CIS 5512 - Operating Systems
Processes & Threads

Professor Qiang Zeng

TEMPLE UNIVERSITY

Some graphs are courtesy of Bovet and Cesati

Previous class…

What are the two different CPU modes?

Kernel mode and user mode

Previous class…

What is the difference between kernel mode and user mode?

1. Privileged instructions, e.g., I/O instructions, can only be issued (when the CPU is) in the kernel mode
2. Some memory address space (i.e., the kernel space) can only be accessed in the kernel mode; this portion of memory stores the kernel code and data

Previous class…

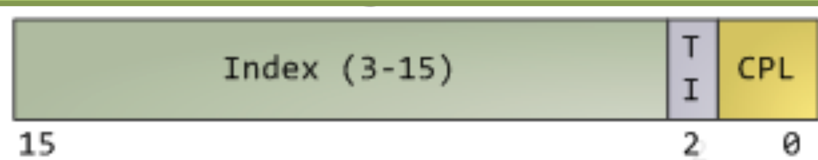
Why are Protection Rings needed?

- **Fault isolation:** the program crash can be captured and handled by a lower ring
- **Privileged instructions** can only be issued in a privileged ring (e.g., ring 0), which makes resource management, isolation and protection possible
- **"Privileged" memory address space** (e.g., the kernel space) can only be accessed in a privileged ring

Previous class…

Given an X86 CPU, how do you tell whether the CPUS is in the kernel mode or user mode

The lowest two bits in the CS (Code Segment) register indicate the **Current Privilege Level** of the CPU. E.g., 00 means that the CPU is in ring 0



Previous class…

What if privileged instructions are executed in user mode?

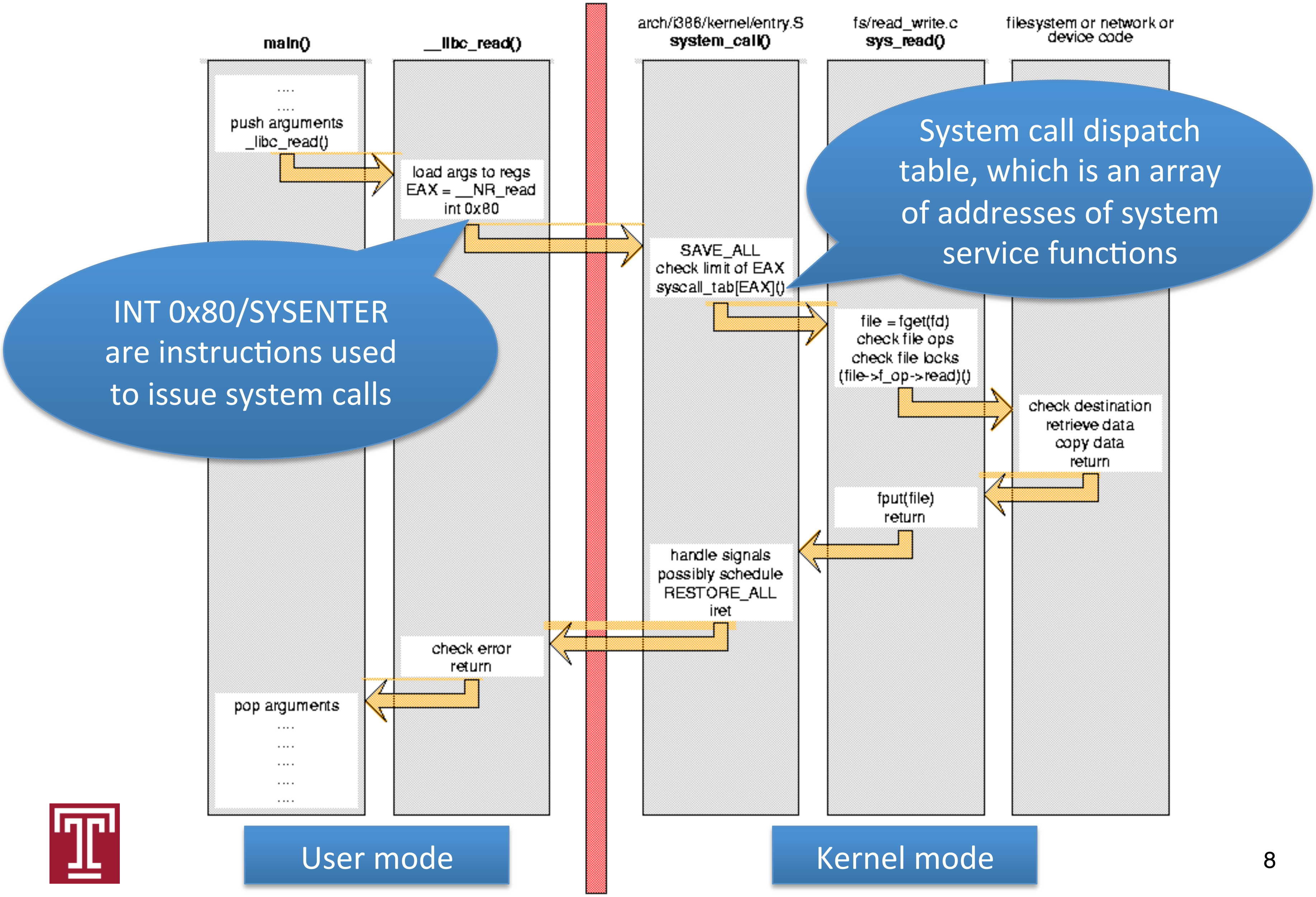
Whenever a privileged instruction is executed, the CPU checks whether it is in the kernel mode; if not, an exception (e.g., in x86, a General Protection Fault) is triggered to end the current process

Previous class…

Given that I/O instructions can only be executed in the kernel mode, how does a user program perform I/O?

System calls. When a system call is invoked, the CPU mode switches to kernel mode and CPU can thus execute privileged instructions, such as I/O instructions

System calls in Linux



Process vs. Thread

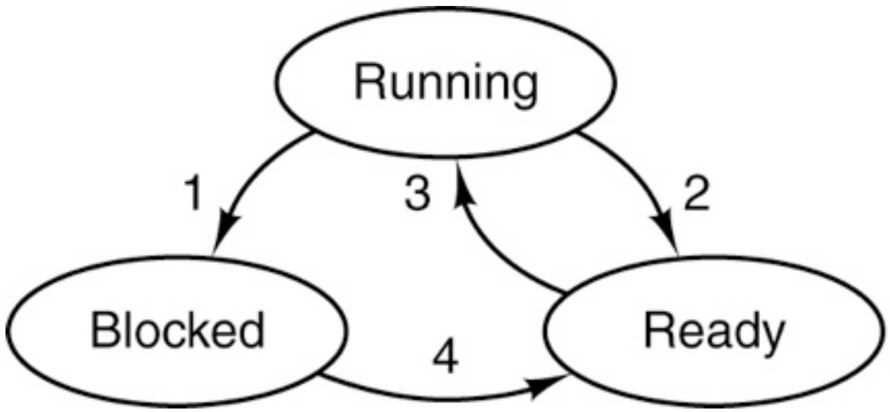
Process

- A process is an executing instance of a program
- Different processes have different memory address spaces
- Resource-heavyweight: significant resources are consumed when creating a new process

Thread

- A thread is the entity within a process that can be scheduled for code execution
- A process has at least one thread
- Threads of a process share a lot of information, such as memory address space, opened files, etc.
- Resource-lightweight

Three basic process states and the transitions



1. Process blocks for input
2. Scheduler picks another process
3. Scheduler picks this process
4. Input becomes available

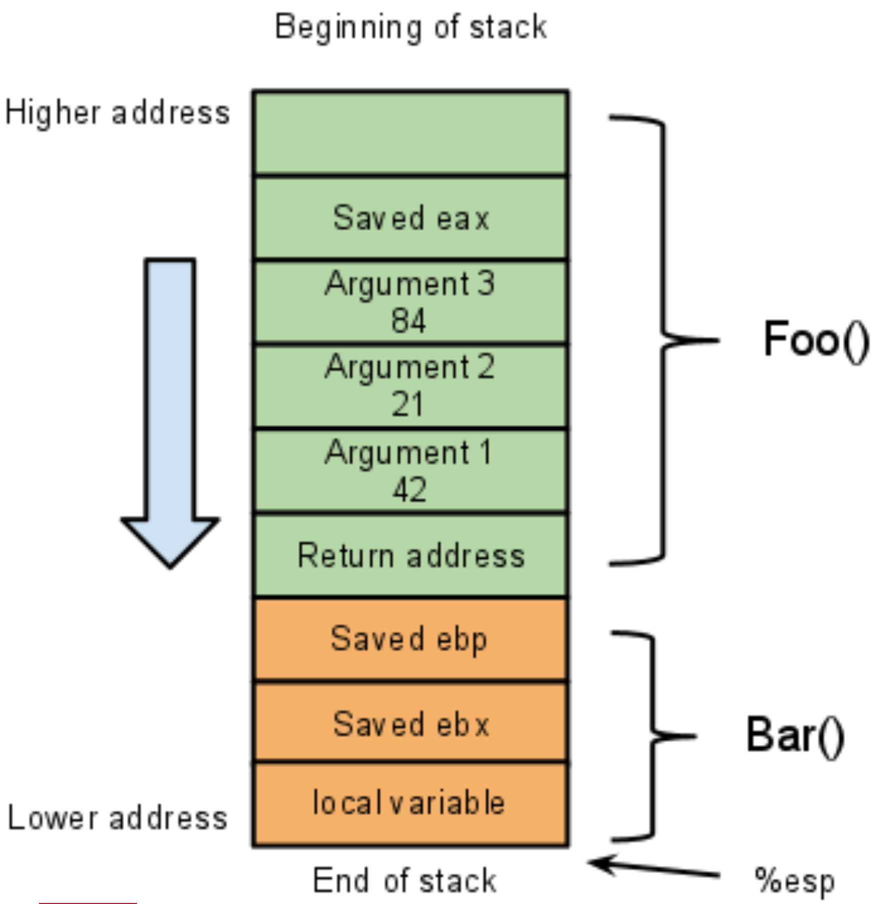
The transitions 1, 2 & 3 involves context switch (or, process switch), which will be discussed next

Call stack

- A call stack is a stack data structure that store information of the active function calls
- A call stack is composed of stack frames (also called activation records or activation frames). Each function call corresponds to a stack frame, which consists of
  - Arguments passed to the routine
  - The return address
  - Saved register values (in order to restore them at return)
  - Local variables
- The call stack grows when a new call is issued, and shrinks when a function call returns

Call stack and calling convention (x86-32 as an example)

- `Bar(42, 21, 84) // invoked by Foo()`



	Cleans Stack	Arguments	Arg Ordering
cdecl	Caller	On the Stack	Right-to-left
fastcall	Callee	ECX,EDX, then stack	Left-to-Right
stdcall	Callee	On the Stack	Left-to-Right
VC++ thiscall	Callee	EDX (this), then stack	Right-to-left
GCC thiscall	Caller	On the Stack (this pointer first)	Right-to-left

Execution context

- The execution context (or *context*; or processor *state*) is the contents of the CPU registers at any point of time
  - Program counter: a specialized register that indicates the current program location
  - Call stack pointer: indicates the top of the kernel-space call stack for the process (will be covered soon)
  - A specialized register that indicates the page table (will be covered in the memory section of the course)
  - Other register values

Caution: the meaning of “state” is ambiguous

- It may refer to *process* state: Running/Blocked/ Ready
- Or, the *processor* state, i.e., the execution context

Where is the context information stored?

- A Process Control Block (PCB) is an instance of a data structure in the kernel memory containing the information needed to manage a particular process. It includes
  - Stored execution context
  - Process ID
  - Process control information, such as the scheduling state, opened file descriptors, accounting information

Linux's PCB: task_struct

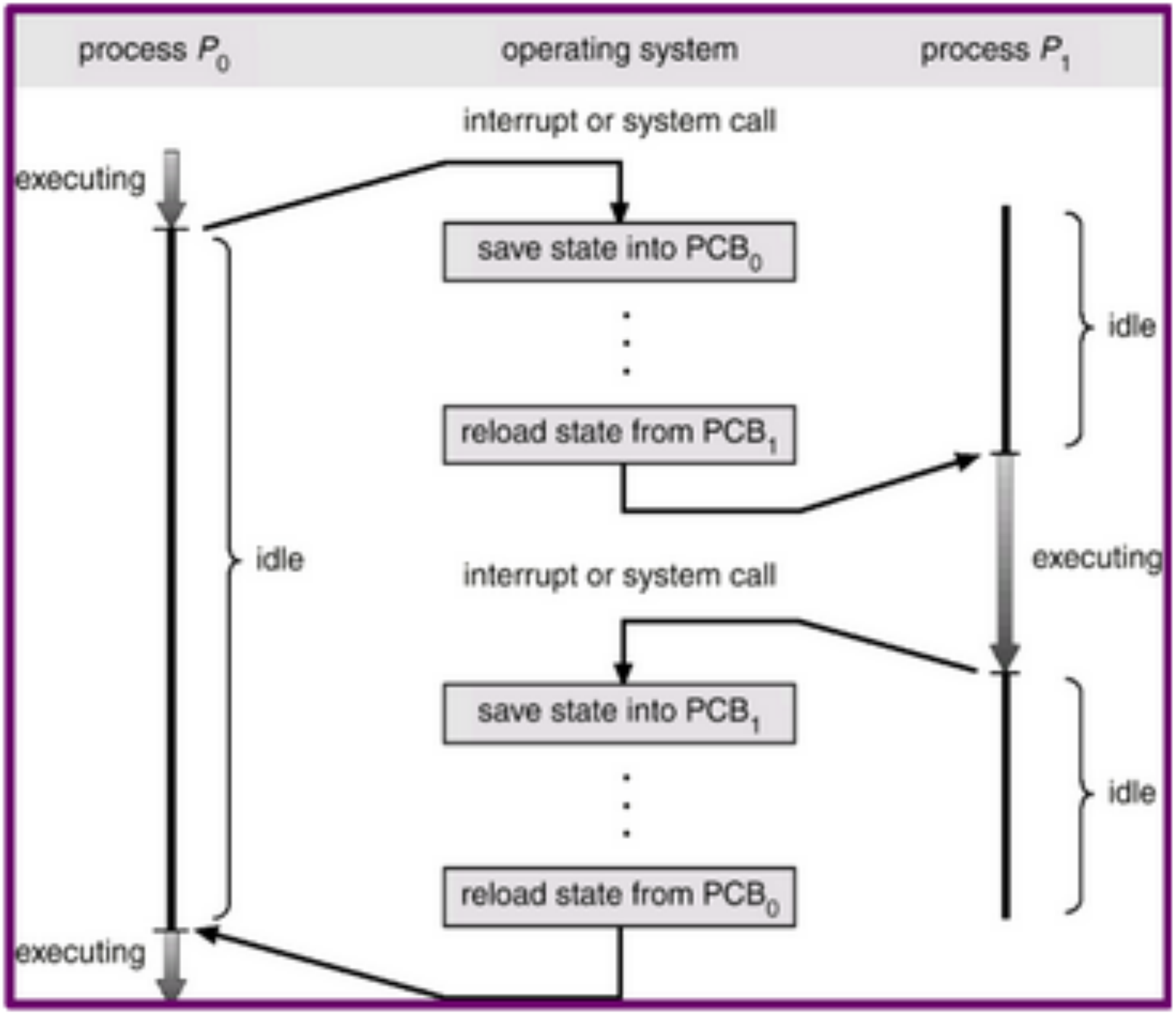
include/linux/sched.h

```
1344 struct task_struct {
1346          void *stack;
1444          pid_t pid; // thread id
1445          pid_t tgid; // thread group id
1527 /* open file information */
1528          struct files_struct *files;
1531 /* signal handlers */
1532          struct signal_struct *signal;
1780          struct thread_struct thread;
```

The execution context is stored in the thread_struct structure

Context switch (or, process switch)

- Context switching, also called *task switch or process switch*, is to suspend the execution of one process on a CPU and to resume execution of another process
  - Store the context of the current process into its PCB
  - The scheduler picks a process in the "ready" list
  - Retrieve the context of the picked process from its PCB and restore the contents of the CPU registers
- The first process is scheduled *out* and the second process is scheduled *in*



process P_0
operating system
process P_1
interrupt or system call
executing
save state into PCB_0
idle
reload state from PCB_1
idle
executing
interrupt or system call
save state into PCB_1
idle
reload state from PCB_0
executing

When does context switching occur?

- A process blocks (due to I/O or synchronization) or exits
- The CPU time slice of the current process is used up

How does the kernel track when the CPU time slice of the current process is used up?

- Assume the timer interrupt has a frequency of 1000hz, i.e., it occurs once per 1ms
- Assume the CPU time slice for a process is 10ms; thus, a counter of the process is set to 10 when it is scheduled in
- Each time the timer interrupt occurs, the interrupt handler (in kernel) will decrement the counter
- When the counter is 0, scheduling occurs: the current process is scheduled out and another is scheduled in

Timer interrupts ensure that the CPU time allocation is under the control of the kernel; i.e., no user process can occupy the CPU longer than it is supposed to

Mode switch

- Mode switch means program execution switches between different CPU modes
  - User -> kernel
  - Kernel -> user
  - Other: kernel <-> hypervisor
- When does the user -> kernel mode switch occur?
  - System calls
  - Interrupts (if CPU is is user mode)
  - Exceptions (if CPU is in user mode)
- We have covered system calls; next, we will introduce interrupts and exceptions

Interrupts, Exceptions and Signals

Type	Triggered by	Examples
Exceptions (or, s/w interrupts)	Instruction execution	breakpoint; page fault; divide-by-zero; system calls
Signals (sent by kernel; handled in userspace)	kill(); sent by exception handler	SIGTRAP; SIGSEGV; SIGFPE
Interrupts (or, h/w interrupts)	interval timer and I/O	timer; input available
Language exceptions (as in C++ and Java)	throw	throw std::invalid_argument(“”);

Exceptions

- Programmed exceptions
  - int 0x80 // old method of issuing system calls
  - int 3 // single-step debugging
- Anomalous executions
  - a/0 //divide by zero
  - p = NULL; a = *p // a kind of page fault

Signals due to exceptions

#	Exception	Exception handler	Signal
0	Divide error	divide_error( )	SIGFPE
1	Debug	debug( )	SIGTRAP
2	NMI	nmi( )	None
3	Breakpoint	int3( )	SIGTRAP
4	Overflow	overflow( )	SIGSEGV
5	Bounds check	bounds( )	SIGSEGV
6	Invalid opcode	invalid_op( )	SIGILL
7	Device not available	device_not_available( )	None
8	Double fault	doublefault_fn( )	None
9	Coprocessor segment overrun	coprocessor_segment_overrun( )	SIGFPE
10	Invalid TSS	invalid_TSS( )	SIGSEGV
11	Segment not present	segment_not_present( )	SIGBUS
12	Stack segment fault	stack_segment( )	SIGBUS
13	General protection	general_protection( )	SIGSEGV
14	Page Fault	page_fault( )	SIGSEGV
15	Intel-reserved	None	None
16	Floating-point error	coprocessor_error( )	SIGFPE
17	Alignment check	alignment_check( )	SIGBUS
18	Machine check	machine_check( )	None
19	SIMD floating point	simd_coprocessor_error( )	SIGFPE

An exception is usually converted to a user space signal

Signals due to IPC

Tips: “kill –l” to list all signal names

- cmd “*kill –signame pid*” or function “*kill(pid, sig)*”: send signals to a process
- The parameter “*pid*” above is very expressive
  - >0: a real pid
  - 0: all processes in the same process group as the sender process
  - -1: all processes for which the sender has permission to send signals
  - When a signal is sent to a process, it can be handled by any thread of the process
- *pthread_kill()*: send signals to a specific thread within the sender’s process
- *tgkill(pid, tid, sig)*: send a signal to thread *tid* in process *pid*. Warning: This is Linux specific
- *sigqueue(pid, sig, value):* send a signal and an associate value to process pid

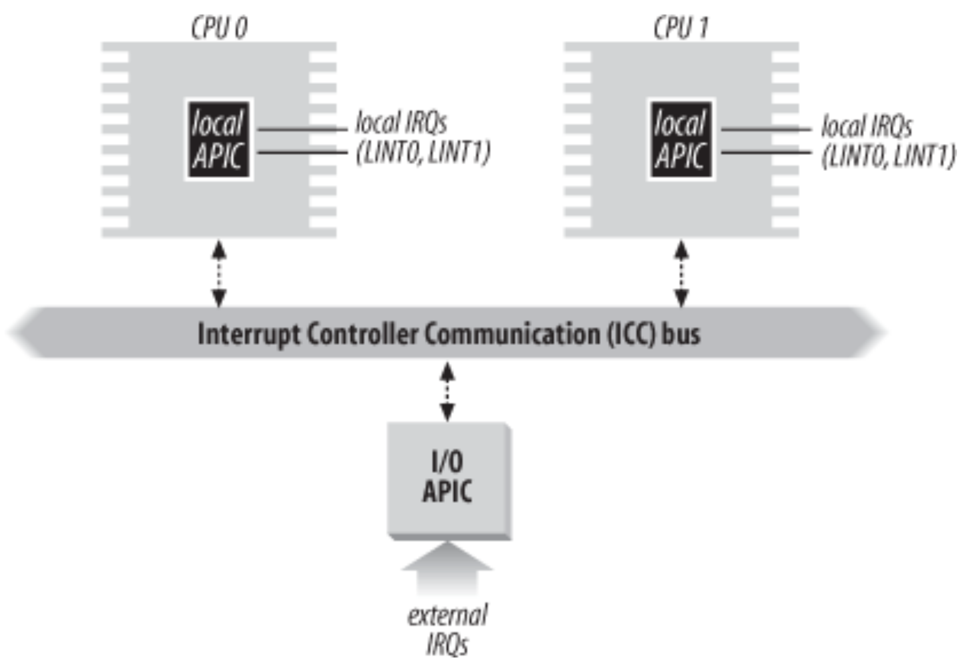
Signal handler

- Signal handlers are shared among threads of a process, while the signal mask is per thread
- If you want to change the default signal handling behaviors, use `sigaction()` to install your own handlers; don't use signal()
  - `signal()` is not reliable in the sense that, upon the invocation of your handler, the default signal handler is restored as default
  - With `signal()`, when your handler is being invoked, the same type of signals are not blocked
  - Plus, `sigaction()` is more capable. For example
    - It supports blocking other signals when your handler is invoked
    - If a blocking system call, e.g., `read/write()`, is interrupted by the signal handling, the system call can be restarted automatically

Linux's new *signal*() implementation supports reliable signals. The implementation actually invokes *sigaction*(). Don't rely on that; other Unix OSes may not be that way

Interrupts and the hardware

- Each interrupt and exception is identified by a number in [0, 255]. Intel calls this number vector
- IRQ: Interrupt ReQuest line
- PIC: Programmable Interrupt Controller
- NMI: Non-Maskable Interrupt
- IPI: Inter-Processor Interrupt (through local APIC)

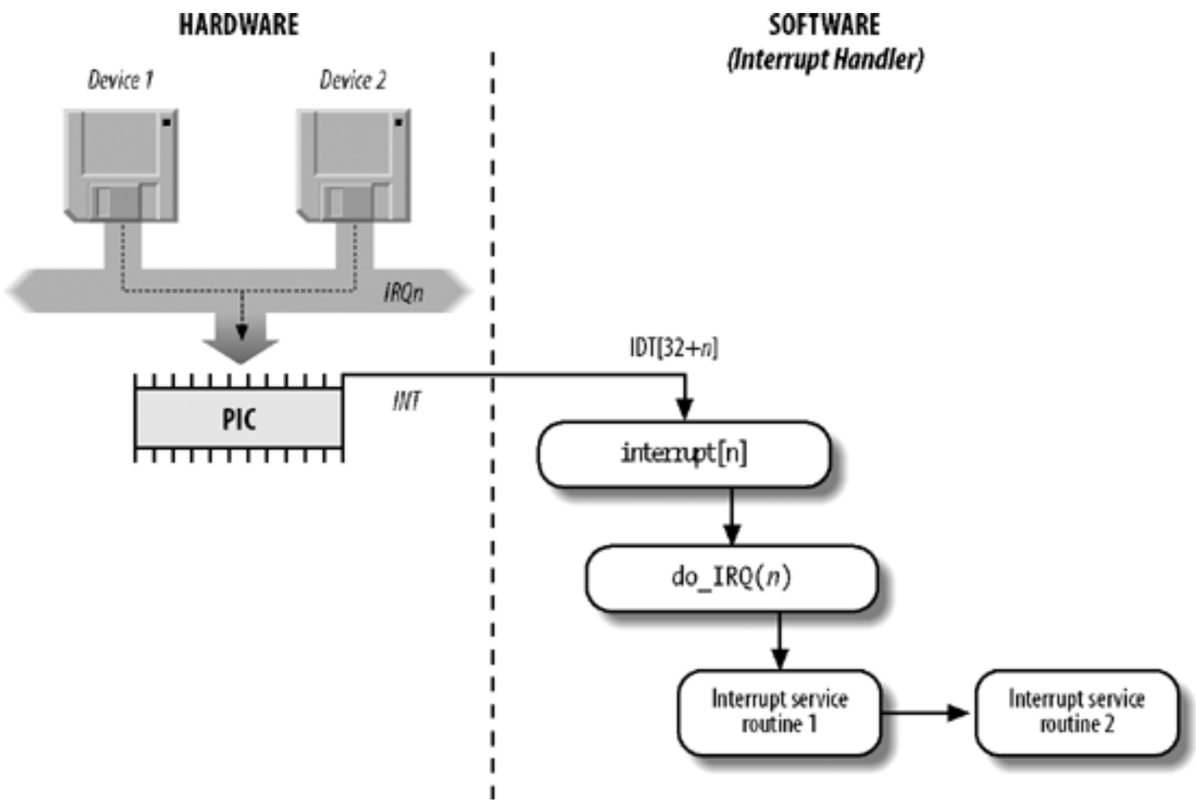


Interrupt Descriptor Table (IDT)

- Used by both Interrupt and Exception handling
- Each entry is a descriptor that refers to an Interrupt or Exception handler
- Difference between the Interrupt entry and the Exception entry
  - CPU will clear the IF flag to disable local interrupts upon handling of an interrupt (using `cli` instruction)
  - IF flag will not be disabled when handling exceptions

Interrupt/exception handling

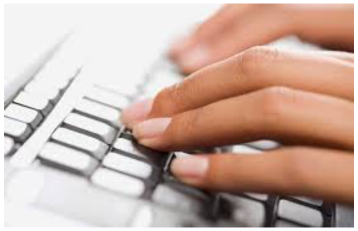
- CPU uses the IDT to jump to a handler automatically. Below shows interrupt handling



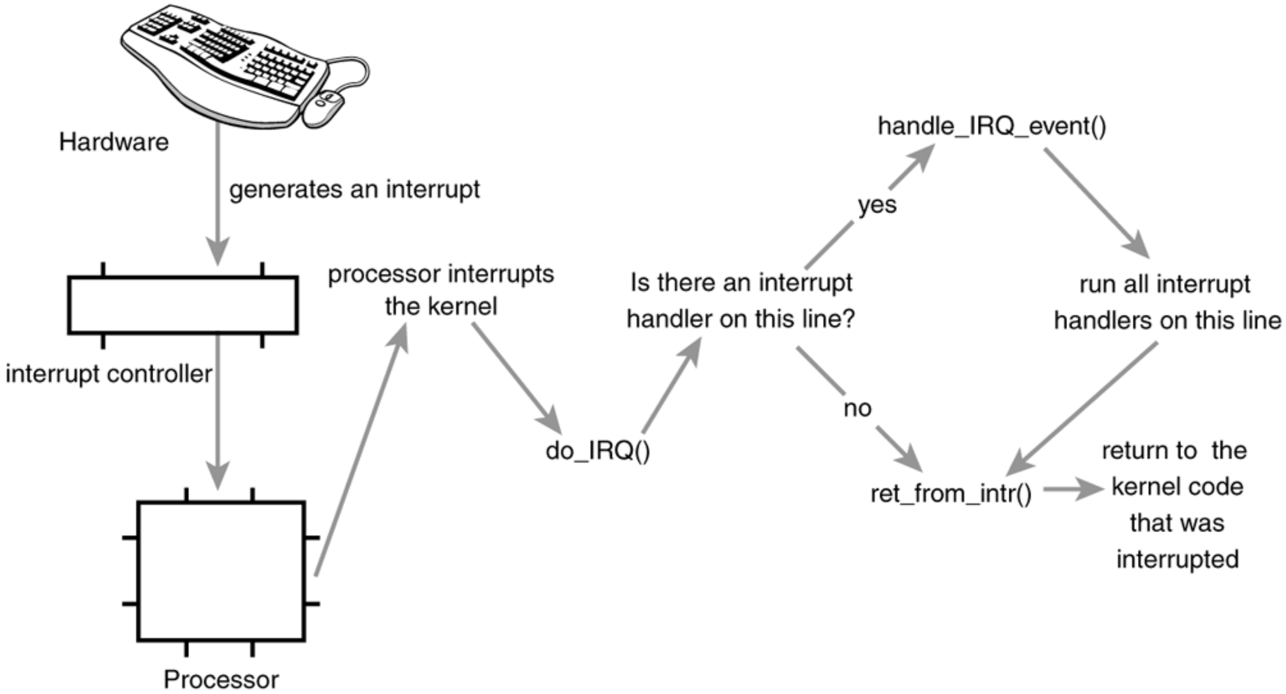
Interrupt/exception handling

- Basic steps:
  - Mode switch to kernel mode if the current mode is user mode
  - Save the current context
  - Invoke the corresponding handler function
  - Restore the context
  - Mode switch back to user mode if the original mode was user mode

What happens upon a keystroke?



- Interrupt handling
  - Hardware part
    - CPU refers to IDT to locate the handler
  - Software part
    - Execution of the handler according to the interrupt number



Which processes have PID 0 and PID 1

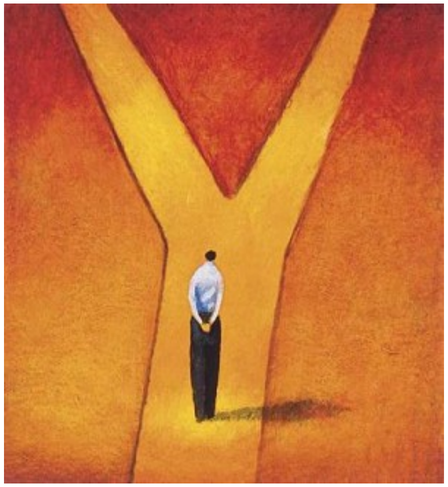
- Try command "`ps -eaf`"
- PID 0: `idle` process
  - The first process
  - Invoke `hlt` instructions when being scheduled to save power
- PID 1: `init` process
  - Initially it is a kernel thread created by `idle`
  - Then `exec(init)` to become a regular process

```
qiang@ubuntu:~$ ps -eaf | head -10
UID        PID  PPID  C STIME TTY          TIME CMD
root         1     0  0 Aug27 ?        00:00:01 /sbin/init
root         2     0  0 Aug27 ?        00:00:00 [kthreadd]
root         3     2  0 Aug27 ?        00:00:00 [migration/0]
root         4     2  0 Aug27 ?        00:00:04 [ksoftirqd/0]
root         5     2  0 Aug27 ?        00:00:00 [watchdog/0]
root         6     2  0 Aug27 ?        00:00:10 [events/0]
root         7     2  0 Aug27 ?        00:00:00 [cpuset]
root         8     2  0 Aug27 ?        00:00:00 [khelper]
root         9     2  0 Aug27 ?        00:00:00 [netns]
```

How is a process created? Userspace view

- `fork()`: create a new process

```
int pid = fork();
if (pid < 0) {
      // error; no process created;
} else if (pid  > 0) {
      // this is the parent process
else { // pid == 0
      // this is the child process
}
```



Parent

```c
int main()
{
    pid_t pid;
    char *message;
    int n;
    pid = fork();
    if (pid < 0) {
        perror("fork failed");
        exit(1);
    }
    if (pid == 0) {
        message = "This is the child\n";
        n = 6;
    } else {
        message = "This is the parent\n";
        n = 3;
    }
    for(; n > 0; n--) {
        printf(message);
        sleep(1);
    }
    return 0;
}
```

Child

```c
int main()
{
    pid_t pid;
    char *message;
    int n;
    pid = fork();
    if (pid < 0) {
        perror("fork failed");
        exit(1);
    }
    if (pid == 0) {
        message = "This is the child\n";
        n = 6;
    } else {
        message = "This is the parent\n";
        n = 3;
    }
    for(; n > 0; n--) {
        printf(message);
        sleep(1);
    }
    return 0;
}
```

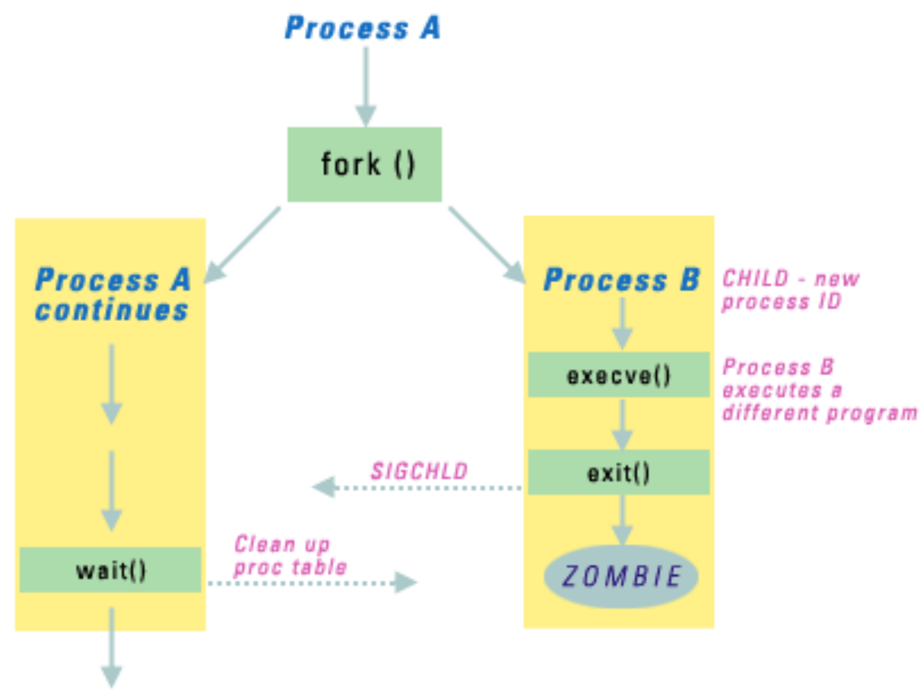
Some APIs critical for implementing shell

- The **exec**() family of functions (execl, execlp, execle, …) changes the program being executed.
  - E.g., `execl("/bin/ls","ls","-l",NULL);`
  - *"/bin/ls" determines the program to be executed, while "ls", "-l" form argv[]*
- The **wait**() system call suspends execution of the calling process until one of its children terminates.

How is `shell` implemented?

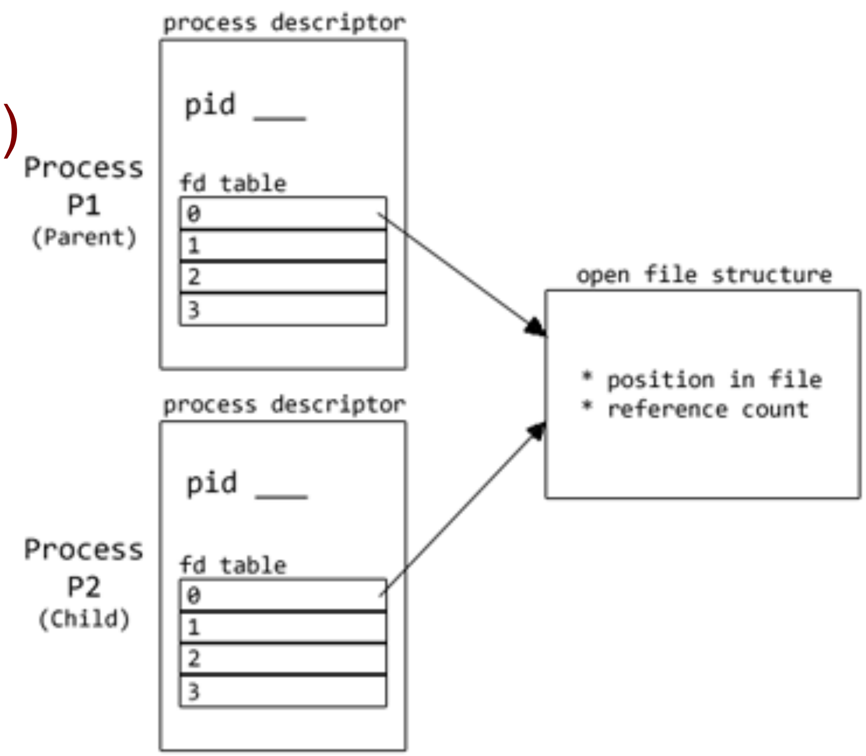
```
char *prog, **args;
int child_pid;

// Read and parse the input a line at a time
while (readAndParseCmdLine(&prog, &args)) {
   child_pid = fork();
   if (child_pid < 0)
      exit(-1);
   if (child_pid == 0) {
       exec(prog, args);
      // NOT REACHED
   } else {
       wait(child_pid);
   }
}
```

Q: How is `system(char* cmd)` implemented?
A: Just remove the loop wrapper of the left



How is fork() implemented in kernel?

- Kernel stack
  - Copied; each has its own
- Address space
  - "Copied"
  - Copy-on-write (later classes)
- PCB
  - Copied with PID changed
  - Including signal mask/ handling and file descriptors
  - A file descriptor is an integer pointing to a file description
  - Thus, file description is shared



Zombie Process in Linux/Unix

- Once a child process exits, it becomes a zombie process with its exit state to be queried by its parent. A zombie process is cleaned up if
  - Its parent calls wait() to retrieve the exit state, or
  - Its parent has expressed no interest in that exit state by installing handler for *SIGCHLD*
- If a parent process exits, its zombie child processes become children of the *init* (pid = 1) process, which periodically reaps zombies
  - Zombie processes occupy precious kernel resources (e.g., PCB), which you want to reclaim ASAP; don't defer it to the *init* process

Take away…

- Process state transition
  - Ready, blocked, running
- Context switch
  - Process switch
- Mode switch
  - System calls
  - Interrupt/exception handling
- Interrupt vs. exception vs. signal
- Calling convention
- fork() and Shell

Interesting Readings

- https://superuser.com/questions/1052231/does-32-or-64-bits-cpu-use-segmentation-addressing-on-linux