TI III: Operating Systems & Computer Networks
Subsystems, Interrupts, and System Calls

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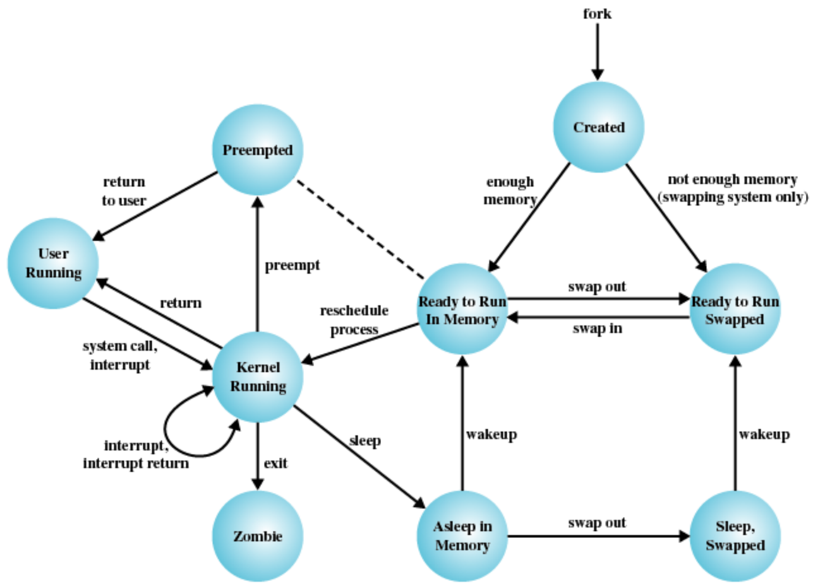

Content

Hierarchical System View

13	Shell	
12	User processes	
11	Directories	Shared and distributed resources
10	Devices	
9	File system	
8	Communications	
7	Virtual memory	
6	Local secondary storage	Pre-processor resources
5	Primitive processes	
4	Interrupts	
3	Procedures	
2	Instruction set	
1	Electronic circuits	Hardware support

4. Interrupts
   - Objects: interrupt service routines (ISRs)
   - Operations: call, mask, unmask
3. Procedures
   - Objects: subroutines, call stack
   - Operations: stack pointer, call, return
2. Instruction Set
   - Objects: stack, microcode compiler, scalar and vector data
   - Operations: add, subtract, load, store, branch, …
1. Electronic Circuits
   - Objects: registers, memory cells, logic gates
   - Operations: register or memory access

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7. Virtual Memory
   - Objects: segments, pages
   - Operations: read, write, load
6. Secondary Storage
   - Objects: blocks of data, device channels
   - Operations: read, write, lock, unlock
5. Primitive processes (program being executed)
   - Objects: simple processes, semaphore, ready lists
   - Operations: suspend, resume, wait, signal

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13. Shell
    - Objects: user programming interface
    - Operations: operations in shell command language
12. User Processes (incl. data on used resources)
    - Objects: user processes
    - Operations: create, terminate, suspend, resume
11. Directories
    - Objects: directories
    - Operations: create, delete, append, remove, search, list
10. Devices
    - Objects: external devices, e.g., printer, display, and keyboard
    - Operations: open, close, read, write
9. File System
    - Objects: named files
    - Operations: create, delete, open, close, read, write
8. Inter-process Communication (IPC)
    - Objects: channels, shared memory
    - Operations: create, delete, open, close, read, write

Questions & Tasks

- Compare this system view with the layered structure from Computer Architecture – which parts do you recognize?
- Compare this system view with the memory hierarchy from Computer Architecture – how can you map the different types of memory to this system view?
- Take your computer, your OS and try to find out the different components of this system view – can you find or identify them all?
- For those used to window-based user interfaces, touch screens, voice interfaces, gesture-controlled gadgets etc. – try to find a shell and play with it! (yes, those were the old days, but you can learn a lot going back to the roots!)

Content

Interrupts - Motivation

A lot of devices are connected to a computer, e.g.,

- Keyboard, hard disk, network interface

These devices occasionally need CPU service:

- Keyboard: a key is pressed
- Hard disk: a task is completed
- Network interface: a packet has arrived

BUT: it is **not predictable** when these devices need to be serviced

How does the CPU find out that a device needs attention?

- Two options: **Interrupts** and **Polling**

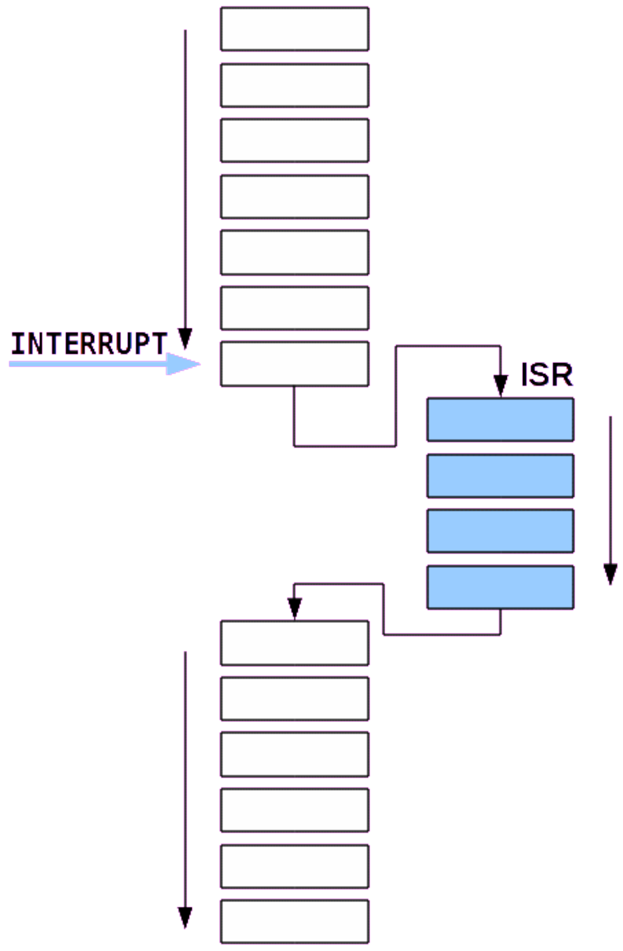
Interrupts versus Polling

Interrupts	Polling
Give each device a wire that it can use to signal the CPU.	Ask the devices periodically if an event has occured.
Like a phone that rings when a call comes in.	Like a phone without a bell: You have to pick it up every few seconds to see if you have a call.
No overhead when no requests pending, efficient use of CPU time.	Takes CPU time even when no requests pending.
Devices are serviced as soon as possible - low latency.	Response time depends on polling rate.

Interrupt Service Routines

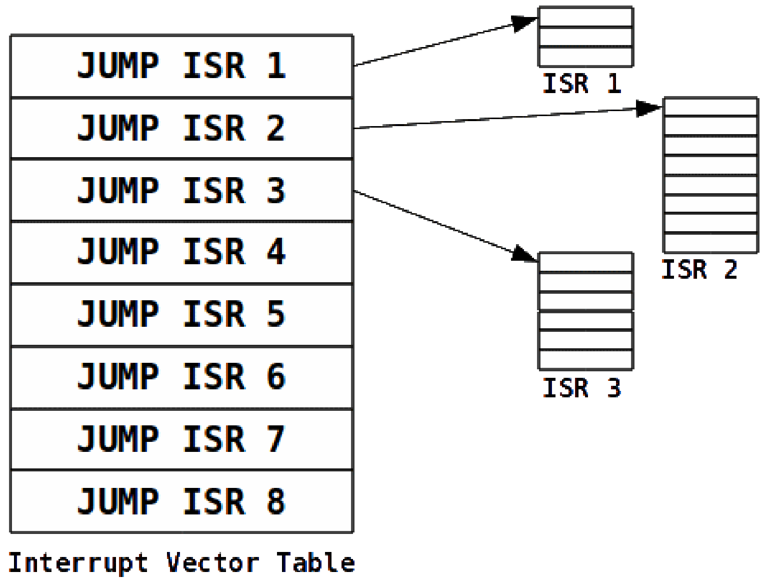
Interrupt handling is performed by the operating system (device drivers) in **interrupt service routines** (ISRs).

Interrupts temporarily discontinue the currently executing application.



Interrupt Vector Table

- **Interrupt vector table** maps interrupts to service routines that handle them
- Table has one entry for each interrupt
- Each entry contains the address of the ISR (interrupt vector)
- Table resides in main memory at a constant address (interrupt base address)
- Interrupt number provides index into the table



Detecting Interrupts

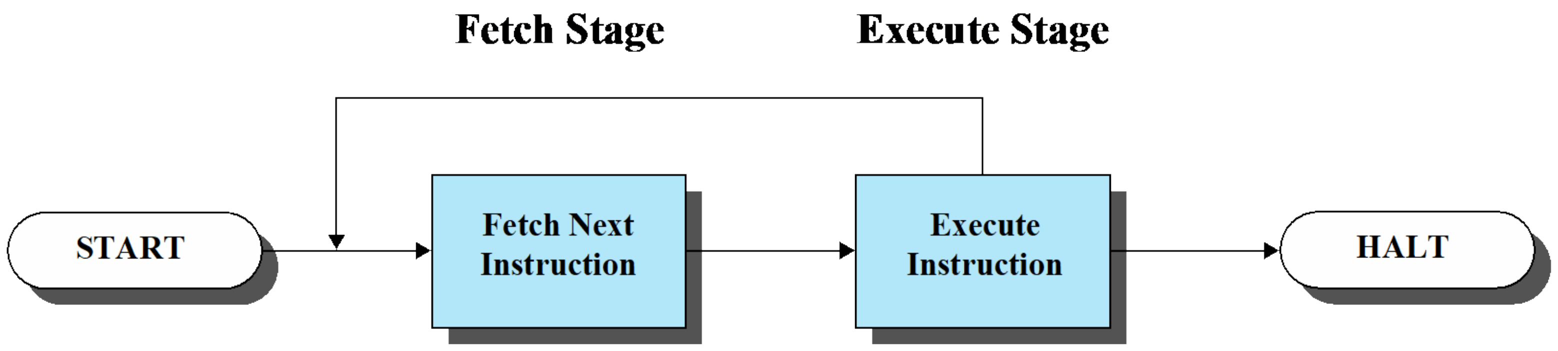


Figure 1.2 Basic Instruction Cycle

Detecting Interrupts

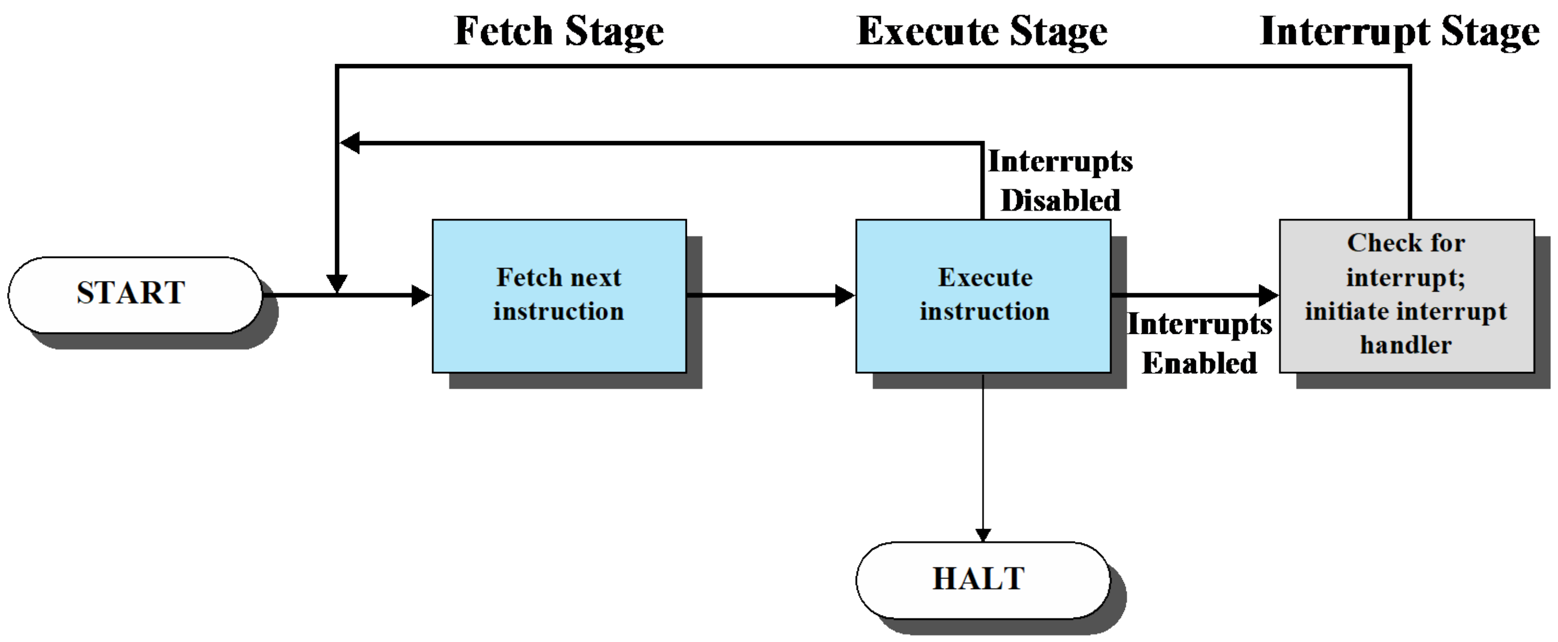
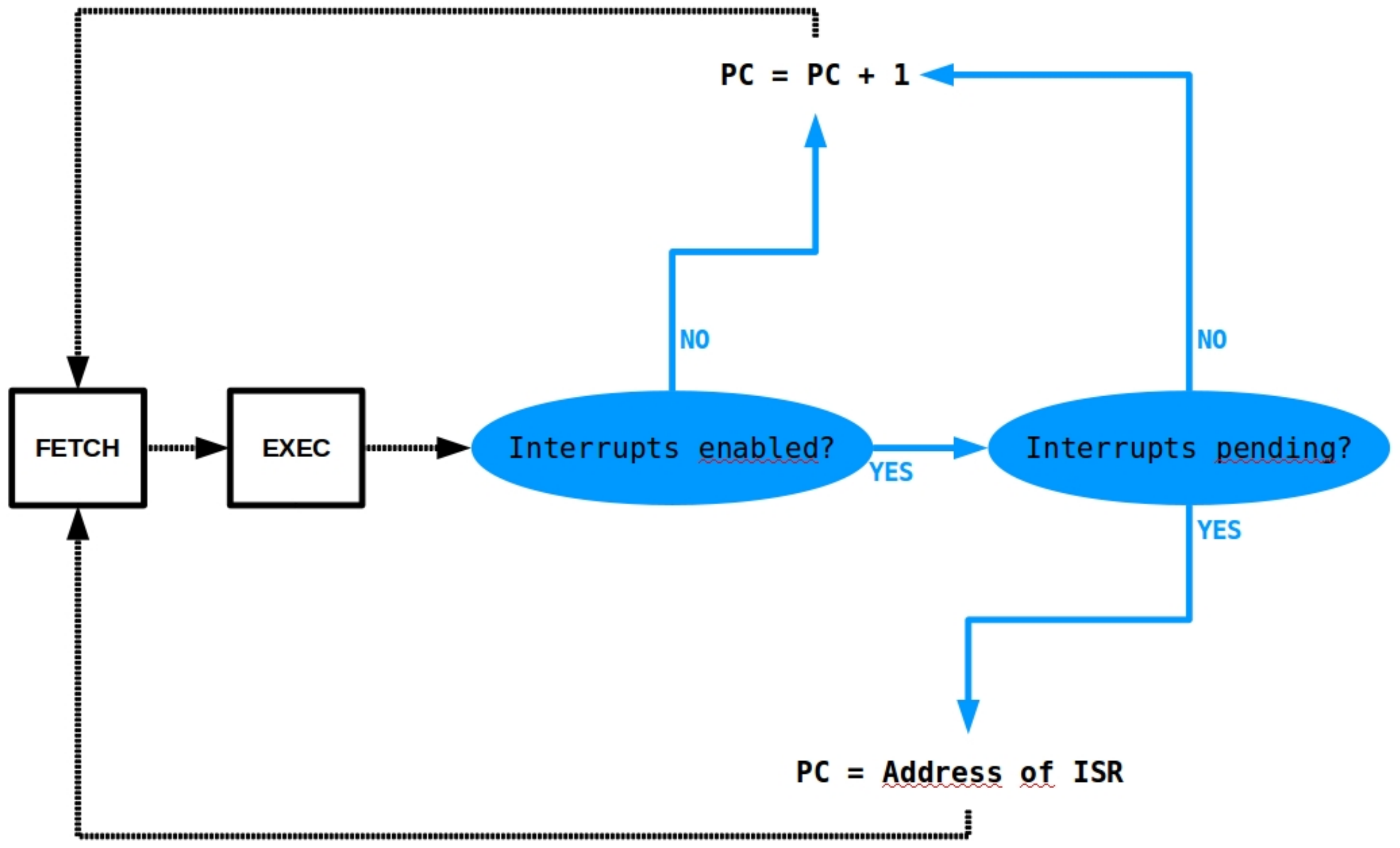


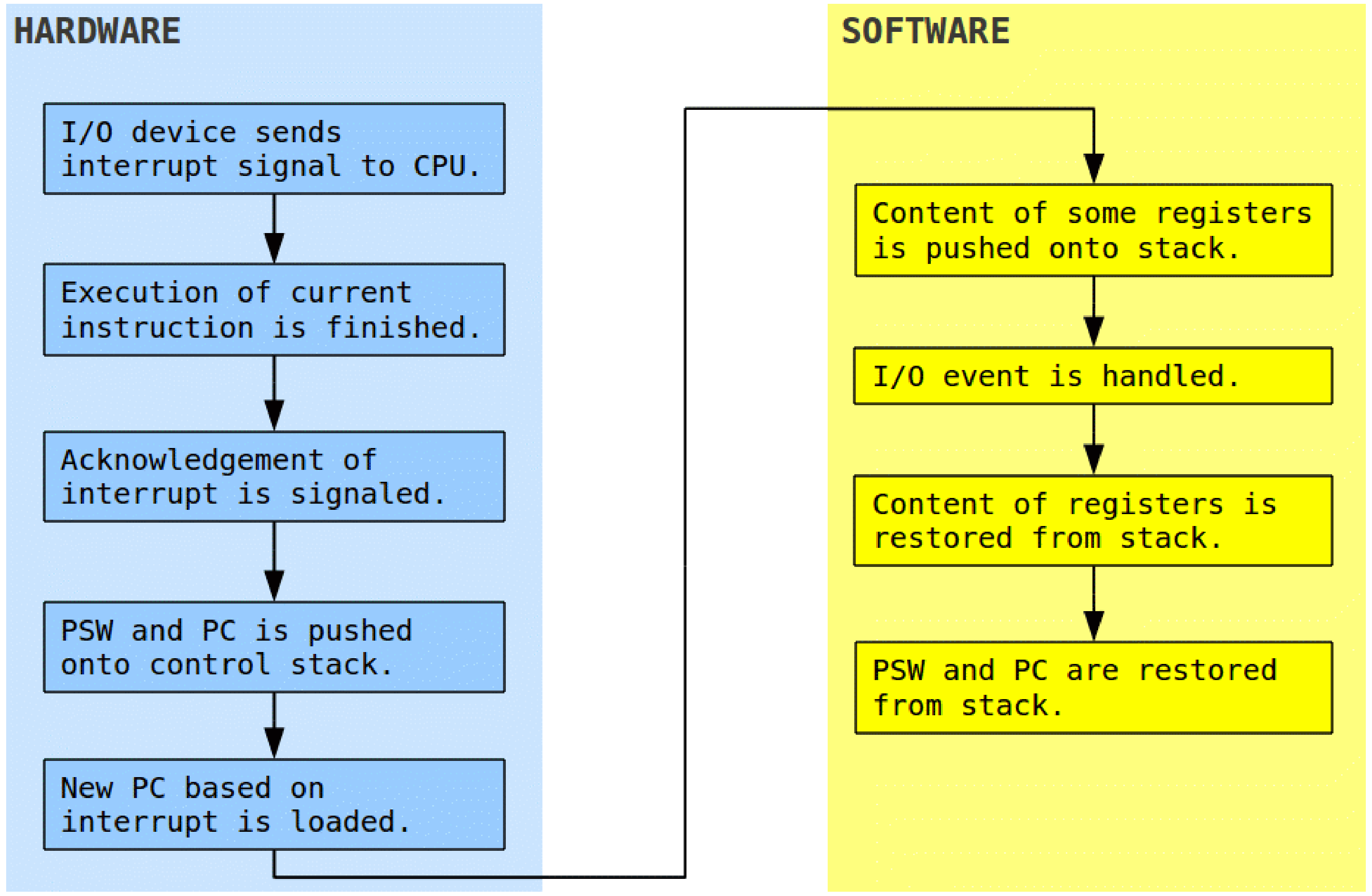
Figure 1.7 Instruction Cycle with Interrupts

Detecting Interrupts



Steps of Interrupt Handling

Example: Handling of an I/O event


HARDWARE
I/O device sends interrupt signal to CPU.
Execution of current instruction is finished.
Acknowledgement of interrupt is signaled.
PSW and PC is pushed onto control stack.
New PC based on interrupt is loaded.
SOFTWARE
Content of some registers is pushed onto stack.
I/O event is handled.
Content of registers is restored from stack.
PSW and PC are restored from stack.

Types of Interrupts

Hardware interrupts (asynchronous)

- Triggered by hardware devices, e.g.,
  - Timer
  - I/O device
  - Printer

Software interrupts (synchronous)

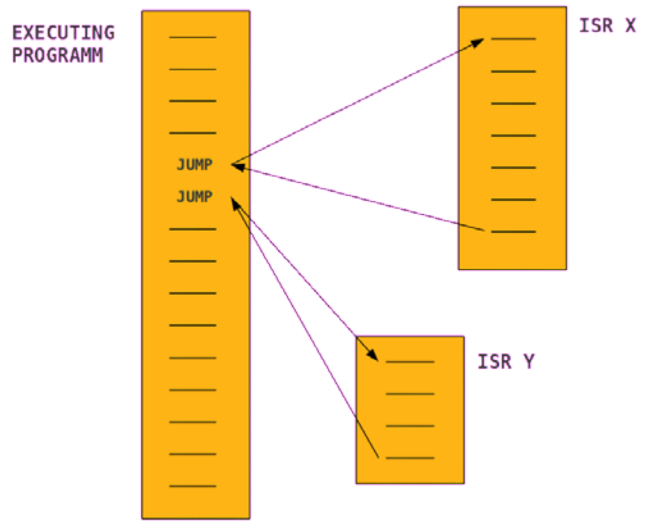
- Triggered within a processor by executing an instruction
- Often used to implement system calls

Exceptions, e.g.,

- Arithmetic overflow, division by zero
- Illegal instruction
- Illegal memory access

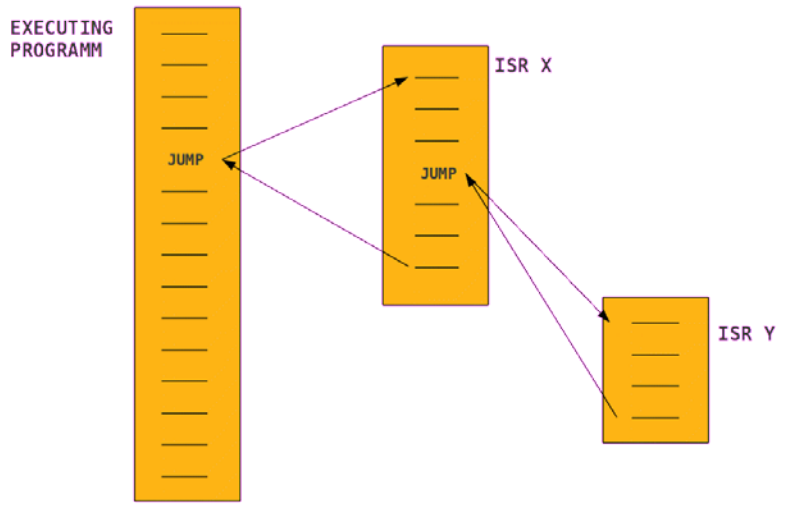
Multiple Interrupts

Sequential interrupt processing:



Delay of interrupt handling **unpredictable** under load

Nested interrupt processing:



Delay depends on interrupt priority level

Highest priority guarantees **constant** delay

Required for real-time applications

Questions & Tasks

- Go back to Computer Architecture if you want to learn more about interrupts!
  - Remember the issues with pipelining, branch prediction etc.
- Polling seems to be a bad idea – come up with scenarios where polling could make sense!
- What should be considered when programming an ISR?
  - Think of timing and registers
- Figure out the interrupts (type, frequency, priority etc.) on your system – are interrupts frequent?

Content

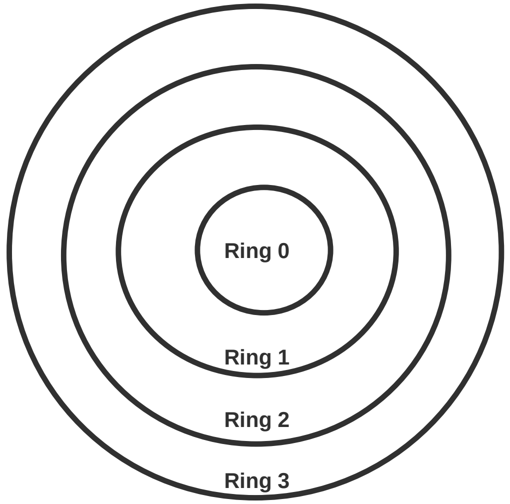
System Calls

User applications access system services by calling **system calls** that are part of the **system interface**.

Typical modes of execution:

- User mode (ring 3):
  - Typical mode for user processes
  - Limited access to hardware features
  - May request privileged services via system calls

- Kernel/privileged/system/control mode (ring 0):
  - Typical mode for kernel of operating system
  - Full access to hardware features
  - Memory access beyond own address space
  - Required for implementation of device drivers (low-level), scheduling, virtual memory



Handling a user request within the kernel implies switching from user to kernel mode.

Context / Mode / Process Switch

“Context switch” may refer to:

Mode switch between user and kernel mode

- Short interruption of current process (e.g. while handling system call)
- No modification of process state required

Process switch between different (user) processes

- *May* occur (depending on scheduler) when flow of control moves from user process to operating system:
  - Interrupt: Response to external asynchronous event
    - Timer interrupt: periodic process switch
    - I/O interrupt: possibly event a process is waiting for
    - Memory fault: Loading of a swapped memory segment with interleaved execution of another process
  - Trap: Response to error caused by process
  - System call: Process requests OS service
- More expensive than mode switch due to process state, processor caches, ...

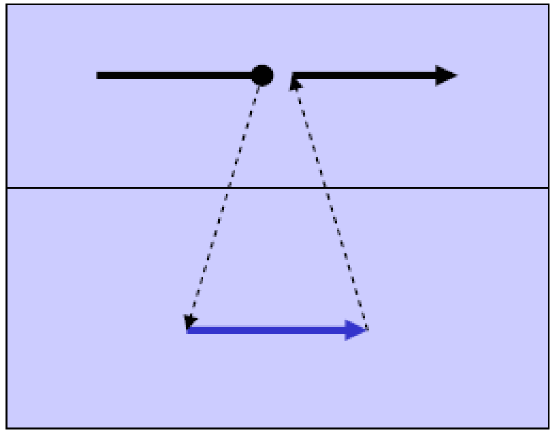
Implementation of Syscalls (1)

Subroutine call into operating system

- Used in very simple operating systems without separate address spaces
  - No hardware-enforced security
  - User processes run with full access to hardware (ring 0)
- Compiler / linker / loader insert call addresses into program
- Interrupt handling terminates with a simple jump back into program (“RETI”)

Example:

- MS-DOS & Embedded Systems

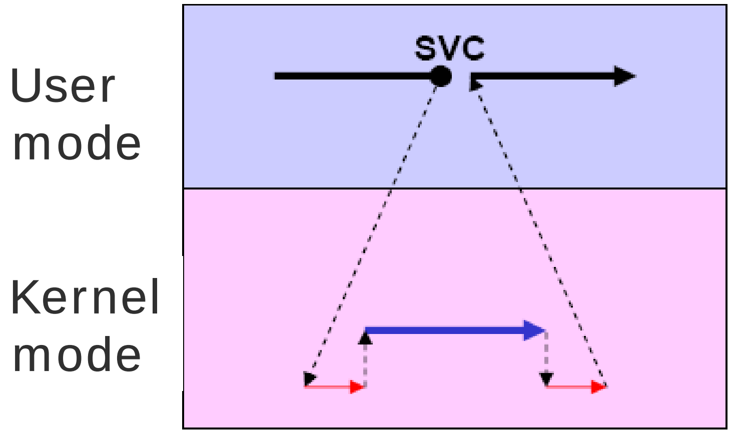


Implementation of Syscalls (2)

Machine-level instruction “system call” (supervisor call, SVC)

- Raises trap / exception / software interrupt
- Interrupt service routine detects cause and branches into corresponding service routine
  - Possibly within same address space, so no process switch
- Compiler inserts parameters for system calls
- Terminates with return

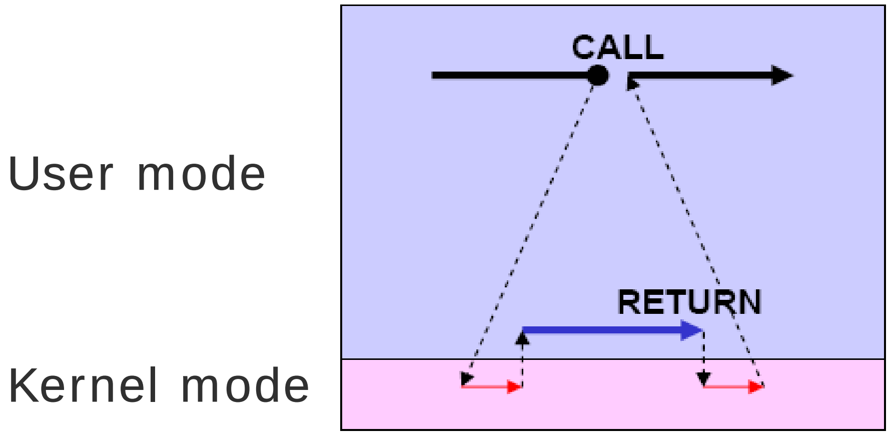
Example: most UNIX kernels



Implementation of Syscalls (3)

Call of system module / object

- Microkernel manages jump into address space of the corresponding system module in response to CALL alarm
  - Process switch required
- Return into calling address space with RETURN

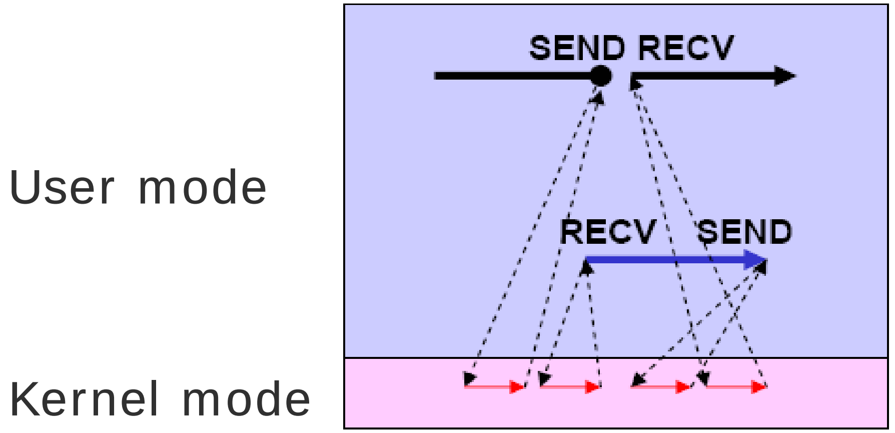


Implementation of Syscalls (4)

Dispatching a task to a system process

- Microkernel dispatches task to corresponding system process in response to SEND alarm
- System process receives task with RECV
  - Process switch required
- Same method used for delivering result

Example: Mach, Minix



Questions & Tasks

- Why having such a “complicated” system like syscalls at all?
- (Real) Micro kernels seem to be a smart idea – think of draw-backs!
- The “simple” implementation of syscalls (version 1) looks pretty unsecure – where could still use this method without headaches?
- The following section gives you some examples – use a disassembler to find such examples, read man pages to find out more about syscalls, follow the link to POSIX resources!

System Calls and System Library

System library hides system calls from programmers

Example **`write()`**:

```
       PUSH  EBX              ; EBX retten
       MOV   EBX,  8(ESP)     ; 1. Parameter
       MOV   ECX, 12(ESP)     ; 2. Parameter
       MOV   EDX, 16(ESP)     ; 3. Parameter
       MOV   EAX, 4           ; 4 steht für „write"
       INT   0x80             ; eigentlicher Systemaufruf
       JBE   DONE             ; kein Fehler
       NEG   EAX              ; Fehlercode
       MOV   errno, EAX
       MOV   EAX, -1
DONE:  POP   EBX              ; EBX wiederherstellen
       RET                    ; Rücksprung
```

Value -1 in register EAX on error

System Calls and System Library

Example: Linux system calls

%eax	Name	Source	%ebx	%ecx	%edx	%esx	%edi
1	sys_exit	kernel/exit.c	int	-	-	-	-
2	sys_fork	arch/i386/kernel/process.c	struct pt_regs	-	-	-	-
3	sys_read	fs/read_write.c	unsigned int	char *	size_t	-	-
4	sys_write	fs/read_write.c	unsigned int	const char *	size_t	-	-
5	sys_open	fs/open.c	const char *	int	int	-	-
6	sys_close	fs/open.c	unsigned int	-	-	-	-
7	sys_waitpid	kernel/exit.c	pid_t	unsigned int *	int	-	-
8	sys_creat	fs/open.c	const char *	int	-	-	-
...							

http://man7.org/linux/man-pages/man2/syscalls.2.html

System Calls and System Library

```
WRITE(2)             Linux Programmer's Manual              WRITE(2)

NAME
       write - write to a file descriptor

SYNOPSIS

       #include <unistd.h>

       ssize_t write(int fd, const void *buf, size_t count);

DESCRIPTION

       write() writes up to count bytes from the buffer pointed buf to the
       file referred to by the file descriptor fd.

       The number of bytes written may be less than count if, for example,
       there is insufficient space on the underlying physical medium, or the
       RLIMIT_FSIZE resource limit is encountered (see setrlimit(2)), or the
       call was interrupted by a signal handler after having written less
       than count bytes.  (See also pipe(7).)
       ...
```

POSIX

Portable Operating System Interface (POSIX)

Standard for operating system API
- IEEE 1003, ISO/IEC 9945

Three main parts:
- POSIX Kernel APIs (system call interface)
- POSIX Commands and Utilities
- POSIX Conformance Testing

Operating system, that implement POSIX:
- INTEGRITY, **Linux**, BSD/OS, A/UX, LynxOS, Mac OS X, MINIX, RTEMS, SkyOS, > **Windows NT**

POSIX Versions

See: http://pubs.opengroup.org/onlinepubs/9699919799/

POSIX.1, Core Services

- (includes Standard ANSI C)
- Process Creation and Control
- Signals (IPC)
- Floating Point Exceptions
- Segmentation Violations (VMM)
- Illegal Instructions
- Bus Errors
- Timers
- File and Directory Operations
- Pipes
- C Library (Standard C)
- I/O Port Interface Control

POSIX.1b, Real-time extensions

- Priority Scheduling
- Real-Time Signals
- Clocks and Timers
- Semaphores
- Message Passing
- Shared Memory
- Asynch and Synch I/O
- Memory Locking

POSIX.1c, Threads extensions

- Thread Creation, Control, and Cleanup
- Thread Scheduling
- Thread Synchronization
- Signal Handling

Content