

Interrupt-Driven Input/Output on the STM32F407 Microcontroller

Textbook: Chapter 11 (Interrupts)

ARM Cortex-M4 User Guide (Interrupts, exceptions, NVIC)

Sections 2.1.4, 2.3 – Exceptions and interrupts

Section 4.2 – Nested Vectored Interrupt Controller

STM32F4xx Tech. Ref. Manual:

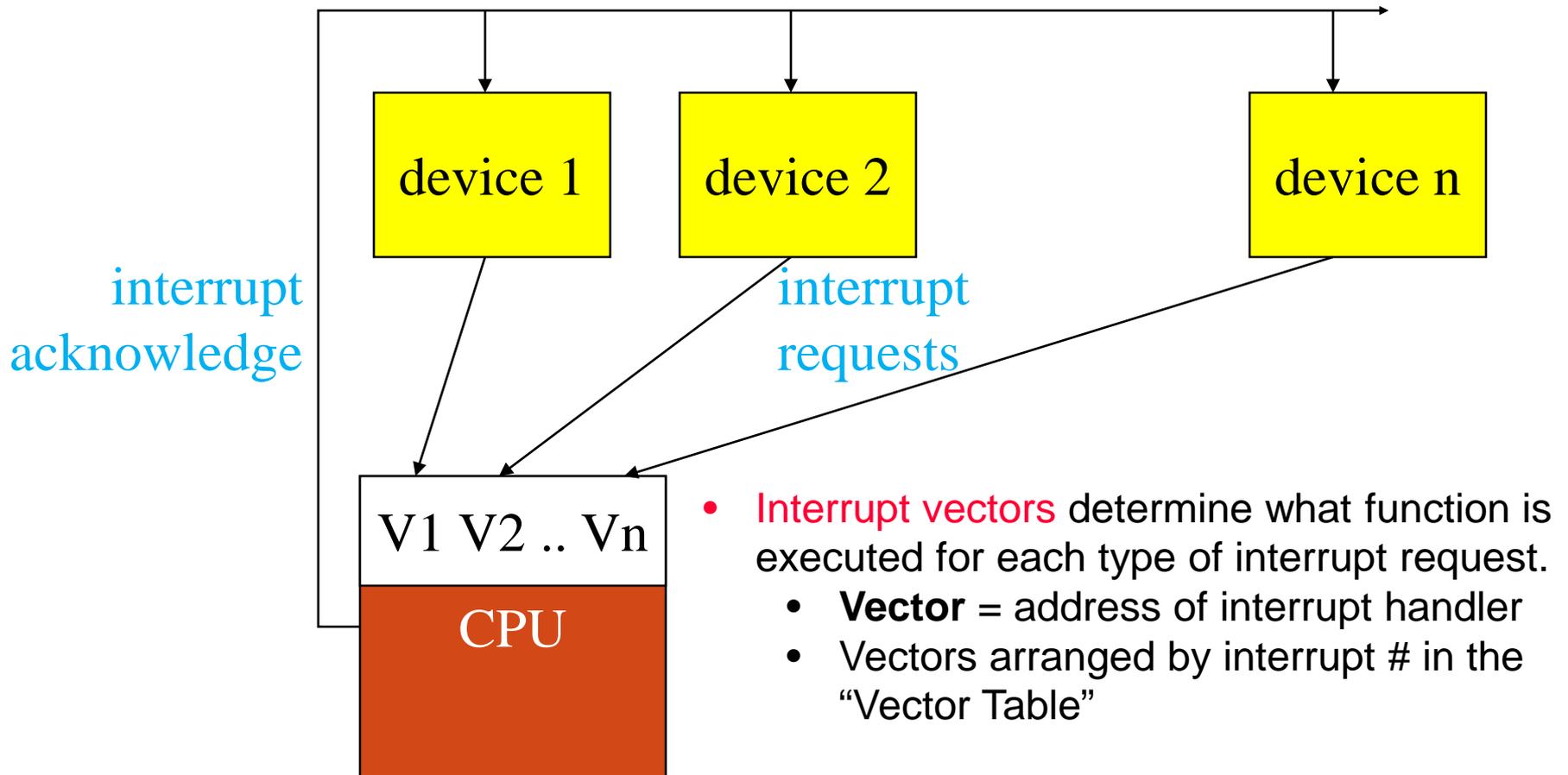
Chapter 8: External interrupt/wakeup lines

Chapter 9: SYSCFG external interrupt config. registers

Outline

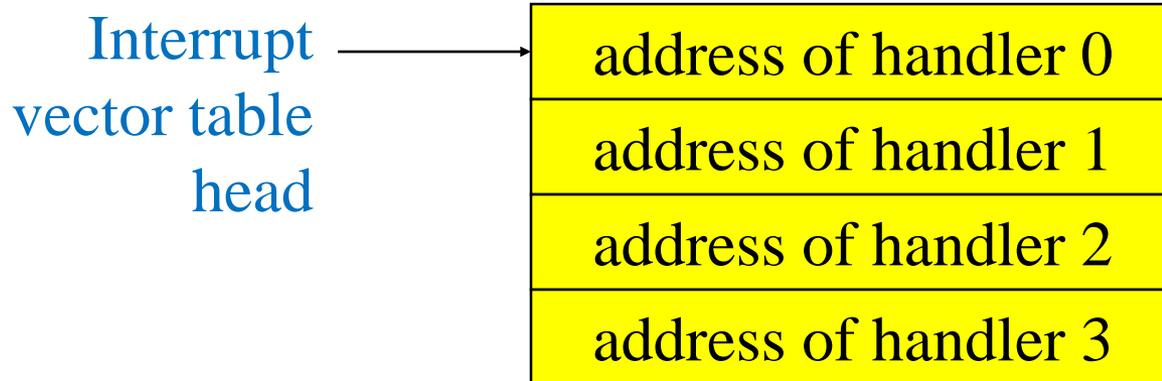
- Interrupt vectors and vector table
- Interrupt masks and priorities
- Cortex Nested Vectored Interrupt Controller (NVIC)
- STM32F4 external interrupt signals (EXTI0 – EXTI15)
- System design when interrupts used

Prioritized, vectored interrupts



Interrupt vectors

- **Interrupt vector** = **address** of handler function
 - Allow different devices to be handled by different code.
- Interrupt vector table:
 - Directly supported by CPU architecture and/or
 - Supported by a separate interrupt-support device/function



Cortex-M CPU and peripheral exceptions

	Priority ¹	IRQ# ²	Notes
Reset	-3/fixed		Power-up or warm reset
NMI	-2/fixed	-14	Non-maskable interrupt from peripheral or software
HardFault	-1/fixed	-13	Error during exception processing or no other handler
MemManage	0/settable	-12	Memory protection fault (MPU-detected)
BusFault	1/settable	-11	AHB data/prefetch aborts
UsageFault	2/settable	-10	Instruction execution fault - undefined instruction, illegal unaligned access
SVCcall	3/settable	-5	System service call (SVC) instruction
DebugMonitor	4/settable		Break points/watch points/etc.
PendSV	5/settable	-2	Interrupt-driven request for system service
SysTick	6/settable	-1	System tick timer reaches 0
IRQ0	7/settable	0	Signaled by peripheral or by software request
IRQ1 (etc.)	8/settable	1	Signaled by peripheral or by software request

CPU Exceptions

Vendor peripheral interrupts
IRQ0 .. IRQ44

¹ Lowest priority # = highest priority
² IRQ# used in CMSIS function calls

Interrupt Vector Table for STM32F4xx Peripherals

Tech. Ref. Manual: Table 43

Also - refer to startup code

Position	Priority	Type of priority	Acronym	Description	Address
0	7	settable	WWDG	Window Watchdog interrupt	0x0000 0040
1	8	settable	PVD	PVD through EXTI line detection interrupt	0x0000 0044
2	9	settable	TAMP_STAMP	Tamper and TimeStamp interrupts through the EXTI line	0x0000 0048
3	10	settable	RTC_WKUP	RTC Wakeup interrupt through the EXTI line	0x0000 004C
4	11	settable	FLASH	Flash global interrupt	0x0000 0050
5	12	settable	RCC	RCC global interrupt	0x0000 0054
6	13	settable	EXTI0	EXTI Line0 interrupt	0x0000 0058
7	14	settable	EXTI1	EXTI Line1 interrupt	0x0000 005C
8	15	settable	EXTI2	EXTI Line2 interrupt	0x0000 0060
9	16	settable	EXTI3	EXTI Line3 interrupt	0x0000 0064
10	17	settable	EXTI4	EXTI Line4 interrupt	0x0000 0068
11	18	settable	DMA1_Stream0	DMA1 Stream0 global interrupt	0x0000 006C
26	33	settable	TIM1_TRG_COM_TIM11	TIM1 Trigger and Commutation interrupts and TIM11 global interrupt	0x0000 00A8
27	34	settable	TIM1_CC	TIM1 Capture Compare interrupt	0x0000 00AC
28	35	settable	TIM2	TIM2 global interrupt	0x0000 00B0
29	36	settable	TIM3	TIM3 global interrupt	0x0000 00B4
30	37	settable	TIM4	TIM4 global interrupt	0x0000 00B8
31	38	settable	I2C1_EV	I ² C1 event interrupt	0x0000 00BC
32	39	settable	I2C1_ER	I ² C1 error interrupt	0x0000 00C0
33	40	settable	I2C2_EV	I ² C2 event interrupt	0x0000 00C4
34	41	settable	I2C2_ER	I ² C2 error interrupt	0x0000 00C8
35	42	settable	SPI1	SPI1 global interrupt	0x0000 00CC

External interrupts

Timer interrupts

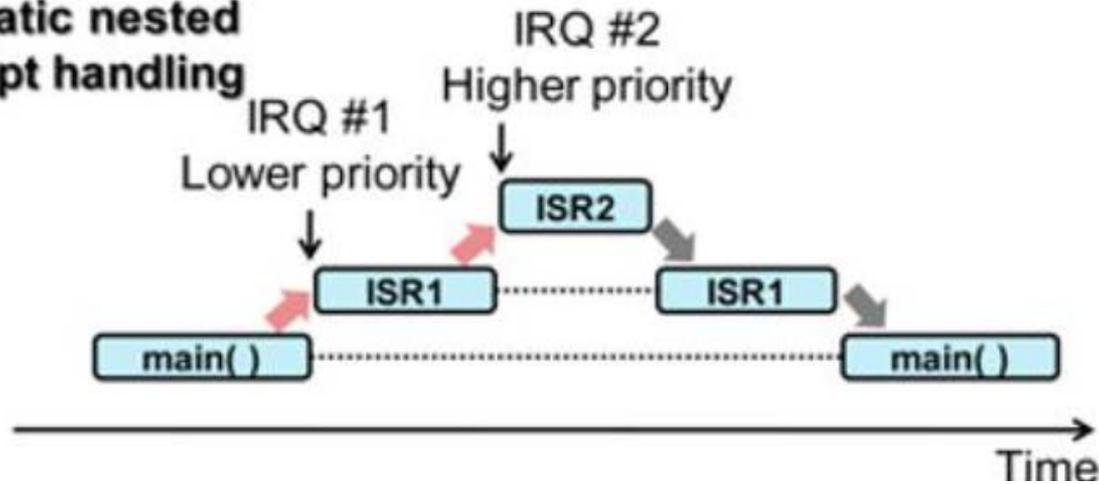
STM32F4 vector table from startup code (*partial*)

```
__Vectors      DCD    __initial_sp      ; Top of Stack
               DCD    Reset_Handler    ; Reset Handler
               DCD    NMI_Handler      ; NMI Handler
               .....
               DCD    SVC_Handler      ; SVCcall Handler
               DCD    DebugMon_Handler ; Debug Monitor Handler
               DCD    0                 ; Reserved
               DCD    PendSV_Handler   ; PendSV Handler
               DCD    SysTick_Handler  ; SysTick Handler
; External Interrupts
               DCD    WWDG_IRQHandler   ; Window WatchDog
               DCD    PVD_IRQHandler    ; PVD via EXTI Line detection
               DCD    TAMP_STAMP_IRQHandler ; Tamper/TimeStamps via EXTI
               DCD    RTC_WKUP_IRQHandler ; RTC Wakeup via EXTI line
               DCD    FLASH_IRQHandler  ; FLASH
               DCD    RCC_IRQHandler    ; RCC
               DCD    EXTI0_IRQHandler  ; EXTI Line0
               DCD    EXTI1_IRQHandler  ; EXTI Line1
               DCD    EXTI2_IRQHandler  ; EXTI Line2
               DCD    EXTI3_IRQHandler  ; EXTI Line3
               DCD    EXTI4_IRQHandler  ; EXTI Line4
```

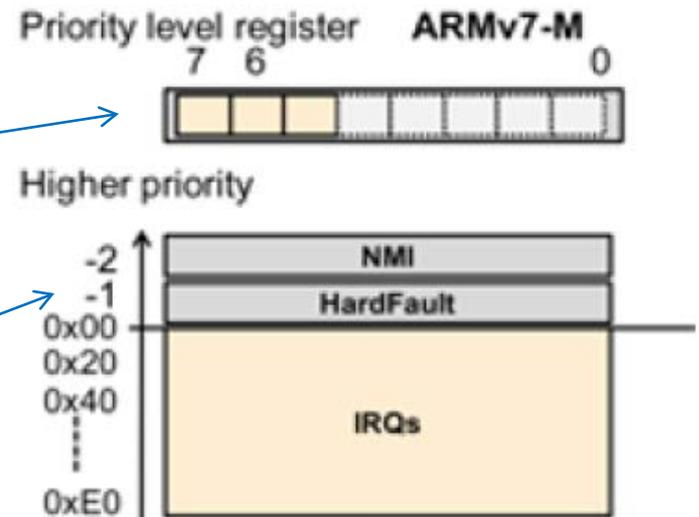
*Use these names
for interrupt
handler functions*

Prioritized interrupts

Automatic nested interrupt handling



- Up to 256 priority levels
 - 8-bit priority value
 - Implementations may use fewer bits
 - STM32F4xx uses upper 4 bits of each priority byte => 16 levels
- NMI & HardFault priorities are fixed
- Lowest # = Highest priority



Interrupt Program Status Register (ISPR)

Bits	Description
Bits 31:9	Reserved
Bits 8:0	ISR_NUMBER: This is the number of the current exception: 0: Thread mode ← No active interrupt 1: Reserved 2: NMI 3: Hard fault 4: Memory management fault 5: Bus fault 6: Usage fault 7: Reserved 10: Reserved 11: SVCall 12: Reserved for Debug 13: Reserved 14: PendSV 15: SysTick 16: IRQ0 ⁽¹⁾ User (vendor) interrupts IRQ0 – IRQ239

ARM Cortex-M Interrupts

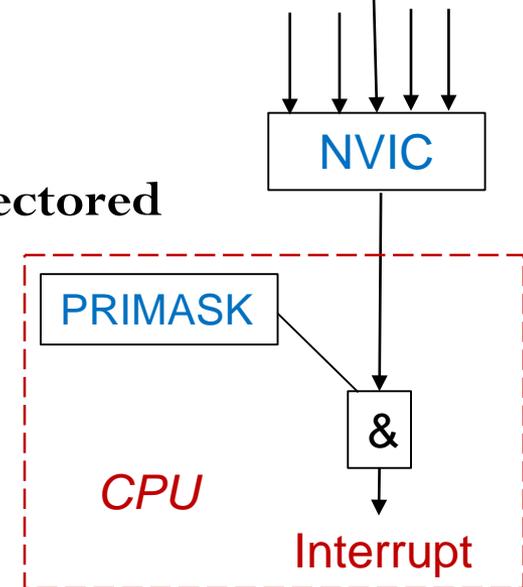
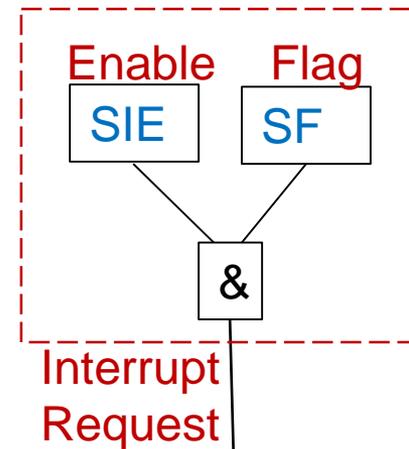
In the Device:

- Each potential interrupt source has a separate **arm (enable)** bit
 - Set for those devices from which interrupts, are to be accepted
 - Deactivate in those devices from which interrupts are not allowed
- Each potential interrupt source has a separate **flag** bit
 - hardware sets the flag when it wishes to request an interrupt (an “event” occurs)
 - software clears the flag in ISR to signify it is processing the request
 - **flags can be tested by software if interrupts not desired**

In the CPU:

- Cortex-M CPUs receive interrupt requests via the **Nested Vectored Interrupt Controller (NVIC)**
 - NVIC sends highest priority request to the CPU
- Interrupt **enable** conditions in processor
 - Global interrupt enable bit, I, in PRIMASK register
 - Priority level, BASEPRI, of allowed interrupts (0 = all)

Peripheral Device Registers:

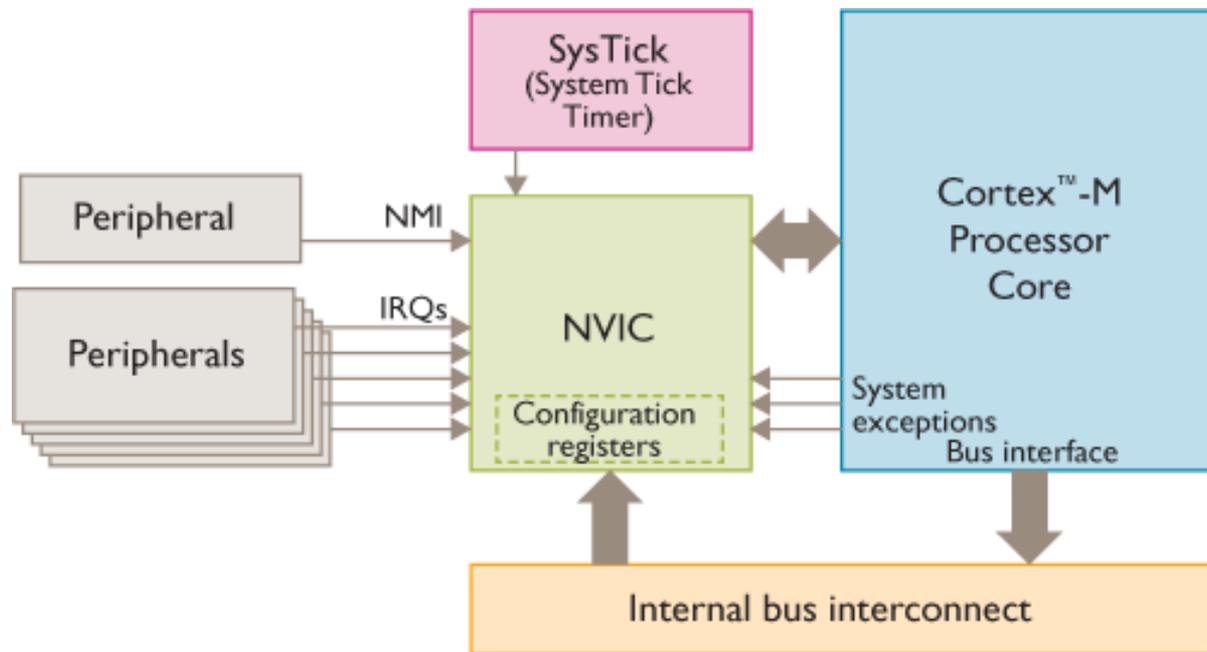


Interrupt Conditions

- Four conditions must be true simultaneously for an interrupt to occur:
 1. **Trigger**: hardware action sets source-specific flag in the peripheral device
 2. **Arm**: control bit for each possible source is set within the peripheral device
 3. **Level**: interrupt level must be less than BASEPRI (base priority)
 4. **Enable**: interrupts globally enabled in CPU (I=0 in PRIMASK)
- Interrupt remains **pending** if trigger is set but any other condition is not true
 - Interrupt serviced once all conditions become true
- Need to **acknowledge** interrupt
 - Clear trigger flag or will get endless interrupts!

Nested Vectored Interrupt Controller

- NVIC manages and prioritizes external interrupts in Cortex-M
 - 45 IRQ sources from STM32L1xx peripherals
- NVIC interrupts CPU with IRQ# of highest-priority IRQ signal
 - CPU uses IRQ# to access the vector table & get intr. handler start address



Nested Vectored Interrupt Controller (NVIC)

- Hardware unit that coordinates interrupts from multiple sources
 - Separate enable flag for each interrupt source (**NVIC_ISER_x/ICER_x**)
 - Define priority level of each interrupt source (**NVIC_IPR_x**)
 - Set/clear interrupts to/from “pending” state (**NVIC_ISPR_x/ICPR_x**)
 - Trigger interrupts through software
- Higher priority interrupts can interrupt lower priority ones
 - Lower priority interrupts are not sent to the CPU until higher priority interrupt service has been completed

NVIC Interrupt Enable Registers

- Three “set interrupt enable” registers –
NVIC_ISER0, NVIC_ISER1
 - Each 32-bit register has a single enable bit for a particular device
 - Write 1 to a bit to set the corresponding interrupt enable bit
 - Writing 0 has no effect

Registers	IRQ numbers	Interrupt numbers
NVIC_ISER0/NVIC_ICER0	0-31	16-47
NVIC_ISER1/NVIC_ICER1	32-63	48-79

- Three corresponding “clear interrupt enable” registers
NVIC_ICER0, NVIC_ICER1
 - Write 1 to clear the interrupt enable bit (disable the interrupt)
 - Writing 0 has no effect

NVIC Set-Clear Pending Registers

- Three interrupt “clear-pending” registers –
NVIC_ICPR0, NVIC_ICPR1
 - Each 32-bit register has a single pending bit for a particular device
 - Write 1 to a bit to remove a pending state from an interrupt
 - Writing 0 has no effect
- Pending state is normally cleared automatically when the processor enters the interrupt handler (ISR)
 - If interrupt signal still active when CPU returns from the ISR, the state changes to pending again (new interrupt triggered)
 - If interrupt signal pulses while CPU is in the ISR, the state changes to pending again (new interrupt triggered)
- Three corresponding interrupt “set-pending” registers
NVIC_ISPR0, NVIC_ISPR1
 - Write 1 to force the interrupt state to pending
 - Writing 0 has no effect

NVIC interrupt priority registers

NVIC_IPRx (x=0..20) – Interrupt Priority Registers

- 8-bit priority field for each interrupts (4-bit field in STM32F4)
 - Four 8-bit priority values per register
 - 0 = highest priority level
 - IPR Register# $x = \text{IRQ\#} \text{ DIV } 4$
 - Byte offset within the IPR register = $\text{IRQ\#} \text{ MOD } 4$

Example: IRQ45

- $45/4 = 11$ with remainder 1 (register NVIC_IPR11, byte offset 1)
 - Write $\text{priority} \ll 8$ to NVIC_IPR11
- $45/32 = 1$ with remainder 13:
 - Write $1 \ll 13$ to NVIC_ISER1

NVIC register addresses

NVIC_ISER0/1/2 = 0xE000E100/104/108

NVIC_ICER0/1/2 = 0xE000E180/184/188

NVIC_ISPR0/1/2 = 0xE000E200/204/208

NVIC_ICPR0/1/2 = 0xE000E280/284/288

NVIC_IPR0/1/2/.../20 = 0xE00E400/404/408/40C/.../500

;Example – Enable EXTI0 with priority 5 (EXTI0 = IRQ6)

NVIC_ISER0 EQU 0xE000E100 ;bit 6 enables EXTI0

NVIC_IPR1 EQU 0xE000E404 ;3rd byte = EXTI0 priority

ldr r0,=NVIC_ISER0

mov r1,#0x0040 ;Set bit 6 of ISER0 for EXTI0

str r1,[r0]

ldr r0,=NVIC_IPR1 ;IRQ6 priority in IPR1[23:16]

ldr r1,[r0] ;Read IPR1

bic r1,#0x00ff0000 ;Clear [23:16] for IRQ6

orr r1,#0x00500000 ;Bits [23:20] = 5

str r1,[r0] ;Upper 4 bits of byte = priority

CMSIS¹ functions

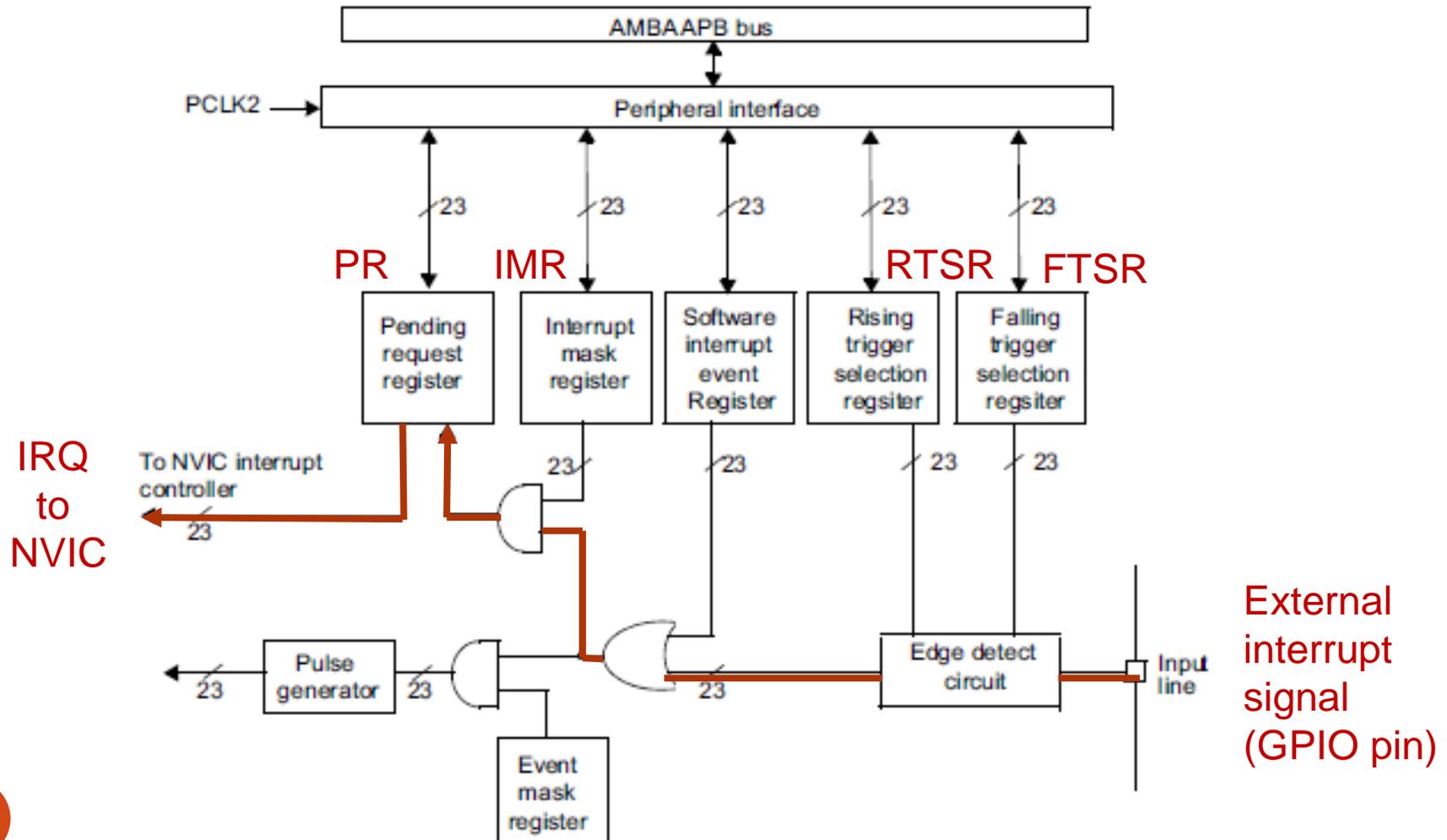
- NVIC_Enable(IRQn_Type IRQn)
- NVIC_Disable(IRQn_Type IRQn)
- NVIC_SetPending(IRQn_Type IRQn)
- NVIC_ClearPending(IRQn_Type IRQn)
- NVIC_GetPending(IRQn_Type IRQn)
- NVIC_SetPriority(IRQn_Type IRQn, unit32_t priority)
- NVIC_GetPriority(IRQn_Type IRQn)

¹CMSIS = Cortex Microcontroller Software Interface Standard

- Vendor-independent hardware abstraction layer for Cortex-M
- Facilitates software reuse
- Other CMSIS functions: System tick timer, Debug interface, etc.

STM32F4xx external interrupt/event controller

- External devices can interrupt CPU via GPIO pins
(Some microcontrollers have dedicated interrupt pins)
- Up to 16 external interrupts (EXTI0-EXTI15), plus 7 internal events



STM32F4xx external interrupt sources

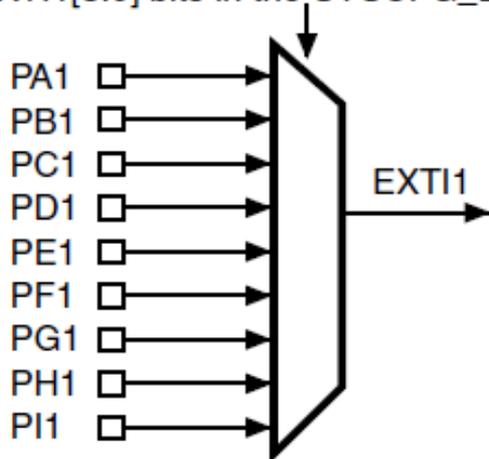
(select in System Configuration Module – SYSCFG)

- 16 multiplexers select GPIO pins as external interrupts EXTI0..EXTI15
- Mux inputs selected via 4-bit fields of EXTICR[k] registers (k=0..3)
 - $EXTIx = 0$ selects PAx, 1 selects PBx, 2 selects PCx, etc.
 - $EXTICR[0]$ selects EXTI3-EXTI0; $EXTICR[1]$ selects EXTI7-EXTI4, etc

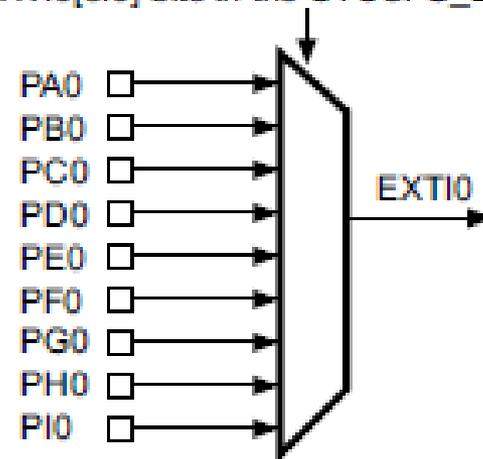
*SYSCFG_EXTICR1 is
SYSCFG->EXTICR[0]*



EXTI1[3:0] bits in the SYSCFG_EXTICR1 register



EXTI0[3:0] bits in the SYSCFG_EXTICR1 register



Example: Select pin PC2 as external interrupt EXTI2

```
SYSCFG->EXTICR[0] &= 0xF0FF; //clear EXTI2 bit field
```

```
SYSCFG->EXTICR[0] |= 0x0200; //set EXTI2 = 2 to select PC2
```

STM32L1xx EXTI configuration registers

- Register bits 15-0 control EXTI15-EXTI0, respectively
- **EXTI_IMR** – interrupt **mask** register
 - 1 unmask (enables) the corresponding interrupt
 - 0 masks (disables) the interrupt
- **EXTI_RTZR/FTSR** – **rising/falling trigger** selection register
 - 1 to enable rising/falling edge to trigger the interrupt/event
 - 0 to ignore the rising/falling edge
- **EXTI_PR** – interrupt **pending** register
 - bit set to 1 by hardware if interrupt/event occurred (*bit is readable*)
 - clear bit by writing 1 (*writing 0 has no effect*)
 - **interrupt handler** must write **1** to this bit to clear the pending state of the interrupt (to cancel the IRQn request)

Example: Configure EXTI2 as rising-edge triggered

```
EXTI->RTSR |= 0x0004;    //Bit2=1 to make EXTI2 rising-edge trig.
```

```
EXTI->IMR   = 0x0004;    //Bit2=1 to enable EXTI2
```

```
EXTI->PR    |= 0x0004;    //Bit2=1 to clear EXTI2 pending status
```

Example: Enable EXTI0 as rising-edge triggered

`;System Configuration Registers`

```
SYSCFG EQU 0x40013800
EXTICR1 EQU 0x08
```

`;External Interrupt Registers`

```
EXTI EQU 0x40013C00
IMR EQU 0x00 ;Interrupt Mask Register
RTSR EQU 0x08 ;Rising Trigger Select
FTSR EQU 0x0C ;Falling Trigger Select
PR EQU 0x14 ;Pending Register
```

`;select PC0 as EXTI0`

```
ldr r1,=SYSCFG ;SYSCFG selects EXTI sources
ldrh r2,[r1,#EXTICR1] ;EXTICR1 = sources for EXTI0 - EXTI3
bic r2,#0x000f ;Clear EXTICR1[3-0] for EXTI0 source
orr r2,#0x0002 ;EXTICR1[3-0] = 2 to select PC0 as EXTI0 source
strh r2,[r1,#EXTICR1] ;Write to select PC0 as EXTI0
```

`;configure EXTI0 as rising-edge triggered`

```
ldr r1,=EXTI ;EXTI register block
mov r2,#1 ;bit #0 for EXTI0 in each of the following registers
str r2,[r1,#RTSR] ;Select rising-edge trigger for EXTI0
str r2,[r1,#PR] ;Clear any pending event on EXTI0
str r2,[r1,#IMR] ;Enable EXTI0
```

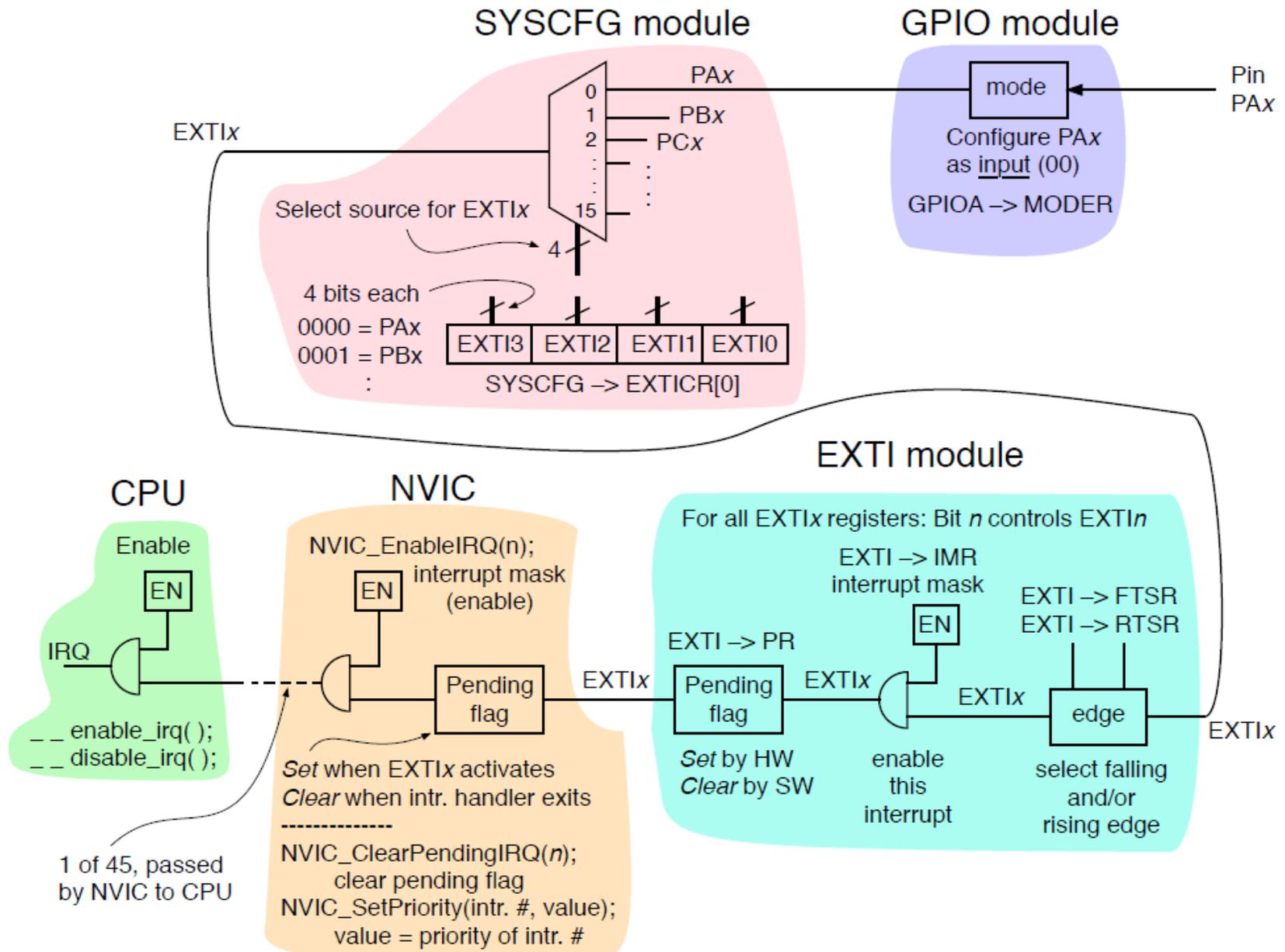
Interrupt Rituals

- Things you must do in every ritual
 - Initialize data structures (counters, pointers)
 - Arm interrupt in the peripheral device
 - Enable a flag to trigger an interrupt
 - Clear the flag (to ignore previous events)
 - Configure NVIC
 - Enable interrupt (**NVIC_ISERx**)
 - Set priority (**NVIC_IPRx**)
 - Enable CPU Interrupts
 - Assembly code **CPSIE I**
 - C code **EnableInterrupts();**

Project setup for interrupt-driven applications

- Write the interrupt handler for each peripheral
 - Clear the flag that requested the interrupt (acknowledge the intr. request)
 - Perform the desired actions, communicating with other functions via shared global variables
 - Use function names from the vector table
Example: *void EXTI4_IRQHandler () { statements }*
- Perform all initialization for each peripheral device:
 - Initialize the device, “arm” its interrupt, and clear its “flag”
Example: External interrupt EXTIIn
 - Configure GPIO pin as a digital input
 - Select the pin as the EXTIIn source (in SYSCFG module)
 - Enable interrupt to be requested when a flag is set by the desired event (rising/falling edge)
 - Clear the pending flag (to ignore any previous events)
 - NVIC
 - Enable interrupt: *NVIC_EnableIRQ (IRQn);*
 - Set priority: *NVIC_SetPriority (IRQn, priority);*
 - Clear pending status: *NVIC_ClearPendingIRQ (IRQn);*
- Initialize counters, pointers, global variables, etc.
- Enable CPU Interrupts: *__enable_irq () ;*

Signal flow/setup for External Interrupt EXT_{Ix}, x = 0...15



Interrupt Service Routine (ISR)

- Things you must do in every interrupt service routine
 - Acknowledge
 - clear flag that requested the interrupt
 - SysTick is exception; automatic acknowledge
 - Maintain contents of R4-R11 (AAPCS)
 - Communicate via shared global variables

Sources of interrupt **overhead**

- Handler execution time.
- Interrupt mechanism overhead.
- Register save/restore.
- Pipeline-related penalties.
- Cache-related penalties.
- **Interrupt “latency”** = time from activation of interrupt signal until event serviced.
- ARM worst-case latency to respond to interrupt is 27 cycles:
 - 2 cycles to synchronize external request.
 - Up to 20 cycles to complete current instruction.
 - 3 cycles for data abort.
 - 2 cycles to enter interrupt handling state.