardware | Program

Call switch() routine
  save regs(A) to proc-struct(A)
  restore regs(B) from proc-struct(B)
  switch to k-stack(B)
return-from-trap (into B)

restore regs(B) from k-stack(B)
move to user mode
jump to B's PC

Process B
…

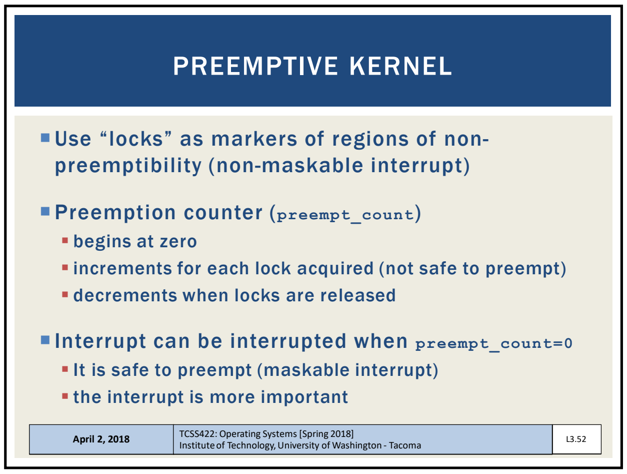
April 2, 2018 TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma L3.50



INTERRUPTED INTERRUPTS

- What happens if during an interrupt (trap to kernel mode), another interrupt occurs?
- Linux
  - < 2.6 kernel: non-preemptive kernel
  - >= 2.6 kernel: preemptive kernel

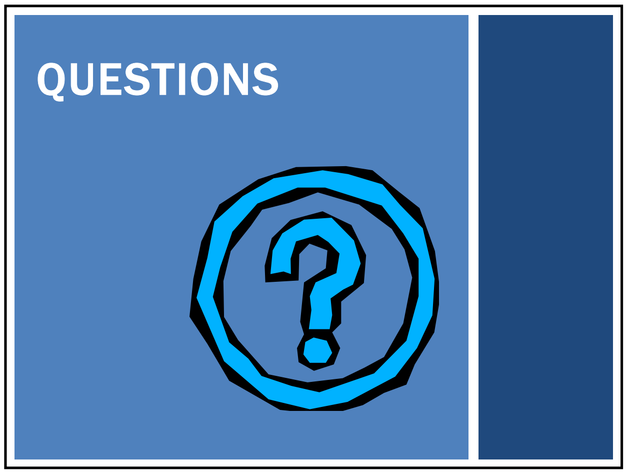
April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.51



PREEMPTIVE KERNEL

- Use "locks" as markers of regions of non-preemptibility (non-maskable interrupt)
- Preemption counter (`preempt_count`)
  - begins at zero
  - increments for each lock acquired (not safe to preempt)
  - decrements when locks are released
- Interrupt can be interrupted when `preempt_count=0`
  - It is safe to preempt (maskable interrupt)
  - the interrupt is more important

April 2, 2018 | TCSS422: Operating Systems [Spring 2018] Institute of Technology, University of Washington - Tacoma | L3.52



QUESTIONS