SYSTEM CALL IMPLEMENTATION

CS124 – Operating Systems

Spring 2024, Lecture 13

User Processes and System Calls

- Previously stated that user applications interact with kernel via system calls
- Typically invoked via a trap instruction
  - An intentional software-generated exception
- The kernel registers a handler for a specific trap
  - `int $0x80` for Linux system calls
  - `int $0x2e` for Windows system calls
  - `int $0x30` for Pintos system calls
- Can't easily pass arguments to system calls on the stack
  - Trap instruction causes CPU to switch operating modes (from user mode to kernel mode)
  - Different operating modes have different stacks

User Processes and System Calls (2)

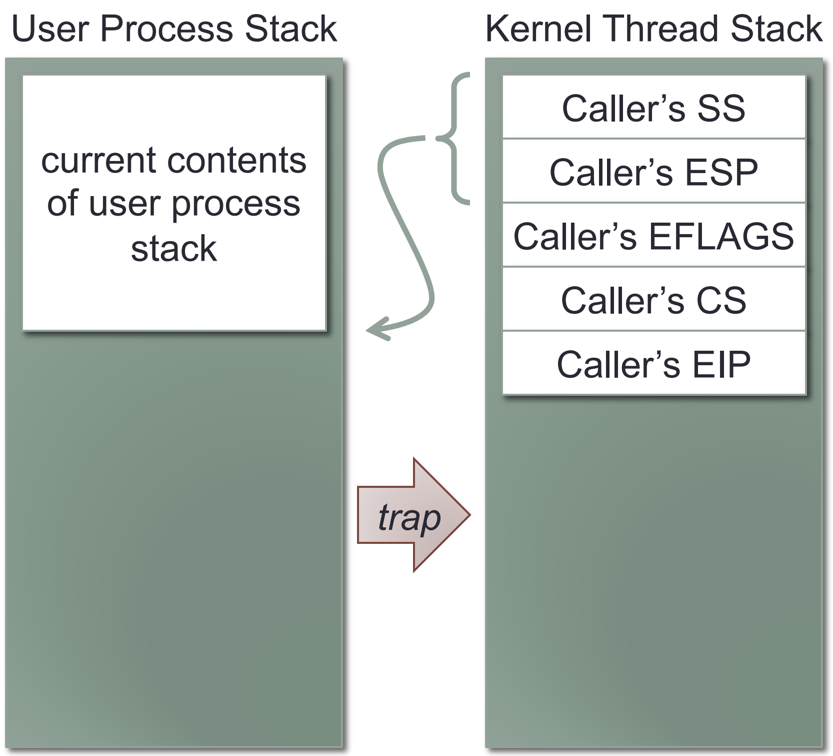
- Typically, arguments to system calls are passed in registers, and the return-value(s) come back in registers
- One of the arguments is an integer indicating which system call to invoke
  - e.g. on Linux and Windows, **`%eax`** is set to operation to perform
  - e.g. on UNIX systems, **`sys/syscall.h`** specifies these numbers
  - Note: UNIX syscall IDs are not uniform across different UNIXes
- Obvious constraint: system-call arguments can't be wider than the registers
- Several possible approaches:
  - Can split larger arguments across multiple registers
  - Can store larger arguments in a struct, then pass a pointer to the struct as an argument

User Processes and System Calls (3)

- The operating system frequently exposes system calls via a standard library
  - e.g. UNIX syscalls are exposed via the C standard library (**`libc`**)
  - e.g. Windows syscalls exposed via the (largely undocumented) Native API (**`ntapi.dll`**)
- The library serves as an intermediary between apps and the operating system
- Some functions are direct wrappers for system calls
  - e.g. **`ssize_t read(int fd, void *buf, size_t nbyte)`**
  - Implementation stores arguments from stack into registers, invokes the system call entry-point (e.g. **`int $0x80`**), and returns result
- Others utilize system call wrappers internally
  - e.g. **`malloc()`** is mainly implemented in user space, but uses system calls to increase the process' heap size

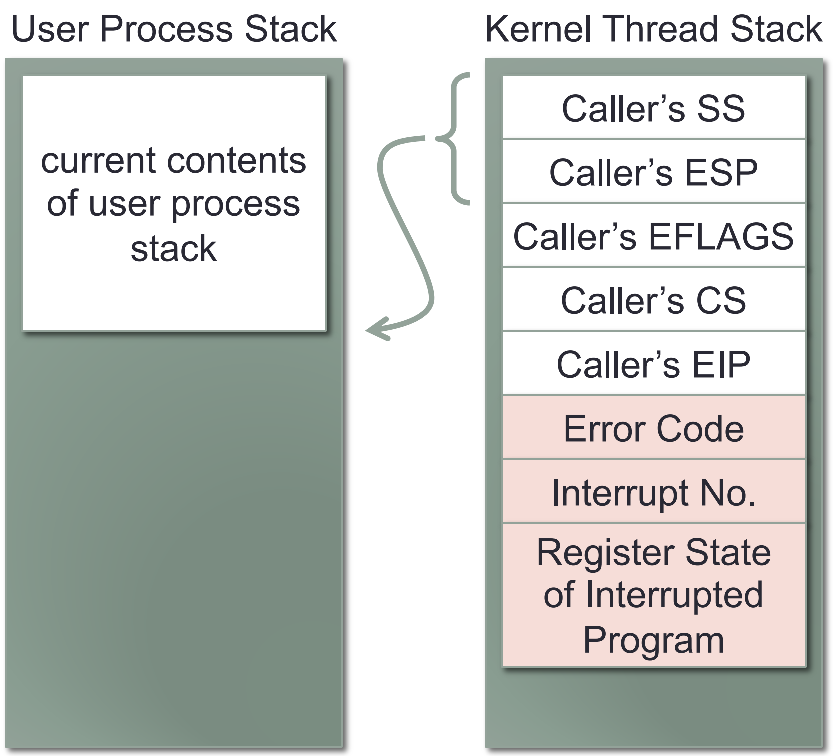
Review: Interrupt Mechanics

- Previously discussed how interrupts and traps are handled on IA32 (see lecture 8 for details)
  - User process has its own stack
  - Executing the trap causes the CPU to switch to the kernel-mode stack associated with the process
- Since system calls change from user mode to kernel mode, IA32 saves a pointer to the previous stack on the new stack
- Next, CPU saves the user process' execution state: **`cs`**, **`eip`** and **`eflags`**



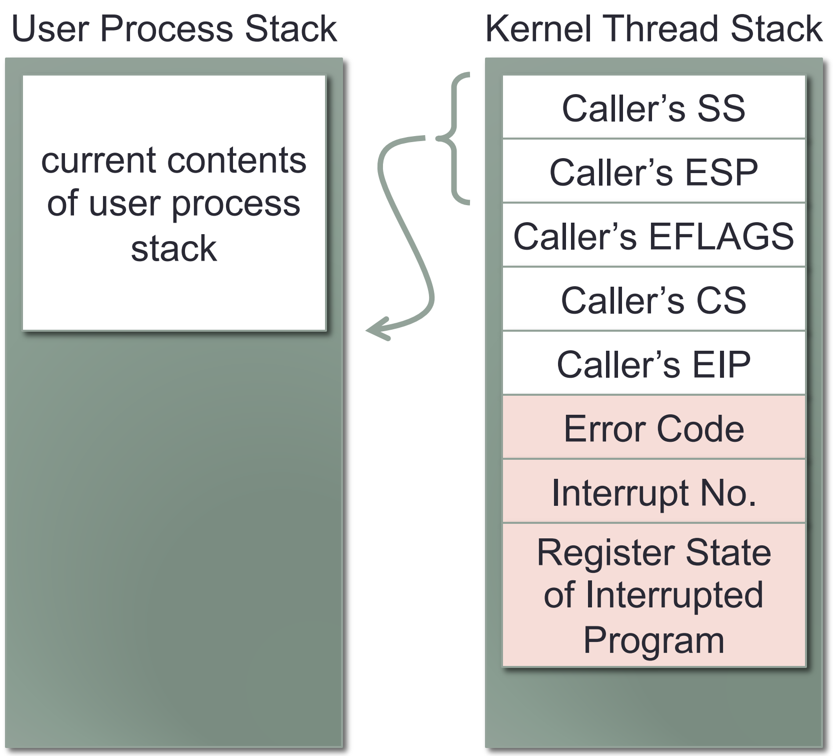
Review: Interrupt Mechanics (2)

- Operating system has a stub for every possible interrupt
- Some interrupts push an error code onto the stack; if not, the OS stub will push a dummy value for consistency
- Next, the stub pushes the interrupt number onto the stack
- Finally, the stub records all register state onto kernel stack
- Now the Interrupt Service Routine (ISR) can run without disrupting the interrupted code



System Call Mechanics

- The operating system exposes the user program's CPU and register state as arguments to the ISR
  - Typically exposed to ISR as a struct with a field for each register
- System call handler needs to receive arguments from the user program
  - Can easily access these values on the kernel stack
- Syscall handler also returns a status result in **`eax`**
  - Can modify user program's **`eax`** on the kernel stack
  - When the kernel returns to the user program, its context is restored
  - Program sees new value of **`eax`**



System Call Mechanics (2)

- The ID of the system call is used to dispatch to a function that implements the system call
  - Called a **system call service routine**
- System call service routines are usually named after their user-mode entry points
  - e.g. **`sys_write()`** implements **`write()`**
  - e.g. **`sys_fork()`** implements **`fork()`**
  - (Aside: these service routines are sometimes called within the kernel implementation to implement more complex operations)
- A system call table holds an array of function pointers to all system call service routines
  - The syscall ID is used to index into this table when making the call

System Call Mechanics (3)

- Need to check the system call ID to ensure it's valid…
  - If it's invalid, return **`ENOSYS`** "Function not implemented" error
- Can easily check that the ID is below the max syscall ID
- If a specific syscall ID below the max is not supported, simply register a service routine that returns ENOSYS

Example: Linux System Calls

- Snippet [paraphrased] of Linux **`system_call()`** handler:

```
    ...  # Save registers onto stack

    # Make sure it's a valid syscall ID
    cmpl $(NR_syscalls), %eax
    jb nobadsys

    # Return-value of syscall() will be in eax
    # as usual, so set value of eax stored on
    # kernel stack to ENOSYS to indicate error
    movl $(-ENOSYS), 24(%esp)
    jmp ret_from_sys_call
nobadsys:
    ...
```

Example: Linux System Calls (2)

- Linux **`system_call()`** handler, continued:

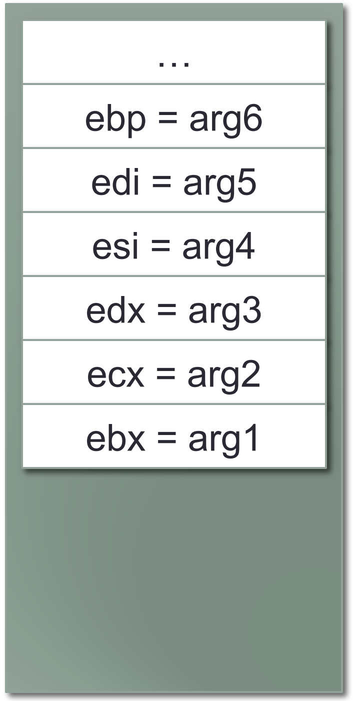
```
    ...
nobadsys:
    # Dispatch to the function in the system-call
    # table corresponding to the specified ID
    # (On IA32, pointers are 4 bytes, so use
    # ID*4 as the address within the table)
    call *sys_call_table(, %eax, 4)

    # Store return-value from routine into
    # location of eax on the kernel stack
    movl %eax, 24(%esp)
    jmp ret_from_sys_call
```

Example: Linux System Calls (3)

- Different syscalls require different numbers of arguments
  - e.g. **`getpid()`** and **`fork()`** require no arguments
  - e.g. **`mmap()`** requires up to six arguments
- System-call arguments are passed from the user process in specific registers
  - **`ebx`** is first argument, **`ecx`** is second argument, etc.
- Syscall service routines are written in C, and expect their arguments on the kernel stack (cdecl calling convention)
- Linux **`system_call()`** handler pushes all of the process' registers onto the kernel stack in a specific order
  - Specifically, the reverse order that registers are used to pass arguments to system calls

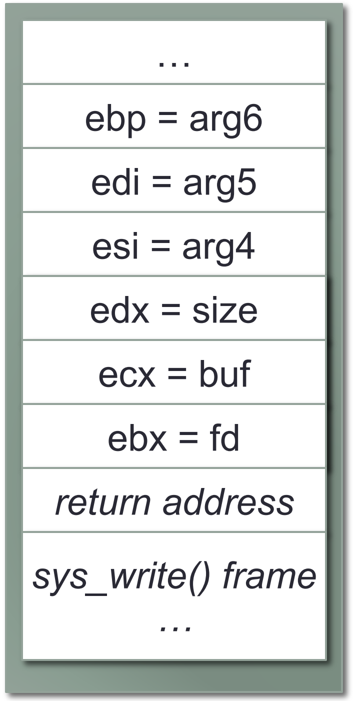
Kernel Thread Stack



Example: Linux System Calls (4)

- Arguments to syscall service routines are pushed in reverse order, following the cdecl calling convention
- Under cdecl, if a function is passed more arguments than it expects, the extra arguments are ignored
- Allows **`system_call()`** to dispatch to all the different service routines, regardless of the number of arguments they take
- e.g. int sys_write(int fd, char *buf, int size)
  - Service routine for write(int fd, char *buf, int size)
- When system_call() dispatches to sys_write(), sys_write() sees only the expected arguments
  - Extra arguments are simply ignored by sys_write()

Kernel Thread Stack



System Calls: Security Holes?

- It goes without saying that the system call service routine must carefully check all arguments to the system call…

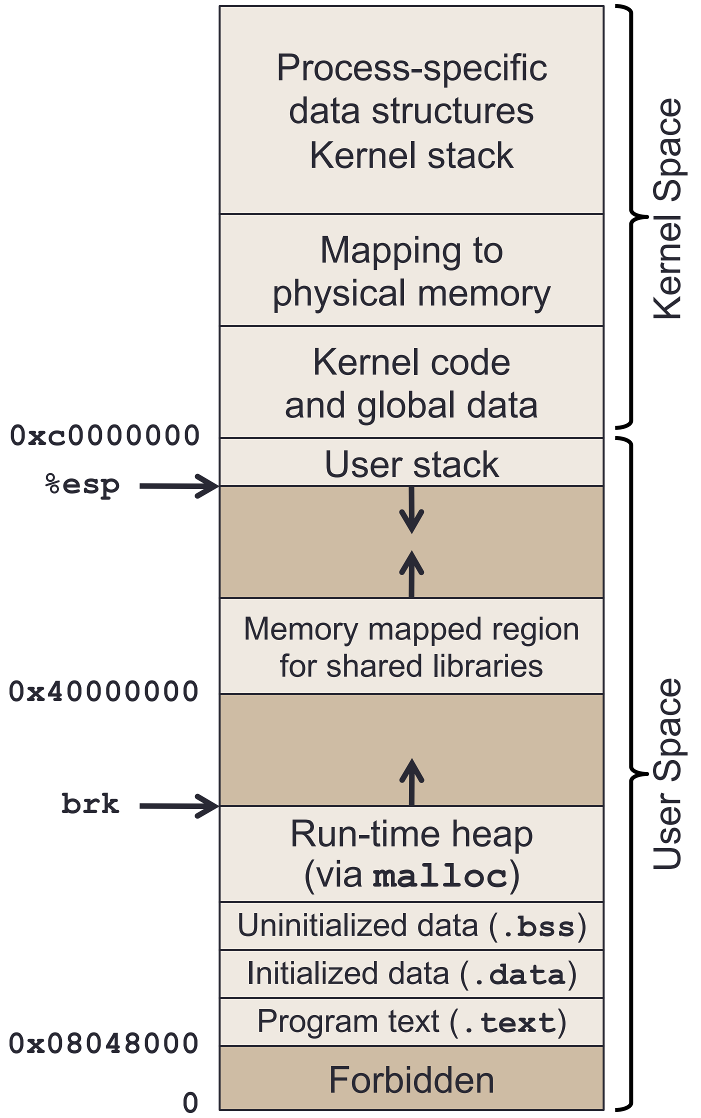
- Are there potential security holes in accepting pointers as arguments to system calls?
- Example: `ssize_t read(int fd, void *buf, size_t nbytes)`
  - Reads bytes from a file descriptor into a buffer
- Caller specifies:
  - The file-descriptor to read
  - A pointer to the buffer to store the data in
  - A number of bytes to read

System Calls: Security Holes?!

- Example: `ssize_t read(int fd, void *buf, size_t nbytes)`
- Generally the pointers are expected to be in user space…
- What if user-mode program specifies an address in kernel's address space?
  - As long as the user-mode program doesn't access this address, it won't cause a general protection fault…
- But, the kernel <u>is</u> allowed to write to this address!
  - If kernel naïvely accepts address from the user program, it could overwrite critical data
- Example: target critical kernel data structures
  - Program opens file containing the data it wants to insert into kernel
  - Program passes that file descriptor and address of kernel struct…

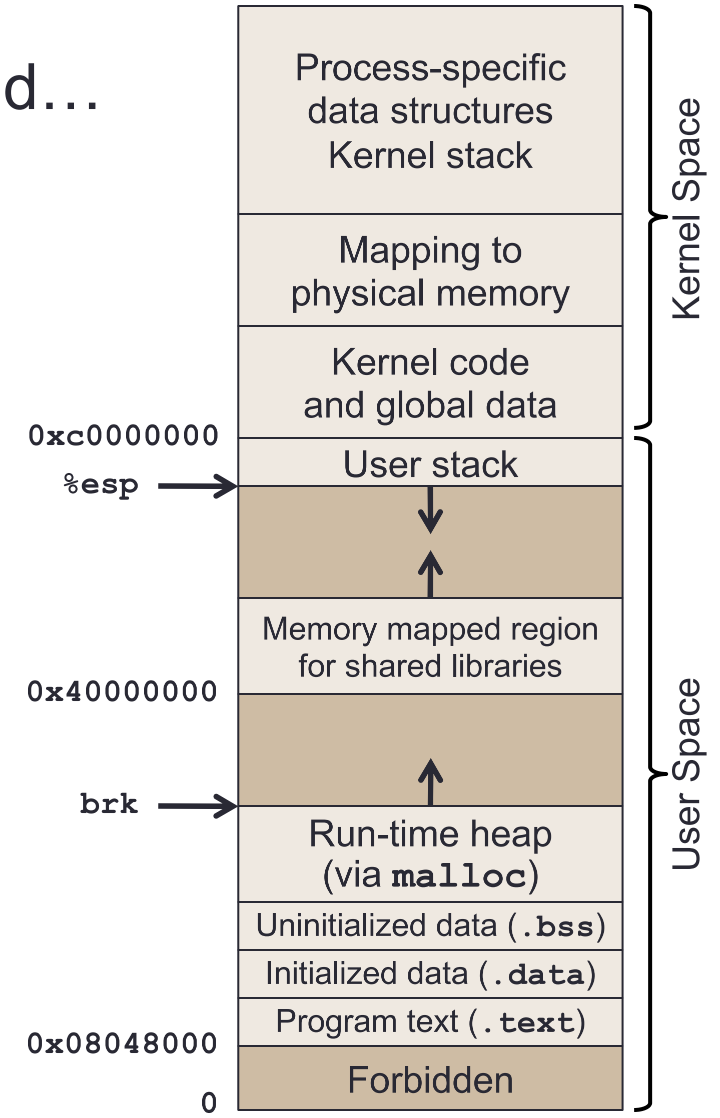
System Calls: Security Holes

- Very important to verify all addresses that come from user-mode programs:
  - Addresses must be in userspace!
  - If an address is in kernel space, it's an access violation
- A fast way to verify addresses:
  - Make sure the address is below the kernel/user address boundary (e.g. 0xc0000000 in 32b-Linux/Pintos, called **PHYS_BASE** in Pintos)



System Calls and Page Faults

- Addresses below kernel/user boundary could still be invalid…
  - e.g. pass a pointer to unallocated memory to a **`read()`** system call
  - e.g. pass a pointer to read-only memory to a **`write()`** system call
- OS will see a page fault or a general protection fault within the kernel
- Problem: this isn't always an error!
  - Many OSes don't allocate virtual memory pages until they are actually accessed
  - Private copy-on-write pages are marked read-only; first attempt to write causes the page to be copied for the writing process



System Calls and Page Faults (2)

- Aside:
  - In the Pintos system-call lab, virtual memory management isn't completed yet, so a page fault does mean an invalid address ☺
- The OS may see memory faults within the kernel:
  - Sometimes these are valid scenarios
  - Sometimes it's an invalid pointer passed to a syscall ☹
  - Sometimes it is a kernel bug ☹ ☹
- Assume there is a way to identify the valid scenarios…
  - (We will examine that question in a few weeks)
- *How do we distinguish between the remaining two cases?*

System Calls and Page Faults (3)

- How to distinguish between:
  - Faults caused by invalid addresses passed to system calls
  - Faults caused by kernel bugs
- Linux has a very interesting solution to this problem
- *How much kernel code actually interacts with user space?*
  - (Remember, the CPU state of user processes is saved onto the kernel stack, which is in kernel space)

System Calls and Page Faults (4)

- The amount of kernel code that interacts with user space is actually very small…

- Linux kernel keeps an **exception table**, which records the addresses of all instructions that touch user space
- In the fault handler, consult the exception table:
  - If the faulting instruction is in the exception table, then the user program passed the kernel a bad pointer
  - Otherwise, it's a kernel bug ☹
- Aside: if it's a kernel bug, Linux performs a **kernel oops**
  - Print out suitable info for a kernel developer to debug the error, and log it to the system log
  - Then terminate the process!
  - Keeps kernel bugs from bringing down the entire system…

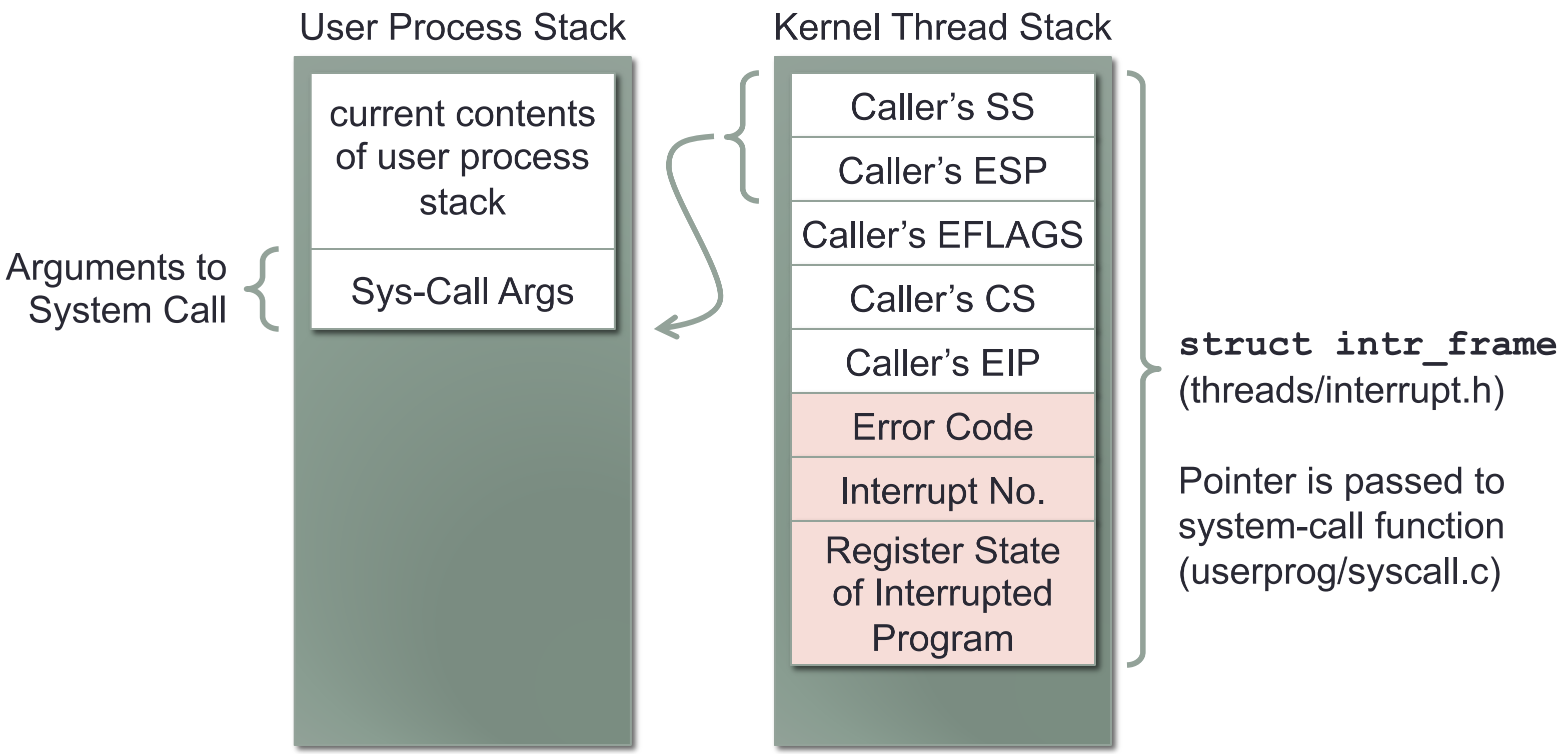
Example Kernel Oops

```
          _________________________________
         < Your System ate a SPARC! Gah! >
          ---------------------------------
                \   ^__^
                 \  (xx)\_______
                    (__)\       )\/\
                     U  ||----w |
                        ||     ||
sshd (pid 19569): Protection id trap (code 27)

     YZrvWESTHLNXBCVMcbcbcbcbOGFRQPDI
PSW: 00000000000001101111110100001111 Not tainted
r00-03  00000000 10435a40 101820e4 1d9cfba0
r04-07  00000001 0007d0a8 000000c9 1d9cfba0
r08-11  00000000 0007d0b0 00000001 fffffff2
r12-15  0006ba00 00068c04 0004d800 0006a404
r16-19  00068c04 0006a404 0006b404 00000001
r20-23  00000001 00000003 0007d0ae 1d9cfbae
r24-27  00000000 00000001 1be099e0 10347010
```

Pintos System Calls

- Pintos doesn't follow the Linux syscall mechanism
  - Syscall arguments are on the user stack, not in the registers
- This complicates the syscall mechanism, but only slightly
- Pictorially:



Pintos System Calls (2)

- **`intr_frame`** struct exposes process machine context
- Note that topmost values on stack appear at bottom of the structure…
  - Recall: C structure members are assigned increasing offsets from start of struct
  - Last struct members have highest addresses
- This struct makes it easy to access the user process' stack contents
  - e.g. retrieve **`esp`** member, cast to **`uint32_t*`**, then access user stack like an array

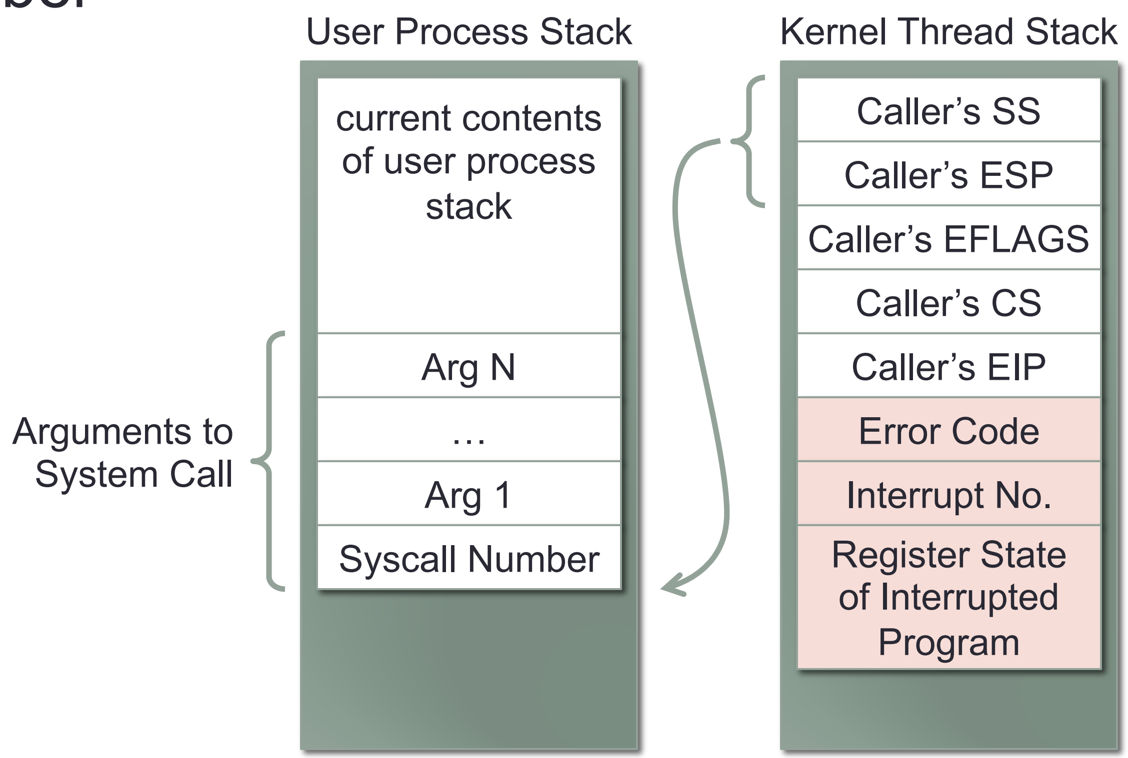
```
struct intr_frame {
  // Pushed by intr_entry (intr-stubs.S).
  // The interrupted task's saved registers.
  uint32_t edi;            // Saved EDI
  uint32_t esi;            // Saved ESI
  uint32_t ebp;            // Saved EBP
  uint32_t esp_dummy;      // Not used
  uint32_t ebx;            // Saved EBX
  ...

  // Pushed by intrNN_stub (intr-stubs.S).
  uint32_t vec_no;  // Interrupt vector no.
  // Sometimes pushed by CPU; otherwise for
  // consistency, 0 is pushed (intrNN_stub).
  uint32_t error_code;

  // Pushed by the CPU.  These are the
  // interrupted task's saved registers.
  void (*eip) (void);   // Next instruction
  uint16_t cs, :16;     // Code segment
  uint32_t eflags;      // Saved CPU flags
  void *esp;            // Saved stack ptr
  uint16_t ss, :16;     // Stack segment
};
```

Pintos System Calls (3)

- Pintos system-call arguments are pushed on the user process stack
  - Arguments themselves are pushed in reverse order
  - Finally, system-call number is pushed
- Caller's **`esp`** points to the system-call number
  - Use syscall number to determine how many arguments are required
- Finally, read in the arguments themselves
  - The kernel is accessing user-space, so it needs to do this carefully



Next Time

- Begin discussing virtual memory abstraction