Threads and Concurrency

key concepts

threads, concurrent execution, timesharing, context switch, interrupts, preemption

reading

Three Easy Pieces: Chapter 26 (Concurrency and Threads)

What is a Thread?

- Threads provide a way for programmers to express *concurrency* in a program.

- A normal *sequential program* consists of a single thread of execution.

- In threaded concurrent programs there are multiple threads of execution, all occuring at the same time.

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 global variables and heap.

    - Each thread's function activations are *private* to that thread.

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);
```

See `kern/include/thread.h`

Why Threads?

- **Reason #1**: parallelism exposed by threads enables parallel execution if the underlying hardware supports it.

  – programs can run faster

- **Reason #2**: parallelism exposed by threads enables better processor utilization

  – if one thread has to *block*, another may be able to run

Review: Sequential Program Execution
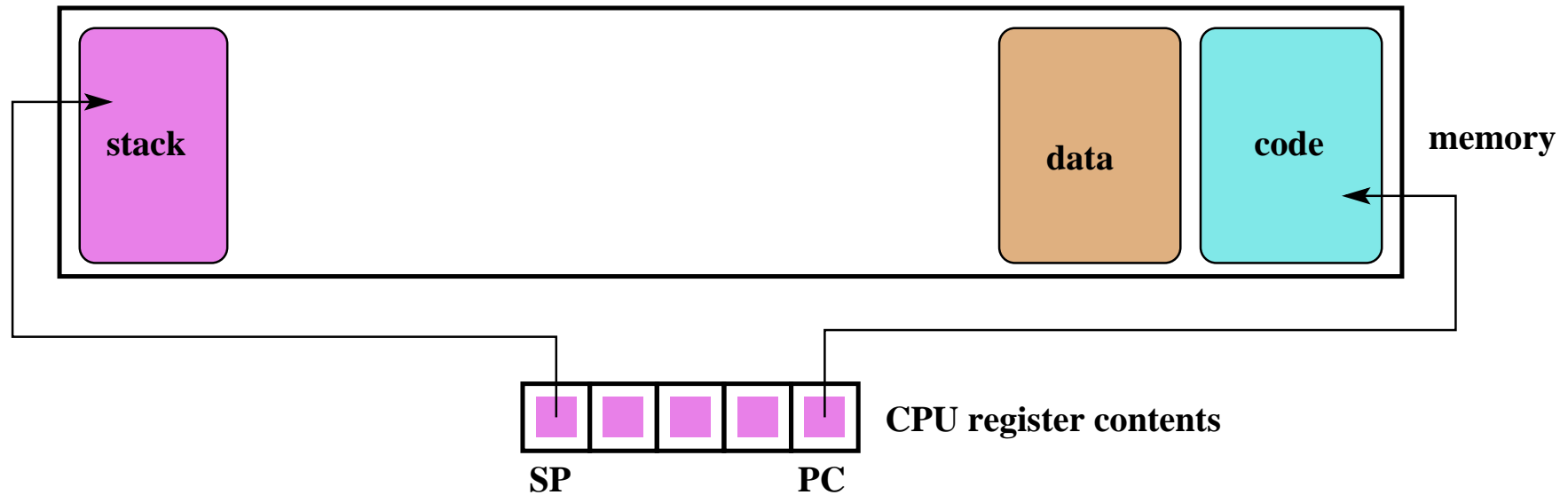
The Fetch/Execute Cycle

1. fetch instruction PC points to

2. decode and execute instruction

3. advance PC

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)			

See `kern/arch/mips/include/kern/regdefs.h`

Review: The Stack


```
FuncA() {

    ...

    FuncB();

    ...

}


FuncB() {

    ...

    FuncC();

    ...

}
```

stack frame(s)

FuncA

FuncB

FuncC

stack growth
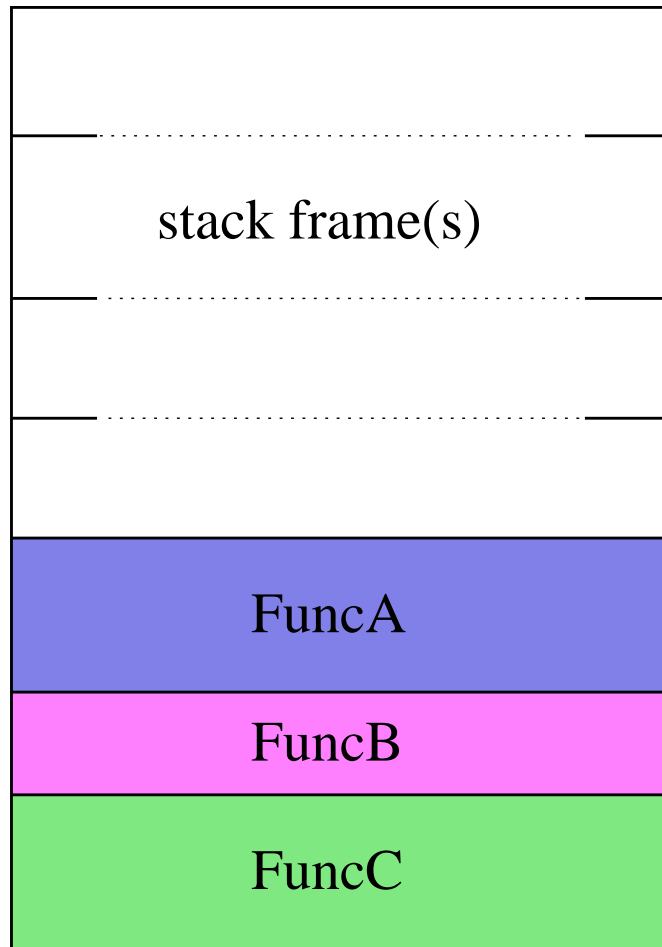
Concurrent Program Execution (Two Threads)
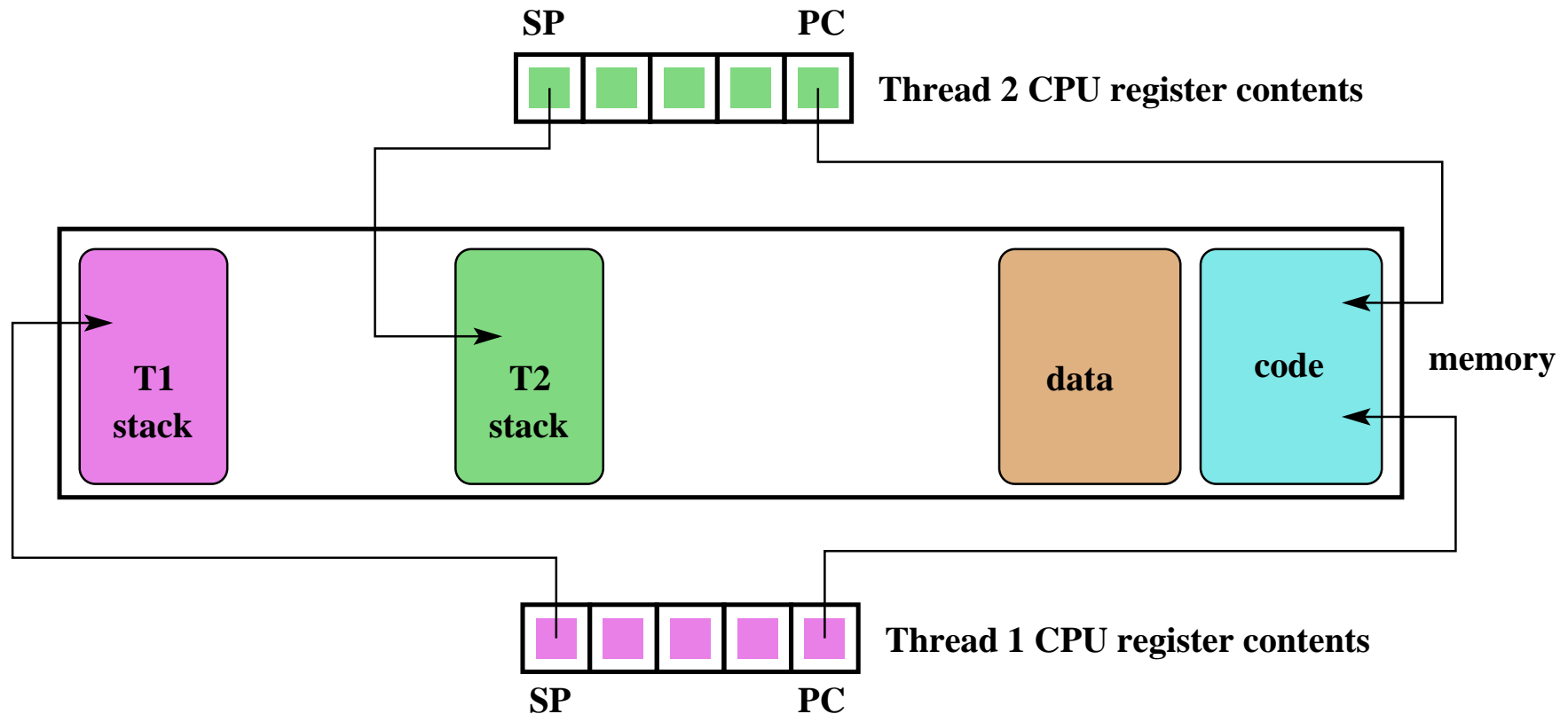
Conceptually, each thread executes sequentially using its private register contents and stack.

Implementing Concurrent Threads

- Option 1: multiple processors, multiple cores, hardware multithreading per core

  - P processors, C cores per processor, M multhreading degree per core $\Rightarrow$ PCM threads can execute *simultaneously*

  - separate register set for each running thread, to hold its *execution context*

- Option 2: *timesharing*

  - multiple threads take turns on the same hardware

  - rapidly switch from thread to thread so that all make progress

In practice, both techniques can be combined.

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

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
```

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

OS/161 Thread Stack after Voluntary Context Switch (`thread_yield()`)

stack frame(s)

thread_yield()
stack frame

thread_switch
stack frame

saved thread context
(switchframe)

stack growth

Thread States

preemption
or thread_yield()

```
ready  ←——————  running
       ——————→
        dispatch
```

got resource or event
(wchan_wakeone/all())

need resource or event
(wchan_sleep())
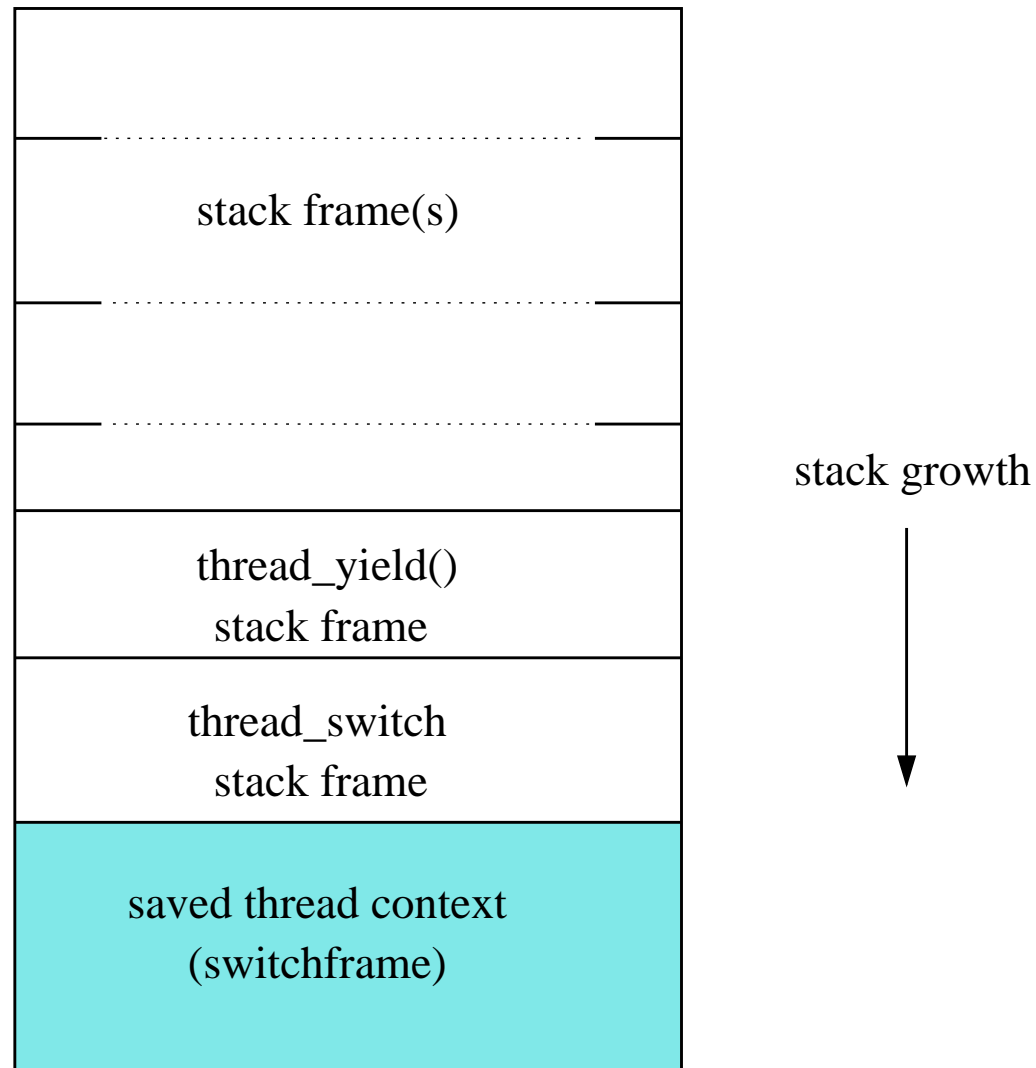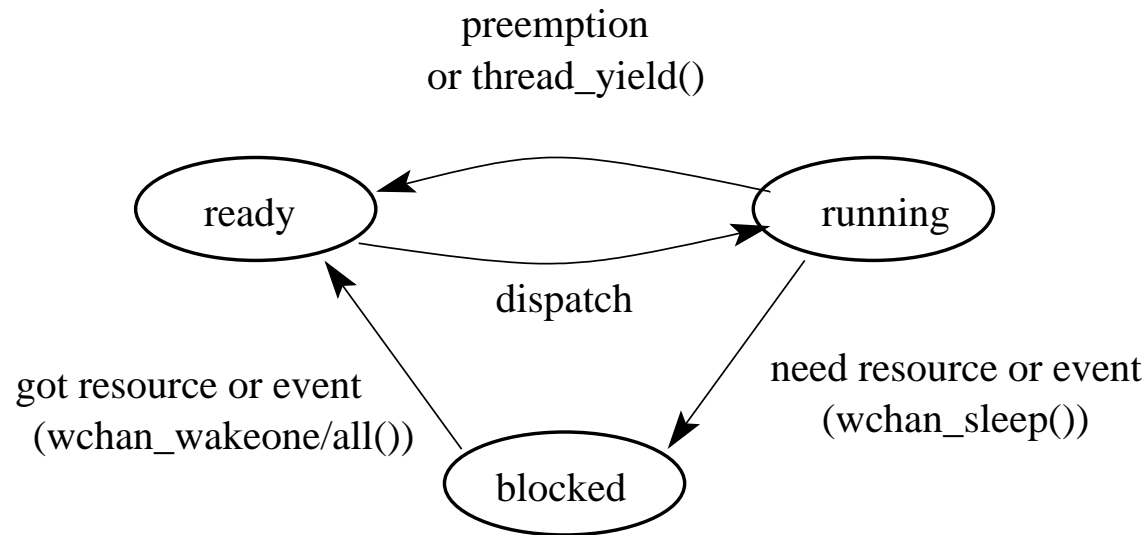
blocked

running: currently executing

ready: ready to execute

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

Preemption

- without preemption, a running thread could potentially run forever, without yielding, blocking, or exiting

- *preemption* means forcing a running thread to stop running, so that another thread can have a chance

- to implement preemption, the thread library must have a means of "getting control" (causing thread library code to be executed) even though the running thread has not called a thread library function

- 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 memory

- at that memory location, the thread library places a procedure called an *interrupt handler*

- the interrupt handler normally:

  1. create 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 in Interrupt
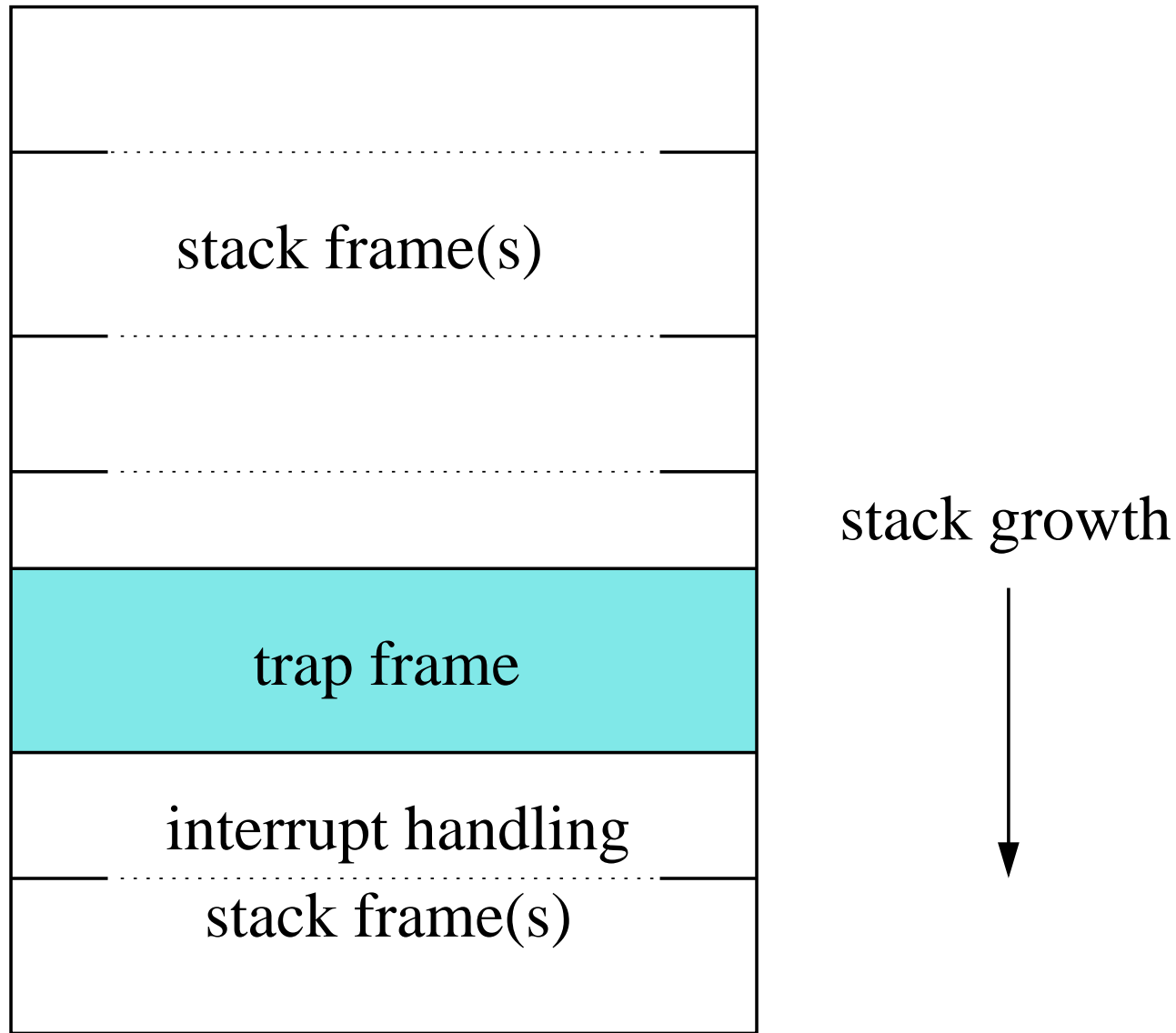
Preemptive Scheduling

- A preemptive scheduler imposes a limit, called the *scheduling quantum* on how long a thread can run before being preempted.

- The quantum is an *upper bound* on the amount of time that a thread can run. It may block or yield before its 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 on the *ready queue*.

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

OS/161 Thread Stack after Preemption

```
┌─────────────────────────┐
│                         │
│ ·························· │
│      stack frame(s)     │
│ ·························· │
│                         │
│ ·························· │
│                         │              stack growth
├─────────────────────────┤
│       trap frame        │                   │
│                         │                   │
├─────────────────────────┤                   │
│   interrupt handling    │                   │
│ ·························· │                   ▼
│      stack frame(s)     │
├─────────────────────────┤
│     thread_yield()      │
│      stack frame        │
├─────────────────────────┤
│    thread_switch()      │
│      stack frame        │
├─────────────────────────┤
│                         │
│  saved thread context   │
│                         │
│     (switchframe)       │
│                         │
└─────────────────────────┘
```
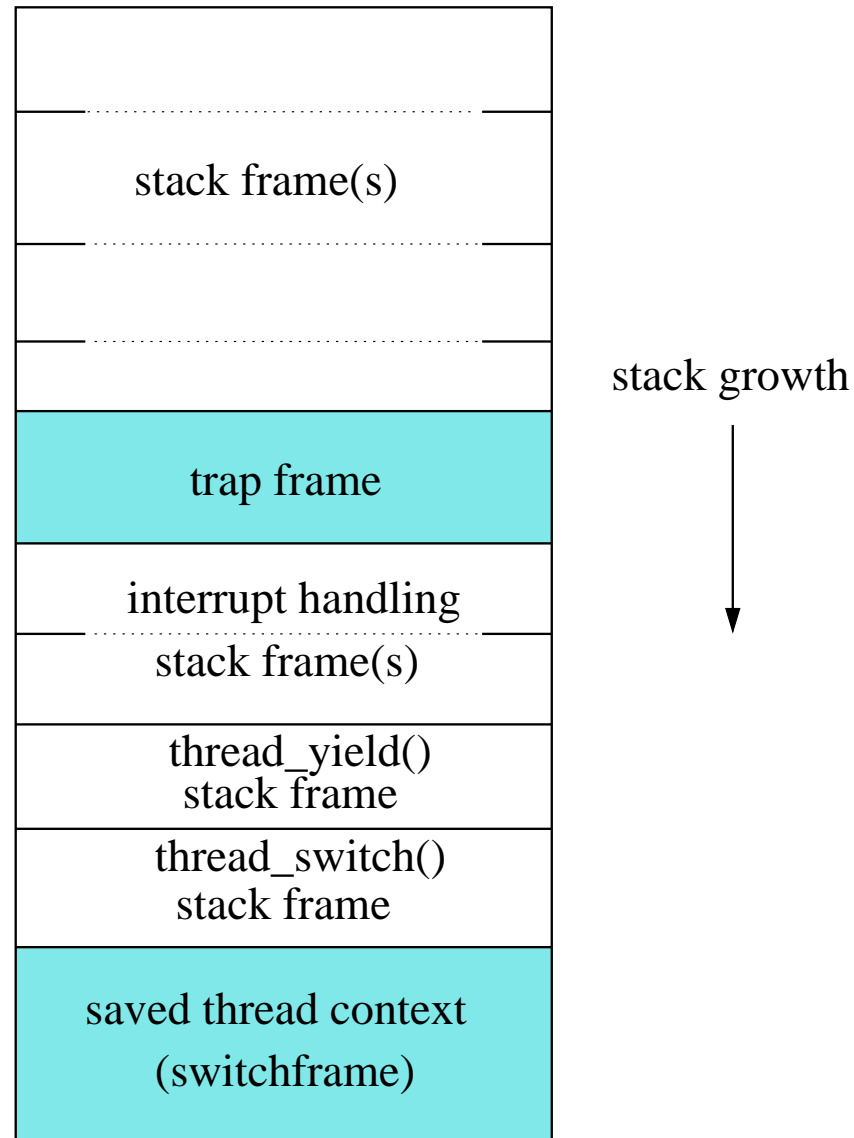
Two-Thread Example (Part 1)

Thread 1 Stack

Thread 2 Stack

program
stack frame(s)

program
stack frame(s)

thread_yield

thread_switch

switch frame
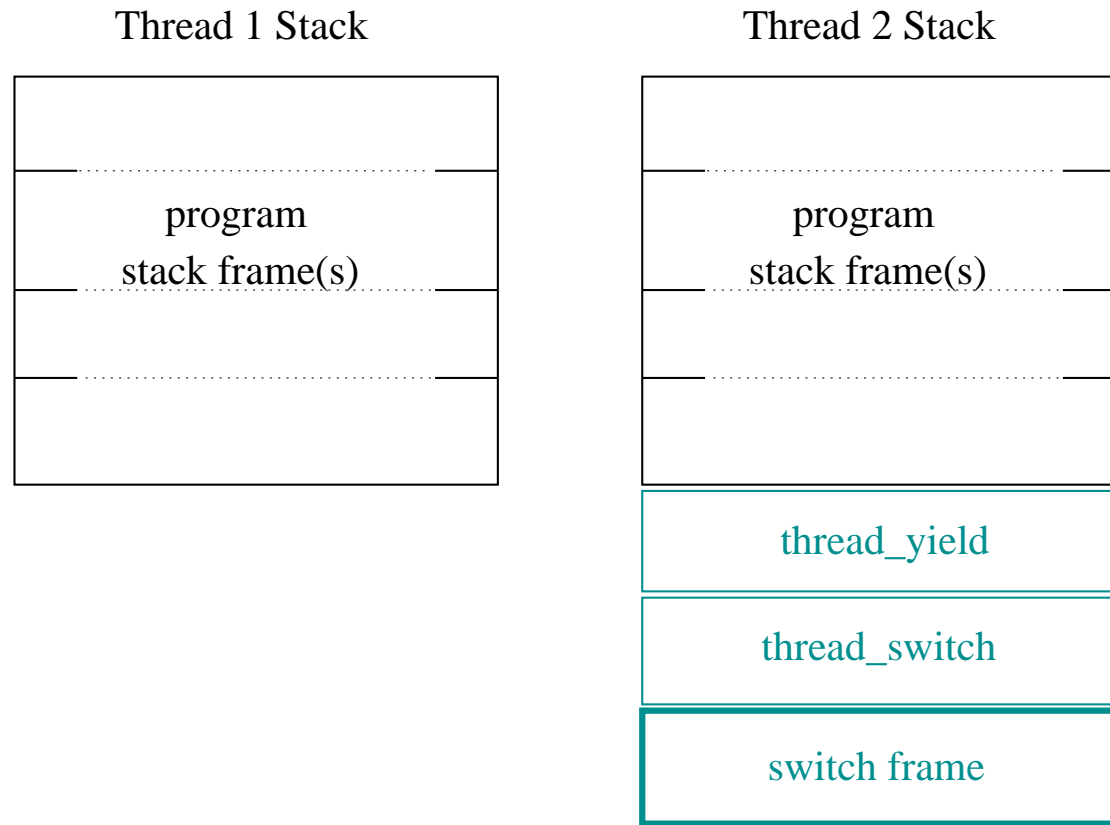
Thread 1 is running, thread two had previously yielded voluntarily.

Two-Thread Example (Part 2)

Thread 1 Stack   Thread 2 Stack

program stack frame(s)

program stack frame(s)

INTERRUPT!

trap frame
interrupt handler

thread_yield
thread_switch
switch frame
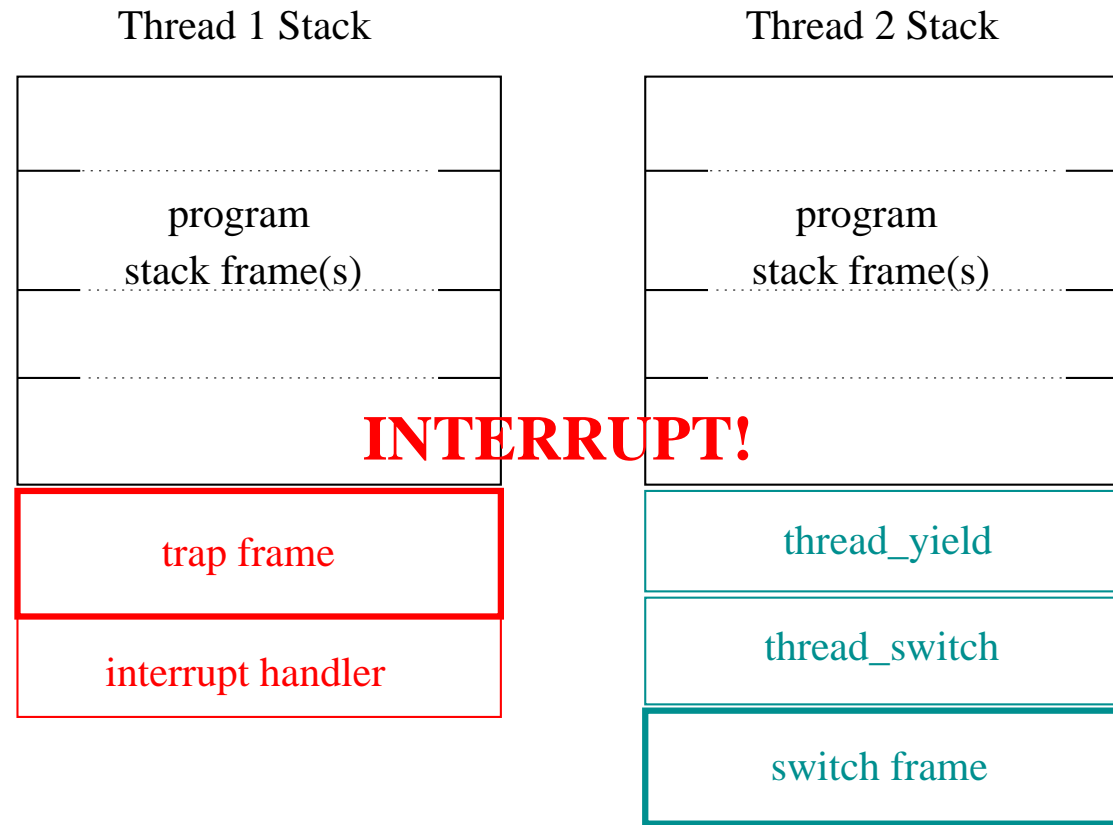
A time interrupt occurs! Interrupt handler runs.

Two-Thread Example (Part 3)

Thread 1 Stack   Thread 2 Stack

```
┌─────────────────────┐          ┌─────────────────────┐
│                     │          │                     │
│      program        │          │      program        │
│   stack frame(s)     │          │   stack frame(s)     │
│                     │          │                     │
│                     │          │                     │
├─────────────────────┤          ├─────────────────────┤
│                     │          │                     │
│     trap frame      │          │    thread_yield     │
│                     │          ├─────────────────────┤
├─────────────────────┤          │                     │
│  interrupt handler  │          │    thread_switch    │
├─────────────────────┤          ├─────────────────────┤
│                     │          │                     │
│    thread_yield     │          │    switch frame     │
│                     │          │                     │
└─────────────────────┘          └─────────────────────┘
```
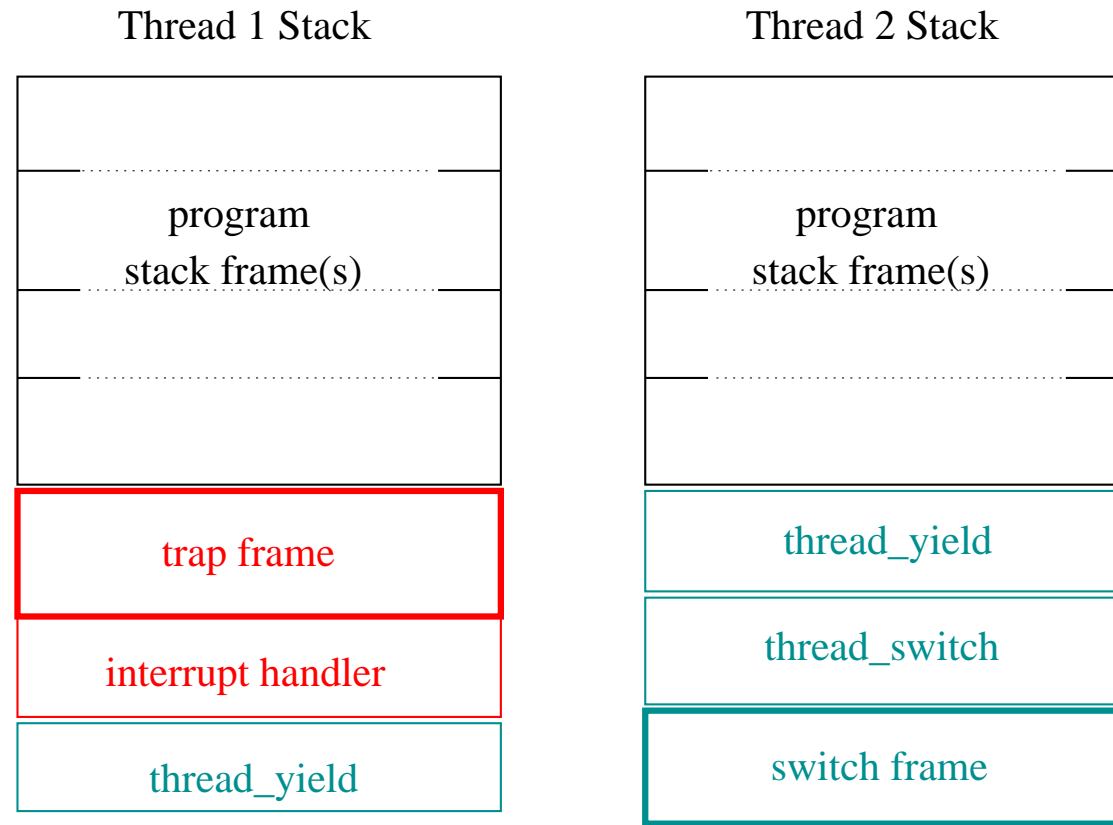
Interrupt handler decides Thread 1 quantum has expired.

Two-Thread Example (Part 4)

Thread 1 Stack   Thread 2 Stack

program
stack frame(s)
trap frame
interrupt handler
thread_yield
thread_switch
switch frame

program
stack frame(s)
thread_yield
thread_switch
switch frame
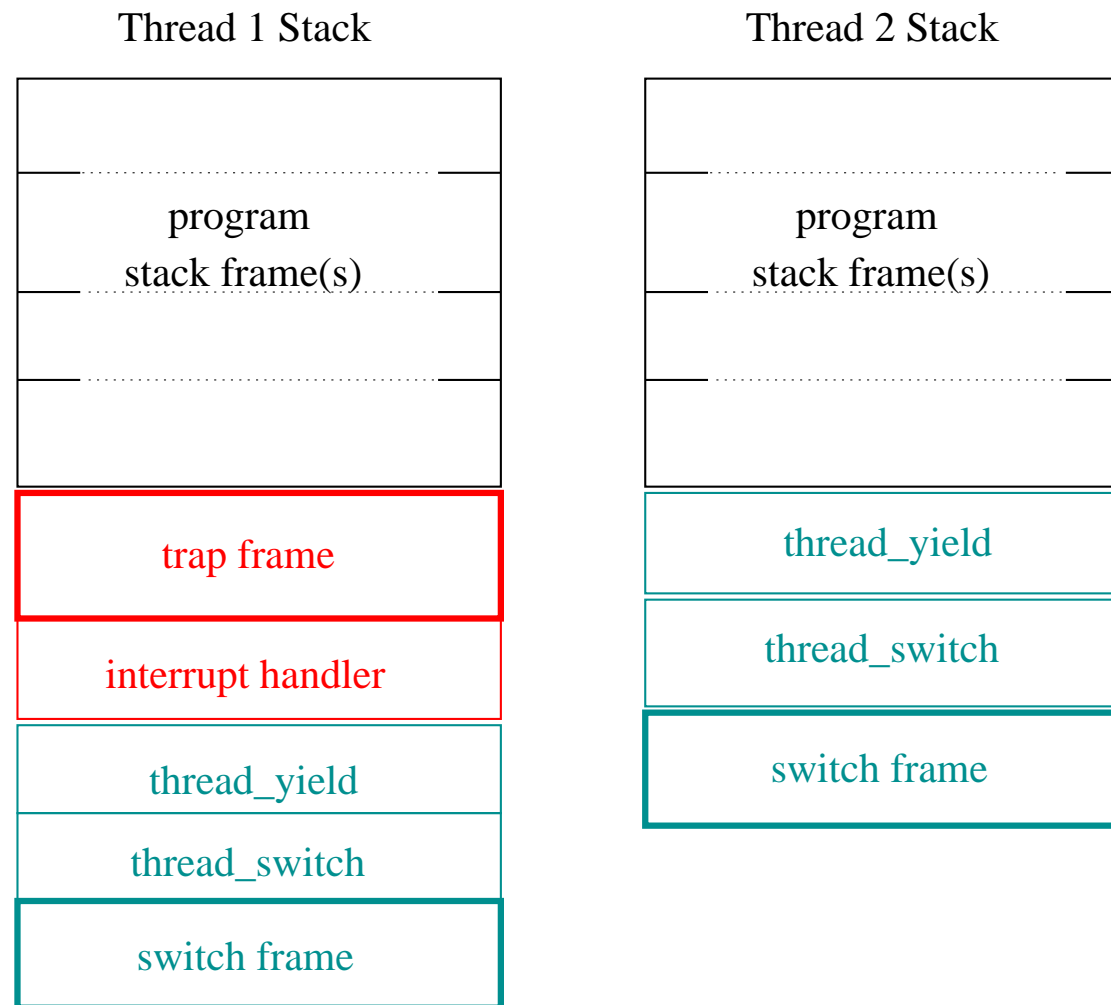
Scheduler chooses Thread 2 to run. Context switch.

Two-Thread Example (Part 5)

Thread 1 Stack

Thread 2 Stack

program stack frame(s)

trap frame
interrupt handler
thread_yield
thread_switch
switch frame

program stack frame(s)
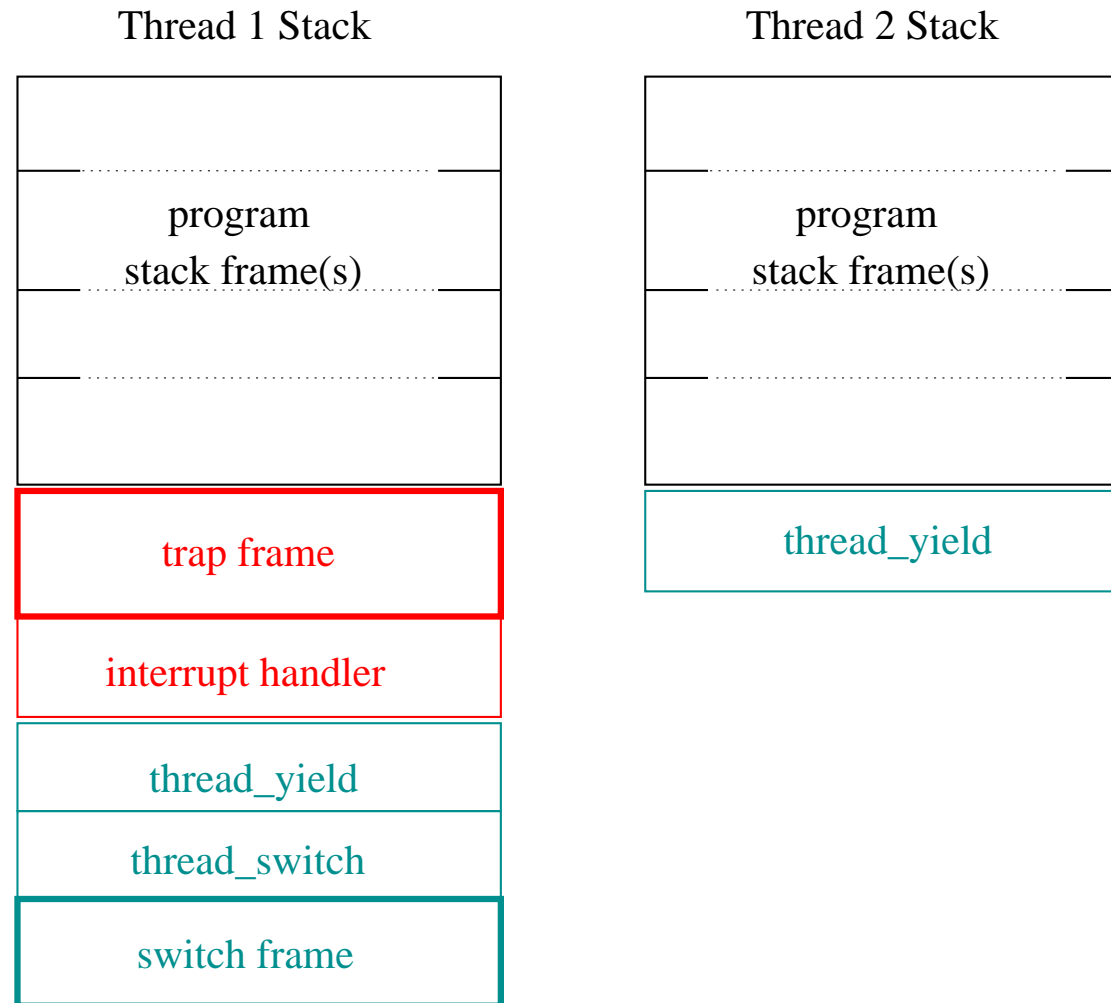
thread_yield

Thread 2 context is restored.

Two-Thread Example (Part 6)

Thread 1 Stack   Thread 2 Stack

program stack frame(s)

program stack frame(s)

trap frame
interrupt handler
thread_yield
thread_switch
switch frame
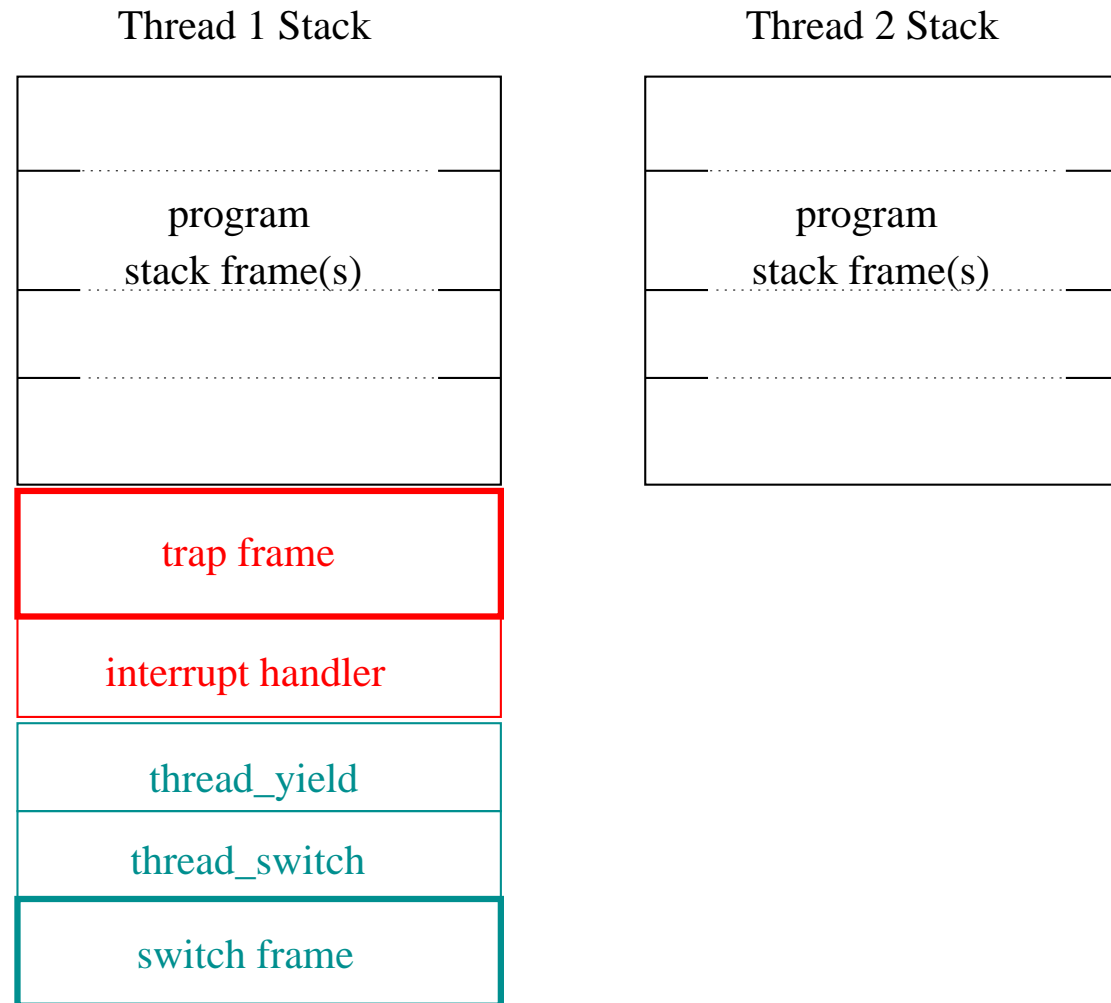
`thread_yield` finishes, Thread 2 program resumes.

Two-Thread Example (Part 7)

Thread 1 Stack   Thread 2 Stack

program
stack frame(s)

program
stack frame(s)

| trap frame |

| interrupt handler |

| thread_yield |

| thread_switch |

| switch frame |

Thread 2 Stack:

| thread_yield |

| thread_switch |

| switch frame |
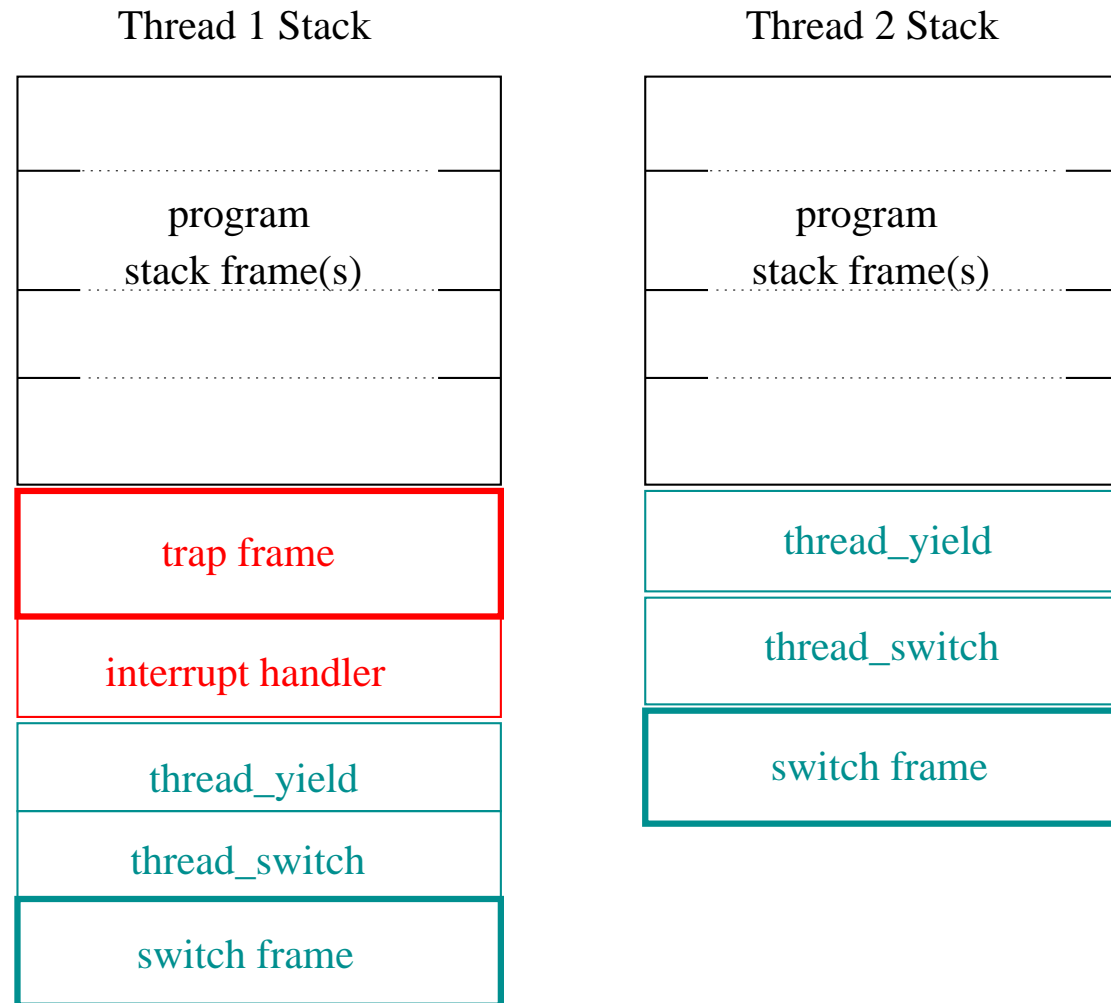
Later, Thread 2 yields again. Scheduler chooses Thread 1.

Two-Thread Example (Part 8)

Thread 1 Stack   Thread 2 Stack

```
┌─────────────────────┐        ┌─────────────────────┐
│ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄ │        │ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄ │
│      program        │        │      program        │
│   stack frame(s)    │        │   stack frame(s)    │
│ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄ │        │ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄ │
│                     │        │                     │
└─────────────────────┘        └─────────────────────┘
┌─────────────────────┐        ┌─────────────────────┐
│                     │        │    thread_yield     │
│     trap frame      │        ├─────────────────────┤
│                     │        │    thread_switch    │
├─────────────────────┤        ├─────────────────────┤
│  interrupt handler  │        │    switch frame     │
└─────────────────────┘        └─────────────────────┘
```
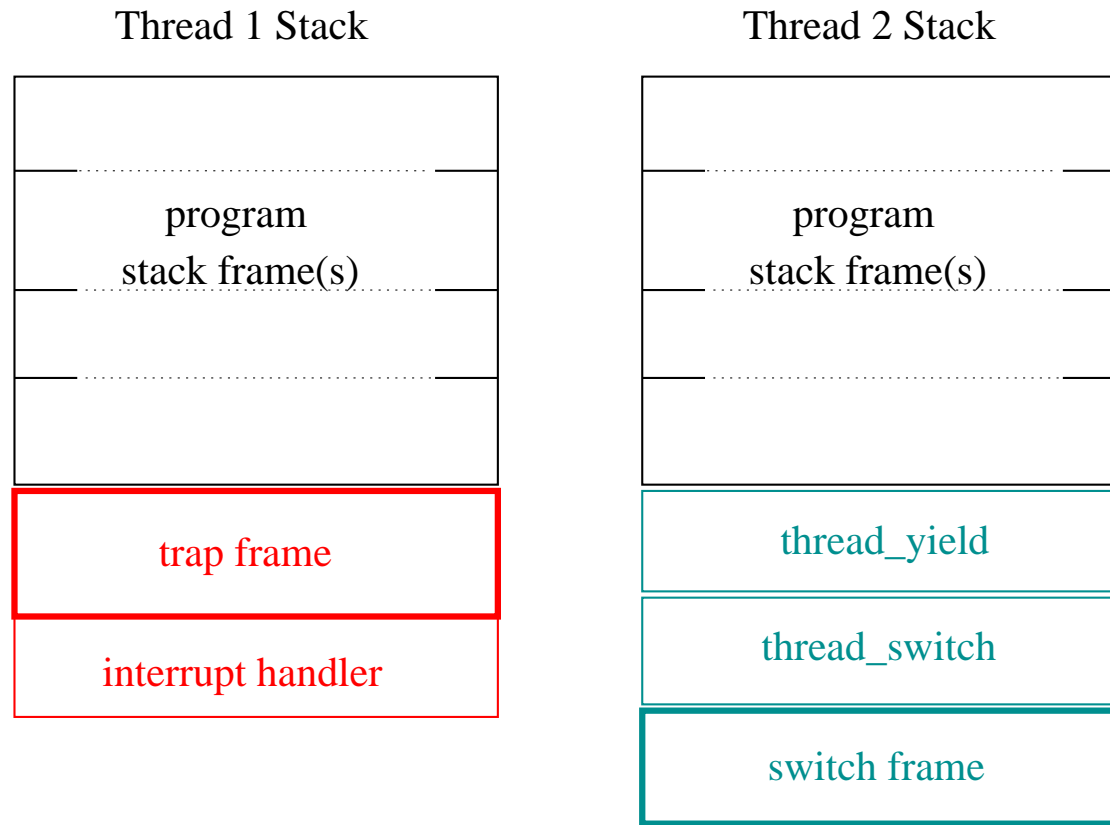
Thread 1 context is restored, interrupt handler resumes.

Two-Thread Example (Part 9)

Thread 1 Stack

Thread 2 Stack

```
┌─────────────────────────┐        ┌─────────────────────────┐
│                         │        │                         │
│ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄ │        │ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄ │
│        program          │        │        program          │
│      stack frame(s)     │        │      stack frame(s)     │
│ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄ │        │ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄ │
│                         │        │                         │
│ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄ │        │ ┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄┄ │
│                         │        │                         │
└─────────────────────────┘        └─────────────────────────┘
                                   ┌─────────────────────────┐
                                   │      thread_yield       │
                                   ├─────────────────────────┤
                                   │      thread_switch      │
                                   ├─────────────────────────┤
                                   │      switch frame       │
                                   └─────────────────────────┘
```
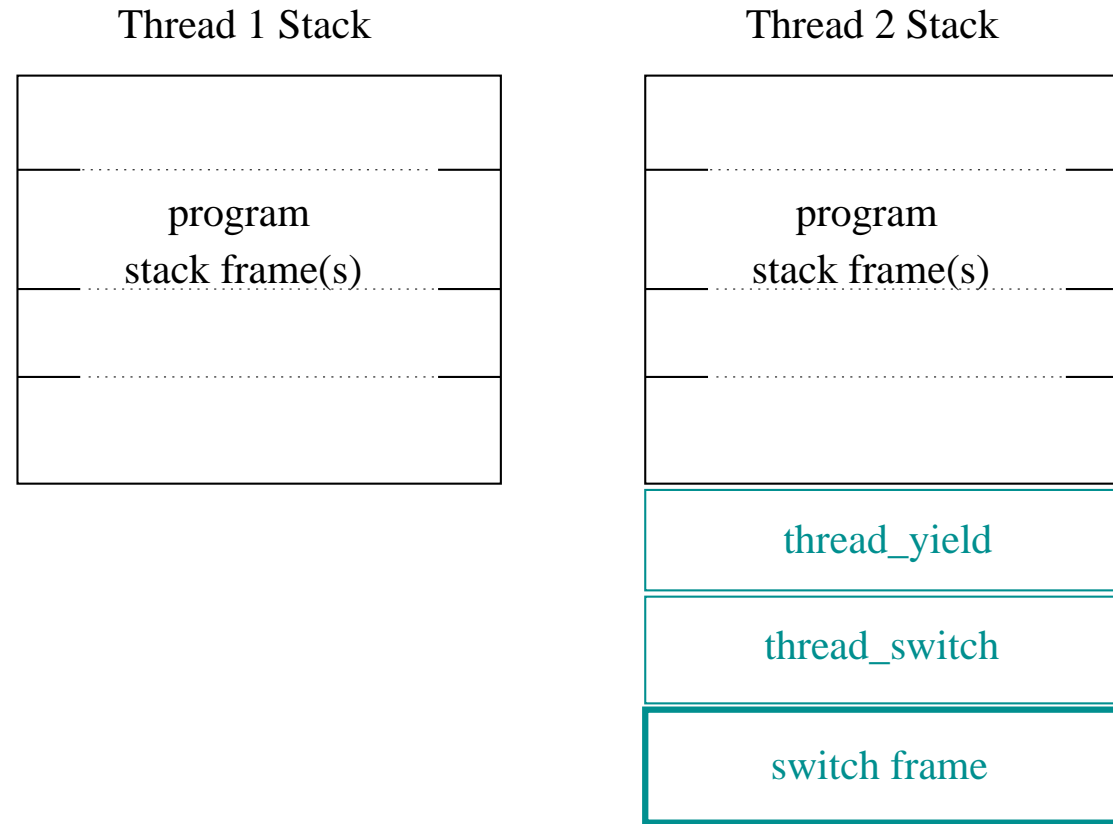
Interrupt handler restores state from trap frame and returns.