# Threads and Concurrency

**key concepts:** threads, concurrent execution, timesharing, context switch, interrupts, preemption

Zille Huma Kamal

David R. Cheriton School of Computer Science
University of Waterloo

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# What is a thread?

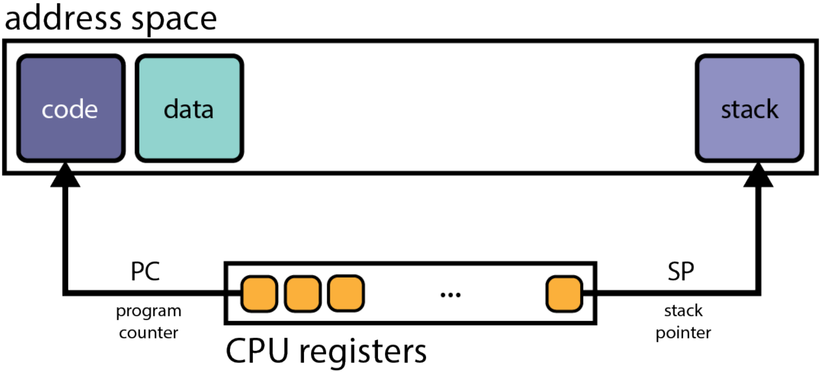
**... a sequence of instructions.**

- A normal **sequential program** consists of a single thread of execution.
- Threads provide a way for programmers to express **concurrency** in a program.
- In threaded concurrent programs there are multiple threads of execution, all occuring at the same time.
  - Threads may perform the same task.
  - Threads may perform different tasks.

Recall: Concurrency

... multiple programs or sequences of instructions running, or appearing to run, at the same time.
On a multicore system, concurrency $\implies$ parallelism
On a single core system, thread execution is interleaved, **appearing** to be executing at the same time.

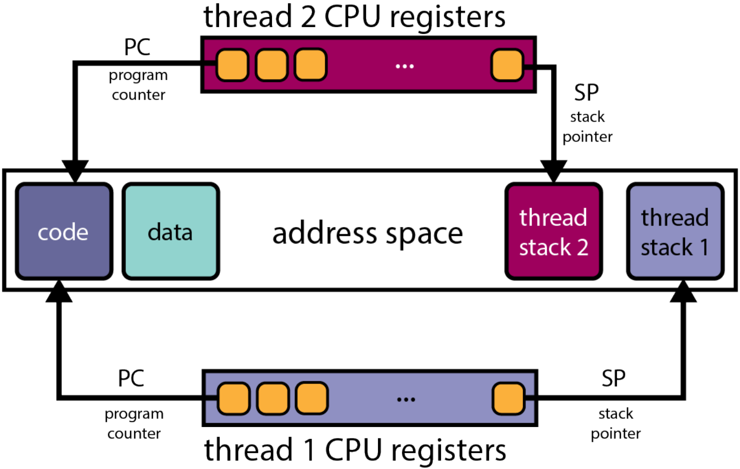
# Review: Sequential Program Execution



**The Fetch/Execute Cycle**

1. **fetch** instruction PC points to
2. decode and **execute** instruction
3. increment the PC

# Concurrent Program Execution (Two Threads)



Conceptually, each thread executes sequentially using its private register contents and stack.

# Why Threads?

1. **Resource Utilization:** blocked/waiting threads give up resources, i.e., the CPU, to others.
2. **Parallelism:** multiple threads executing simultaneously; improves performance.
3. **Responsiveness:** dedicate threads to UI, others to loading/long tasks.

### Blocking

Threads may **block**, ceasing execution for a period of time, or, until some condition has been met. When a thread blocks, it is not executing instructions—the CPU is idle. Concurrency lets the CPU execute a different thread during this time. **CPU time is money!**

# Implementing Concurrent Threads

What options exist?

1. **Hardware support.** $P$ processors, $C$ cores, $M$ multithreading per core $\Rightarrow$ $PCM$ threads can execute **simultaneously**.
2. **Timesharing.** Multiple threads take turns on the same hardware; rapidly switching between threads so all make progress.
3. **Hardware support + Timesharing.** $PCM$ threads running simultaneously with timesharing.

Example: Intel i9-9900X

… 10 cores, each core can run 2 threads (multithreading degree). Therefore, $P = 1$, $C = 10$, and $M = 2$, so $PCM = 20$ threads can run simultaneously.
Note that while cores of a single processor share caches (L2, L3), threads execute separately.

# How should we implement threads?

We can implement threads in the kernel through system calls, just like we create processes.
Limitations:

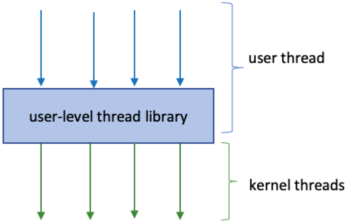
- latency for syscall is 100s of cycles w.r.t to function call, which is a few cycles
- memory requirements are similar to heavier weight processes

Alternatively, implement user-level threads in user-level library.
One kernel thread per process.
Limitations:

- cannot take advantage of multiple cores

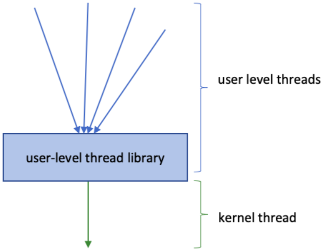
Consider the **n:m** threading model, where we have `n` user threads and `m` kernel threads

# One is to One threading



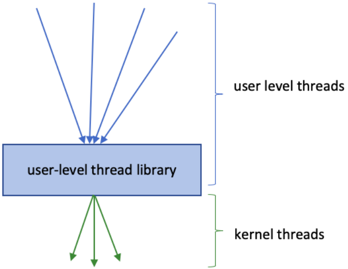
- **1:1** threading, for each user thread, create a kernel thread
- higher degree of concurrency than n:1
- higher degree of parellism, on a multiprocessor system
- System Contention Scope (SCS) - kernel threads compete for CPU
- used by Linux and Windows
- limitation: thread creation and management overhead

# Many is to One threading



- **n** $>$ **m and m = 1** many is to one
- n user level threads, only m=1 kernel level thread
- blocking system call by a thread, blocks entire process
- Green threads - thread API for Solaris and early Java
- Process Content Scope - threads in the process compete for scheduling
- limitation: cannot leverage parallelism of multicore systems

# n is to m threading



- **n $>$ m and m $>$ 1**
- for n user threads there are m kernel threads
- most flexible and complicated
- PCS and SCS
- limiting kernel threads not an issue in today's increasingly higher number of processing cores on a system
- a variation is the **2-level model** on Solaris 2.2 to 8, introduced light weight process (LWP)

# User level Thread Library: POSIX pthread API

- `int pthread_create (pthread_t *thread_t,`
  `pthread_attr_t *attr,`
  `void *(*fn)(void *),`
  `void *arg);`
    - Create a new thread identified by `thread_t` with optional attributes `attr` within the calling process
    - `attr` includes attributes such as stack size, scheduling priority, etc.
    - `thread_t` is created to start executing function `fn` with argument `arg`
- `void pthread_exit(void *return_value);`
    - Destroy the calling thread and makes `return_value` available for any successful `pthread_join`
- `int pthread_join(pthread_t thread_t, void **return_value);`
    - Wait for thread `thread_t` to exit and retrieve the return value
- `void pthread_yield();`
    - calling thread voluntarily releases CPU
- Plus lots of support for synchronization

# Other User level thread libraries

- **OpenMP** a cross-platform library, simple multi-processing and thread API
- **GPGPU Programming** general-purpose GPU programming APIs, e.g. nVidia's CUDA, create/run threads on GPU instead of CPU
- **Go routines in Golang**
  - light-weight,running 100k go routines is practical
  - on top of kernel threads (n:m threading model)
  - Multi-core scalability and efficient user-level threads

**Concurrency and Threads**

- originated in 1950s to improve CPU utilization during I/O operations
- "modern" timesharing originated in the 1960s

# OS/161 Threaded Concurrency Examples

Key ideas from the examples:

- A thread can create new threads using `thread_fork`
- New theads start execution in a function specified as a parameter to `thread_fork`
- The original thread (which called `thread_fork`) and the new thread (which is created by the call to `thread_fork`) proceed concurrently, as two simultaneous sequential threads of execution.
- All threads **share** access to the program's memory
  - code
  - data: global variables
  - heap
  - open file descriptors
- Each thread's stack frames are **private** to that thread; each thread has its own stack.

**In the OS**

A thread is represented as a structure or object, known as Thread Control Block (TCB).

# OS/161's Thread Interface

- create a new thread:

```
int thread_fork(
 const char *name,          // name of new thread
 struct proc *proc,         // thread's process
 void (*func)               // new thread's function
  (void *, unsigned long),
 void *data1,               // function's first param
 unsigned long data2        // function's second param
);
```

- terminate the calling thread:

```
void thread_exit(void);
```

- volutarily yield execution:

```
void thread_yield(void);
```

- **join** a common thread function to force one thread to block until another finishes; **NOT** offered by OS/161

See `kern/include/thread.h`

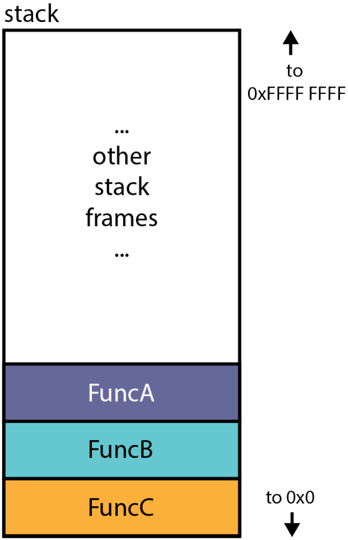
# Timesharing and Context Switches

- When **timesharing**, the switch from one thread to another is called a **context switch**
- What happens during a context switch:
  1. decide which thread will run next (scheduling)
  2. save register contents of current thread
  3. load register contents of next thread
- **Thread context** must be saved/restored carefully, since thread execution continuously changes the context

**Timesharing**

… each thread gets a small amount of time to execute on the CPU, when it expires, a context switch occurs. Threads **share** the CPU, giving the user the illusion of multiple programs running at the same time.

# Review: The Stack



```
FuncA() {
    ...
    FuncB();
    ...
}

FuncB() {
    ...
    FuncC();
    ...
}
```

**Recall:**

Functions push arguments (a0-a3), return address, local variables, and temporary-use registers onto the stack.

# Review: MIPS Registers

| num | name | use | num | name | use |
|---|---|---|---|---|---|
| 0 | z0 | always zero | 24-25 | t8-t9 | temps (caller-save) |
| 1 | at | assembler reserved | 26-27 | k0-k1 | kernel temps |
| 2 | v0 | return val/syscall # | 28 | gp | global pointer |
| 3 | v1 | return value | 29 | sp | stack pointer |
| 4-7 | a0-a3 | subroutine args | 30 | s8/fp | frame ptr (callee-save) |
| 8-15 | t0-t7 | temps (caller-save) | 31 | ra | return addr (for jal) |
| 16-23 | s0-s7 | saved (callee-save) | | | |

- conventions enforced in compiler; used in OS
- **caller-save:** it is the responsibility of the calling function to save/restore values in these registers
- **callee-save:** it the the responsibility of the called function to save/restore values in these registers before/after use

callee/caller save strategy attempts to minimize the callee saving values the caller does not use

# Context Switch on the MIPS (1 of 2)

```
/* See kern/arch/mips/thread/switch.S */

switchframe_switch:
  /* a0: address of switchframe pointer of old thread. */
  /* a1: address of switchframe pointer of new thread. */

   /* Allocate stack space for saving 10 registers. 10*4 = 40 */
   addi sp, sp, -40

   sw   ra, 36(sp)  /* Save the registers */
   sw   gp, 32(sp)
   sw   s8, 28(sp)
   sw   s6, 24(sp)
   sw   s5, 20(sp)
   sw   s4, 16(sp)
   sw   s3, 12(sp)
   sw   s2, 8(sp)
   sw   s1, 4(sp)
   sw   s0, 0(sp)

   /* Store the old stack pointer in the old thread */
   sw   sp, 0(a0)
```

# Context Switch on the MIPS (2 of 2)

```
/* Get the new stack pointer from the new thread */
lw   sp, 0(a1)
nop            /* delay slot for load */

/* Now, restore the registers */
lw   s0, 0(sp)
lw   s1, 4(sp)
lw   s2, 8(sp)
lw   s3, 12(sp)
lw   s4, 16(sp)
lw   s5, 20(sp)
lw   s6, 24(sp)
lw   s8, 28(sp)
lw   gp, 32(sp)
lw   ra, 36(sp)
nop                  /* delay slot for load */

/* and return. */
j ra
addi sp, sp, 40      /* in delay slot */
.end switchframe_switch
```

# Switchframe Notes

- `switchframe_switch` is called by C function thread_switch
    - thread_switch is the **caller**; it will save/restore the **caller-save** registers
    - switchframe_switch is the **callee**; it must save/restore the **callee-save** registers
    - switchframe_switch, saves **callee-save** registers to the old thread stack; it restores the **callee-save** registers from the new thread's stack
- MIPS R3000 is pipelined; **delay-slots** are used to protect against:
    - **load-use hazards**, where loaded values are used in the next instruction
    - **control hazards**, where we don't know which instruction to fetch next

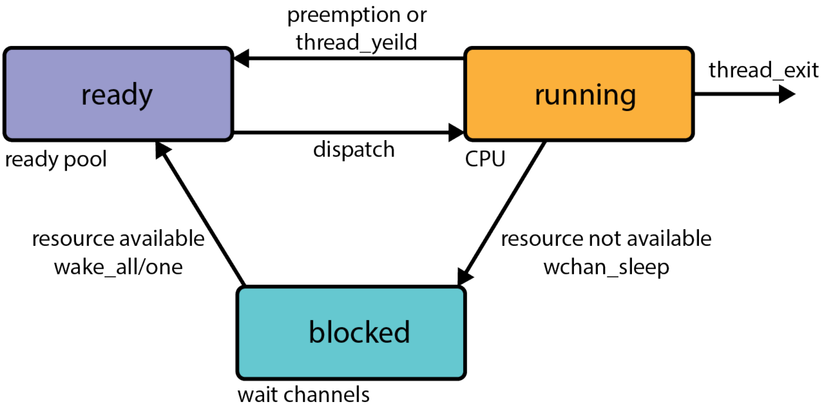
# What Causes Context Switches?

- the running thread calls **thread_yield**
  - running thread **voluntarily** allows other threads to run
- the running thread calls **thread_exit**
  - running thread **is terminated**
- the running thread **blocks**, via a call to **wchan_sleep**
  - more on this later . . .
- the running thread is **preempted**
  - running thread **involuntarily** stops running

**The OS**

... strives to maintain high CPU utilization. Hence, in addition to timesharing, context switches occur whenever a thread ceases to execute instructions.

# Thread States

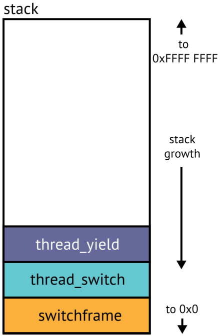


**running:** currently executing

**ready:** ready to execute

**blocked:** waiting for something, so not ready to execute.

# OS/161 Thread Stack after Voluntary Context Switch



- program calls `thread_yield`, to yield the CPU
- `thread_yield` calls `thread_switch`, to perform a context switch
- `thread_switch` chooses a new thread, calls `switchframe_switch` to perform low-level context switch

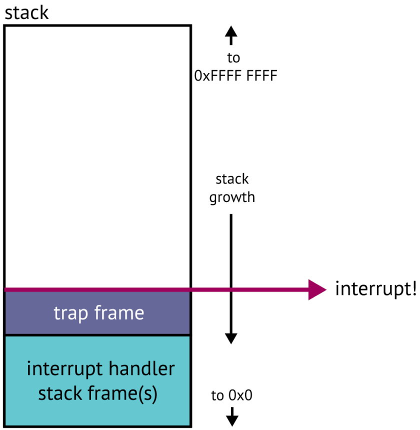
# Timesharing and Preemption

- **timesharing**—concurrency achieved by rapidly switching between threads
  - how rapidly? impose a limit on CPU time, the **scheduling quantum**
  - the quantum is an **upper bound** on how long a thread can run before it must yield the CPU
- how do you stop a running thread, that never yields, blocks or exits when the quantum expires?
  - **preemption** forces a running thread to stop running, so that another thread can have a chance
  - to implement preemption, the OS must have a means of "getting control"
  - this is normally accomplished using **interrupts**

# Review: Interrupts

- an **interrupt** is an event that occurs during the execution of a program
- interrupts are caused by system devices (hardware), e.g., a timer, a disk controller, a network interface
- when an interrupt occurs, the hardware automatically transfers control to a fixed location in kernel memory
- at that memory location, is a procedure called an **interrupt handler**
- the interrupt handler normally:
  1. creates a **trap frame** to record thread context at the time of the interrupt
  2. determines which device caused the interrupt and performs device-specific processing
  3. restores the saved thread context from the trap frame and resumes execution of the thread

# OS/161 Thread Stack after an Interrupt

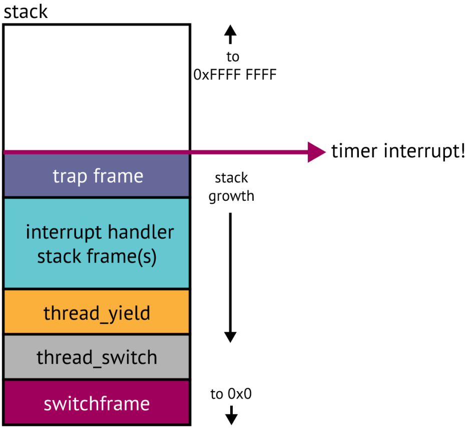


# Preemptive Scheduling

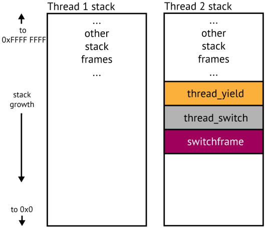
- A preemptive scheduler uses the **scheduling quantum** to impose a time limit on running threads
- Threads may block or yield before their quantum has expired.
- Periodic timer interrupts allow running time to be tracked.
- If a thread has run too long, the timer interrupt handler preempts the thread by calling `thread_yield`.
- The preempted thread changes state from running to ready, and it is placed in the **ready queue**.
- Each time a thread goes from ready to running, the runtime starts out at 0. Runtime does not accumulate.

OS/161 threads use **preemptive round-robin scheduling**.

# OS/161 Thread Stack after Preemption

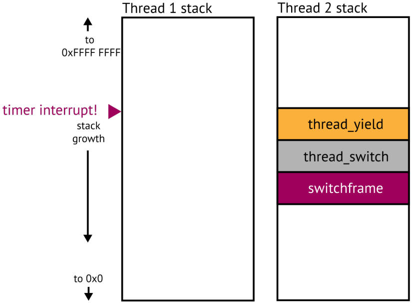


# Two-Thread Example - 1



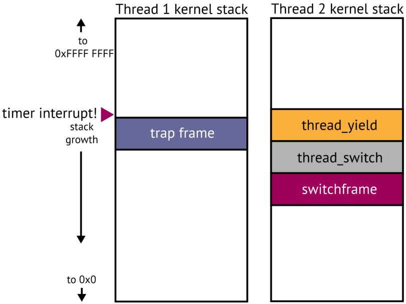
Thread 1 is **RUNNING**. Thread 2 is **READY**, having called `thread_yield` previously.

# Two-Thread Example - 2



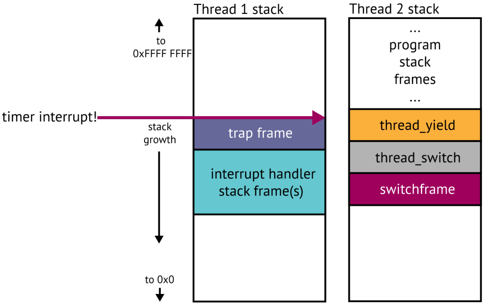
A timer interrupt occurs.

# Two-Thread Example - 3



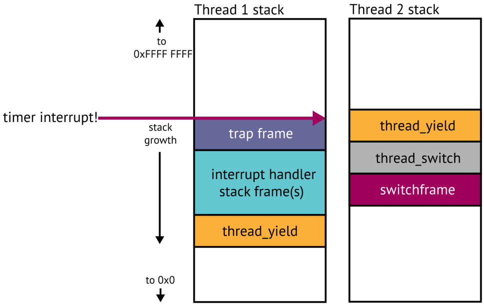
Thread 1 is preempted, a trapframe is created to save its context.

# Two-Thread Example - 4



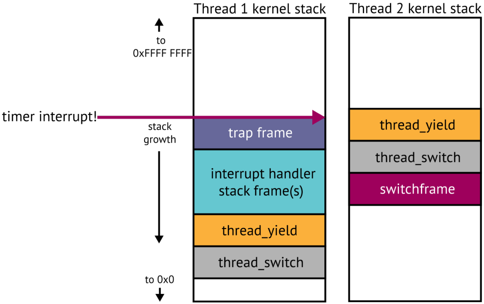
The timer interrupt handler determines what happened, and, calls the appropriate handler.

# Two-Thread Example - 5



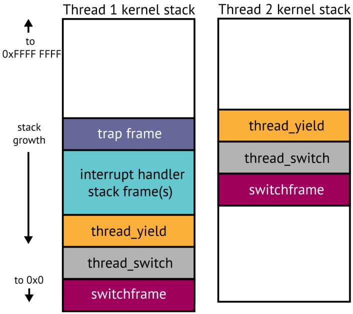
Thread 1 has exceeded its quantum. Yield the CPU to another thread, call thread_yield.

# Two-Thread Example - 6



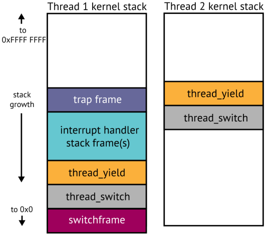
High-level context switch: choose new thread, save caller-save registers.

# Two-Thread Example - 7



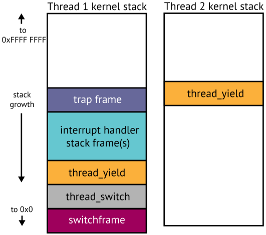
Low-level context switch. Save callee-save registers.

# Two-Thread Example - 8



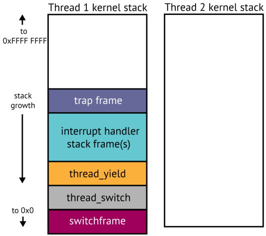
Thread 2 is now **RUNNING**, Thread 1 is now **READY**. Thread 2 returns from low-level context switch, restoring callee-save registers.

# Two-Thread Example - 9



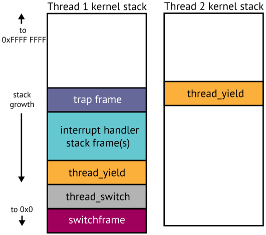
Return from high-level context switch, restoring caller-save registers.

# Two-Thread Example - 10



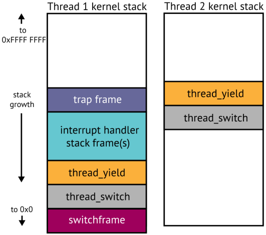
Return from yield. Context is fully restored. Thread 2 is now running its regular program.

# Two-Thread Example - 11



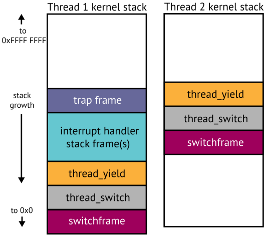
Thread 2 yields.

# Two-Thread Example - 12



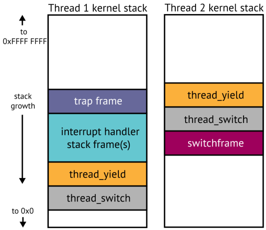
High-level context switch.

# Two-Thread Example - 13



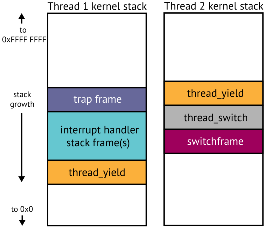
Low-level context switch.

# Two-Thread Example - 14



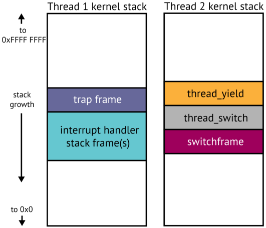
Thread 1 is now **RUNNING**. Thread 2 is now **READY**. Return from low-level context switch.

# Two-Thread Example - 15



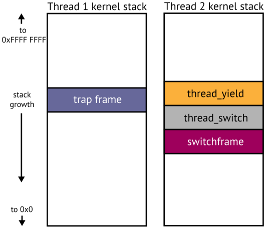
Return from high-level context switch.

# Two-Thread Example - 16



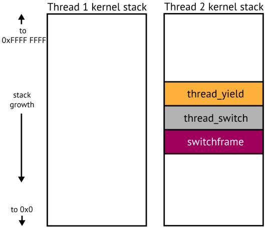
Return from yield.

# Two-Thread Example - 17



Return from interrupt handling functions.

# Two-Thread Example - 18



Restore thread 1's context (stored in the trapframe), return to regular program.

# Food for thought...

How to implement process management system calls in a multi-threaded process

- if a calling thread calls **fork**, should we
  1. create a new process with all threads of the parent process?
  2. create a new process with only the calling thread from the parent process duplicated?

  Linux implements option 2, since Native POSIX Threading Library(NPTL) assumes this. There are variants of `fork`, such as `clone` and `rfork` found in Linux and FreeBSD
- if a thread calls **execv**, should we replace entire process, including all threads?
- signal handling, shoud we
  1. deliver signals to all threads of a process?
  2. deliver signals to the thread that generated the signal?
  3. deliver to a specific thread that receives all signals for the process?