CS 4284
Systems Capstone

Processes and Threads

Godmar Back

Processes & Threads

Overview

- Definitions
- How does OS execute processes?
  - How do kernel & processes interact
  - How does kernel switch between processes
  - How do interrupts fit in
- What’s the difference between threads/processes
- Process States
- Priority Scheduling

Process

- These are all possible definitions:
  - A program in execution
  - An instance of a program running on a computer
  - Schedulable entity (*)
  - Unit of resource ownership
  - Unit of protection
  - Execution sequence (*) + current state (*) + set of resources

(*) can be said of threads as well

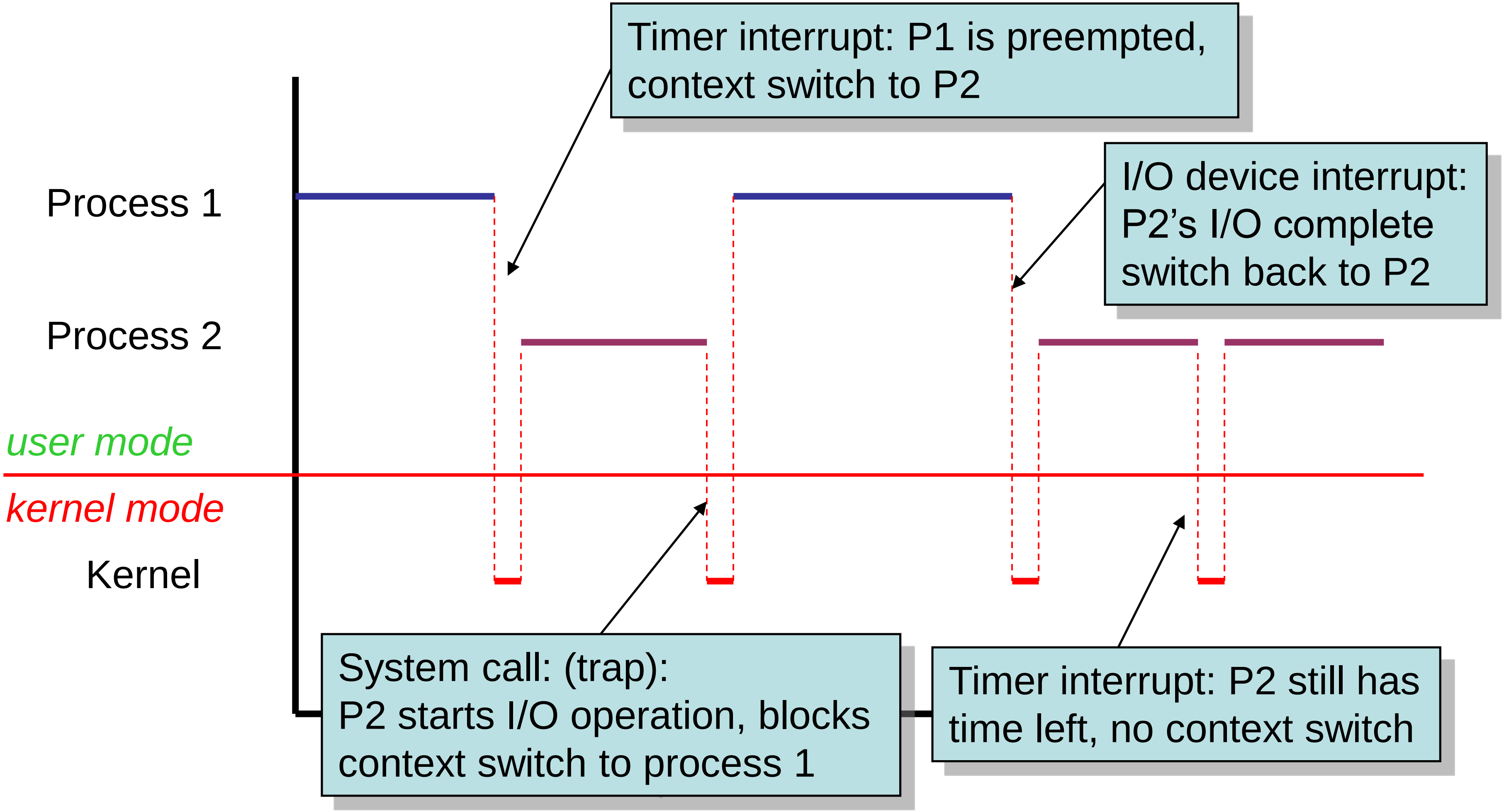
Alternative definition

- Thread:
  - Execution sequence + CPU state (registers + stack)
- Process:
  - n Threads + Resources shared by them (specifically: accessible heap memory, global variables, file descriptors, etc.)
- In most contemporary OS, n >= 1.
- In Pintos, n=1: a process is a thread – as in traditional Unix.
  - Following discussion applies to both threads & processes.

Context Switching

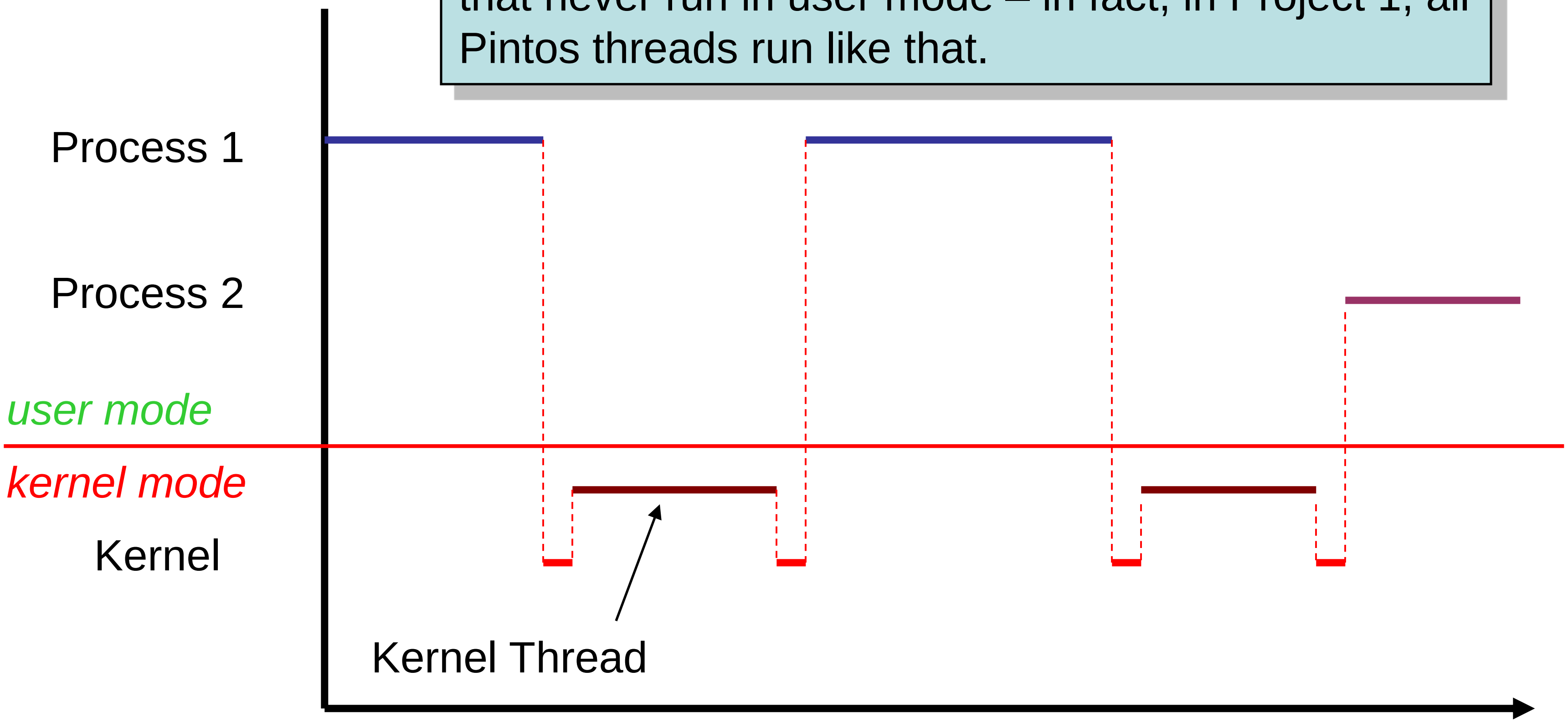
- Multiprogramming: switch to another process if current process is (momentarily) blocked
- Time-sharing: switch to another process periodically to make sure all process make equal progress
  - this switch is called a context switch.
- Must understand how it works
  - how it interacts with user/kernel mode switching
  - how it maintains the illusion of each process having ~~the~~ a CPU to itself (process must not notice being switched in and out!)

Context Switching



Aside: Kernel Threads

Most OS (including Pintos) support kernel threads that never run in user mode – in fact, in Project 1, all Pintos threads run like that.



Careful: “kernel thread” not the same as kernel-level thread (KLT) – more on KLT later

Mode Switching: User → Kernel

- Can be for reasons *external* or *internal* to CPU
- External (aka hardware) interrupt:
  - timer/clock chip, I/O device, network card, keyboard, mouse
  - IPI (interprocessor interrupt from another CPU)
  - are asynchronous (with respect to the executing program)
- Internal interrupt (aka software interrupt, trap, or exception)
  - can be intended: for system call (process wants to enter kernel to obtain services, via dedicated instructions)
  - or unintended (usually): fault/exception (attempt to access unmapped memory, division by zero, attempt to execute privileged instruction in user mode, illegal instructions, bus error, alignment error, etc.)
  - are synchronous
- CPU + Kernel code save state of the CPU

Mode Switching: Kernel → User

- Uses *iret* instruction
- Kernel must have restored user state, then iret will restore the user stack and continue the user process in user mode.
- Side note: Kernel can control the state that should be restored
  - Used for signal delivery, or for bootstrapping (first state that's restored is synthetic/fake in that it does not result from a prior mode switch.)

Context vs Mode Switching

- Mode switch guarantees kernel gains control when needed
  - To react to external events
  - To handle error situations
  - Entry into kernel is **controlled**
- Not all mode switches lead to context switches
  - Kernel code's logic decides when – subject of scheduling
- Mode switch always hardware supported
  - Context switch (typically) not – this means many options for implementing it!

Implementing Processes

- To maintain illusion, must remember a process's information when not currently running
- Process Control Block (PCB)
  - Identifier (*)
  - Value of registers, including stack pointer (*)
  - Information needed by scheduler: process state (whether blocked or not) (*)
  - Resources held by process: file descriptors, memory pages, etc.

(*) applies to TCB (thread control block) as well

PCB vs TCB

- In 1:1 systems (Pintos), TCB==PCB
  - **`struct thread`**
  - add informatio… as projects progress
- In 1:n syst
  - TCB cont
    schedulin
    process t
  - PCB cont
    about res

```
struct thread
  {
    tid_t tid;                          /* Thread identifier. */
    enum thread_status status;  /* Thread state. */
    char name[16];                     /* Name. */
    uint8_t *stack;                     /* Saved stack pointer. */
    struct list_elem elem;            /* List element. */
    /* others you'll add as needed. */
};
```

IMPLEMENTING CONTEXT SWITCHES

Steps in context switch: high-level

- Save the current process's execution state to its PCB
- Update current's PCB as needed
- Choose next process N
- Update N's PCB as needed
- Restore N's PCB execution state
  - May involve reprogramming MMU

Execution State

- Saving/restoring execution state is highly tricky:
  - Must save state without destroying it
- Registers
  - On x86: eax, ebx, ecx, …
- Stack
  - Special area in memory that holds activation records: e.g., the local (automatic) variables of all function calls currently in progress
  - Saving the stack means retaining that area & saving a pointer to it (“stack pointer” = esp)

The Stack, seen from C/C++

int a;
static int b;
int c = 5;
struct S
  {
    int t;
  } s;
	void func(int d)
	{
	  static int e;
	  int f;
	  struct S w;
	  int *g = new int[10];
	}

A.: On stack: d, f, w (including w.t), g

Not on stack: a, b, c, s (including s.t), e, g[0]…g[9]

Switching Procedures

- Inside kernel, context switch is implemented in some procedure (function) called from C code
  - Appears to caller as a procedure call
- Must understand how to switch procedures (call/return)
- Procedure calling conventions
  - Architecture-specific
  - Defined by ABI (application binary interface), implemented by compiler
  - Pintos uses SVR4 ABI

x86 Calling Conventions

- Caller saves caller-saved registers as needed
- Caller pushes arguments, right-to-left on stack via push assembly instruction
- Caller executes CALL instruction: save address of next instruction & jump to callee
- Callee executes:
  - Saves callee-saved registers if they'll be destroyed
  - Puts return value (if any) in eax
- Callee returns: pop return address from stack & jump to it
- Caller resumes: pop arguments off the stack
- Caller restores caller-saved registers, if any

Example

```
int globalvar;

int
callee(int a, int b)
{
    return a + b;
}

int
caller(void)
{
    return callee(5, globalvar);
}
```

```
callee:
        pushl   %ebp
        movl    %esp, %ebp
        movl    12(%ebp), %eax
        addl    8(%ebp), %eax
        leave
        ret

caller:
        pushl   %ebp
        movl    %esp, %ebp
        pushl   globalvar
        pushl   $5
        call    callee
        popl    %edx
        popl    %ecx
        leave
        ret
```

Pintos Context Switch (1)

```
static void
schedule (void)
{
  struct thread *cur = running_thread ();
  struct thread *next = next_thread_to_run ();
  struct thread *prev = NULL;
  if (cur != next)
    prev = switch_threads (cur, next);
retlabel:  /* not in actual code */
  thread_schedule_tail (prev);
}

uint32_t thread_stack_ofs = offsetof (struct thread, stack);
```

Stack

…
next
cur
&retlabel

esp

- threads/thread.c, threads/switch.S

Pintos Context Switch (2)

```
switch_threads:  // switch_thread (struct thread *cur, struct thread *next)
        # Save caller's register state.
        # Note that the SVR4 ABI allows us to destroy %eax, %ecx, %edx,
        # but requires us to preserve %ebx, %ebp, %esi, %edi.
        pushl %ebx; pushl %ebp; pushl %esi; pushl %edi

        # Get offsetof (struct thread, stack).
        mov thread_stack_ofs, %edx

        # Save current stack pointer to old thread's stack.
        movl SWITCH_CUR(%esp), %eax          } cur->stack = esp
        movl %esp, (%eax,%edx,1)

        # Restore stack pointer from new thread's stack.
        movl SWITCH_NEXT(%esp), %ecx         } esp = next->stack
        movl (%ecx,%edx,1), %esp

        # Restore caller's register state.
        popl %edi; popl %esi; popl %ebp; popl
        ret
```

Stack

…
next
cur
&retlabel
ebx
ebp
esi
edi

esp

esp

```
#define SWITCH_CUR 20
#define SWITCH_NEXT 24
```

Famous Quote For The Day

```
/*
 * If the new process paused because it was
 * swapped out, set the stack level to the last call
 * to savu(u_ssav).  This means that the return
 * which is executed immediately after the call to aretu
 * actually returns from the last routine which did
 * the savu.
 *
 * You are not expected to understand this.
 */
```

If the new process paused because it was swapped out, set the stack level to the last call to savu(u_ssav). This means that the return which is executed immediately after the call to aretu actually returns from the last routine which did the savu.

You are not expected to understand this.

- Source: Dennis Ritchie, Unix V6 slp.c (context-switching code) as per [The Unix Heritage Society](tuhs.org) (tuhs.org); gif by Eddie Koehler.

Side Note

- If you read the full text of the "You are not expected to understand this" you'll learn that the code given was actually broken because it depended on a specific compiler and disregarded procedure calling conventions with respect to register saving.

Pintos Context Switch (3)

- All state is stored on outgoing thread's stack, and restored from incoming thread's stack
  - Each thread has a 4KB page for its stack
  - Called "kernel stack" because it's only used when thread executes in kernel mode
  - Mode switch automatically switches to kernel stack
    - x86 does this in hardware, curiously.
- switch_threads assumes that the thread that's switched in was suspended in switch_threads as well.
  - Must fake that environment when switching to a thread for the first time.
- Aside: none of the thread switching code uses privileged instructions:
  - that's what makes user-level threads (ULT) possible

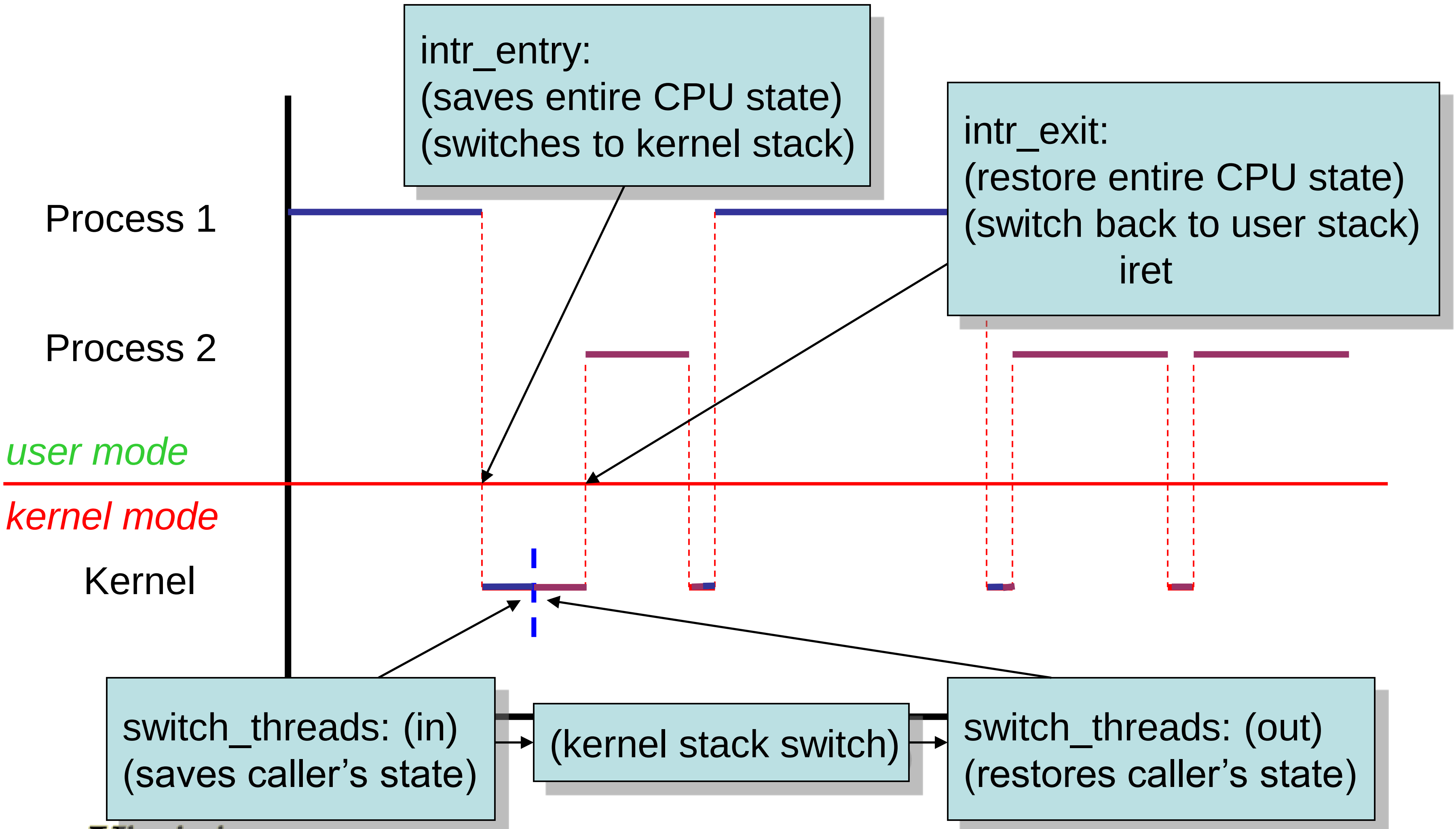
Pintos Kernel Stack

- One page of memory captures a process's kernel stack + PCB
- Don't allocate large objects on the stack:

```
void
kernel_function(void)
{
    char buf[4096]; // DON'T
    // KERNEL STACK OVERFLOW
    // guaranteed
}
```

```
4 kB +---------------------------------+
     |          kernel stack           |
     |                |                |
     |                |                |
     |                V                |
     |         grows downward          |
     |               ...               |
     |               ...               |
     |       switch_threads's          |
     |       stack frame <---+         |
     |                       |         |
     |                       |         |
     |                       |         |
     |                       |         |
     +-----------------------+---------+
     |              magic    |         |
     |                :      |         |
     |              stack---+          |
     |               name              |
     |              status             |
0 kB +---------------------------------+
```

Context Switching, Take 2



External Interrupts & Context Switches

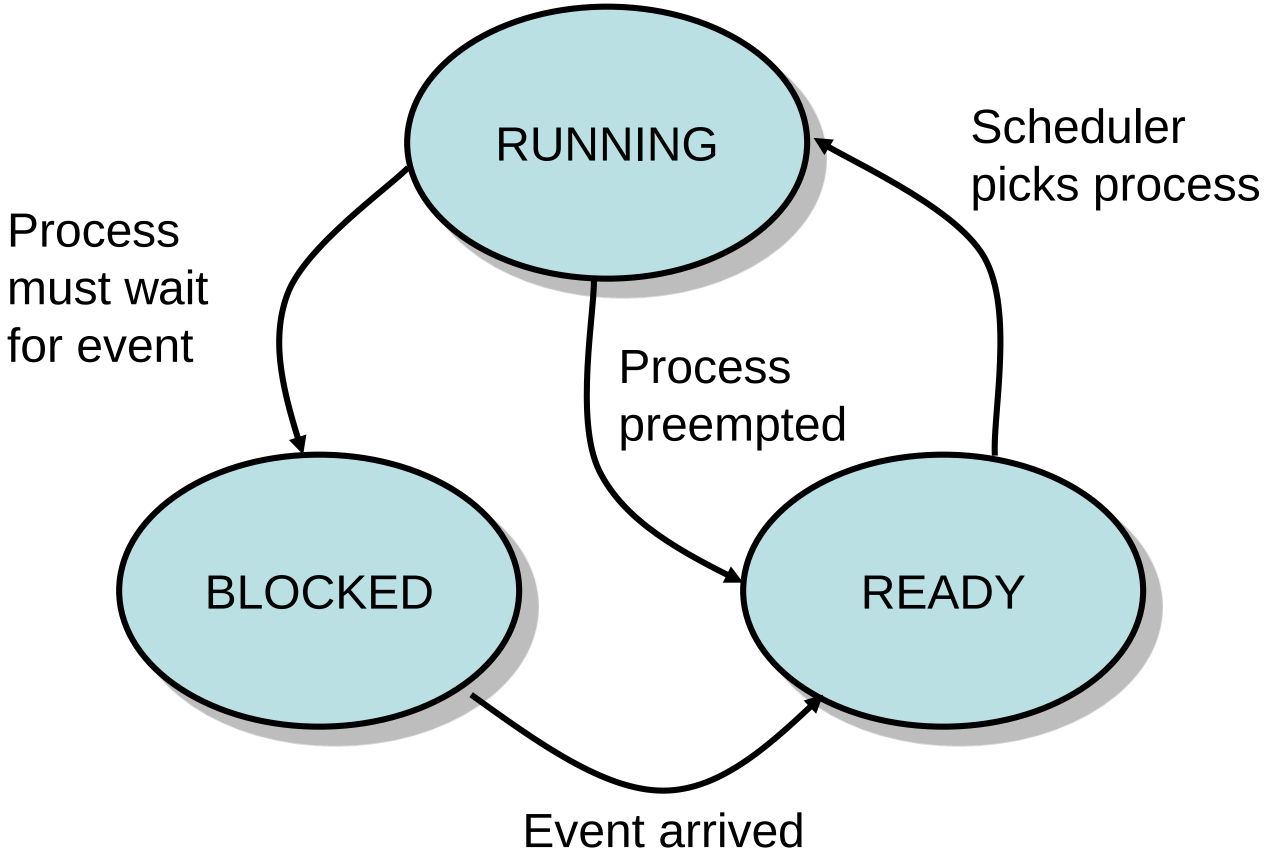
```
intr_entry:
        /* Save caller's registers. */
        pushl %ds; pushl %es; pushl %fs; pushl %gs; pushal

        /* Set up kernel environment. */
        cld
        mov $SEL_KDSEG, %eax                    /* Initialize segment registers. */
        mov %eax, %ds; mov %eax, %es
        leal 56(%esp), %ebp                     /* Set up frame pointer. */

        pushl %esp
        call intr_handler    /* Call interrupt handler. Context switch happens in there*/
        addl $4, %esp
        /* FALL THROUGH */
intr_exit:                          /* Separate entry for initial user program start */
       /* Restore caller's registers. */
       popal; popl %gs; popl %fs; popl %es; popl %ds
       iret   /* Return to current process, or to new process after context switch. */
```

Context Switching: Summary

- Context switch means to save the current and restore next process's execution context
- Context Switch != Mode Switch
  - Although mode switch often precedes context switch
- Asynchronous context switch happens in interrupt handler
  - Usually last thing before leaving handler
- Have ignored so far when to context switch & why $\rightarrow$ next

PROCESS STATES & EVENTS

Process States



- Only 1 process (per CPU) can be in RUNNING state

Process Events

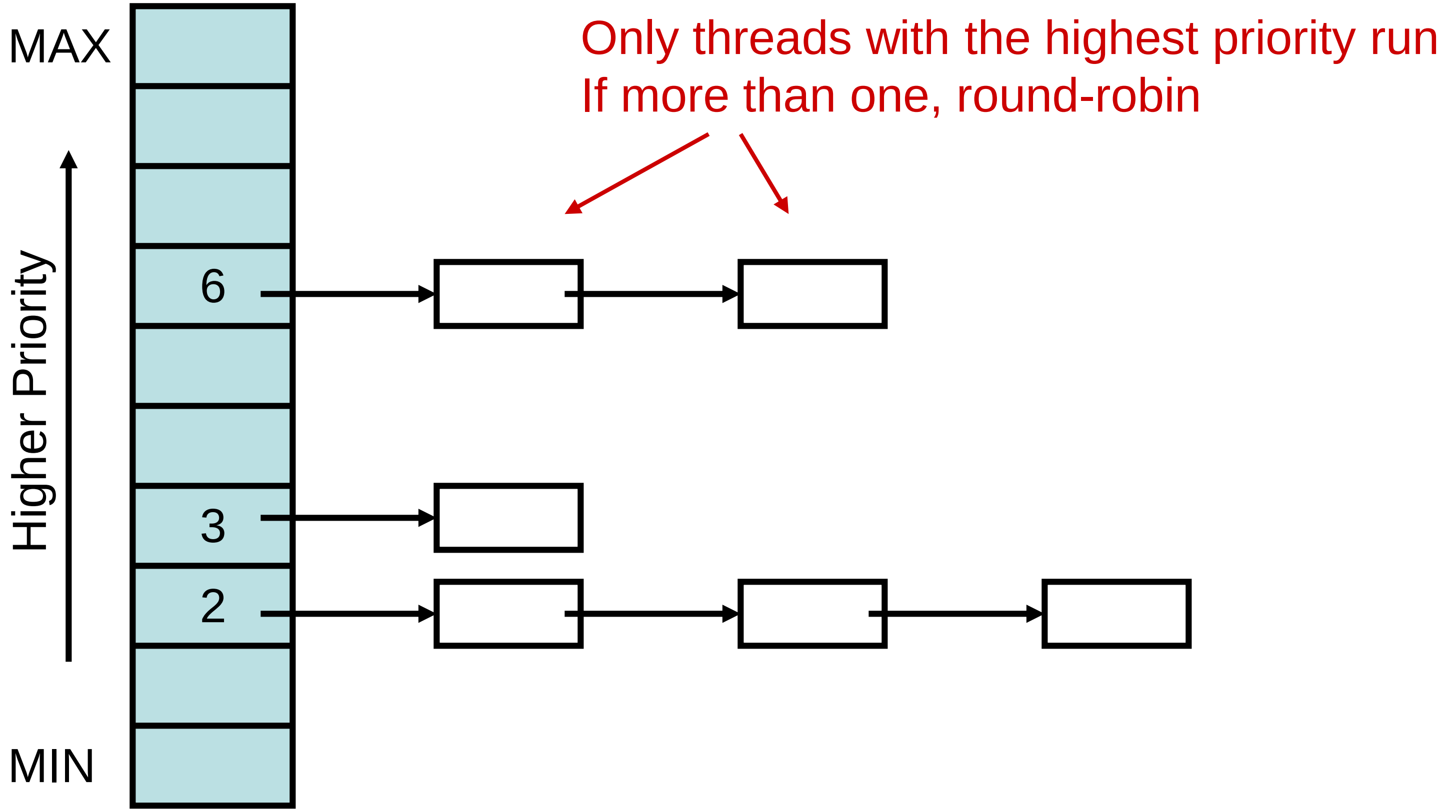
- What's an event?
  - External event:
    - disk controller completes sector transfer to memory
    - network controller signals that new packet has been received
    - clock has advanced to a predetermined time
  - Events that arise from process interaction:
    - a resource that was previously held by some process is now available (e.g., lock_release)
    - an explicit signal is sent to a process (e.g., cond_signal)
    - a process has exited or was killed
    - a new process has been created

Process Lists

- All ready processes are inserted in a "ready list" data structure
  - Running process typically not kept on ready list
  - Can implement as multiple (real) ready lists, e.g., one for each priority class
- All blocked processes are kept on lists
  - List usually associated with event that caused blocking – usually one list per object that's causing events
- Most of scheduling involves simple and clever ways of manipulating lists (r/b trees nowadays)

SCHEDULING CONCEPTS & POLICIES

Priority Based Scheduling



- Done in Linux (pre 2.6.23), Windows, (previous semester) Pintos

Priority Based Scheduling (2)

- Advantage:
  - Dead simple: the highest-priority process runs
  - Q.: what is the complexity of finding which process that is?
- Disadvantage:
  - Not fair: lower-priority processes will never run
  - Hence, must adjust priorities somehow
- Many schedulers used in today's general purpose and embedded OS work like this
  - Only difference is how/whether priorities are adjusted to provide fairness and avoid starvation
  - Exception: Linux "completely-fair scheduler" uses different scheme which project 1 is based on

Reasons for Preemption

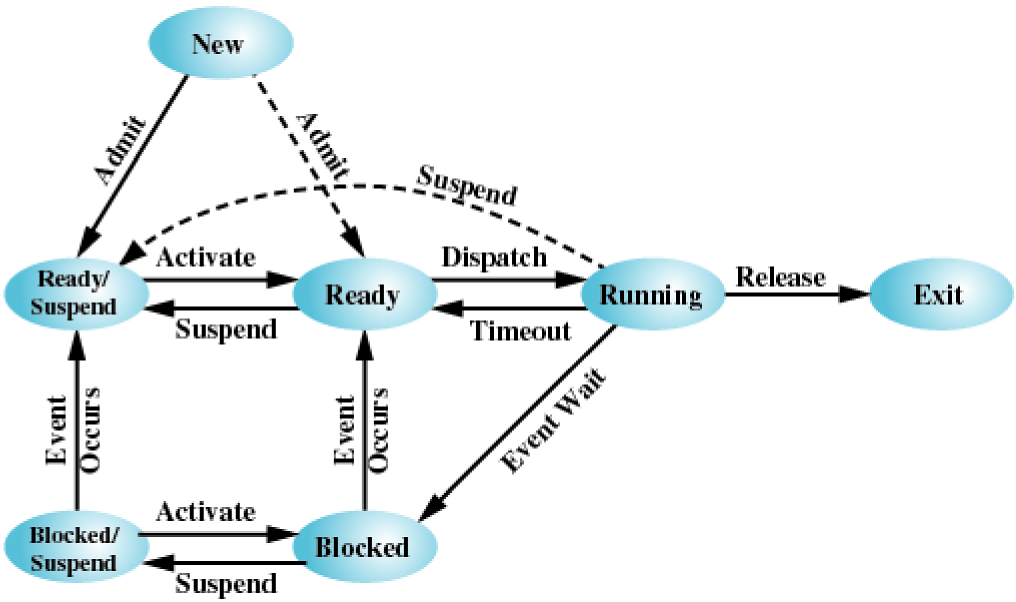
- Generally two: quantum expired or change in priorities
- Reason #1:
  – A process of higher importance than the one that's currently running has just become ready
- Reason #2:
  – Time Slice (or Quantum) expired
- Question: what's good about long vs. short time slices?

I/O Bound vs CPU Bound Procs

- Processes that usually exhaust their quanta are said to be CPU bound
- Processes that frequently block for I/O are said to be I/O bound
- Q.: what are examples of each?

- What policy should a scheduler use to juggle the needs of both?

Process States w/ Suspend

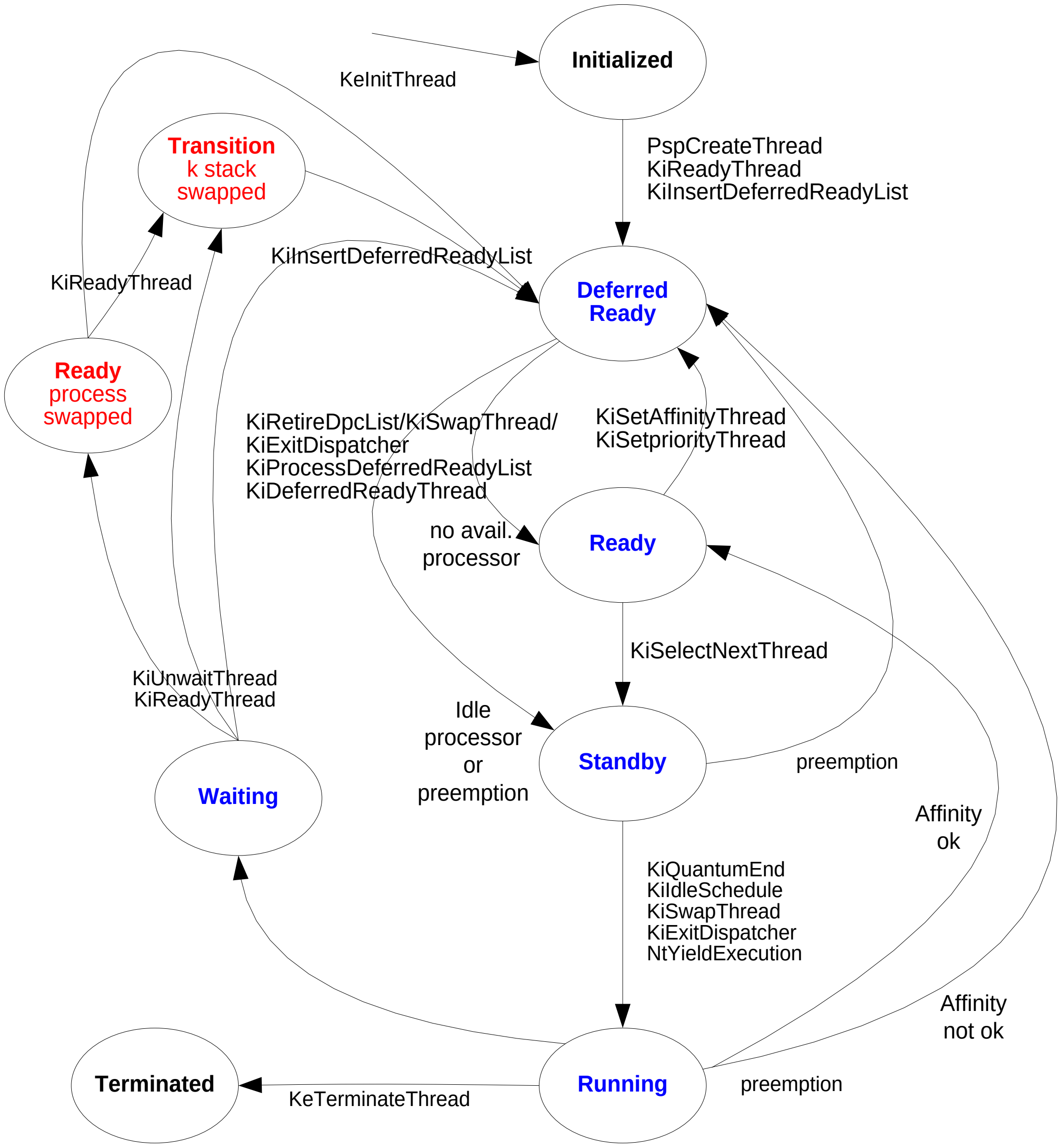


(b) With Two Suspend States

- Can be useful sometimes to suspend processes
  - By user request: ^Z in Linux shell/job control
  - By OS decision: swapping out entire processes (Solaris & Windows do that, Linux doesn't)

Windows XP

- Thread state diagram in an industrial kernel



- Source: Dave Probert, Windows Internals – Copyright Microsoft 2003

Windows XP

- Priority scheduler uses 32 priorities
- Scheduling class determines range in which priority are adjusted
- Source: Microsoft® Windows® Internals, Fourth Edition: Microsoft Windows Server™