EECS 373
Design of Microprocessor-Based Systems

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Lecture 6: Interrupts
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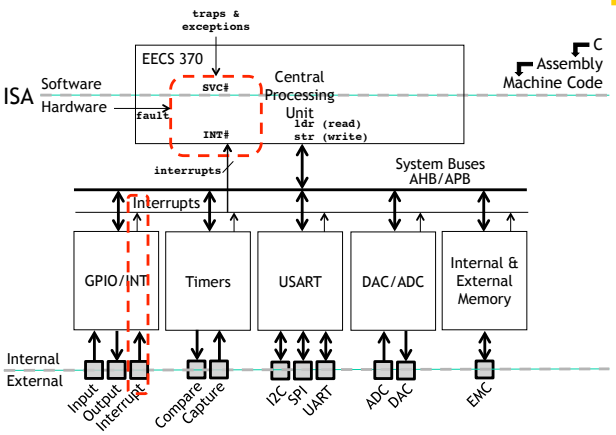
Slides developed in part by Mark Brehob

Announcements

- Additional GSI/IA office hours (OH)
  - Pat Pannuto 10-11am MW in EECS Learning Center
    - (Glass rooms between BBB and Dow)

Interrupts, traps, exceptions, and faults



Interrupts

Merriam-Webster:
- "to break the uniformity or continuity of"

- Informs a program of some external events
- Breaks execution flow

Key questions:
- Where do interrupts come from?
- How do we save state for later continuation?
- How can we ignore interrupts?
- How can we prioritize interrupts?
- How can we share interrupts?

Interrupts

Interrupt (a.k.a. exception or trap):
- An event that causes the CPU to stop executing current program
- Begin executing a special piece of code
  - Called an **interrupt handler** or **interrupt service routine** (ISR)
    - Typically, the ISR does some work
    - Then resumes the interrupted program

Interrupts are really glorified procedure calls, except that they:
- **can occur between any two instructions**
- are "transparent" to the running program (usually)
- are not explicitly requested by the program (typically)
- call a procedure at an address determined by the type of interrupt, not the program

Two basic types of interrupts (1/2)

- Those caused by an instruction
  - Examples:
    - TLB miss
    - Illegal/unimplemented instruction
    - div by 0
    - SVC (supervisor call, e.g.: SVC #3)
  - Names:
    - Trap, exception

Two basic types of interrupts (2/2)

- Those caused by the external world
  - External device
  - Reset button
  - Timer expires
  - Power failure
  - System error
- Names:
  - interrupt, external interrupt

Why are interrupts useful? Example: I/O Data Transfer

Two key questions to determine how data is transferred to/from a non-trivial I/O device:

1. How does the CPU know when data is available?
   a. Polling
   b. Interrupts
2. How is data transferred into and out of the device?
   a. Programmed I/O
   b. Direct Memory Access (DMA)

How it works

- Something tells the processor core there is an interrupt
- Core transfers control to code that needs to be executed
- Said code "returns" to old program
- Much harder then it looks.
  - Why?

Devil is in the details

- How do you figure out *where* to branch to?
- How to you ensure that you can get back to where you started?
- Don't we have a pipeline? What about partially executed instructions?
- What if we get an interrupt while we are processing our interrupt?
- What if we are in a "critical section?"

Where

- If you know *what* caused the interrupt then you want to jump to the code that handles that interrupt.
  - If you number the possible interrupt cases, and an interrupt comes in, you can just branch to a location, using that number as an offset (this is a branch table)
  - If you don't have the number, you need to *poll* all possible sources of the interrupt to see who caused it.
    - Then you branch to the right code

Get back to where you once belonged

- Need to store the return address somewhere.
  - Stack *might* be a scary place.
    - *That* would involve a load/store and might cause an interrupt (page fault)!
  - So a dedicated register seems like a good choice
    - But that might cause problems later…
    - What happens if another interrupt happens?

Modern architectures

- A modern processor has *many* (often 50+) instructions in-flight at once.
  - What do we do with them?
- Drain the pipeline?
  - What if one of them causes an exception?
- Punt all that work
  - Slows us down
- What if the instruction that caused the exception was executed before some other instruction?
  - What if that other instruction caused an interrupt?

Nested interrupts

- If we get one interrupt while handling another what to do?
  - Just handle it
    - But what about that dedicated register?
    - What if I'm doing something that can't be stopped?
  - Ignore it
    - But what if it is important?
  - Prioritize
    - Take those interrupts you care about. Ignore the rest
    - Still have dedicated register problems.

Critical section

- We probably need to ignore some interrupts but take others.
  - Probably should be sure ***our*** code can't cause an exception.
  - Use same prioritization as before.
- What about instructions that shouldn't be interrupted?
  - Disable interrupts while processing an interrupt?

Our processor

- Over 100 interrupt sources
  - Power on reset, bus errors, I/O pins changing state, data in on a serial bus etc.
- Need a great deal of control
  - Ability to enable and disable interrupt sources
  - Ability to control where to branch to for each interrupt
  - Ability to set interrupt priorities
    - Who wins in case of a tie
    - Can interrupt **A** interrupt the ISR for interrupt **B**?
      - If so, **A** can "preempt" **B**.
- All that control will involve memory mapped I/O.
  - And given the number of interrupts that's going to be a pain

SmartFusion interrupt sources

Table 7-5 • SmartFusion Interrupt Sources

Cortex-M3 NVIC Input	IRQ Label	IRQ Source
NMI	WDOGTIMEOUT_IRQ	WATCHDOG
INTISR[0]	WDOGWAKEUP_IRQ	WATCHDOG
INTISR[1]	BROWNOUT1_5V_IRQ	VR/PSM
INTISR[2]	BROWNOUT3_3V_IRQ	VR/PSM
INTISR[3]	RTCMATCHEVENT_IRQ	RTC
INTISR[4]	PU_N_IRQ	RTC
INTISR[5]	EMAC_IRQ	Ethernet MAC
INTISR[6]	M3_IAP_IRQ	IAP
INTISR[7]	ENVM_0_IRQ	ENVM Controller
INTISR[8]	ENVM_1_IRQ	ENVM Controller
INTISR[9]	DMA_IRQ	Peripheral DMA
INTISR[10]	UART_0_IRQ	UART_0
INTISR[11]	UART_1_IRQ	UART_1
INTISR[12]	SPI_0_IRQ	SPI_0
INTISR[13]	SPI_1_IRQ	SPI_1
INTISR[14]	I2C_0_IRQ	I2C_0
INTISR[15]	I2C_0_SMBALERT_IRQ	I2C_0
INTISR[16]	I2C_0_SMBSUS_IRQ	I2C_0
INTISR[17]	I2C_1_IRQ	I2C_1
INTISR[18]	I2C_1_SMBALERT_IRQ	I2C_1
INTISR[19]	I2C_1_SMBSUS_IRQ	I2C_1
INTISR[20]	TIMER_1_IRQ	TIMER
INTISR[21]	TIMER_2_IRQ	TIMER
INTISR[22]	PLLLOCK_IRQ	MSS_CCC
INTISR[23]	PLLLOCKLOST_IRQ	MSS_CCC
INTISR[24]	ABM_ERROR_IRQ	AHB BUS MATRIX
INTISR[25]	Reserved	Reserved
INTISR[26]	Reserved	Reserved
INTISR[27]	Reserved	Reserved
INTISR[28]	Reserved	Reserved
INTISR[29]	Reserved	Reserved
INTISR[30]	Reserved	Reserved
INTISR[31]	FAB_IRQ	FABRIC INTERFACE
INTISR[32]	GPIO_0_IRQ	GPIO
INTISR[33]	GPIO_1_IRQ	GPIO
INTISR[34]	GPIO_2_IRQ	GPIO

INTISR[64]	ACE_PC0_FLAG0_IRQ	ACE
INTISR[65]	ACE_PC0_FLAG1_IRQ	ACE
INTISR[66]	ACE_PC0_FLAG2_IRQ	ACE
INTISR[67]	ACE_PC0_FLAG3_IRQ	ACE
INTISR[68]	ACE_PC1_FLAG0_IRQ	ACE
INTISR[69]	ACE_PC1_FLAG1_IRQ	ACE
INTISR[70]	ACE_PC1_FLAG2_IRQ	ACE
INTISR[71]	ACE_PC1_FLAG3_IRQ	ACE
INTISR[72]	ACE_PC2_FLAG0_IRQ	ACE
INTISR[73]	ACE_PC2_FLAG1_IRQ	ACE
INTISR[74]	ACE_PC2_FLAG2_IRQ	ACE
INTISR[75]	ACE_PC2_FLAG3_IRQ	ACE
INTISR[76]	ACE_ADC0_DATAVALID_IRQ	ACE
INTISR[77]	ACE_ADC1_DATAVALID_IRQ	ACE
INTISR[78]	ACE_ADC2_DATAVALID_IRQ	ACE
INTISR[79]	ACE_ADC0_CALDONE_IRQ	ACE
INTISR[80]	ACE_ADC1_CALDONE_IRQ	ACE
INTISR[81]	ACE_ADC2_CALDONE_IRQ	ACE
INTISR[82]	ACE_ADC0_CALSTART_IRQ	ACE
INTISR[83]	ACE_ADC1_CALSTART_IRQ	ACE
INTISR[84]	ACE_ADC2_CALSTART_IRQ	ACE
INTISR[85]	ACE_COMP0_FALL_IRQ	ACE
INTISR[86]	ACE_COMP1_FALL_IRQ	ACE
INTISR[87]	ACE_COMP2_FALL_IRQ	ACE
INTISR[88]	ACE_COMP3_FALL_IRQ	ACE
INTISR[89]	ACE_COMP4_FALL_IRQ	ACE
INTISR[90]	ACE_COMP5_FALL_IRQ	ACE
INTISR[91]	ACE_COMP6_FALL_IRQ	ACE
INTISR[92]	ACE_COMP7_FALL_IRQ	ACE
INTISR[93]	ACE_COMP8_FALL_IRQ	ACE
INTISR[94]	ACE_COMP9_FALL_IRQ	ACE
INTISR[95]	ACE_COMP10_FALL_IRQ	ACE

54 more ACE specific interrupts

GPIO_3_IRQ to GPIO_31_IRQ cut

Table 7.1 List of System Exceptions

Exception Number	Exception Type	Priority	Description
1	Reset	–3 (Highest)	Reset
2	NMI	–2	Nonmaskable interrupt (external NMI input)
3	Hard fault	–1	All fault conditions if the corresponding fault handler is not enabled
4	MemManage fault	Programmable	Memory management fault; Memory Protection Unit (MPU) violation or access to illegal locations
5	Bus fault	Programmable	Bus error; occurs when Advanced High-Performance Bus (AHB) interface receives an error response from a bus slave (also called *prefetch abort* if it is an instruction fetch or *data abort* if it is a data access)
6	Usage fault	Programmable	Exceptions resulting from program error or trying to access coprocessor (the Cortex-M3 does not support a coprocessor)
7–10	Reserved	NA	—
11	SVC	Programmable	Supervisor Call
12	Debug monitor	Programmable	Debug monitor (breakpoints, watchpoints, or external debug requests)
13	Reserved	NA	—
14	PendSV	Programmable	Pendable Service Call
15	SYSTICK	Programmable	System Tick Timer

Table 7.2 List of External Interrupts

Exception Number	Exception Type	Priority
16	External Interrupt #0	Programmable
17	External Interrupt #1	Programmable
…	…	…
255	External Interrupt #239	Programmable

And the interrupt vectors (in startup_a2fxxxm3.s found in CMSIS, startup_gcc)

```
g_pfnVectors:
    .word  _estack
    .word  Reset_Handler
    .word  NMI_Handler
    .word  HardFault_Handler
    .word  MemManage_Handler
    .word  BusFault_Handler
    .word  UsageFault_Handler
    .word  0
    .word  0
    .word  0
    .word  0
    .word  SVC_Handler
    .word  DebugMon_Handler
    .word  0
    .word  PendSV_Handler
    .word  SysTick_Handler
    .word  WdogWakeup_IRQHandler
    .word  BrownOut_1_5V_IRQHandler
    .word  BrownOut_3_3V_IRQHandler
.............. (they continue)
```

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How to change where to go on an interrupt? Answer: edit the interrupt vector table [IVT]

```
23 g_pfnVectors:
24     .word  _estack
25     .word  Reset_Handler
26     .word  NMI_Handler
27     .word  HardFault_Handler
28     .word  MemManage_Handler
29     .word  BusFault_Handler
30     .word  UsageFault_Handler
31     .word  0
32     .word  0
```

```
192 /*=====================================
193  * Reset_Handler
194  */
195     .global Reset_Handler
196     .type   Reset_Handler, %function
197 Reset_Handler:
198 _start:
```


Enabling and disabling interrupt sources

- Interrupt Set Enable and Clear Enable
  - 0xE000E100-0xE000E11C, 0xE000E180-0xE000E19C

0xE000E100	SETENA0	R/W	0	Enable for external interrupt #0–31 bit[0] for interrupt #0 (exception #16) bit[1] for interrupt #1 (exception #17) ... bit[31] for interrupt #31 (exception #47) Write 1 to set bit to 1; write 0 has no effect Read value indicates the current status
0xE000E180	CLRENA0	R/W	0	Clear enable for external interrupt #0–31 bit[0] for interrupt #0 bit[1] for interrupt #1 ... bit[31] for interrupt #31 Write 1 to clear bit to 0; write 0 has no effect Read value indicates the current enable status

Configuring the NVIC (2)

- Set Pending & Clear Pending
  - 0xE000E200-0xE000E21C, 0xE000E280-0xE000E29C

0xE000E200	SETPEND0	R/W	0	Pending for external interrupt #0–31 bit[0] for interrupt #0 (exception #16) bit[1] for interrupt #1 (exception #17) ... bit[31] for interrupt #31 (exception #47) Write 1 to set bit to 1; write 0 has no effect Read value indicates the current status
0xE000E280	CLRPEND0	R/W	0	Clear pending for external interrupt #0–31 bit[0] for interrupt #0 (exception #16) bit[1] for interrupt #1 (exception #17) ... bit[31] for interrupt #31 (exception #47) Write 1 to clear bit to 0; write 0 has no effect Read value indicates the current pending status

Configuring the NVIC (3)

- Interrupt Active Status Register
  - 0xE000E300-0xE000E31C

Address	Name	Type	Reset Value	Description
0xE000E300	ACTIVE0	R	0	Active status for external interrupt #0–31 bit[0] for interrupt #0 bit[1] for interrupt #1 ... bit[31] for interrupt #31
0xE000E304	ACTIVE1	R	0	Active status for external interrupt #32–63
...	–	–	–	–

Interrupt types

- Two main types
  - Level-triggered
  - Edge-triggered

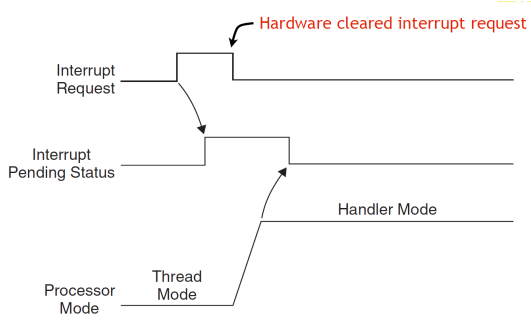
Level-triggered interrupts

- Signaled by asserting a line low or high
- Interrupting device drives line low or high and holds it there until it is serviced
- Device deasserts when directed to or after serviced
- Can share the line among multiple devices (w/ OD+PU)
- Active devices assert the line
- Inactive devices let the line float
- Easy to share line w/o losing interrupts
- But servicing increases CPU load → example
- And requires CPU to keep cycling through to check
- Different ISR costs suggests careful ordering of ISR checks
- Can't detect a new interrupt when one is already asserted

Edge-triggered interrupts

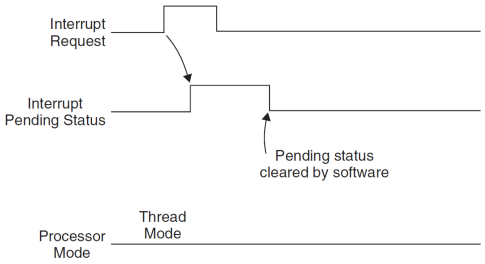
- Signaled by a level *transition* (e.g. rising/falling edge)
- Interrupting device drive a pulse (train) onto INT line
- What if the pulse is too short? Need a pulse extender!
- Sharing *is* possible...under some circumstances
- INT line has a pull up and all devices are OC/OD.
- Devices *pulse* lines
- Could we miss an interrupt? Maybe...if close in time
- What happens if interrupts merge? Need one more ISR pass
- Must check trailing edge of interrupt
- Easy to detect "new interrupts"
- Benefits: more immune to unserviceable interrupts
- Pitfalls: spurious edges, missed edges
- Source of "lockups" in early computers

Pending interrupts



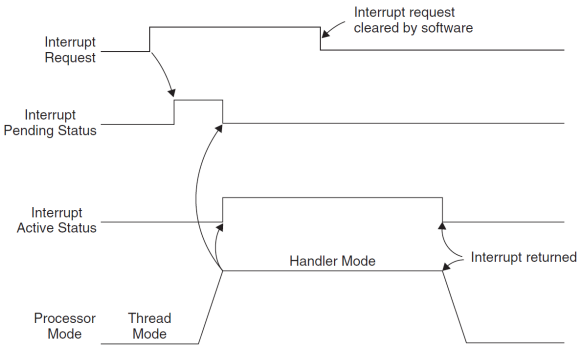
The normal case. Once Interrupt request is seen, processor puts it in "pending" state even if hardware drops the request.
IPS is cleared by the hardware once we jump to the ISR.

This figure and those following are from *The Definitive Guide to the ARM Cortex-M3, Section 7.4*

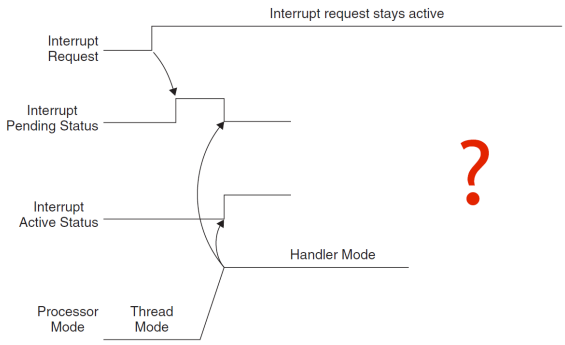


In this case, the processor never took the interrupt because we cleared the IPS by hand (via a memory-mapped I/O register)

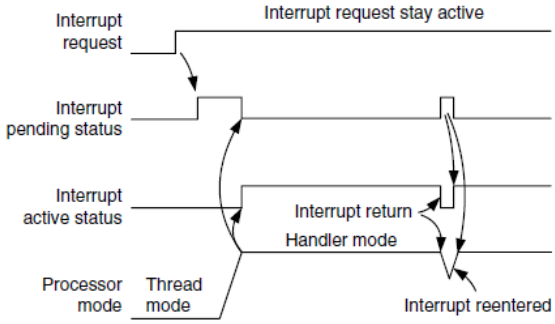
Active Status set during handler execution



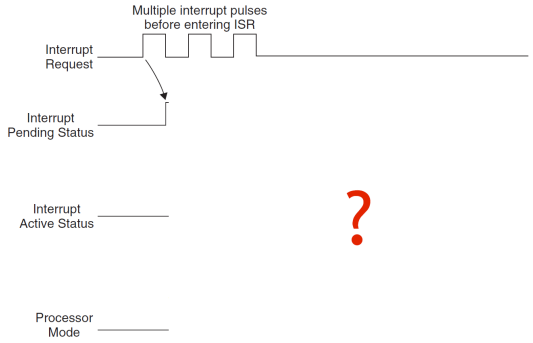
Interrupt Request not Cleared



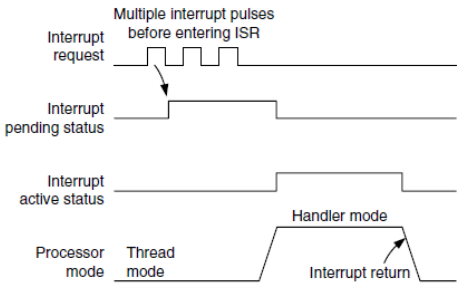
Answer



Interrupt pulses before entering ISR



Answer



New Interrupt Request after Pending Cleared