Interrupt-Driven Input/Output

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
Interrupt-driven operations

- An **interrupt** is an event that initiates the automatic transfer of software execution from one program thread to an **interrupt handler** (or interrupt service routine)

- Event types:
  - Signal from a “device” (keyboard, data converter, etc.)
    - Device external to the CPU (possibly within a microcontroller)
    - Signals that a device needs, or is able to provide service
      (i.e. device goes from “busy” to “ready”)
    - Asynchronous to the current program thread
    - Allow CPU to do other work until device needs service!
  - An internal event or “exception” caused by an instruction
    Ex. invalid memory address, divide by 0, invalid op code
  - A software interrupt instruction
    Ex. ARM Cortex SVC (supervisor call) instruction
Interrupt I/O

- Busy/wait very inefficient.
  - CPU can’t do other work while testing device.
  - Hard to do simultaneous I/O.
- **But** – OK if the CPU has nothing else to do, or if the program cannot otherwise continue
- An interrupt handler is executed **only** when a device requires service
Interrupt Processing

Hardware

Busy

Done

Busy

Main Thread

Interrupt Thread

Hardware needs service

Saves execution state

ISR provides service

Restores execution state

time

Bard, Gerstlauer, Valvano, Yerraballi
Interrupts in control systems

Continuous loop

1. Initialize System
2. Input Data From Sensors
3. Compute Outputs According to Control Strategy
4. Output Data to Control Mechanism

With interrupts

1. Initialize System
2. Input Data From Sensors
3. Compute Outputs According to Control Strategy
4. Output Data to Control Mechanism
5. Interrupt Service Routine
6. Interrupt Handler

Handling an interrupt request
1. Suspend main thread
2. Save state and jump to handler
3. Execute interrupt handler
4. Restore state and return to main
5. Resume main thread

CPU in "Thread Mode"

CPU in "Handler Mode"
Interrupt interface

CPU and device handshake:
- device asserts interrupt request to signal the CPU;
- CPU asserts interrupt acknowledge when it responds to the interrupt;
- device de-asserts interrupt request.
Cortex-M structure

Nested Vectored Interrupt Controller
Coordinates multiple Interrupt sources
Cortex CPU registers

- Two processor modes:
  - Thread mode for User tasks
  - Handler mode for O/S tasks and exceptions
- Stack-based exception model
- Vector table contains addresses

PSR has priority of current process
PRIMASK has intr. enable (I) bit
BASEPRI has allowed intr. priority

Process SP, Main SP (selected at reset)
Cortex-M4 processor operating modes

- **Thread** mode – normal processing
- **Handler** mode – interrupt/exception processing
- **Privilege levels** = User and Privileged
  - Supports basic “security” & memory access protection
  - Supervisor/operating system usually privileged
Cortex-M Interrupt Processing
(much of this transparent when using C)

1. Interrupt signal detected by CPU
2. Suspend main program execution
   • finish current instruction
   • save CPU state (push registers onto stack)
   • set LR to 0xFFFFFFFF9 (indicates interrupt return)
   • set IPSR to interrupt number
   • load PC with ISR address from vector table
3. Execute interrupt service routine (ISR)
   • save other registers to be used in the ISR\(^1\)
   • clear the “condition” that requested the interrupt
   • perform the requested service
   • communicate with other routines via global variables
   • restore any registers saved by the ISR\(^1\)
4. Return to and resume main program by executing \textbf{BX LR}
   • saved state is restored from the stack, including PC (see next slide)

\(^1\) C compiler takes care of saving/restoring registers
Exception return

- The exception mechanism detects when the processor has completed an exception handler.
  - **EXC_RETURN** value (0xFFFFFFFF9) was loaded into LR on exception entry (after stacking PC and original LR)
- Exception return occurs when:
  1. Processor is in **Handler** mode
  2. **EXC_RETURN** loaded to PC by executing one of these instructions:
     - **LDM** or **POP** that loads the PC
     - **LDR** with PC as the destination
     - **BX** using any register
Example: Interrupt-driven printing

STB* tells printer to begin printing character on DATA8-1

Printer

DATA8-1

STRB*

BUSY

ACK*

PB7-0

PB8

PB9

PB10

Printer finished
Initialize PB pins for printer

InitPrinter
; enable clock to GPIOB
  ldr  r0,=RCC ; clock control registers
  ldr  r1,[r0,#AHB1ENR] ; get current values
 orr  r1,#0x02 ; enable GPIOB clock
  str  r1,[r0,#AHB1ENR] ; update values
; PB7-0=outputs (data), PB8=output (STRB*), PB9-10 inputs
  ldr  r0,=GPIOB
  ldr  r1,[r0,#MODER] ; get current MODER
  ldr  r2,=0x003fffff ; clear bits for PB10-0
  bic  r1,r2 ; clear bits
  ldr  r2,=0x00015555 ; PB10-9 input, PB8-0 output
  orr  r1,r2 ; set bits
  str  r1,[r0,#MODER] ; update MODER
; Set initial value of STRB* = 1
  mov  r1,#0x0100 ; select pin PB8 (STRB*)
  strh r1,[r0,#BSRRL] ; PB8 = STRB* = 1 initially
  bx   lr ; return
Program-controlled solution
(no interrupt)

```asm
ldr r0,=GPIOB
ldr r1,=string ;string = char array
Loop:  ldrb r2,[r1],#1 ;get next character
cmp r2,#0 ;NULL?
  beq Return ;quit on NULL
  strb r2,[r0,#ODR] ;character to printer (PB7-PB0)
  mov r2,#0x0100 ;strobe = PB8
  strh r2,[r0,#BSRRH] ;Reset PB8=0 (strobe pulse high-to-low)
  strh r2,[r0,#BSRRL] ;Set PB8=1 (strobe pulse low-to-high)
Wait:  ldrh r2,[r0,#IDR] ;check PB9 (BUSY)
tst r2,#0x0200 ;test BUSY bit
  bne Wait ;repeat while BUSY=1
  b Loop ;next character
Return: bx lr
```

Time “lost”
waiting for
BUSY = 0.
Interrupt-driven solution

;Printer ISR – Send next character when ACK received from printer.
;   Saved_Pointer variable contains address of next character

PrintISR  ldr    r0,=Saved_Pointer ;pointer variable address
        ldr    r1,[r0] ;retrieve saved data pointer
        ldrb   r2,[r1],#1 ;get next character
        str    r1,[r0] ;save pointer for next interrupt
        cmp    r2,#0 ;NULL character?
        beq    Return ;quit on NULL
        ldr    r0,=GPIOB ;GPIOB register address block
        strb   r2,[r0,#ODR] ;character to printer (PB7-PB0)
        mov    r2,#0x0100 ;strobe = PB8
        strh   r2,[r0,#BSRRH] ;Reset PB8=0 strobe pulse high->low
        strh   r2,[r0,#BSRRL] ;Set PB8=1 strobe pulse low->high
        Return bx    lr ;return from ISR

No new interrupt request if no new strobe pulse.
Example: Interrupt-driven keyboard

- PA<sub>7-0</sub>
- PA<sub>8</sub>
- DATA<sub>8-1</sub>
- DATA_VALID

DATA<sub>8-1</sub> = pressed key# while DATA_VALID = 1
Initialize PA pins for keyboard

InitKeyboard
; enable clock to GPIOA
  ldr  r0,=RCC           ; clock control registers
  ldr  r1,[r0,#AHB1ENR]  ; get current values
  orr  r1,#0x01          ; enable GPIOA clock
  str  r1,[r0,#AHB1ENR]  ; update values
; PA7-0=inputs (data), PA8=input (DATA_VALID)
  ldr  r0,=GPIOA
  ldr  r1,[r0,#MODER]    ; get current MODER
  ldr  r2,=0x0003ffff    ; clear bits for PA8-0
  bic  r1,r2             ; clear bits for input mode
  str  r1,[r0,#MODER]    ; update MODER
  bx   lr                 ; return
Program-controlled solution
(no interrupt)

;Read key numbers and store in String array until ENTER pressed
  ldr    r0,=GPIOA
  ldr    r1,=String ;String = char array
  Wait: ldrh  r2,[r0,#IDR] ;check PA8 = DATA_VALID
         tst   r2,#0x0100 ;test DAVA_VALID bit
         beq   Wait ;repeat while DATA_VALID = 0
         and   r2,#0x00ff ;mask DATA_VALID (key# = PA7-PA0)

;Homework problem: returned code in r0 instead of the following
  mov    r3,#0 ;NULL character
  strb   r3,[r1] ;save NULL in String (for now)
  cmp    r2,#0x0D ;ENTER key?
  beq    Return ;quit on ENTER
  strb   r2,[r1],#1 ;replace NULL with key#
  b       Wait ;next character
Return: bx   lr

Time “lost” waiting for key press.
Interrupt-driven solution

;Key ISR – Get character when DATA_VALID pulsed.
;Saved_Pointer variable contains address at which to store next character

KeyISR  ldr    r0,=Saved_Pointer  ;pointer variable address
        ldr    r1,[r0]              ;retrieve saved pointer
        ldr    r2,=GPIOA
        ldrb   r3,[r2,#IDR]         ;read key# = PA7-PA0
        mov    r4,#0                ;NULL character code
        strb   r4,[r1]              ;save NULL in String (for now)
        cmp     r3,#0x0D             ;ENTER key (ASCII code for ENTER)
        beq     Return              ;quit on ENTER
        strb    r3,[r1],#1           ;replace NULL with key#
        str     r1,[r0]              ;save incremented pointer

Return   bx     lr              ;return from ISR
Main program setup

```assembly
__main

; Configure the I/O ports

; Set up printing of a character string
ldr   r0,=String ; pointer to character string
ldr   r1,=Saved_Pointer ; variable address
str   r0,[r1] ; save string pointer for ISR
cpsie i ; enable interrupts
bl    PrintISR ; print the 1st character
; others printed when CPU interrupted
; when printer changes BUSY->READY

;****** rest of the program

AREA   D1,DATA
Saved_Pointer  dcd   0
String      dcb   "This is a string",0
```