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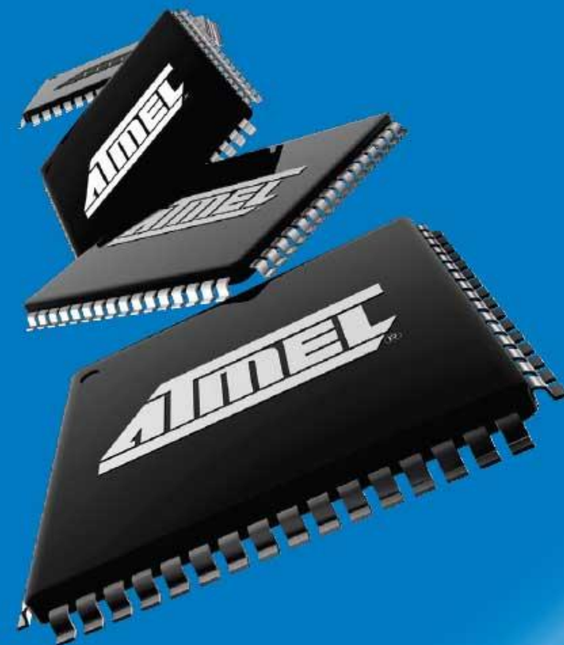


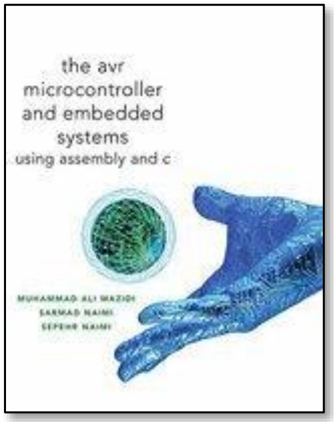
The Real World of External Interrupts

February 2009

Everywhere You Are®

ATmega Interrupts

Reading



The AVR Microcontroller and Embedded Systems using Assembly and C)
by Muhammad Ali Mazidi, Sarmad Naimi, and Sepehr Naimi

Chapter 10: AVR Interrupt Programming in Assembly and C

Section 10.1: AVR Interrupts

Section 10.4: Interrupt Priority in the AVR

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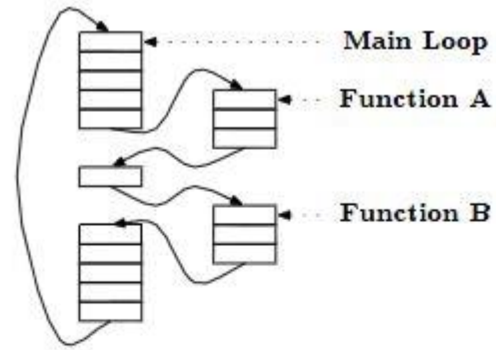
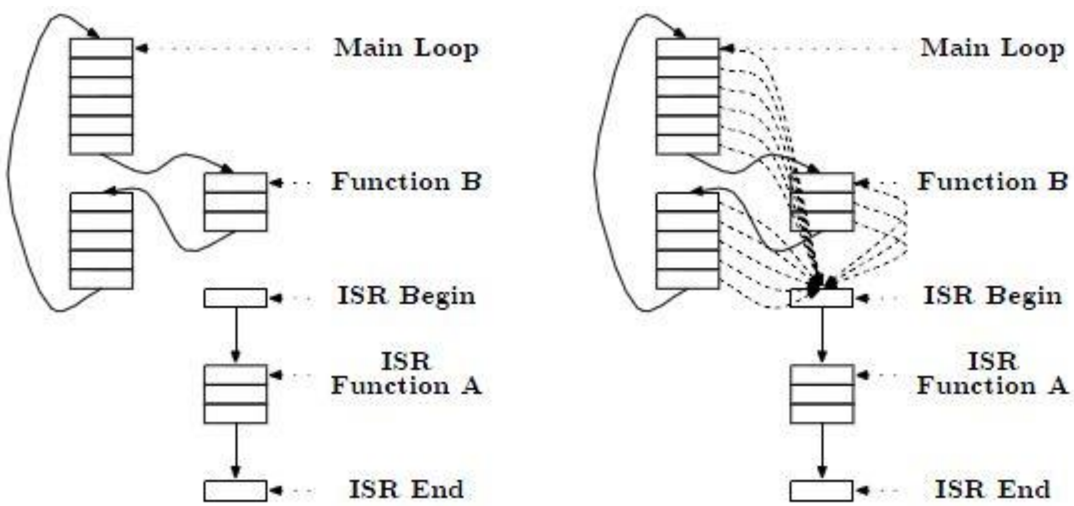
INTERRUPT BASICS



- A microcontroller normally executes instructions in an orderly fetch-execute sequence as dictated by a user-written program.
- However, a microcontroller must also be ready to handle unscheduled, events that might occur inside or outside the microcontroller.
- The interrupt system onboard a microcontroller allows it to respond to these internally and externally generated events. By definition we do not know when these events will occur.
- When an interrupt event occurs, the microcontroller will normally complete the instruction it is currently executing and then transition program control to an Interrupt Service Routine (ISR). These ISR, which handles the interrupt.
- Once the ISR is complete, the microcontroller will resume processing where it left off before the interrupt event occurred.



(a) Program with ISR (b) ISR called from anywhere

The Main Reasons You Might Use Interrupts[1]

- To detect external and pin change events (e.g. rotary encoders, button presses)
- Serial data transfer events (USB, SPI, I2C, and USART)
- Watchdog timer (e.g. if nothing happens after 8 seconds, interrupt me)
- Timer interrupts - used for comparing/overflowing timers
- ADC conversions (analog to digital)
- EEPROM ready for use
- Flash memory ready

[1] Source: Gammon Software Solutions forum – What are interrupts?

ATmega32U4 Interrupt Vector Table

- The ATmega32U4 provides support for 42 different interrupt sources. These interrupts and the separate Reset Vector each have a separate program vector located at the lowest addresses in the **Flash program memory** space.
- The complete list of vectors is shown in Table 11-6 “Reset and Interrupt Vectors in ATMega32U4. Each Interrupt Vector occupies **two instruction words**.
- The list also determines the **priority levels** of the different interrupts. The lower the address the higher is the priority level. RESET has the highest priority, and next is INT0 – the External Interrupt Request 0.

ATmega32U4 Interrupt Vector Table

Vector No	Program Address	Source	Interrupt Definition	Arduino/C++ ISR() Macro Vector Name
1	0x0000	RESET	Reset	
2	0x0002	INT0	External Interrupt Request 0 (pin D0)	(INT0_vect)
3	0x0004	INT1	External Interrupt Request 1 (pin D1)	(INT1_vect)
4	0x0006	INT2	External Interrupt Request 2 (pin D2)	(INT2_vect)
5	0x0008	INT3	External Interrupt Request 3 (pin D3)	(INT3_vect)
6	0x000A	Reserved	Reserved	
7	0x000C	Reserved	Reserved	
8	0x000E	INT6	External Interrupt Request 6 (pin E6)	(INT6_vect)
9	0x0010	Reserved		
10	0x0012	PCINT0	Pin Change Interrupt Request 0 (pins PB7 to PB0)	(PCINT0_vect)
11	0x0014	USB General	USB General Interrupt request	(USB_GENERAL_vect)
12	0x0016	USB Endpoint	USB Endpoint Interrupt request	(USB_ENDPOINT_vect)
13	0x0018	WDT	Watchdog Time-out Interrupt	(WDT_vect)
14	0x001A	Reserved	Reserved	
15	0x001C	Reserved	Reserved	
16	0x001E	Reserved	Reserved	
17	0x0020	TIMER1 CAPT	Timer/Counter1 Capture Event	(TIMER1_CAPT_vect)
18	0x0022	TIMER1 COMPA	Timer/Counter1 Compare Match A	(TIMER1_COMPA_vect)
19	0x0024	TIMER1 COMPB	Timer/Counter1 Compare Match B	(TIMER1_COMPB_vect)
20	0x0026	TIMER1 COMPC	Timer/Counter1 Compare Match C	(TIMER1_COMPC_vect)
21	0x0028	TIMER1 OVF	Timer/Counter1 Overflow (see note)	(TIMER1_OVF_vect)
22	0x002A	TIMER0 COMPA	Timer/Counter0 Compare Match A	(TIMER0_COMPA_vect)
23	0x002C	TIMER0 COMPB	Timer/Counter0 Compare Match B	(TIMER0_COMPB_vect)
24	0x002E	TIMER0 OVF	Timer/Counter0 Overflow	(TIMER0_OVF_vect)
25	0x0030	SPI, STC	SPI Serial Transfer Complete	(SPI_STC_vect)
26	0x0032	USART, RX	USART Rx Complete	(USART_RX_vect)
27	0x0034	USART, UDRE	USART, Data Register Empty	(USART_UDRE_vect)
28	0x0036	USART, TX	USART, Tx Complete	(USART_TX_vect)

29	0x0038	ANALOG COMP	Analog Comparator	(ANALOG_COMP_vect)
30	0x003A	ADC	ADC Conversion Complete	(ADC_vect)
31	0x003C	EE READY	EEPROM Ready	(EE_READY_vect)
32	0x003E	TIMER3 CAPT	Timer/Counter3 Capture Event	(TIMER3_CAPT_vect)
33	0x0040	TIMER3 COMPA	Timer/Counter3 Compare Match A	(TIMER3_COMPA_vect)
34	0x0042	TIMER3 COMPB	Timer/Counter3 Compare Match B	(TIMER3_COMPB_vect)
35	0x0044	TIMER3 COMPC	Timer/Counter3 Compare Match C	(TIMER3_COMPC_vect)
36	0x0046	TIMER3 OVF	Timer/Counter3 Overflow	(TIMER3_OVF_vect)
37	0x0048	TWI	2-wire Serial Interface (I2C)	(TWI_vect)
38	0x004A	SPM READY	Store Program Memory Ready	(SPM_READY_vect)
39	0x004C	TIMER4 COMPA	Timer/Counter4 Compare Match A	(TIMER4_COMPA_vect)
40	0x004E	TIMER4 COMPB	Timer/Counter4 Compare Match B	(TIMER4_COMPB_vect)
41	0x0050	TIMER4 COMPD	Timer/Counter4 Compare Match D	(TIMER4_COMPD_vect)
42	0x0052	TIMER4 OVF	Timer/Counter4 Overflow	(TIMER4_OVF_vect)
43	0x0054	TIMER4 FPF	Timer/Counter4 Fault Protection Interrupt	(TIMER4_FPF_vect)

Note: Timer 1 not available when servos are attached to the 3DoT board.

ATMEGA32U4 INTERRUPT PROCESSING

- ①When an interrupt occurs, ②the microcontroller completes the current instruction and ③stores the address of the next instruction on the stack
- It also turns off the interrupt system to prevent further interrupts while one is in progress. This is done by ④clearing the SREG Global Interrupt Enable I-bit.

Bit	7	6	5	4	3	2	1	0	
0x3F (0x5F)	**I**	**T**	**H**	**S**	**V**	**N**	**Z**	**C**	**SREG**
Read/Write	R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

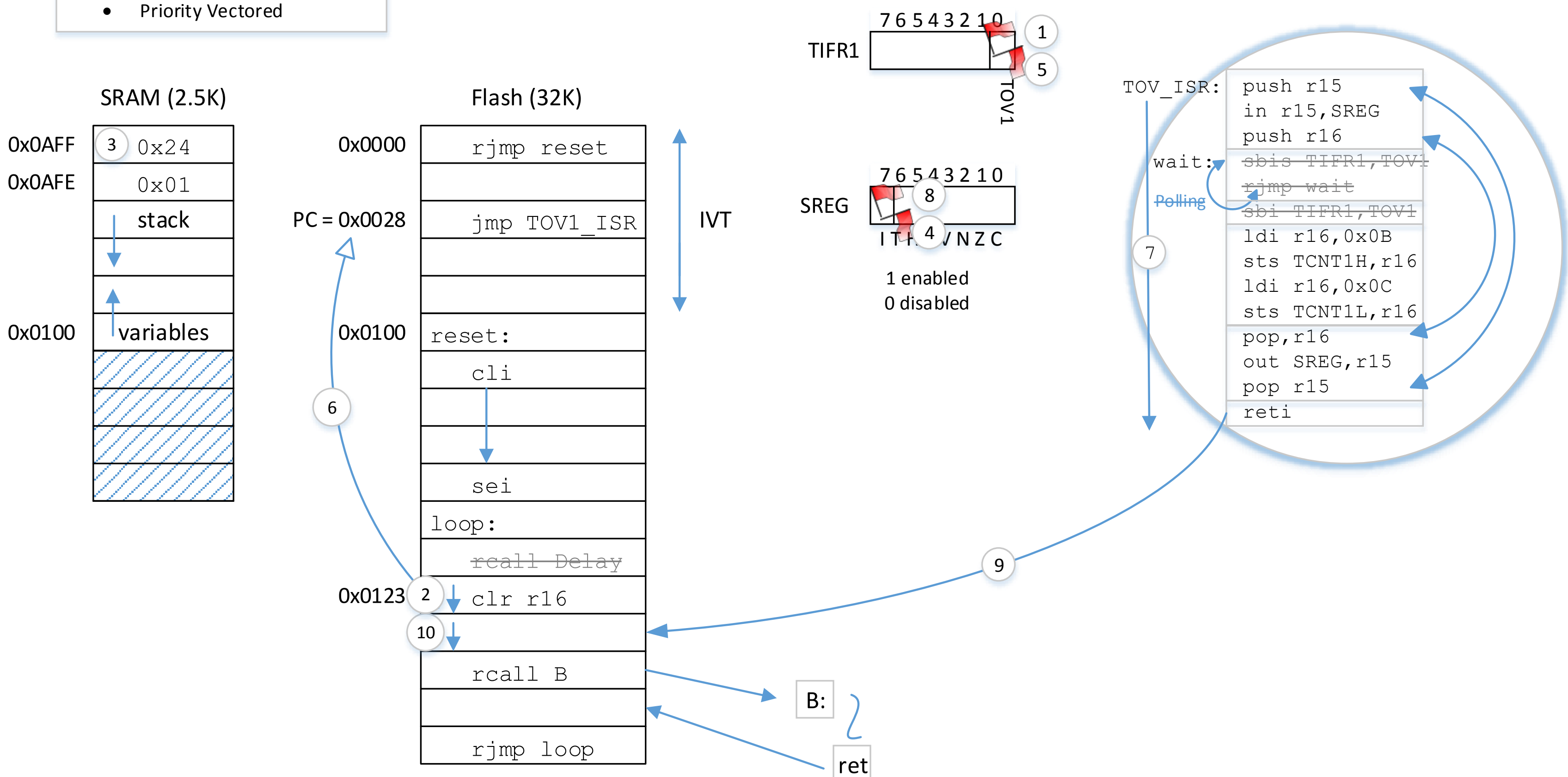
- The ⑤Interrupt flag bit is cleared for Type 1 Interrupts only (see the next page for Type definitions).
- The execution of the ISR is performed by ⑥loading the beginning address of the ISR specific for that interrupt into the program counter. The AVR processor starts running the ISR.
- ⑦Execution of the ISR continues until the return from interrupt instruction (`reti`) is encountered. The ⑧SREG I-bit is automatically set when the `reti` instruction is executed (i.e., Interrupts enabled).
- When the AVR exits from an interrupt, it will always ⑨return to the interrupted program and ⑩execute one more instruction before any pending interrupt is served.
- The Status Register is not automatically stored when entering an interrupt routine, nor restored when returning from an interrupt routine. This must be handled by software.

```
push  reg_F
in    reg_F,SREG
  :
out   SREG,reg_F
pop   reg_F
```

ATmega32U4 Interrupt Processing – By the Numbers

Working with Peripheral Subsystems

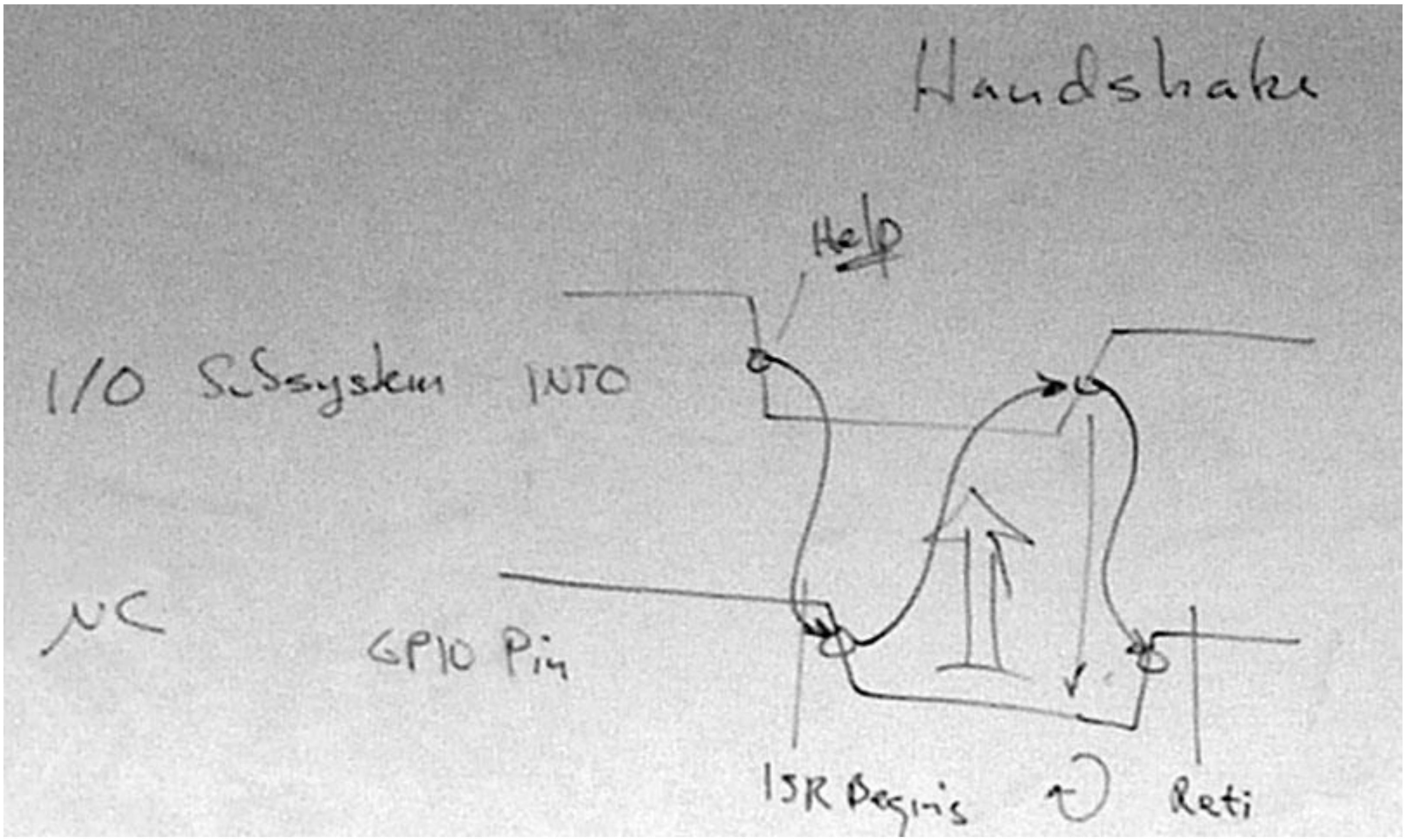
- Polling
- Interrupts
  - Polling
  - Priority Vectored



ATmega32U4 Interrupt Processing – Type 1 –

- The user software can write logic one to the I-bit to enable **nested interrupts**. All enabled interrupts can then interrupt the current interrupt routine.
    - The SREG I-bit is automatically set to logic one when a Return from Interrupt instruction – RETI – is executed.
- There are basically two types of interrupts…
    - The **first type (Type 1)** is triggered by an event that sets the Interrupt Flag. For these interrupts, the Program Counter is vectored to the actual Interrupt Vector in order to execute the interrupt handling routine, and **hardware clears the corresponding Interrupt Flag**.
        - If the same interrupt condition occurs while the corresponding interrupt enable bit is cleared, the Interrupt Flag will be set and remembered until the interrupt is enabled, or the flag is cleared by software (interrupt cancelled).
        - Interrupt Flag can be cleared by writing a logic one to the flag bit position(s) to be cleared.
    - If one or **more interrupt conditions** occur while the Global Interrupt Enable (SREG I) bit is cleared, the corresponding Interrupt Flag(s) will be set and remembered until the Global Interrupt Enable bit is set on return (`reti`), and will then be **executed by order of priority**.

- The **second type (Type 2)** of interrupts will trigger as long as the interrupt condition is present. These interrupts do not necessarily have Interrupt Flags. If the interrupt condition disappears before the interrupt is enabled, the interrupt will not be triggered.



WHEN WRITING AN INTERRUPT SERVICE ROUTINE (ISR)[2]

- As a general rule get in and out of ISRs as quickly as possible. For example do not include timing loops inside of an ISR.
- If you are writing an Arduino program
  - Don't add delay loops or use function **delay()**
  - Don't use function **Serial.print(*val*)**
  - Make variables shared with the main code **volatile**
  - Variables shared with main code may need to be protected by "critical sections" (see below)
  - Toggling interrupts off and on is not recommended. The default in the Arduino is for interrupts to be enabled. Don’t disable them for long periods or things like timers won't work properly.

[2] Source: Gammon Software Solutions forum – What are interrupts?

Program Initialization and the Interrupt Vector Table (IVT)

- Start by jumping over the Interrupt Vector Table

```
RST_VECT:
   rjmp   reset
```

- Add jumps in the IVT to your ISR routines

```
.ORG INT0addr       // 0x0002 External Interrupt 0
   jmp    INT0_ISR
.ORG OVF1addr
   jmp    TOVF1_ISR
```

- Initialize Variables, Configure I/O Registers, and Set Local Interrupt Flag Bits

```
reset:
   lds   r16, EICRA     // EICRA Memory Mapped Address 0x69
   sbr   r16, 0b00000010
   cbr   r16, 0b00000001
   sts   EICRA, r16     // ISC0=[10] (falling edge)
   sbi   EIMSK, INT0    // Enable INT0 interrupts
```

- Enable interrupts at the end of the initialization section of your code.

```
   sei                  // Global Interrupt Enable

loop:
```

THE INTERRUPT SERVICE ROUTINE (ISR)

```
; -- Interrupt Service Routine --
INT0_ISR:
  push   reg_F
  in     reg_F,SREG
  push   r16
  ; Load
  ; Do Something
  ; Store
  pop   r16
  out   SREG,reg_F
  pop   reg_F
  reti
; ---------------------------------------------------------
```

PREDEFINED ARDUINO IDE INTERRUPTS[3]

- When you push the reset button the ATmega32U4 automatically runs an Arduino Boot program located in a separate Boot Flash section at the top of program memory. If compiled within the Arduino IDE, the Boot program loads your compiled program with these interrupts enabled.

  24 0x002E TIMER0 OVF Timer/Counter0 Overflow (TIMER0_OVF_vect)

- The `millis()` and `micros()` function calls make use of the "timer overflow" feature utilize timer 0. The ISR runs roughly 1000 times a second, and increments an internal counter which effectively becomes the `millis()` counter (see On your own question).

  11 0x0014 USB General

  12 0x0016 USB Endpoint

- The hardware serial library uses interrupts to handle incoming and outgoing serial data. Your program can now be doing other things while data in an SRAM buffer is sent or received. You can check the status of the buffer by calling the `Serial.available()` function.

- **On your own**. Given that you are using 8-bit Timer/Counter 0, you have set TCCR0B bits CS02:CS01:CS00 = 0b011 ($clk_{I/O}$/64), and the system clock f_{clk} = 8 MHz, what value would you preload into the Timer/Counter Register TCNT0 to get a interrupt 1000 times a second.

Source: Gammon Software Solutions forum – this blog also covers how to work with all the interrupts in C++ and the Arduino scripting language.

[3] While the USART interface is part of the bootloader, Timer 0 is installed as part of the IDE Library.

Programming the Arduino to Handle External Interrupts[4]

- Variables shared between ISRs and normal functions should be declared "`volatile`". This tells the compiler that such variables might change at any time, and thus the compiler should not "optimize" the code by placing a copy of the variable in one of the general purpose processor registers (R31..R0). Specifically, the processor must reload the variable from SRAM whenever it is referenced.

```
int pin = 13;
volatile int state = LOW;
```

- Add jumps in the IVT to ISR routine, configure External Interrupt Control Register A (EICRA), and enable local and global Interrupt Flag Bits.

```
 void setup()
{
  pinMode(pin, OUTPUT);
  attachInterrupt(0, blink, CHANGE);
}
```

[4] Read ATmega32U4 External Interrupts to learn more about this example.

PROGRAMMING THE ARDUINO TO HANDLE EXTERNAL INTERRUPTS - CONTINUED[5]

- Write Interrupt Service Routine (ISR)

```
void blink()
{
  state = !state;
}
```

- To disable interrupts globally (clear the I bit in SREG) call the `noInterrupts()` function. To once again enable interrupts (set the I bit in SREG) call the `interrupts()` function.

- Again – Toggling interrupts ON and OFF is not recommended. For a discussion of when you may want to turn interrupts off, read Gammon Software Solutions forum – Why disable Interrupts?

[5] Read ATmega32U4 External Interrupts to learn more about this example.