Interrupt Programming

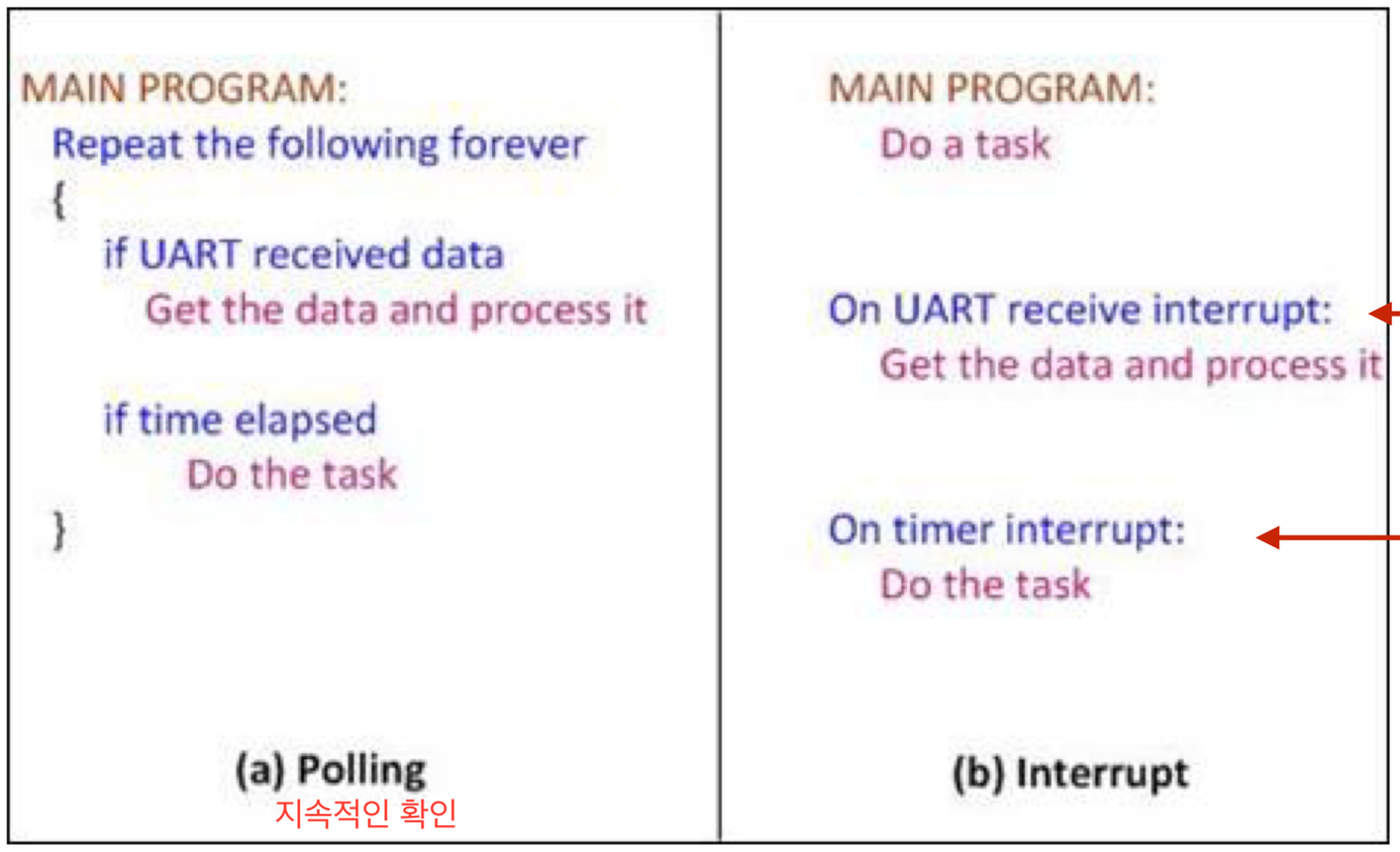
Lesson 06

Interrupts and Exceptions in ARM Cortex-M

인터럽트 (Interrupt)

- 현재 실행 중인 프로그램과는 별개로 비동기적으로 발생하는 이벤트(event)
- 인터럽트가 발생하면 CPU는 실행중인 프로그램을 중단하고 인터럽트 핸들러 (interrupt handler) 혹은 인터럽트 서비스 루틴 (interrupt service routine: ISR)이라고 불리는 특별한 코드를 실행
- ISR의 실행이 종료되면 일반적으로 원래 실행중이던 프로그램으로 복귀

Interrupts vs. Polling



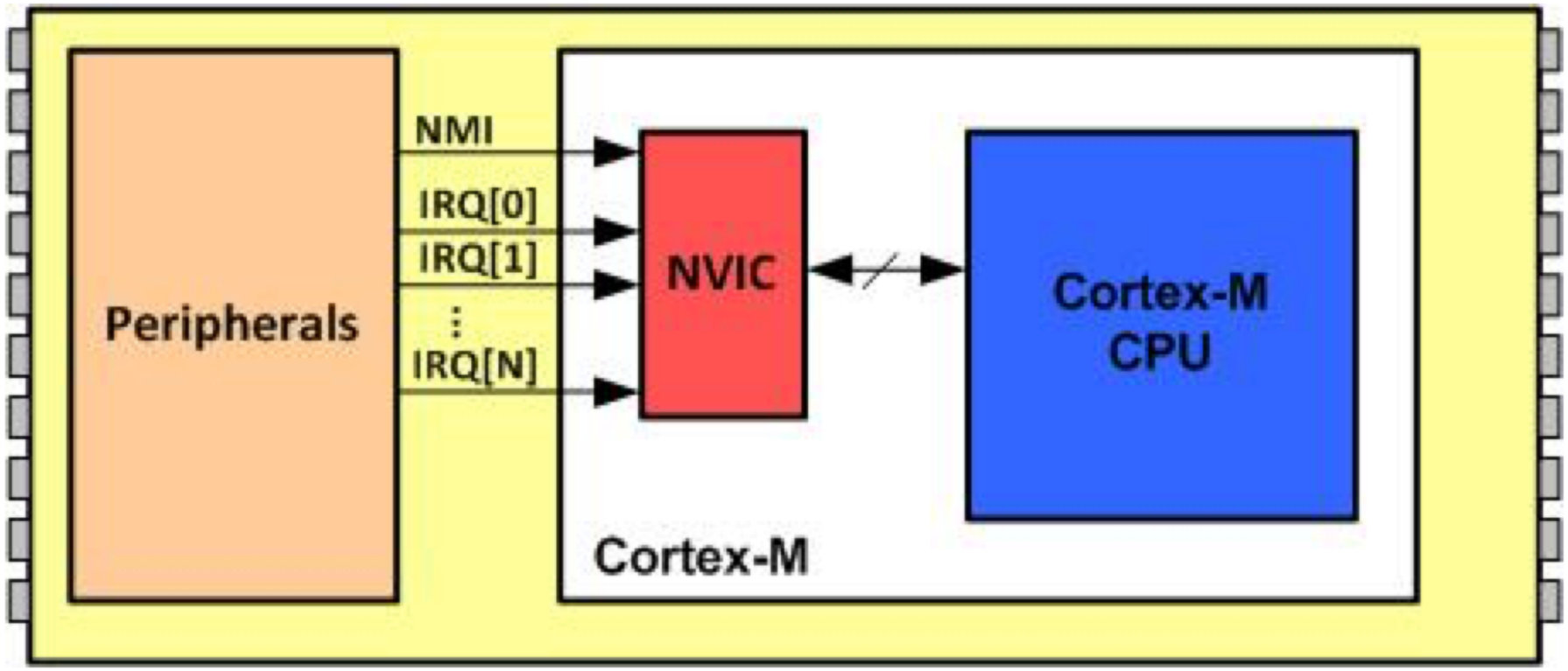
Some questions ?

- 인터럽트 발생시 어떤 핸들러를 실행해야 하는지 그리고 그 핸들러는 어디에 있는지 어떻게 알수 있나? interrupt vector table
- 인터럽트 처리 후 어떻게 원래 수행하던 코드로 돌아올 수 있나?
- 인터럽트를 처리하는 도중에 다른 인터럽트가 발생하면 ? 우선순위 기반 처리
- **Critical section**에 있는 도중에 인터럽트가 발생하면 ?

세마포어~

NVIC

- **Cortex-M4에서 인터럽트는 Nested Vectored Interrupt Controller (NVIC)이라고 불리는 장치에 의해 제어된다** (Classical ARM 혹은 Cortex-A와 Cortex-R 시리즈에서는 다른 방식으로 처리됨)
- **외부 장치로부터의 인터럽트를 허용하려면 NVIC에서 해당 장치의 인터럽트를 enable하고 우선순위(priority)를 지정해야 한다.**



Cortex-M has on-chip interrupt controller called
NVIC (Nested Vector Interrupt Controller)

Interrupt Vector Table

- 인터럽트 핸들러의 주소를 저장하는 테이블
- 메모리의 최하위 **1024** 바이트에 위치
- **255**개의 인터럽트에 대한 핸들러의 주소를 저장 (**0**번지에는 **SP**의 초기값이 저장)

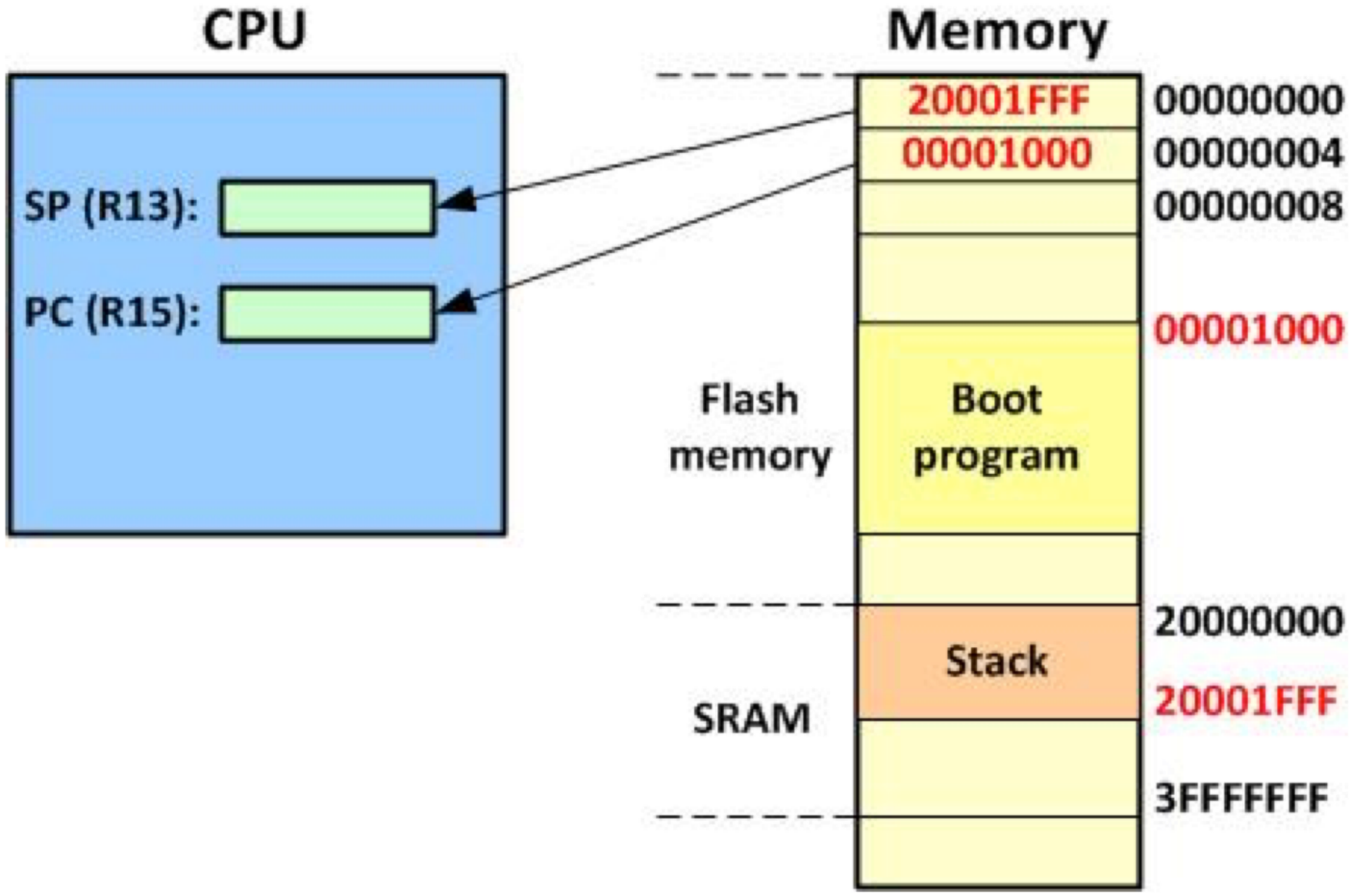
Interrupt Vector Table

Interrupt #	Interrupt	Memory Location (Hex)
	Stack Pointer initial value	0x00000000
1	Reset	0x00000004
2	NMI	0x00000008
3	Hard Fault	0x0000000C
4	Memory Management Fault	0x00000010
5	Bus Fault	0x00000014
6	Usage Fault (undefined instructions, divide by zero, unaligned memory access,....)	0x00000018
7	Reserved	0x0000001C
8	Reserved	0x00000020
9	Reserved	0x00000024
10	Reserved	0x00000028
11	SVCall	0x0000002C
12	Debug Monitor	0x00000030
13	Reserved	0x00000034
14	PendSV	0x00000038
15	SysTick	0x0000003C
16	IRQ for peripherals	0x00000040
17	IRQ for peripherals	0x00000044
...	...	...
255	IRQ for peripherals	0x000003FC

predefined by Cortex-M

defined by SOC chip

Predefined Interrupts: Reset Interrupt



Reset Interrupt의 처리

Predefined Interrupts

- **Reset**
- **Non-Maskable Interrupt (NMI)**
- **Exceptions (Faults)**
  - usage fault - divide by zero, unaligned memory access, undefined instruction
  - bus fault
  - hard fault - writing to clock-disabled register
  - memory management fault - writing to read-only region, page fault
- **SVCall (Supervisor call) and PendSV (pendable service call)**
  - software interrupt
  - used to gain a privileged access mode
- **Debug Monitor**
  - used to perform single-stepping by debugger
- **SysTick**
  - for multitasking OS

IRQ Peripheral Interrupts

- **INT16 ~ INT255**
- **Timer, ADC, Serial COM,** 외부 하드웨어 인터럽트 등 다양한 주변 장치들에 할당 (SOC 칩마다 다름)

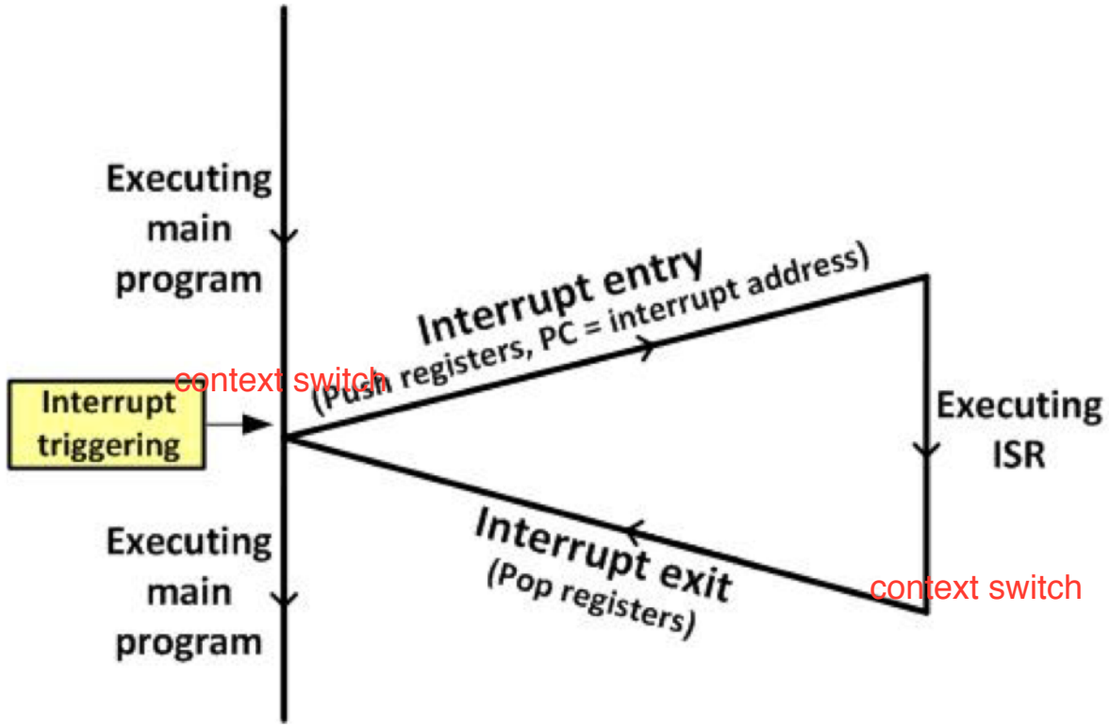
프로그램이 수행 될려면 PC에 프로그램이 들어가야 하는데 이것은 소프트웨어적으로 수행될 수 없다
하드웨어적으로 강제적으로 수행한다.

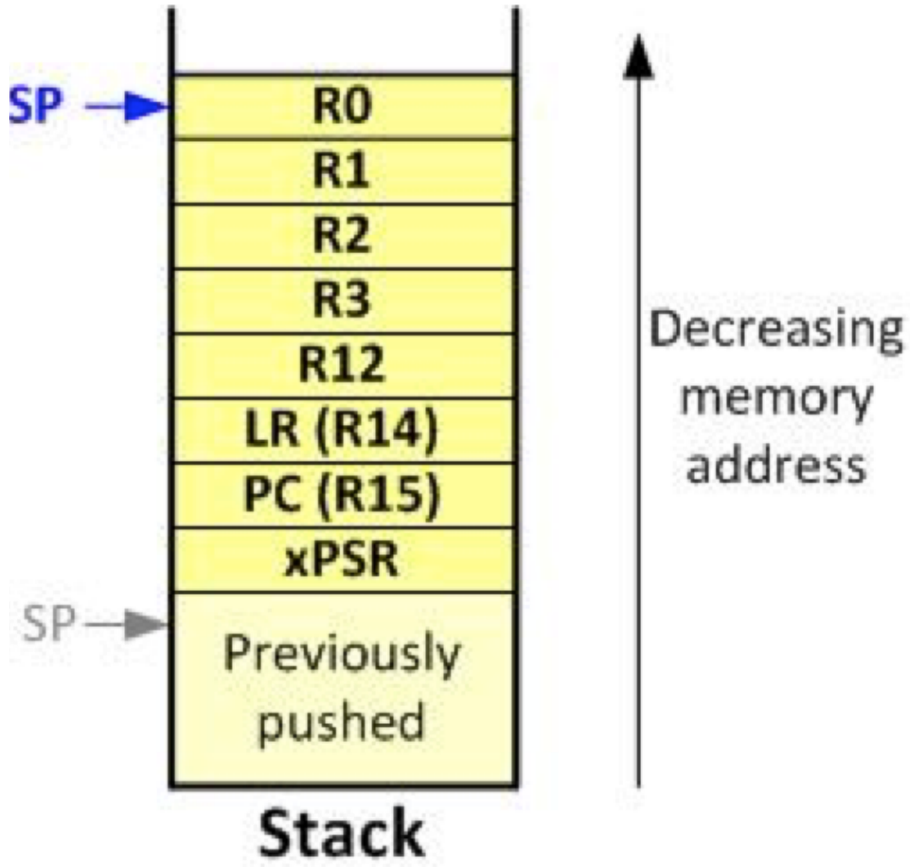
Context Switch

인터럽트 시에 기존 프로그램에서 사용하는 레지스터 값을 다른 곳에 복사하고
인터럽트가 끝난 후 그대로 복원

cpu의 현재 상태를 알 수 있는 flag값들

- **인터럽트가 발생되면 CPSR, PC, LR, R12, R3, R2, R1, R0 레지스터의 값이 스택에 자동으로 저장됨** 모든 값이 아닌 중요한 몇 레지스터 값만 저장
- **ISR이 그 밖의 다른 레지스터를 사용할 경우 추가로 스택에 저장하고 종료 직전에 복원해야 한다.**





ARM Cortex-M에서 인터럽트의 처리

1. CPSR, PC, LR, R12, R3, R2, R1, R0 레지스터의 값이 순서대로 스택에 push된다.
2. Floating point coprocessor의 레지스터 값들이 스택에 저장된다. (만약 lazy stacking이 enable되어 있으면 실제 값은 저장되지 않고 SP만 증가함)
3. CPU는 Handler Mode로 바뀌고 LR에는 31~5번째 비트가 모두 1인 주소가 저장된다.
4. INT number에 4를 곱한 값을 PC에 load하여 ISR로 분기한다.
5. ISR이 종료되면 LR 레지스터의 값을 보고 Handler Mode임을 인식한다. 스택에 저장해두었던 레지스터의 값들을 복원하고 원래 실행하던 프로그램으로 복귀한다.

인터럽트 우선순위 (Interrupt Priority)

Interrupt #	Interrupt	Priority Level
0	*Stack Pointer initial value*	
1	Reset	-3 Highest
2	NMI	-2
3	Hard Fault	-1
4	Memory Management Fault	Programmable
5	Bus Fault	Programmable
6	Usage Fault (undefined instructions, divide by zero, unaligned memory access,....)	Programmable
7	Reserved	Programmable
8	Reserved	Programmable
9	Reserved	Programmable
10	Reserved	Programmable
11	SVCall	Programmable
12	Debug Monitor	Programmable
13	Reserved	Programmable
14	PendSV	Programmable
15	SysTick	Programmable
16	IRQ for peripherals	Programmable
17	IRQ for peripherals	Programmable
...	...	Programmable
255	IRQ for peripherals	Programmable

고정

설정가능
(0 ~ 7)

숫자가 작을 수록
높은 우선순위

인터럽트 우선순위 (Interrupt Priority)

- 동시에 여러 개의 인터럽트가 발생하면 가장 높은 우선순위를 가진 인터럽트가 먼저 처리되고 다른 인터럽트들은 대기해야 함
- 중첩된 인터럽트 (Nested Interrupt)
  - ISR을 실행하는 도중에 더 높은 우선순위의 인터럽트가 발생하면 실행중인 ISR을 중지하고 새로운 (높은 우선순위의) ISR이 실행됨

ARM Cortex-M Processor Modes

- **ARM Cortex-M은 2가지 실행 모드를 가짐**
  - Thread (Application) mode
  - Handler (Exception) mode
- **ARM Cortex-M이 처음 시작되어 reset 핸들러를 실행하고 빠져나오면 자동으로 Thread 모드가 됨**
- **인터럽트가 발생하면 Handler 모드로 변경되고, ISR로부터 return되면 다시 Thread 모드로 돌아옴**
- **LR 레지스터의 값으로 Handler 모드인지 Thread 모드인지 판단**

I/O Port Interrupt Programming

TM4C123H6MP.h: IRQ 할당

ARABOJA

```
typedef enum {
/* ------------------  Cortex-M4 Processor Exceptions Numbers  ------------------------- */
   Reset_IRQn                    = -15,      /*!<   1  Reset Vector                          */
   NonMaskableInt_IRQn           = -14,      /*!<   2  Non maskable Interrupt                */
   HardFault_IRQn                = -13,      /*!<   3  Hard Fault, all classes of Fault      */
   MemoryManagement_IRQn         = -12,      /*!<   4  Memory Management, MPU mismatch       */
   BusFault_IRQn                 = -11,      /*!<   5  Bus Fault, Memory Access Fault        */
   UsageFault_IRQn               = -10,      /*!<   6  Usage Fault, Undef Instruction        */
   SVCall_IRQn                   =  -5,      /*!<  11  System Call via SVC instruction       */
   DebugMonitor_IRQn             =  -4,      /*!<  12  Debug Monitor                          */
   PendSV_IRQn                   =  -2,      /*!<  14  Pendable request                       */
   SysTick_IRQn                  =  -1,      /*!<  15  System Tick Timer                      */
/* ------------------  TM4C1232H6PM Specific Interrupt Numbers  ------------------ */
   GPIOA_IRQn                    =   0,      /*!<   0  GPIOA                        */
   GPIOB_IRQn                    =   1,      /*!<   1  GPIOB                        */
   GPIOC_IRQn                    =   2,      /*!<   2  GPIOC                        */
   GPIOD_IRQn                    =   3,      /*!<   3  GPIOD                        */
   GPIOE_IRQn                    =   4,      /*!<   4  GPIOE                        */
   UART0_IRQn                    =   5,      /*!<   5  UART0                        */
   UART1_IRQn                    =   6,      /*!<   6  UART1                        */
   SSI0_IRQn                     =   7,      /*!<   7  SSI0                         */
   I2C0_IRQn                     =   8,      /*!<   8  I2C0                         */
```

TM4C123H6MP.h: IRQ 할당

```
    ADC0SS0_IRQn                = 14,     /*!< 14  ADC0SS0                 */
    ADC0SS1_IRQn                = 15,     /*!< 15  ADC0SS1                 */
    ADC0SS2_IRQn                = 16,     /*!< 16  ADC0SS2                 */
    ADC0SS3_IRQn                = 17,     /*!< 17  ADC0SS3                 */
    WATCHDOG0_IRQn              = 18,     /*!< 18  WATCHDOG0               */
    TIMER0A_IRQn                = 19,     /*!< 19  TIMER0A                 */
    TIMER0B_IRQn                = 20,     /*!< 20  TIMER0B                 */
    TIMER1A_IRQn                = 21,     /*!< 21  TIMER1A                 */
    TIMER1B_IRQn                = 22,     /*!< 22  TIMER1B                 */
    TIMER2A_IRQn                = 23,     /*!< 23  TIMER2A                 */
    TIMER2B_IRQn                = 24,     /*!< 24  TIMER2B                 */
    COMP0_IRQn                  = 25,     /*!< 25  COMP0                   */
    COMP1_IRQn                  = 26,     /*!< 26  COMP1                   */
    SYSCTL_IRQn                 = 28,     /*!< 28  SYSCTL                  */
    FLASH_CTRL_IRQn             = 29,     /*!< 29  FLASH_CTRL              */
    GPIOF_IRQn                  = 30,     /*!< 30  GPIOF                   */
    GPIOG_IRQn                  = 31,     /*!< 31  GPIOG                   */
    UART2_IRQn                  = 33,     /*!< 33  UART2                   */
    …

} IRQn_Type;
```

GPIO Port F의 모든 핀에게 1개의 IRQ가 할당되어 있음
따라서 어떤 핀인지를 알아내는 것은 ISR이 해야할 일

PORTF 인터럽트 레지스터

- 시스템이 시작될 때 모든 인터럽트는 기본적으로 **disable**됨
- 인터럽트를 **enable**하기 위한 **3**단계:
  1. Enable the interrupt **for a specific peripheral module** 장치에서 인터럽트 발생
  2. Enable the interrupts **at the NVIC module** NVIC에서 발생
  3. Enable the interrupt **globally** 한번에 다 키고 끈다

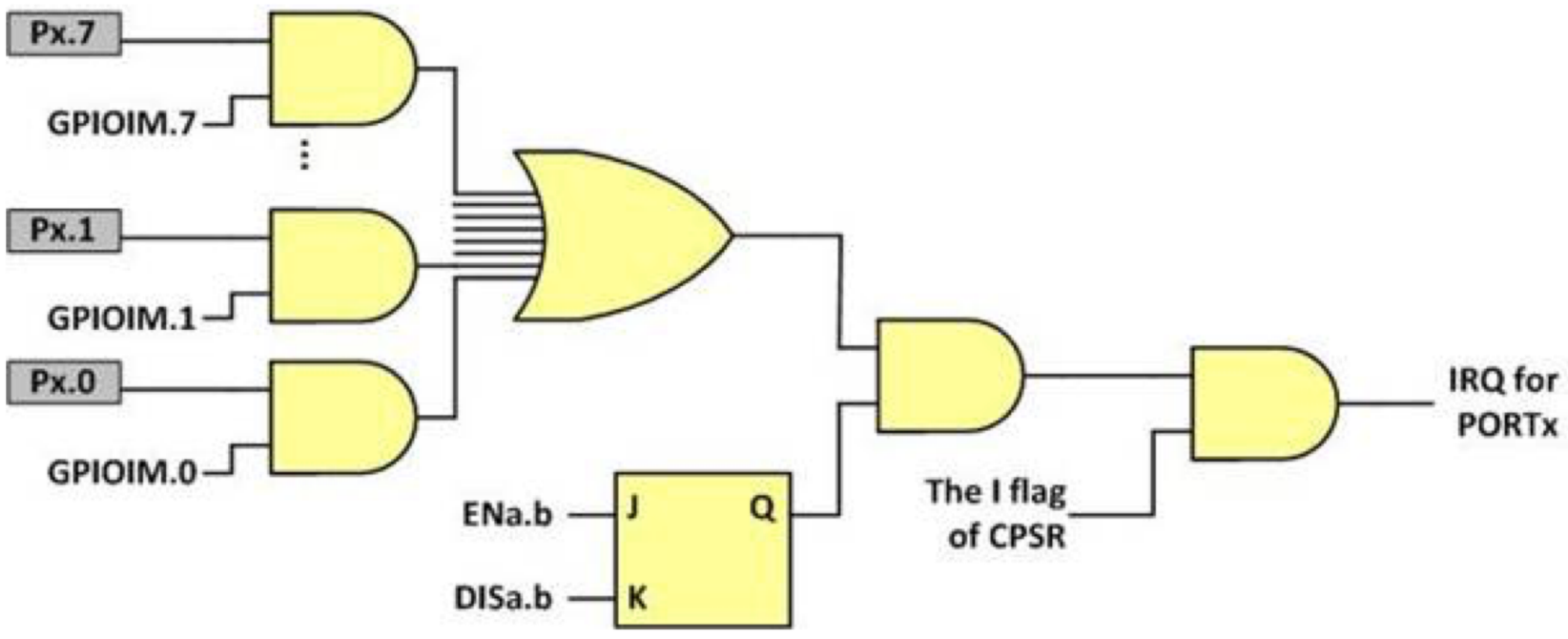


Figure 6-8: Interrupt enabling with all 3 levels

제1단계: GPIOIM

- **I/O Port의 인터럽트를 enable하기 위해서 GPIO Interrupt Mask (GPIOIM) 레지스터를 설정해야 함**

	D31	.....	D8	D7	D6	D5	D4	D3	D2	D1	D0	
GPIOIM:	Reserved			IME Px.7	IME Px.6	IME Px.5	IME Px.4	IME Px.3	IME Px.2	IME Px.1	IME Px.0	0x410

Note: D0 to D7 are used to enable/disable the interrupt for pins 0 to 7 of the port.
1: Enable interrupt
0: Disable interrupt (mask the interrupt)

Figure 6-9: GPIO Interrupt Mask (GPIOIM)

```
GPIOF->IM |= 0x1
```

PF0핀의 인터럽트를 enable

제2단계: NVIC Registers

- **Interrupt Vector Table의 각 항목마다 NVIC의 레지스터에 하나의 enable 비트가 있음**
- **각각의 레지스터가 32개의 IRQ 인터럽트를 담당**

Figure 6-10: Interrupts 0–31 Set Enable (ENo)

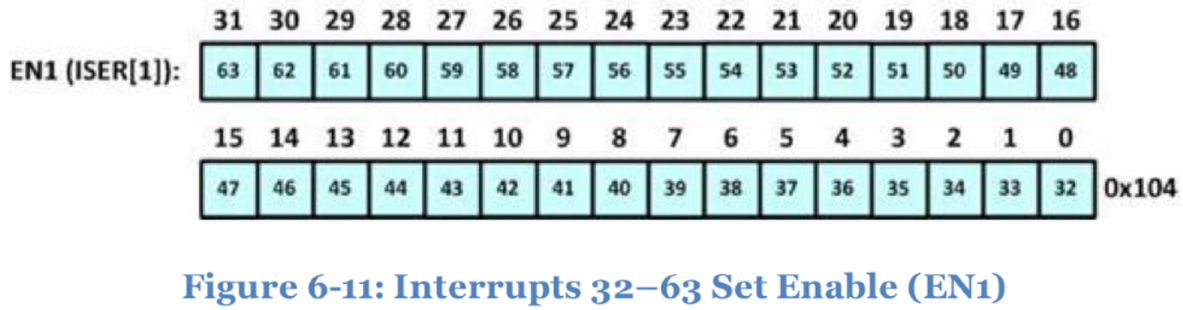


Figure 6-11: Interrupts 32–63 Set Enable (EN1)

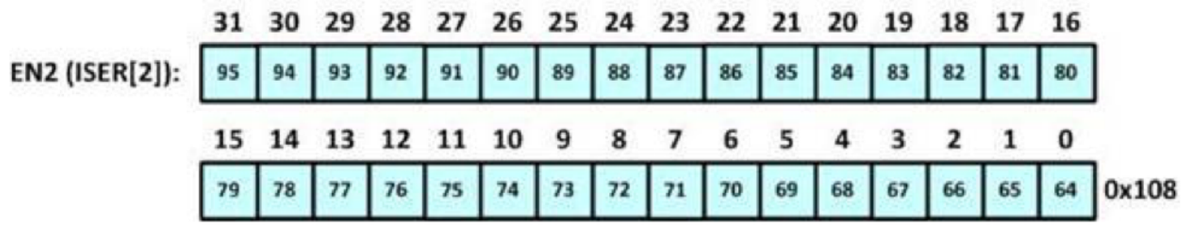


Figure 6-12: Interrupts 64–95 Set Enable (EN2)

⋮

```
NVIC->ISER[0] |= 0x40000000    /* To enable INT30 */
```

Interrupts set enable register

제2단계: NVIC Registers

인터럽트를 enable하려면
Interrupt Set Enable (ISER)에 써야한다.

```
NVIC->ISER[0] |= 0x40000000
/* enable INT30 */
```

혹은

```
void NVIC_EnableIRQ(30);
```

in CMSIS header file

혹은

```
void NVIC_EnableIRQ(GPIOF_IRQn);
```

defined in core_cm4.h

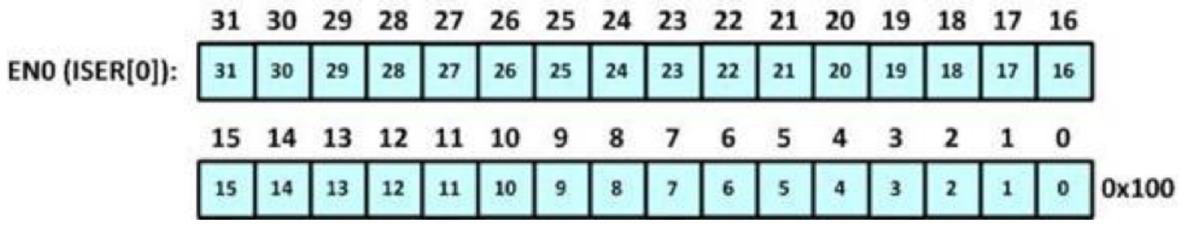


Figure 6-10: Interrupts 0–31 Set Enable (EN0)

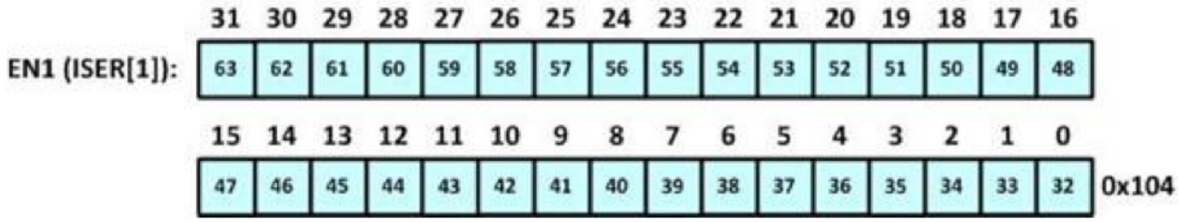


Figure 6-11: Interrupts 32–63 Set Enable (EN1)

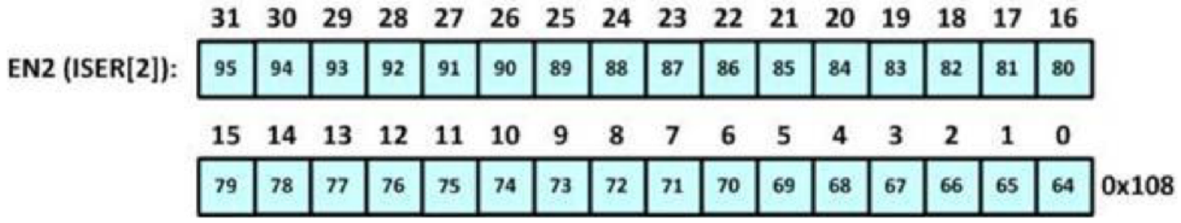


Figure 6-12: Interrupts 64–95 Set Enable (EN2)

⋮

Disable Interrupts

인터럽트를 disable하려면
Interrupt Clear Enable (ICER)에 써야한다.

```
NVIC->ICER[0] |= (1<<5)
/* disable UART0 Interrupt */
```

혹은

```
void NVIC_DisableIRQ(UART0_IRQn);
```

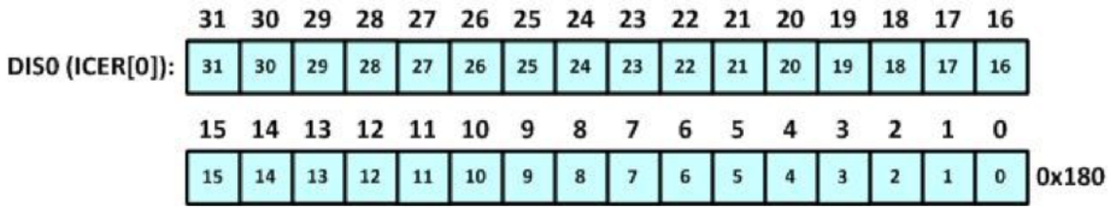


Figure 6-14: Interrupts 0–31 Clear Enable (DIS0)

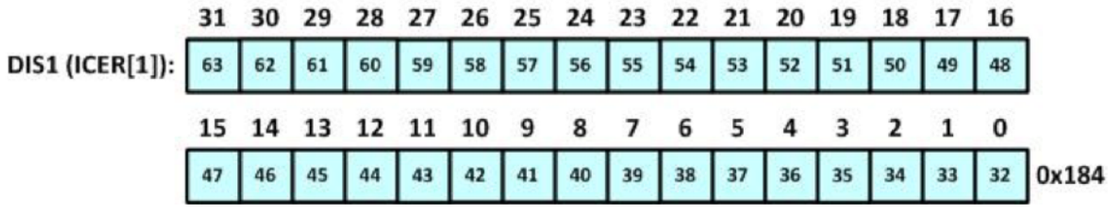
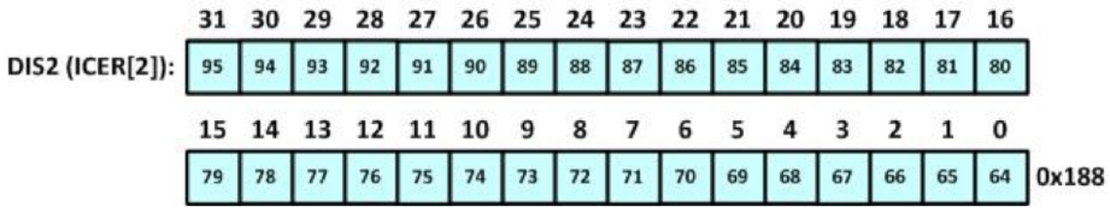


Figure 6-15: Interrupts 32–63 Clear Enable (DIS1)



제3단계: Global Interrupt Enable/Disable

- **critical한 작업을 하는 동안 하나의 instruction으로 모든 인터럽트를 mask 하기 위해서 제공되는 기능**
- **CMSIS의 pseudo-function**

```
__enable_irq();     /* Enable interrupt Globally */
__disable_irq();    /* Disable interrupt Globally */
```

Summary: Enable the Interrupts for PF0

```
GPIOF->IM |= 0x11                 /* unmask interrupts for PF4 and PF0 */
NVIC->ISER[0] = 0x40000000;       /*enable INT30 (bit 30 of ISER[0] */
__enable_irq();                   /* global enable IRQs */
```

IRQ Priority

- **NVIC 레지스터**
- **각각의 IRQ number에 대해서 1byte로 우선순위 지정**
- **가장 왼쪽, 즉 상위 3비트가 0~7까지의 우선순위를 지정**

```
NVIC->IP[INTERUPT_NUMBER] |= PRIORITY << 5;
NVIC->IP[30] |= 3 << 5;   /* set priority level 3 */
```

Interrupt Trigger Point

- **5가지 중에 선택**

1. low-level trigger
2. high-level trigger
3. rising-edge-trigger
4. falling-edge trigger
5. both edge (rising and falling) trigger

Interrupt Trigger Point

- 먼저 GPIO Interrupt Sense (GPIOIS) 레지스터로 level인지 edge인지 선택

	D31	.....	D8	D7	D6	D5	D4	D3	D2	D1	D0	
GPIOIS:	Reserved			IS Px.7	IS Px.6	IS Px.5	IS Px.4	IS Px.3	IS Px.2	IS Px.1	IS Px.0	0x404

Note: D0 to D7 are used to choose between edge and level sense for pins 0 to 7 of the port.
0: Edge-sensitive
1: Level-sensitive

Figure 6-19: GPIO Interrupt Sense (GPIOIS)

- GPIO Interrupt Event (GPIOIEV) 레지스터로 low인지 high인지, 혹은 falling인지 rising인지 선택

	D31	.....	D8	D7	D6	D5	D4	D3	D2	D1	D0	
GPIOIEV	Reserved			IEV7	IEV6	IEV5	IEV4	IEV3	IEV2	IEV1	IEV0	0x40C

Note: D0 to D7 are used to choose between edge and level sense for pins 0 to 7 of the port.
0: A falling edge or a Low level on the corresponding pin triggers an interrupt
1: A rising edge or a High level on the corresponding pin triggers an interrupt

Interrupt Trigger Point

IS.n (interrupt sense)	IEV.n (Interrupt Event)	
0	0	Falling edge
0	1	Rising edge
1	0	Low level
1	1	High level

```
GPIOF->IS &= ~0x11  /* mask bit 4, 0, edge sensitive */

GPIOF->IBE &= ~0x11

GPIOF->IEV &= ~0x11  /* falling edge trigger */
```

GPIO Interrupt Both Edges (GPIOIBE)를 clear해주지 않으면 무조건 both edge trigger가 됨

Toggle Red LED

```
/* Toggle red LED on PF1 continuously. Upon pressing either SW1 or SW2, the green
LED of PF3 should toggle for three times.*/

#include "TM4C123GH6PM.h"

void delayMs(int n);

int main(void)
{
    SYSCTL->RCGCGPIO |= 0x20;    /* enable clock to PORTF */
```

PF4 PF0

switch 2를 사용하기 위한 경우에만 사용

```
 /* PORTF0 has special function, need to unlock to modify */
 GPIOF->LOCK = 0x4C4F434B;    /* unlock commit register */
 GPIOF->CR = 0x01;            /* make PORTF0 configurable */
 GPIOF->LOCK = 0;             /* lock commit register */
```

← Commit Control

```
 /* configure PORTF for switch input and LED output */
 GPIOF->DIR &= ~0x11;  입0출1  /* make PORTF0 and 4 input for switch */
 GPIOF->DIR |= 0x0E;          /* make PORTF3, 2, 1 output for LEDs */
 GPIOF->DEN |= 0x1F;          /* make PORTF4-0 digital pins */
 GPIOF->PUR |= 0x11;          /* enable pull up for PORTF0 and 4 */
```

Toggle Red LED

```
/* configure PORTF4, 0 for falling edge trigger interrupt */
GPIOF->IS  &= ~0x11;        /* make bit 4, 0 edge sensitive */
GPIOF->IBE &= ~0x11;        /* trigger is controlled by IEV */
GPIOF->IEV &= ~0x11;        /* falling edge trigger */
GPIOF->ICR |= 0x11;         /* clear any prior interrupt */
GPIOF->IM  |= 0x11;         /* unmask interrupt */

/* enable interrupt in NVIC and set priority to 3 */
NVIC->IP[30] = 3 << 5;     /* set interrupt priority to 3 */
NVIC->ISER[0] |= 0x40000000;  /* enable IRQ30 (D30 of ISER[0]) */
    __enable_irq(); /* global enable IRQs */

    /* toggle the red LED (PF1) continuously */
    while(1)
    {
        GPIOF->DATA |= 0x02;
        delayMs(500);
        GPIOF->DATA &= ~0x02;
        delayMs(500);
    }
}
```

both edge 해제

트리거 포인트 설정

이전 인터럽트 해제

우선순위 3으로 설정

Toggle Red LED

```
/* SW1 is connected to PF4 pin, SW2 is connected to PF0. */
/* Both of them trigger PORTF interrupt */
void GPIOF_Handler(void)
{
    int i;
    volatile int readback;
    /* toggle green LED (PF3) three times */
    for (i = 0; i < 3; i++)
    {
        GPIOF->DATA |= 0x08;
        delayMs(500);
        GPIOF->DATA &= ~0x08;
        delayMs(500);
    }
    GPIOF->ICR |= 0x11;           /* clear the interrupt flag before return */
    readback = GPIOF->ICR;        /* a read to force clearing of interrupt flag */
}

/* delay n milliseconds (16 MHz CPU clock) */
void delayMs(int n)
{
    int i, j;
    for(i = 0 ; i < n; i++)
        for(j = 0; j < 3180; j++)
        {}  /* do nothing for 1 ms */
}
```

ISR에서 return하기 전에 interrupt flag를 clear해주어야 한다. GPIO Interrupt Clear Register에 1을 써주면 clear된다. 하지만 이 write는 buffered되므로 즉시 효과를 발휘하지 않는다. 그래서 flag를 한 번 read해준다.

TM4C123H6MP.h의 수정

```
/* PORTF0 has special function, need to unlock to modify */
GPIOF->LOCK = 0x4C4F434B;   /* unlock commit register */
GPIOF->CR = 0x01;           /* make PORTF0 configurable */
GPIOF->LOCK = 0;            /* lock commit register */
```

- **GPIO Commit Control**
  - 특정 GPIO 핀들은 특별한 기능으로 할당되어 있음 (PC[3:0]은 JTAG/SWD, PD7과 PF0는 NMI)
  - 이 핀들에 대해서 GPIOAFSEL, GPIOPUR, GPIODEN 등의 설정은 보호되어 있음
  - 이를 해제하려면 GPIOLOCK을 unlock하고 GPIOCR을 set해야 함
- **GPIOA_Type 구조체에서**

```
__I uint32_t  CR;           /*!< GPIO Commit
```

을 찾아서

```
__IO uint32_t  CR;          /*!< GPIO Commit
```

로 수정한다.

Startup Code에서

```
#include <stdint.h>

void ResetISR(void);
static void NmiSR(void);
static void FaultISR(void);
static void IntDefaultHandler(void);

void GPIOF_Handler(void);

:
```

GPIOF 인터럽트 핸들러의 prototype을 추가해준다.

Startup Code에서

```
__attribute__ ((section(".intvecs")))
void (* const g_pfnVectors[])(void) =
{
    (void (*)(void))((uint32_t)pui32Stack + sizeof(pui32Stack)),
                                            // The initial stack pointer
    ResetISR,                               // The reset handler
    NmiSR,                                  // The NMI handler
    FaultISR,                               // The hard fault handler
    IntDefaultHandler,                      // The MPU fault handler
    IntDefaultHandler,                      // The bus fault handler
    IntDefaultHandler,                      // The usage fault handler
    0,                                      // Reserved
    0,                                      // Reserved
    0,                                      // Reserved
    0,                                      // Reserved
     :
    IntDefaultHandler,                      // Analog Comparator 0
    IntDefaultHandler,                      // Analog Comparator 1
    IntDefaultHandler,                      // Analog Comparator 2
    IntDefaultHandler,                      // System Control (PLL, OSC, BO)
    IntDefaultHandler,                      // FLASH Control
    GPIOF_Handler,                          // GPIO Port F
    IntDefaultHandler,                      // GPIO Port G
    IntDefaultHandler,                      // GPIO Port H
    IntDefaultHandler,                      // UART2 Rx and Tx
    IntDefaultHandler,                      // SSI1 Rx and Tx
```

30번 IRQ의 위치에 핸들러의 주소를 넣는다.

입터럽트 핀의 분별: GPIOMIS

```
/* SW1 is connected to PF4 pin, SW2 is connected to PF0. Both of them trigger PORTF
interrupt */
void GPIOF_Handler(void)
{
    int i;
    volatile int readback;

    while (GPIOF->MIS != 0)
    {
        if (GPIOF->MIS & 0x10) /* is it SW1(PF4)? */
{   /* GPIOF4 pin interrupt */
    /* toggle green LED (PF3) three times */
    for (i = 0; i < 3; i++)
    {
        GPIOF->DATA |= 0x08;
        delayMs(500);
        GPIOF->DATA &= ~0x08;
        delayMs(500);
    }
    GPIOF->ICR |= 0x10;         /* clear the interrupt flag */
    readback = GPIOF->ICR;      /* a read to force clearing of
                                       interrupt flag */
}
```

Each of PORTF pin interrupt sets a pin in the GPIOMIS register. The ISR can poll the bits of GPIOMIS to find out which pin is requesting interrupt.

입터럽트 핀의 분별: GPIOMIS

```
else if (GPIOF->MIS & 0x01) /* then it must be SW2(PF0) */
{   /* GPIOF0 pin interrupt */
    /* toggle blue LED (PF2) three times */
    for (i = 0; i < 3; i++)
    {
        GPIOF->DATA |= 0x04;
        delayMs(500);
        GPIOF->DATA &= ~0x04;
        delayMs(500);
    }
    GPIOF->ICR |= 0x01;      /* clear the interrupt flag */
        readback = GPIOF->ICR;  /* a read to force clearing of
                                   interrupt flag */
    }
    else
    {
        /* We should never get here. */
        /* But if we do, clear all pending interrupts. */
        GPIOF->ICR = GPIOF->MIS;
        readback = GPIOF->ICR;   /* a read to force clearing of
                                    interrupt flag */
    }
  }
}
```

UART Serial Port Interrupt Programming

Enable UART Interrupt

	D31 ….. D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0	
UARTIM:	Reserved	9BITIM	Reser.	OEIM	BEIM	PEIM	FEIM	RTIM	TXIM	RXIM	reserved		CTSIM	Reser.	0x038

bit	Name	Description
1	CTSIM	1: an interrupt is made when the CTSRIS bit of UARTRIS is set, 0: masked (disabled)
4	RXIM	1: an interrupt is made when the RXRIS bit of UARTRIS is set, 0: masked (disabled)
5	TXIM	1: an interrupt is made when the TXRIS bit of UARTRIS is set, 0: masked (disabled)
6	RTIM	1: an interrupt is made when the RTSRIS bit of UARTRIS is set, 0: masked (disabled)
7	FEIM	1: an interrupt is made when the FERIS bit of UARTRIS is set, 0: masked (disabled)
8	PEIM	1: an interrupt is made when the PERIS bit of UARTRIS is set, 0: masked (disabled)
9	BEIM	1: an interrupt is made when the BERIS bit of UARTRIS is set, 0: masked (disabled)
10	OEIM	1: an interrupt is made when the OERIS bit of UARTRIS is set, 0: masked (disabled)
12	9BITIM	1: an interrupt is made when the 9BITRIS bit of UARTRIS is set, 0: masked (disabled)

Receiving Data

- **IRQ5 is assigned to UART0**
- **Enable the receive interrupt in UART0:**

```
UART0->IM |= 0x0010;  /* enable RX interrupt */
NVIC->ISER[0] |= 0x00000020;  /* enable IRQ5 */
__enable_irq();
```

Using UART0 Interrupt

```
#include "tm4c123gh6pm.h"

int main(void)
{
    SYSCTL->RCGCUART |= 1;     /* provide clock to UART0 */
    SYSCTL->RCGCGPIO |= 1;     /* enable clock to PORTA */

    SYSCTL->RCGCGPIO |= 0x20; /* enable clock to PORTF */

    /* UART0 initialization */
    UART0->CTL = 0;          /* disable UART0 */
    UART0->IBRD = 104;       /* 16MHz/16=1MHz, 1MHz/104=9600 baud rate */
    UART0->FBRD = 11;        /* fraction part, see Example 4-4 */
    UART0->CC = 0;           /* use system clock */
    UART0->LCRH = 0x60;      /* 8-bit, no parity, 1-stop bit, no FIFO */

    UART0->IM |= 0x0010;     /* enable RX interrupt */

    UART0->CTL = 0x301;      /* enable UART0, TXE, RXE */
```

UART0를 사용하기 위해서는 UART0와 GPIOA 포트에 클럭을 제공해야 한다,

LED를 점멸하기 위해서 GPIOF에 clock을 제공

3장의 코드에서 추가된 부분. 인터럽트를 enable한다.

Using UART0 Interrupt

```
/* UART0 TX0 and RX0 use PA0 and PA1. Set them up. */
GPIOA->DEN = 0x03;       /* Make PA0 and PA1 as digital */
GPIOA->AFSEL = 0x03;     /* Use PA0,PA1 alternate function */
GPIOA->PCTL = 0x11;      /* configure PA0 and PA1 for UART */

GPIOF->DIR = 0x0E;       /* 핀 1~3을 출력으로 설정 */
GPIOF->DEN = 0x0E;      /* 핀 1~3을 digital enable */
GPIOF->DATA = 0;

/* enable interrupt in NVIC and set priority to 6 */
NVIC->IP[5] = 3 << 5;   /* set interrupt priority to 3 */
NVIC->ISER[0] |= 0x00000020;  /* enable IRQ5 for UART0 */

__enable_irq(); /* global enable IRQs */

    for(;;)
    {
    }
}
```

UART0_Handler

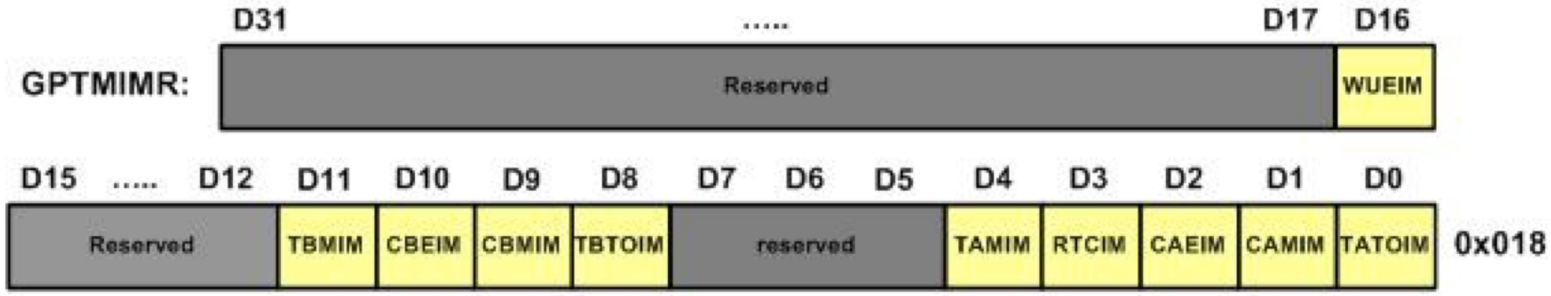
GPIOF_Handler와 마찬가지로 startup code를 수정한다.

Masked Interrupt Status (MIS) 레지스터의 D4비트를 검사

```
void UART0_Handler(void)
{
    volatile int readback;

    char c;

    if ( UART0->MIS & 0x0010 )
    {
        c = UART0->DR;          /* read the received data */
        GPIOF->DATA = c << 1;  /* shift left and write it to LEDs */
        UART0->ICR = 0x0010;    /* clear Rx interrupt flag */
        readback = UART0->ICR; /* a read to force clearing of interrupt flag */
    }
    else
    {
        /* should not get here. But if it does, */
        UART0->ICR = UART0->MIS; /* clear all interrupt flags */
        readback = UART0->ICR;
    }
}
```

Timer Interrupt Programming

GPTM Interrupt Mask



bit	Name	Description
0	TATOIM	Timer A Time-out Interrupt Mask (0: interrupt is disabled, 1: interrupt is enabled)
1	CAMIM	Timer A Capture mode Match Interrupt Mask (0: interrupt is disabled, 1: enabled)
2	CAEIM	Timer A Capture Mode Event Interrupt Mask (0: interrupt is disabled, 1: enabled)
3	RTCIM	RTC Interrupt Mask (0: interrupt is disabled, 1: interrupt is enabled)
4	TAMIM	Timer A Match Interrupt Mask (0: interrupt is disabled, 1: interrupt is enabled)
8	TBTOIM	Timer B Time-out Interrupt Mask (0: interrupt is disabled, 1: interrupt is enabled)
9	CBMIM	Timer B Capture mode Match Interrupt Mask (0: interrupt is disabled, 1: enabled)
10	CBEIM	Timer B Capture Mode Event Interrupt Mask (0: interrupt is disabled, 1: enabled)
11	TBMIM	Timer B Match Interrupt Mask (0: interrupt is disabled, 1: interrupt is enabled)
16	WUEIM	32/64-Bit Wide GPTM Write Update Error Interrupt Mask (0: disabled, 1: enabled)

To enable TIMER1A and TIMER2A,

```
NVIC->ISER[0] |= 0x00200000; /*enable IRQ21 */
NVIC->ISER[0] |= 0x00800000; /*enable IRQ23 */
```

TIMER1A toggles Red LED(PF1), TIMER2A toggles Green LED (PF3)

```
/* Timer1A is configure to timeout once every second. In the interrupt handler, the
red LED is toggled. Timer2A is configure to timeout at 10 Hz. In the interrupt
handler, the green LED is toggled. The infinite loop in the main program is
blinking the blue LED while the interrupts are going on. */

#include "TM4C123GH6PM.h"

int main (void)
{
    /* enable clock to GPIOF at clock gating control register */
    SYSCTL->RCGCGPIO |= 0x20;
    /* enable the GPIO pins for the LED (PF3, 2 1) as output */
    GPIOF->DIR = 0x0e;
    /* enable the GPIO pins for digital function */
    GPIOF->DEN = 0x0e;

    timer1A_init(); /* setup timer1A interrupt */
    timer2A_init(); /* setup timer2A interrupt */

    __enable_irq(); /* global enable IRQs */

    while(1)
    {
        GPIOF->DATA ^= 4;        /* toggle blue LED */
        delayMs(500);            /* wait for half second */
    }
}
```

TIMER1A toggles Red LED(PF1), TIMER2A toggles Green LED (PF3)

```
/* Setup Timer1A to create 1 Hz interrupt */
void timer1A_init(void)
{
    SYSCTL->RCGCTIMER |= 2;      /* enable clock to Timer Block 1 */

    TIMER1->CTL = 0;             /* disable Timer1 before initialization */
    TIMER1->CFG = 0x04;          /* 16-bit option */
    TIMER1->TAMR = 0x02;         /* periodic mode and down-counter */
    TIMER1->TAPR = 250;          /* 16000000 Hz / 250 = 64000 Hz */
    TIMER1->TAILR = 64000;       /* 64000 Hz / 64000 = 1 Hz */
    TIMER1->ICR = 0x1;           /* clear the Timer1A timeout flag */

    TIMER1->IMR |= 0x01;         /* enable Timer1A timeout interrupt */

    TIMER1->CTL |= 0x01;         /* enable Timer1A after initialization */

    NVIC->ISER[0] |= 0x00200000; /* enable IRQ21 (D21 of ISER[0]) */
}
```

TIMER1A toggles Red LED(PF1), TIMER2A toggles Green LED (PF3)

```
/* Setup Timer2A to create 10 Hz interrupt */
void timer2A_init(void)
{
    SYSCTL->RCGCTIMER |= 4;      /* enable clock to Timer Block 2   */
    TIMER2->CTL = 0;             /* disable Timer2 before initialization */
    TIMER2->CFG = 0x04;          /* 16-bit option */
    TIMER2->TAMR = 0x02;         /* periodic mode and down-counter */
    TIMER2->TAPR = 250;          /* 16000000 Hz / 250 = 64000 Hz */
    TIMER2->TAILR = 6400;        /* 64000 Hz / 6400 = 10 Hz */
    TIMER2->ICR = 0x1;           /* clear the Timer2A timeout flag */
    TIMER2->IMR |= 0x01;         /* enable Timer2A timeout interrupt */
    TIMER2->CTL |= 0x01;         /* enable Timer2A after initialization */
    NVIC->ISER[0] |= 0x00800000;  /* enable IRQ23 (D23 of ISER[0]) */
}
```

TIMER1A toggles Red LED(PF1), TIMER2A toggles Green LED (PF3)

```
void TIMER1A_Handler(void)
{
    volatile int readback;

    if (TIMER1->MIS & 0x1)        /* Timer1A timeout flag */
    {
        GPIOF->DATA ^= 2;         /* toggle red LED */
        TIMER1->ICR = 0x1;        /* clear the Timer1A timeout flag */
        readback = TIMER1->ICR;   /* to force clearing of interrupt flag */
    }
    else
    {   /* should not get here, but if we do */
        TIMER1->ICR = TIMER1->MIS;  /* clear all flags */
        readback = TIMER1->ICR;     /* to force clearing of interrupt flag */
    }
}
```

TIMER1A toggles Red LED(PF1), TIMER2A toggles Green LED (PF3)

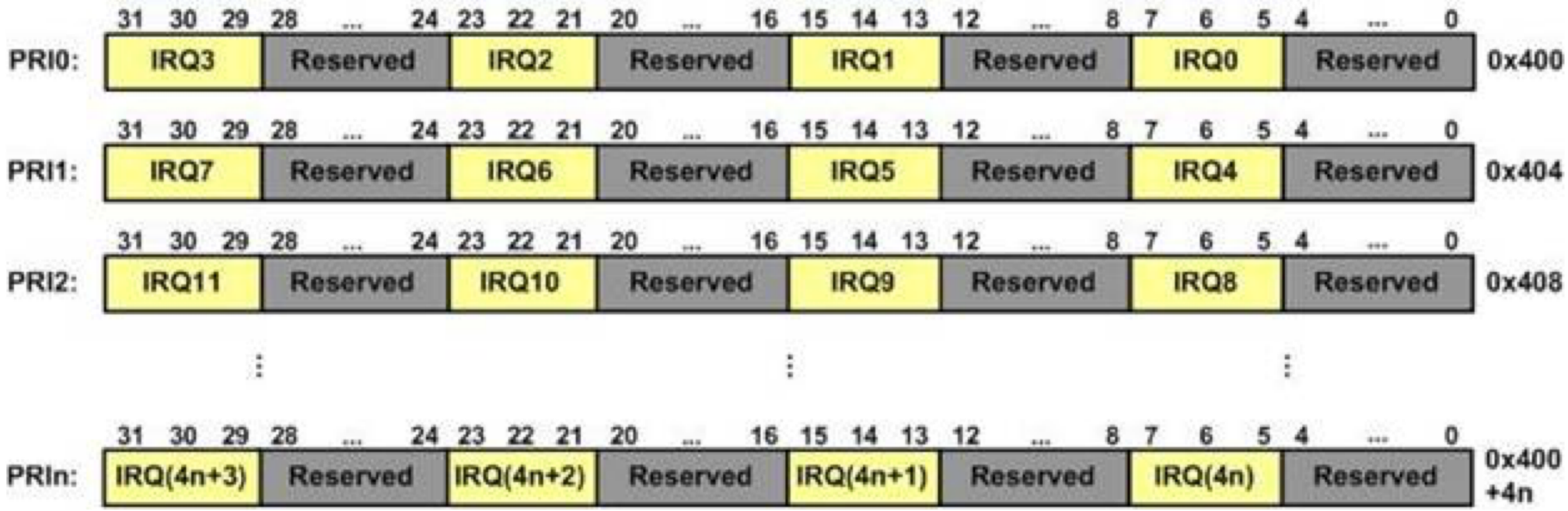
```
void TIMER2A_Handler(void)
{
    volatile int readback;
    if (TIMER2->MIS & 0x1)          /* Timer2A timeout flag */
    {
        GPIOF->DATA ^= 8;           /* toggle green LED */
        TIMER2->ICR = 0x1;          /* clear the Timer2A timeout flag */
        readback = TIMER2->ICR;     /* to force clearing of interrupt flag */
    }
    else
    {   /* should not get here, but if we do */
        TIMER2->ICR = TIMER2->MIS;  /* clear all flags */
        readback = TIMER2->ICR;     /* to force clearing of interrupt flag */
    }
}

/* delay n milliseconds (16 MHz CPU clock) */
void delayMs(int n)
{
    int i, j;
    for(i = 0 ; i < n; i++)
        for(j = 0; j < 3180; j++)
        {}  /* do nothing for 1 ms */
}
```

Interrupt Priority Programming

Interrupt Priority

- **처음 3개의 인터럽트가 highest priority를 가짐**
  - Reset (-3), NMI (-2), Hard Fault (-1)
- **다른 모든 인터럽트는 모두 동일한 우선순위 0을 가짐**
- **동일 우선순위에서는 IRQ번호가 낮을 수록 높은 우선순위**

PRI registers and Priority Grouping



- **To assign IRQn a priority p,**

```
NVIC->IP[n] = p << 5;  or
void NVIC_SetPriority(IRQn_Type IRQn, unit32_t priority);
```

Interrupt Priority Demo

```
/* Timer1A is setup to interrupt at 1 Hz. In timer interrupt handler, the red LED
is turned on and a delay 500 ms function is called. The LED is turned off at the
end of the delay. */

/* Timer2A is setup to interrupt at 10 Hz. In timer interrupt handler, the green
LED is turned on and a delay 20 ms function is called. The LED is turned off at the
end of the delay. */

/* When Timer1A has higher priority, the Timer2A interrupts are blocked by Timer1A
interrupt handler. You can see that when the red LED is on, the green LED is not
blinking. When Timer2A has higher priority, the Timer1A interrupt handler is
preempted by Timer2A interrupts and the green LED is blinking all the time. */


#include "TM4C123GH6PM.h"

void Timer1_init(void);
void Timer2_init(void);
void delayMs(int n);
```

Interrupt Priority Demo

```
int main (void)
{
    /* enable clock to GPIOF at clock gating control register */
    SYSCTL->RCGCGPIO |= 0x20;
    /* enable the GPIO pins for the LED (PF3, 2 1) as output */
    GPIOF->DIR = 0x0e;
    /* enable the GPIO pins for digital function */
    GPIOF->DEN = 0x0e;

    Timer1_init();
    Timer2_init();
    __enable_irq();

    while(1)
    {
    }
}
```

Interrupt Priority Demo

```
void TIMER1A_Handler(void)
{
    volatile int readback;

    GPIOF->DATA |= 2;    /* turn on red LED */
    delayMs(500);
    GPIOF->DATA &= ~2;   /* turn off red LED */
    TIMER1->ICR = 0x1;
    readback = TIMER1->ICR; /* a read to force clearing of interrupt flag */
}

void TIMER2A_Handler(void)
{
    volatile int readback;

    TIMER2->ICR = 0x1;
    GPIOF->DATA |= 8;    /* turn on green LED */
    delayMs(20);
    GPIOF->DATA &= ~8;   /* turn off green LED */
    readback = TIMER2->ICR;/* a read to force clearing of interrupt flag */
}
```

Interrupt Priority Demo

```
void Timer1_init(void)
{
    SYSCTL->RCGCTIMER |= 2; /* enable clock to Timer Module 1 */
    TIMER1->CTL = 0;        /* disable Timer1 before initialization */
    TIMER1->CFG = 0x04;     /* 16-bit option */
    TIMER1->TAMR = 0x02;    /* periodic mode and up-counter */
    TIMER1->TAPR = 250;     /* 16000000 Hz / 250 = 64000 Hz */
    TIMER1->TAILR = 64000;  /* 64000 Hz / 64000 = 1 Hz */
    TIMER1->ICR = 0x1;      /* clear the Timer1A timeout flag */
    TIMER1->IMR |= 0x01;    /* enable Timer1A timeout interrupt */
    TIMER1->CTL |= 0x01;    /* enable Timer1A after initialization */

    NVIC->IP[21] = 4 << 5;  /* set interrupt priority to 4 */

    NVIC->ISER[0] |= 0x00200000;    /* enable IRQ21 (D21 of ISER[0]) */
}
```

Interrupt Priority Demo

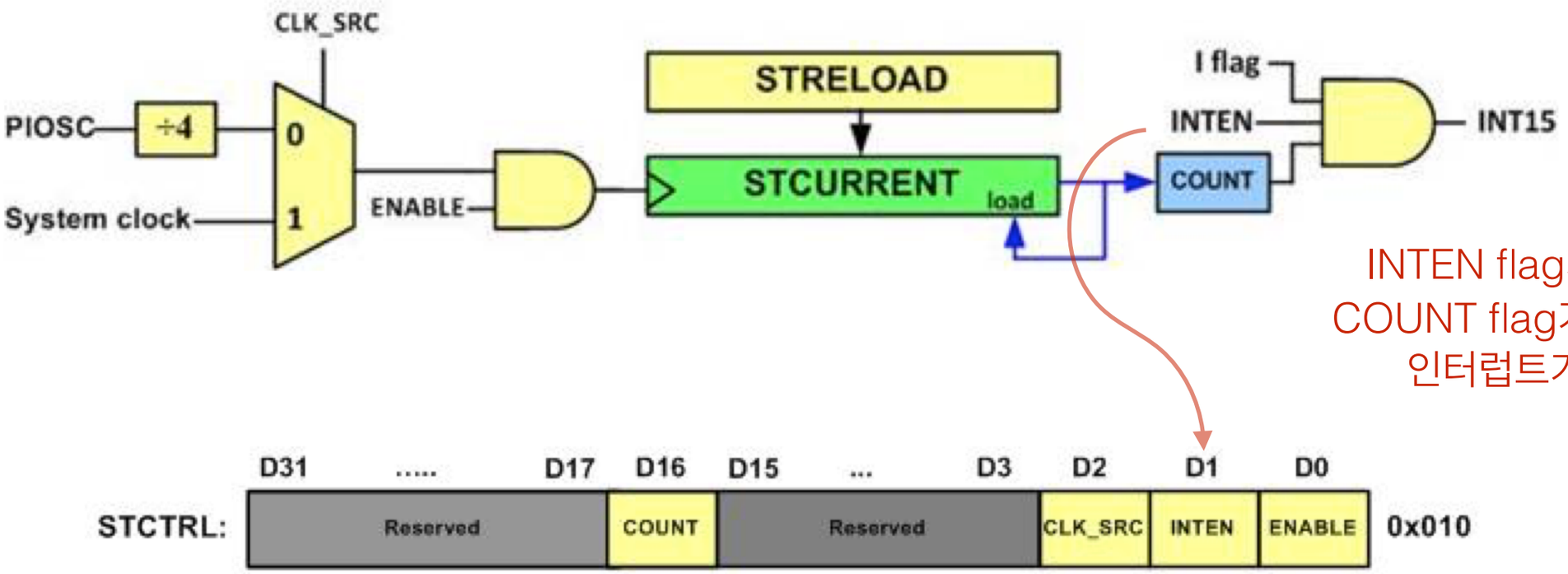
```
void Timer2_init(void)
{
    SYSCTL->RCGCTIMER |= 4; /* enable clock to Timer Module 2 */
    TIMER2->CTL = 0;        /* disable Timer2 before initialization */
    TIMER2->CFG = 0x04;     /* 16-bit option */
    TIMER2->TAMR = 0x02;    /* periodic mode and up-counter */
    TIMER2->TAPR = 250;     /* 16000000 Hz / 250 = 64000 Hz */
    TIMER2->TAILR = 6400;   /* 64000 Hz / 6400 = 10 Hz */
    TIMER2->ICR = 0x1;      /* clear the Timer1A timeout flag */
    TIMER2->IMR |= 0x01;    /* enable Timer2A timeout interrupt */
    TIMER2->CTL |= 0x01;    /* enable Timer2A after initialization */
    NVIC->IP[23] = 5 << 5;  /* set timer2A interrupt priority to 5 */
    NVIC->ISER[0] |= 0x00800000;    /* enable IRQ23 (D23 of ISER[0]) */
}

/* delay n milliseconds (16 MHz CPU clock) */
void delayMs(int n)
{
    int32_t i, j;
    for(i = 0 ; i < n; i++)
        for(j = 0; j < 3180; j++)
        {}  /* do nothing for 1 ms */
}
```

실습

1. 타이머 인터럽트를 이용하여 1초 단위로 내부 **RGB LED**가 **000**에서 **111**까지 2진 카운터로 작동하도록 프로그램을 작성하라. 스위치를 누르면 **000**으로 **reset**되는 기능을 추가하라.
2. 노트북으로부터 시리얼로 **000~111** 사이의 값을 전송받아 **RGB LED**를 켜는 프로그램을 작성하라. 시리얼 수신 부분을 인터럽트로 구현하라.

SysTick Programming and Interrupt

SysTick의 구조

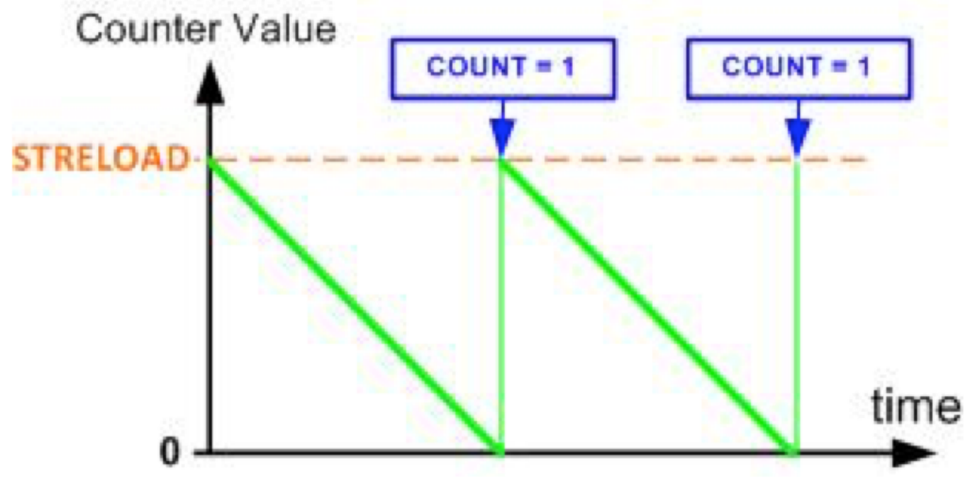


bit	Name	Description
0	ENABLE	Enable (0: the counter is disabled, 1: enables SysTick to begin counting down)
1	INTEN	Interrupt Enable 0: Interrupt generation is disabled, 1: when SysTick counts to 0 an interrupt is generated
2	CLK_SRC	Clock Source 0: Precision internal oscillator (PIOSC) divided by 4 1: System clock
16	COUNT	Count Flag 0: the SysTick has not counted down to zero since the last time this bit was read 1: the SysTick has counted down to zero *Note: this flag is cleared by reading the STRCTL or writing to CTCURRENT register.*

Figure 6-24: SysTick Control and Status Register (STCTRL)

Using SysTick with Interrupt

- **Used to initiate an action on a periodic basis**
- **Interrupt #15 is assigned to the SysTick**



- **Toggle RED LED of PF1 every second**
  - RELOAD value = 16,000,000-1
  - Since SysTick is an internal interrupt,
    - the COUNT flag is cleared automatically when the interrupt occurs.
    - we must use the CTLR register to enable the interrupt

SysTick Interrupt

```
/* Toggle the red LED using the SysTick interrupt. This program sets up the SysTick to
interrupt at 1 Hz. The system clock is running at 16 MHz. 1sec/62.5ns=16,000,000 for RELOAD
register. In the interrupt handler, the red LED is toggled. */

#include "TM4C123GH6PM.h"

int main (void)
{
    /* enable clock to GPIOF at clock gating control register */
    SYSCTL->RCGCGPIO |= 0x20;
    /* enable the GPIO pins for the LED (PF3, 2, 1) as output */
    GPIOF->DIR = 0x0e;
    /* enable the GPIO pins for digital function */
    GPIOF->DEN = 0x0e;

    /* Configure SysTick */
    SysTick->LOAD = 16000000-1;   /* reload with number of clocks per second */
    SysTick->CTRL = 7;      /* enable SysTick interrupt, use system clock */

    __enable_irq();         /* global enable interrupt */

    while (1)  { }
}

void SysTick_Handler(void)
{
    GPIOF->DATA ^= 2;    /* toggle the red LED */
}
```

An Extremely Simple RTOS

(http://users.ece.utexas.edu/~valvano/arm/index.htm)

main.c

```
#include "TM4C123GH6PM.h"
#include <stdint.h>
#include "os.h"

#define TIMESLICE TIME_2MS    // thread switch time in system time units

uint32_t Count1;   // number of times thread1 loops
uint32_t Count2;   // number of times thread2 loops
uint32_t Count3;   // number of times thread3 loops
```

main.c

```
void Task1(void){
  Count1 = 0;
  for(;;){
    Count1++;
    GPIOD->DATA ^= 0x02;       // toggle PD1
  }
}

void Task2(void){
  Count2 = 0;
  for(;;){
    Count2++;
    GPIOD->DATA ^= 0x04;       // toggle PD2
  }
}

void Task3(void){
  Count3 = 0;
  for(;;){
    Count3++;
    GPIOD->DATA ^= 0x08;       // toggle PD3
  }
}
```

main.c

```
int main(void){

    OS_Init();      // initialize, disable interrupts, 50 MHz

    SYSCTL->RCGCGPIO |= 0x08;     // activate clock for Port D
    while((SYSCTL->RCGCGPIO & 0x08) == 0){}; // allow time to stabilize

    GPIOD->DIR |= 0x0E;
    GPIOD->AFSEL &=  ~0x0E;       // disable alt funct on PD3-1
    GPIOD->DEN |= 0x0E;           // enable digital I/O on PD3-1

    GPIOD->PCTL &= 0xFFFF000F;    // configure PD3-1 as GPIO
    GPIOD->AMSEL &= ~0x0E;        // disable analog functionality on PD3-1

    OS_AddThreads(&Task1, &Task2, &Task3);

    OS_Launch(TIMESLICE); // doesn't return, interrupts enabled in here

    return 0;             // this never executes
}
```

os.h

```
#ifndef __OS_H
#define __OS_H  1

#define TIME_1MS  50000
#define TIME_2MS  2*TIME_1MS

void OS_Init(void);

int OS_AddThreads(void(*task0)(void),
                  void(*task1)(void),
                  void(*task2)(void));

void OS_Launch(uint32_t theTimeSlice);

#endif
```

OS.C

```
#include "TM4C123GH6PM.h"
#include <stdint.h>
#include "os.h"

#define NVIC_SYS_PRI3_R         (*((volatile uint32_t *)0xE000ED20))

// function definitions in osasm.s
void DisableInterrupts(void);    // Disable interrupts
void EnableInterrupts(void);     // Enable interrupts
int32_t StartCritical(void);
void EndCritical(int32_t primask);
void StartOS(void);
```

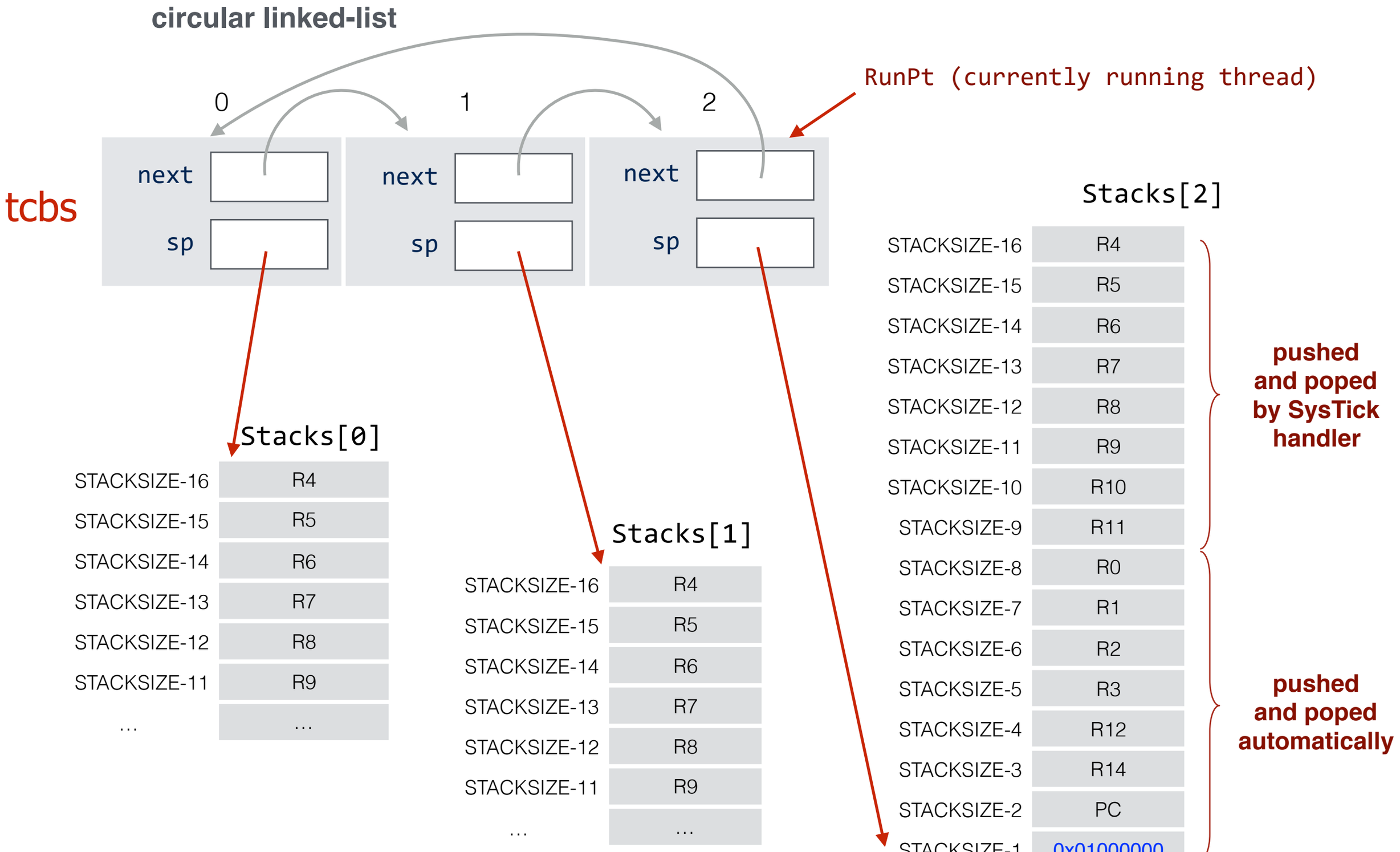
```
#define NUMTHREADS   3          // maximum number of threads
#define STACKSIZE    100        // number of 32-bit words in stack
```

```
struct tcb{
    int32_t *sp;        // pointer to stack
    struct tcb *next;   // link to the tcb of the next thread
};
typedef struct tcb tcbType;
```

```
tcbType tcbs[NUMTHREADS];
tcbType *RunPt;
```

```
int32_t Stacks[NUMTHREADS][STACKSIZE];
```

Thread Control Blocks



OS.C

```
void OS_Init(void){
    DisableInterrupts();
    SysTick->CTRL = 0;  // disable SysTick during setup
    SysTick->VAL = 0;
}
```

```
void SetInitialStack(int i){
    tcbs[i].sp = &Stacks[i][STACKSIZE-16]; // thread stack pointer
    Stacks[i][STACKSIZE-1] = 0x01000000;   // thumb bit, PSR
    Stacks[i][STACKSIZE-3] = 0x14141414;   // R14
    Stacks[i][STACKSIZE-4] = 0x12121212;   // R12
    Stacks[i][STACKSIZE-5] = 0x03030303;   // R3
    Stacks[i][STACKSIZE-6] = 0x02020202;   // R2
    Stacks[i][STACKSIZE-7] = 0x01010101;   // R1
    Stacks[i][STACKSIZE-8] = 0x00000000;   // R0
    Stacks[i][STACKSIZE-9] = 0x11111111;   // R11
    Stacks[i][STACKSIZE-10] = 0x10101010;  // R10
    Stacks[i][STACKSIZE-11] = 0x09090909;  // R9
    Stacks[i][STACKSIZE-12] = 0x08080808;  // R8
    Stacks[i][STACKSIZE-13] = 0x07070707;  // R7
    Stacks[i][STACKSIZE-14] = 0x06060606;  // R6
    Stacks[i][STACKSIZE-15] = 0x05050505;  // R5
    Stacks[i][STACKSIZE-16] = 0x04040404;  // R4
}
```

```
int OS_AddThreads(void(*task0)(void),
                  void(*task1)(void),
                  void(*task2)(void)){
    int32_t status;
    status = StartCritical();
    tcbs[0].next = &tcbs[1]; // 0 points to 1
    tcbs[1].next = &tcbs[2]; // 1 points to 2
    tcbs[2].next = &tcbs[0]; // 2 points to 0
    SetInitialStack(0);
    Stacks[0][STACKSIZE-2] = (int32_t)(task0); // PC
    SetInitialStack(1);
    Stacks[1][STACKSIZE-2] = (int32_t)(task1); // PC
    SetInitialStack(2);
    Stacks[2][STACKSIZE-2] = (int32_t)(task2); // PC

    RunPt = &tcbs[0];       // thread 0 will run first
    EndCritical(status);
    return 1;
}
```

```
void OS_Launch(uint32_t theTimeSlice){
    SysTick->LOAD = theTimeSlice - 1; // reload value
    SysTick->CTRL = 3;  // enable, core clock and interrupt arm

    StartOS();                   // start on the first task
}
```

osasm.s

download this file

```
EXTERN  RunPt                   ; currently running thread
EXPORT  DisableInterrupts
EXPORT  EnableInterrupts
EXPORT  StartOS
EXPORT  SysTick_Handler
EXPORT  StartCritical
EXPORT  EndCritical
```

```
        SECTION .text : CODE (2)
```

```
DisableInterrupts
        CPSID   I                       ; __disable_irq();
        BX      LR                    ; returns
```

```
EnableInterrupts
        CPSIE   I                     ; __enable_irq();
        BX      LR
```

osasm.s

```
SysTick_Handler                 ; 1) Saves R0-R3,R12,LR,PC,PSR
        CPSID   I               ; 2) Prevent interrupt during switch
        PUSH    {R4-R11}        ; 3) Save remaining regs r4-11
        LDR     R0, =RunPt      ; 4) R0=pointer to RunPt, old thread
        LDR     R1, [R0]        ;    R1 = *RunPt i.e., R1 = &(RunPt->sp);

        STR     SP, [R1]        ; 5) Save SP into TCB; SP = RunPt->sp;

        LDR     R1, [R1,#4]     ; 6) R1 = RunPt->next
        STR     R1, [R0]        ;    RunPt = R1

        LDR     SP, [R1]        ; 7) new thread SP; SP = RunPt->sp;

        POP     {R4-R11}        ; 8) restore regs r4-11
        CPSIE   I               ; 9) tasks run with interrupts enabled
        BX      LR              ; 10) restore R0-R3,R12,LR,PC,PSR
```

osasm.s

address of RunPt

```
StartOS
        LDR     R0, =RunPt          ; R0 = &RunPt;
        LDR     R2, [R0]            ; R2 = *RunPt, i.e., R2 = &(RunPt->sp);

        LDR     SP, [R2]            ; first thread SP; SP = RunPt->sp;

        POP     {R4-R11}            ; restore regs r4-11
        POP     {R0-R3}             ; restore regs r0-3
        POP     {R12}
        POP     {LR}                ; discard LR from initial stack

stacksize-2  POP     {LR}           ; start location
stacksize-1  POP     {R1}           ; discard PSR

        CPSIE   I                   ; Enable interrupts at processor level
        BX      LR                  ; start first thread
```

function pointer
of first thread
(return address로 사용됨)

osasm.s

```
StartCritical
        MRS    R0, PRIMASK  ; save old status
        CPSID  I            ; mask all (except faults)
        BX     LR

EndCritical
        MSR    PRIMASK, R0
        BX     LR

        END
```

MRS:
Move the contents of a special register to a general-purpose register.

MSR:
Move the contents of a general-purpose register into the specified special register.

PRIMASK:
The PRIMASK register prevents activation of all exceptions with configurable priority.