CAB202 Topic 9 – Timers and Interrupts

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Contents

Roadmap

Previously, on CAB202:

7. Teensy – Introduction to Microcontrollers; Digital Input/Output; Bitwise operations.
8. LCD Display – sending digital signals to a device; directly controlling the LCD display.

This week:

9. **Timers and Interrupts – asynchronous programming.**

Still to come:

10. Serial Communication – communicating with another computer.
11. Analogue to Digital Conversion; Pulse Width Modulation.
12. Assignment 2 Q&A.

References

Recommended reading:

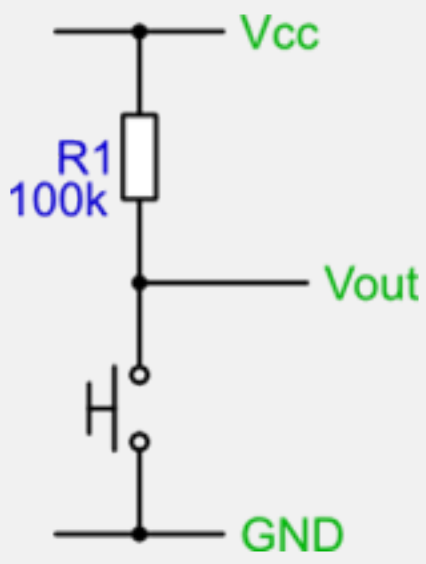
- Blackboard→Learning Resources→Microcontrollers→atmega32u4 datasheet.pdf.

De-bouncing (a problem that can be solved with interrupts)

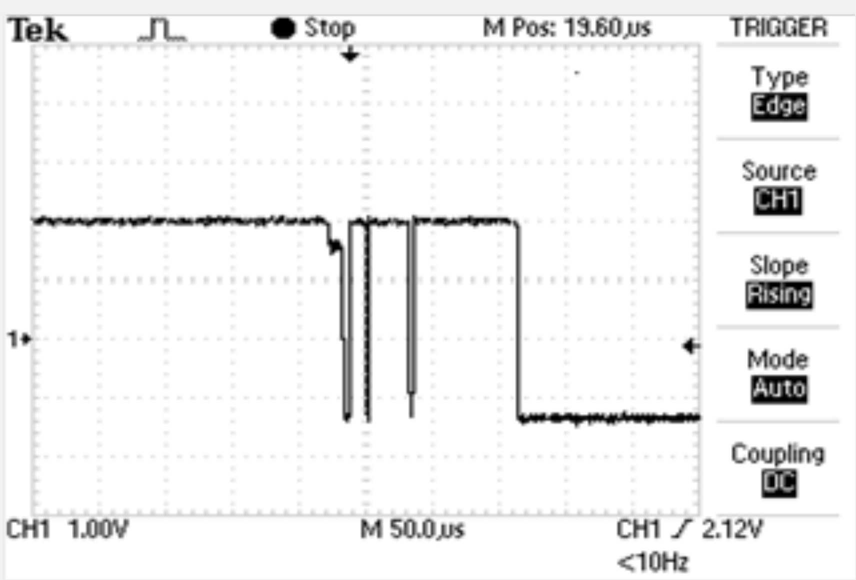
The problem

Switches are prone to a phenomenon known as *bouncing*, in which spurious “click” events are detected.

- Consider a pull-up resistor:



- When the switch opens and closes, current flows in an interrupted pattern while the connection is made, then settles to either on or off.



- Bouncing matters when we want precise recognition of “click” events.
  - A button click is recognised when a switch is *pressed* and then *released* as part of a single gesture.
  - This corresponds to a switch transitioning from *open* to *closed* and then back to *open*.

The **BounceDemo** program illustrates bouncing.

```
/*
**      BounceDemo.c
**
**      Demonstrates bouncing effect in tactile switch.
**
**      Lawrence Buckingham, QUT, September 2017.
**      (C) Queensland University of Technology.
*/
#include <stdint.h>
#include <stdio.h>
#include <avr/io.h>
#include <avr/interrupt.h>
#include <util/delay.h>
#include <cpu_speed.h>

#include <graphics.h>
#include <macros.h>
#include "lcd_model.h"

void draw_all(void);
void draw_int( uint8_t x, uint8_t y, int value, colour_t colour );

void setup(void) {
        set_clock_speed(CPU_8MHz);
        lcd_init(LCD_DEFAULT_CONTRAST);
        draw_all();
```

```
        CLEAR_BIT(DDRD, 1); // up
        CLEAR_BIT(DDRF, 6); // left_button
}

uint16_t counter = 0;
char buffer[10];

void process(void) {
        // Detect a Click on left button
        if ( BIT_IS_SET(PINF, 6) ) {
                while ( BIT_IS_SET(PINF, 6) ) {
                        // Block until button released.
                }
                // Button has now been pressed and released...
                counter ++;
        }

        // Display and wait if joystick up.
        if ( BIT_IS_SET(PIND, 1) ) {
                draw_all();

                while ( BIT_IS_SET(PIND, 1) ) {
                        // Block until joystick released.
                }
        }
}

int main(void) {
        setup();

        for ( ;; ) {
                process();
        }
}
// -------------------------------------------------
// Helper functions.
// -------------------------------------------------
void draw_all( void ) {
        clear_screen();
        draw_string( 0, 0, "BounceDemo", FG_COLOUR );
        draw_string( 0, 10, "Clk lft to count, FG_COLOUR );
        draw_string( 0, 20, "Joystk up to view", FG_COLOUR );
        draw_int(10, 30, counter, FG_COLOUR);
        show_screen();
}

void draw_int(uint8_t x, uint8_t y, int value, colour_t colour) {
        snprintf(buffer, sizeof(buffer), "%d", value );
        draw_string(x, y, buffer, colour);
}
```

This program uses a polling approach to detect click events on the left button (SW0 in the pin-out diagram).

- Click-detection is done in the **`process`** function. The logic is very simple:
    - If the left switch is closed, wait for it to become open, and then register a *click*.
    - Waiting with a loop in this way is called *busy waiting* – the CPU repeatedly executes the test in the while loop until the condition becomes false, at which point the program can move on.
    - Busy-waiting is avoided wherever possible because it locks the CPU up doing nothing, and because it may result in unpredictable delays.
- Bouncing happens on a very short timescale relative to the physical act of pressing and releasing the switch, so it is quite a challenge to demonstrate on purpose.
    - If we introduce any significant delay, the effect is obscured.
    - To make the effect visible, this program performs absolutely minimal processing.
    - When a left button-click is detected, a counter increments silently.
    - To view the current value of the counter, push the joystick up.
    - Try multiple clicks on the left button and then display them by pressing joystick up. Do the clicks and display values match?

Delay-based de-bouncing (which is not very good)

Idea

About the simplest work-around is to try to take advantage of the short duration of the transient behaviour.

- This click-detection algorithm is almost identical to the polling algorithm above.

- We introduce a short delay just after the button-press is detected, but before the busy-wait that detects the button-release.
- The hope is that the contact has closed properly by the time we enter the wait loop.

Implementation

Simple delay-based de-bouncing is demonstrated in **`DelayDebounceDemo.c`**:

```c
/*
**      DelayDebounceDemo.c
**
**      Demonstrates simple delay-based de-bounce in tactile switch.
**
**      Lawrence Buckingham, QUT, September 2017.
**      (C) Queensland University of Technology.
*/
#include <stdint.h>
#include <stdio.h>
#include <avr/io.h>
#include <avr/interrupt.h>
#include <util/delay.h>
#include <cpu_speed.h>

#include <graphics.h>
#include <macros.h>
#include "lcd_model.h"

#define DEBOUNCE_MS (150)

void draw_all(void);
void draw_int( uint8_t x, uint8_t y, int value, colour_t colour );

void setup(void) {
        set_clock_speed(CPU_8MHz);
        lcd_init(LCD_DEFAULT_CONTRAST);
        draw_all();
        CLEAR_BIT(DDRD, 1); // up
        CLEAR_BIT(DDRF, 6); // left_button
}

uint16_t counter = 0;
char buffer[10];

void process(void) {
        // Detect a Click on left button
        if ( BIT_IS_SET(PINF, 6) ) {
                _delay_ms(DEBOUNCE_MS);

                while ( BIT_IS_SET(PINF, 6) ) {
                        // Block until button released.
                }
                // Button has now been pressed and released...
                counter ++;
        }

        // Display and wait if joystick up.
        if ( BIT_IS_SET(PIND, 1) ) {
                draw_all();

                while ( BIT_IS_SET(PIND, 1) ) {
                        // Block until joystick released.
                }
        }
}

int main(void) {
        setup();

        for ( ;; ) {
                process();
        }
}
// -------------------------------------------------
// Helper functions.
// -------------------------------------------------
void draw_all( void ) {
        clear_screen();
        draw_string( 0, 0, "DelayDebounceDemo", FG_COLOUR );
        draw_string( 0, 10, "Clk lft to count, FG_COLOUR );
        draw_string( 0, 20, "Joystk up to view", FG_COLOUR );
        draw_int(10, 30, counter, FG_COLOUR);
        show_screen();
}

void draw_int(uint8_t x, uint8_t y, int value, colour_t colour) {
        snprintf(buffer, sizeof(buffer), "%d", value );
        draw_string(x, y, buffer, colour);
}
```

Pros and Cons

Introducing a delay between detection of button-press and button-release "kind of" works. But it has some problems.

- If the delay is too short, it just doesn't work.
- If the delay is too long, then the user may click faster than we can detect.
- It is still unreliable because it still depends heavily on how fast the user do button-presses.
- Regardless of the delay duration, synchronous click detection in this way is a bad idea.
    - When we block the main event loop, everything stops until the click is detected.

Non-blocking de-bouncing (which is much better but not quite ideal)

Idea

Both algorithms above rely on a two-phase procedure to detect a click:

1. Detect that the button is pressed.
2. Wait for the button to be released.

The busy wait is the main problem: the event loop stalls while we wait for the button to be released. In the present section we examine an elegant non-blocking solution.

- This algorithm hinges on the idea that at any given time the switch may be undergoing rapid on/off transitions due to bouncing, but that eventually the switch will settle to a stable configuration, at which point the button is either *definitely pressed* or *definitely not pressed*.
    - Initially, we have no opinion as to the configuration.
    - As time passes we accumulate a log of evidence which sways between the two options: *definitely pressed* or *definitely not pressed*.
    - If enough evidence accumulates one way or the other, we accept the option.
    - We then start again.
- To decide if the button is in a stable configuration, we repeatedly (at high frequency) sample the button state.
    - Every time we see the switch is closed, our opinion moves toward the conclusion that the button *may be* definitely pressed.
    - If we see the switch closed many times without ever seeing it open, we conclude that the button *is* definitely pressed.
    - Every time we see the switch open, we conclude that the button cannot possibly be definitely pressed, and our opinion moves toward the opposite conclusion, namely that the button *may not be* definitely pressed.
    - If we see the switch open many times without ever seeing it closed, we conclude that the button *is not* definitely pressed.

Implementation

An implementation of this algorithm is provided in **`NonblockingDebounceDemo.c`**:

```
/*
**      NonblockingDebounceDemo.c
**
**      A non-blocking poll-based de-bounce in tactile switch.
**      (Adapted from unattributed source code used in CAB202
**      Semester 1, 2017)
**
**      Lawrence Buckingham, QUT, September 2017.
**      (C) Queensland University of Technology.
*/
#include <stdint.h>
#include <stdio.h>
#include <avr/io.h>
#include <avr/interrupt.h>
#include <util/delay.h>
```

```c
#include <cpu_speed.h>

#include <graphics.h>
#include <macros.h>
#include "lcd_model.h"

typedef enum { false, true } bool;

void draw_all(void);
void draw_int(uint8_t x, uint8_t y, int value, colour_t colour);
bool left_button_clicked(void);

void setup(void) {
	set_clock_speed(CPU_8MHz);
	lcd_init(LCD_DEFAULT_CONTRAST);
	draw_all();
	CLEAR_BIT(DDRD, 1); // up
	CLEAR_BIT(DDRF, 6); // left_button
}

// State machine for "button pressed"
bool pressed = false;
uint16_t closed_num = 0;
uint16_t open_num = 0;

#define THRESHOLD (1000)

bool left_button_clicked(void) {
	// Detect a Click on left button
	bool was_pressed = pressed;

	if ( BIT_IS_SET(PINF, 6) ) {
		closed_num++;
		open_num = 0;

		if ( closed_num  > THRESHOLD ) {
			if ( !pressed ) {
				closed_num = 0;
			}

			pressed = true;
		}
	}
	else {
		open_num++;
		closed_num = 0;

		if ( open_num > THRESHOLD ) {
			if ( pressed ) {
				open_num = 0;
			}

			pressed = false;
		}
	}

	return was_pressed && !pressed;
}

// Auxiliary variables
uint16_t counter = 0;
char buffer[10];

void process(void) {
	if ( left_button_clicked() ) {
		counter++;
	}

	// Display and wait if joystick up.
	if ( BIT_IS_SET(PIND, 1) ) {
		draw_all();

		while ( BIT_IS_SET(PIND, 1) ) {
			// Block until joystick released.
		}
	}
}

int main(void) {
	setup();

	for ( ;; ) {
		process();
	}
}
// --------------------------------------------------
// Helper functions.
// --------------------------------------------------
void draw_all(void) {
	clear_screen();
	draw_string(0, 0, "DelayDebounceDemo", FG_COLOUR);
	draw_string(0, 10, "Clk lft to count, FG_COLOUR);
```

```
        draw_string(0, 20, "Joystk up to view", FG_COLOUR);
        draw_int(10, 30, counter, FG_COLOUR);
        show_screen();
}

void draw_int(uint8_t x, uint8_t y, int value, colour_t colour) {
        snprintf(buffer, sizeof(buffer), "%d", value);
        draw_string(x, y, buffer, colour);
}
```

The algorithm is implemented in the **`left_button_clicked`** function.

- We use a boolean variable called **`pressed`** to record whether the button is *definitely pressed* or *definitely not pressed*.
- Along with **`pressed`**, we keep a pair of counters.
  - **`open_num`** is the number of consecutive times the switch has been observed to be open.
  - **`closed_num`** is the number of consecutive times the switch has been observed to be closed.
- Every time we poll the switch state, we update one or more of these three variables.
  - If the switch is closed, we increment **`closed_num`** and restore **`open_num`** to 0. If **`open_num`** passes a threshold (in this case, **`1000`**), we assign **`pressed = true`** –; *definitely pressed*.
  - If the switch is open, we increment **`open_num`** and restore **`closed_num`** to 0. If **`closed_num`** passes the threshold, we assign **`pressed = false`** –; not *definitely pressed*.
- Each time we settle on a switch state, we reset the counters and the accumulation process starts again.

Pros and Cons

This non-blocking de-bounce method is pretty good.

- The boolean **`pressed`** variable is a reliable indication of the true state of the button.
- Click tests based on transitions between **`pressed == true`** and **`pressed == false`** are very reliable.

Perceived problems:

- The decision depends on **`THRESHOLD`**, which must be just right.
  - The correct value will depend not only on the microcontroller clock speed, but also on the time between calls to **`left_button_clicked`**.
  - Performance may not be consistent due to factors elsewhere in the program.
  - *The algorithm polls the switch in the main event loop, which means we can never guarantee reliable performance*.

De-bouncing conclusion

- We have demonstrated switch bounce, and examined a two ways to address the problem.
- A non-blocking algorithm has been developed which is very good, but still relies on polling.
- To perfect the algorithm, we need a way to sample the physical state of the switch at a fairly high and constant frequency. **Hint: Timers and Interrupts**.
- *This forms one of the Topic 9 Portfolio exercises*.

ATMega32U4 Timers

Timer Introduction

A timer is a semi-autonomous subsystem which runs alongside the CPU.

- *Refer: ATMega32U4 Datasheet, Chapters 12–14*.
- The timer executes a very simple program which listens to a clock signal.
  - By default, ATMega32U4 timers use use the built-in system clock which runs at 8,000,000 cycles per second (8MHz).
  - Clock signal can also come from external source.

- After a fixed number of clock cycles, the timer updates a counter which occupies one or two 8-bit I/O registers.
- The counter updates continuously as long as the timer is enabled.
- When the counter reaches its maximum value, it wraps back to zero.
  - The timer can also trigger an interrupt when the counter overflows.
  - This is covered in the next section.
- In addition to timekeeping, timers can be used to generate waveforms which in turn control external devices.
  - Removing processing load from CPU.
  - Pulse Width Modulation (PWM) will be covered in Topic 11.

ATMega32U4 has four timers:

- Timer 0: an 8 bit timer (counter ranges from 0 to 255)
- Timer 1, 3: 16 bit timers (counter range from 0 to 65,535)
- Timer 4: fast 10 bit timer (range from 0 to 1023)

Each timer has a set of dedicated registers.

Timer0 registers (Datasheet, Section 13.8)

Each timer has a set of dedicated control and counter registers. Details are shown for Timer 0; you can look up the datasheet to find the corresponding registers for Timers 1, 3, and 4.

- `TCCR0A` – Timer/Counter Control Register 0 A:

Bits	7	6	5	4	3	2	1	0
Name	`COM0A1`	`COM0A0`	`COM0B1`	`COM0B0`	-	-	`WGM01`	`W`
Read/Write	R/W	R/W	R/W	R/W	R	R	R/W	R
initially	0	0	0	0	0	0	0	0

  - `COM0Ax` = Compare Match Output A Mode: leave this at 0
  - `COM0Bx` = Compare Match Output B Mode: leave this at 0
  - `WGM0x` = Waveform Generation Mode: leave this at 0
  - **TL;DR – For our current purposes either ignore, or assign 0, to this register**

- `TCCR0B` – Timer/Counter Control Register 0 B:

Bits	7	6	5	4	3	2	1	0
Name	`FOC0A`	`FOC0B`	-	-	`WGM02`	`CS02`	`CS01`	`C`
Read/Write	W	W	R	R	R/W	R/W	R/W	R
initially	0	0	0	0	0	0	0	0

  - `FOC0x` = Force output compare: leave these at 0.
  - `WGM02` = Waveform Generation Mode: leave this at 0.
  - `CS02,CS01,CS00` = Clock Select.
    Datasheet P 105.
    These bits taken together form a 3-bit number which tells the timer how frequently to update the counter.
    The system clock speed is *pre-scaled* by dividing by the designated factor for each Clock Select combination.
    Figures in this table assume that the CPU speed is set to 8MHz in the `setup` *phase.*
    Values are:

`CS02:0`	Counter updates…
`0b000`	Never (Timer/Counter stopped)
`0b001`	Every clock cycle (No pre-scaling) == 8,000,000 ticks/sec
`0b010`	Every 8 clock cycles == 1,000,000 ticks/sec
`0b011`	Every 64 clock cycles == 125,000 ticks/sec
`0b100`	Every 256 clock cycles == 31,250 ticks/sec
`0b101`	Every 1024 clock cycles == 7812.5 ticks/sec

`0b110`	External clock source on T0 pin. Clock on falling edge.
`0b111`	External clock source on T0 pin. Clock on rising edge.

- We will not be using CS02:0 == 6 or CS02:0 == 7.

- **`TCNT0`** – Timer/Counter Register 0: an 8-bit numeric value. **Where the count is stored.**
- **`OCR0A`** – Output Compare Register 0 A: an 8-bit numeric value. We will not be using this.
- **`OCR0B`** – Output Compare Register 0 B: an 8-bit numeric value. We will not be using this.
- **`TIMSK0`** – Timer/Counter Interrupt Mask Register 0:

Bits	7	6	5	4	3	2	1	0
Name	-	-	-	-	-	**`OCIE0B`**	**`OCIE0A`**	**`T`**
Read/Write	R	R	R	R	R	R/W	R/W	R
initially	0	0	0	0	0	0	0	0

  - **`OCIE0B`** = Force output compare: leave these at 0
  - **`OCIE0A`** = Force output compare: leave these at 0
  - **`TOIE0`** = Enable Timer Overflow Interrupt.

Case study: Set Up and Read Time From Timer0

In the present section we set up Timer 0, and see how to read the value of the clock.

- First, decide how fast we want the Timer/Counter register to update.
- Timer 0 is an 8 bit timer, so the Timer/Counter register will overflow every 256 ticks.
- We know the number of ticks per second from the datasheet, so we can calculate how long it will take for the timer to count from 0 to 255 (the overflow period) and how many times the counter will overflow per second (the overflow frequency).
  Definition: Frequency = 1 / Period.
  Figures in this table assume that the CPU speed is set to 8MHz in the **`setup`** *phase.*

`CS02:0`	Pre-scaler	Counter frequency	Overflow period = 256/freq	Overflow frequency
`0b000`	0	0	n/a	n/a
`0b001`	1	8MHz	0.000032s	31.25kHz
`0b010`	8	1MHz	0.000256s	3.90625kHz
`0b011`	64	125kHz	0.002048s	488.28125Hz
`0b100`	256	31.25kHz	0.008192s	122.0703125Hz
`0b101`	1024	7.8125kHz	0.032768s	30.517578125Hz

- Using the table, and balancing the update speed against our needs, we choose a pre-scaler.
- To set up Timer 0 to overflow about 30 times per second, we choose **`CS02:0 == 0b101 == 5`**, which corresponds to a pre-scaler of 1024.
- Starting the timer then consists of:
  - Set **`TCCR0A = 0;`**
  - Set **`TCCR0B = 5;`**
- To read the timer, we access **`TCNT0`**.
  - The value of the counter is a number of ticks.
  - To convert from ticks back to seconds, we multiply by the pre-scaler and divide by clock speed.
  - **`#define FREQ 8000000.0`**
    `#define PRESCALE 1024.0` …
    `double time = TCNT0 * PRESCALE / FREQ;`

This procedure is demonstrated in **`ReadTimer0.c`**

```
/*
**      ReadTimer0.c
**
**      Demonstrates how to set up Timer0 in normal mode and
**      read the Timer/Counter. Effectively, displays 8-bit
**      numbers at lightning speed.
**
```

```
**      See OverflowTimer0.c for use of the Timer Overflow
**      interrupt.
**
**      Lawrence Buckingham, QUT, September 2017.
**      (C) Queensland University of Technology.
*/
#include <stdint.h>
#include <stdio.h>
#include <avr/io.h>
#include <avr/interrupt.h>
#include <util/delay.h>
#include <cpu_speed.h>

#include <graphics.h>
#include <macros.h>
#include "lcd_model.h"

#define FREQ     (8000000.0)
#define PRESCALE (1024.0)

void draw_double(uint8_t x, uint8_t y, double value, colour_t colour);

void setup(void) {
        set_clock_speed(CPU_8MHz);
        lcd_init(LCD_DEFAULT_CONTRAST);
        lcd_clear();

        // Timer 0 in normal mode, with pre-scaler 1024 ==> ~30Hz overflow.
        TCCR0A = 0;
        TCCR0B = 5;

        /*
        Alternatively:
                CLEAR_BIT(TCCR0B,WGM02);
                SET_BIT(TCCR0B,CS02);
                CLEAR_BIT(TCCR0B,CS01);
                SET_BIT(TCCR0B,CS00);
        */
}

char buffer[20];

void process(void) {
        double time = TCNT0 * PRESCALE / FREQ;
        clear_screen();
        draw_string(0, 0, "TCNT0 = ", FG_COLOUR);
        draw_double(10, 10, time, FG_COLOUR);
        show_screen();
}

int main(void) {
        setup();

        for ( ;; ) {
                process();
        }
}

// -------------------------------------------------
// Helper functions.
// -------------------------------------------------

void draw_double(uint8_t x, uint8_t y, double value, colour_t colour) {
        snprintf(buffer, sizeof(buffer), "%f", value);
        draw_string(x, y, buffer, colour);
}
```

The Timer Overflow Interrupt

Caveat

Today we introduce interrupts in a superficial manner. We will encounter them again in subsequent topics.

What's an interrupt?

Refer: Datasheet Section 4.8, Section 9.

An *interrupt* is a signal which is generated in response to an internal or external event (or change of state).

Examples:

- Pin change.
- Serial transfer complete

- Timer overflow
- + plenty more.

Special functions called *Interrupt Service Routines* (also referred to as *interrupt handlers*) can be set up to process interrupts and are called in response to an event.

- A list of interrupt vectors may be found on datasheet, p61.
- Implementing an ISR is much the same as any other function.
- The main difference is that we use one of the pre-defined macros to declare our interrupt.
- In the present section, we will implement an ISR for the Timer 0 Overflow interrupt.
- The ISR will be called automatically every time the Timer/Counter 0 register overflows (this is the event that triggers the interrupt).

When an interrupt occurs and an ISR is implemented for that interrupt:

1. The CPU temporarily stops whatever it is doing, but keeps a record of the state of the computation.
2. It then turns off interrupts so the ISR can run unimpeded.
3. The ISR is called, like a regular function.
4. After the ISR finishes, the CPU re-enables interrupts and then continues where it left off.

ISRs must use special global variables to transfer data.

- ISRs cannot accept parameters, and cannot return a value.
- Variables that may be changed by an ISR must be marked with the `volatile` keyword.
- `volatile` ensures that the compiler generates the right instructions to let other non-ISR code read the variables.

Implementing Timer Overflow ISR

This subsection shows how to implement a Timer Overflow ISR for Timer 0.

- Timer setup is much the same as the previous example.
- We add two more instructions:
    - `TIMSK0 = 1;` enables the Timer Overflow interrupt for Timer 0. The same result would be obtained in this program by writing `TIMSK0 |= (1<<TOIE0);` – clarity is in the eye of the beholder.
    - `sei();` enables interrupts.
- The ISR is defined as a function with the signature `ISR(TIMER0_OVF_vect)`.

This procedure is demonstrated in `TimerOverflow0.c`

```
/*
**      TimerOverflow0.c
**
**      Demonstrates how to set up a Timer Overflow ISR
**      for Timer 0, and uses it to implement a digital
**      time counter.
**
**      Lawrence Buckingham, QUT, September 2017.
**      (C) Queensland University of Technology.
*/
#include <stdint.h>
#include <stdio.h>
#include <avr/io.h>
#include <avr/interrupt.h>
#include <util/delay.h>
#include <cpu_speed.h>

#include <graphics.h>
#include <macros.h>
#include "lcd_model.h"

#define FREQ     (8000000.0)
#define PRESCALE (1024.0)

void draw_double(uint8_t x, uint8_t y, double value, colour_t colour);

void setup(void) {
        set_clock_speed(CPU_8MHz);
```

```
        lcd_init(LCD_DEFAULT_CONTRAST);
        lcd_clear();

        // Timer 0 in normal mode, with pre-scaler 1024 ==> ~30Hz overflow.
        // Timer overflow on.
        TCCR0A = 0;
        TCCR0B = 5;
        TIMSK0 = 1;

        /*
        Alternatively:
                CLEAR_BIT(TCCR0B,WGM02);
                SET_BIT(TCCR0B,CS02);
                CLEAR_BIT(TCCR0B,CS01);
                SET_BIT(TCCR0B,CS00);
                SET_BIT(TIMSK0, TOIE0);
        */

        // Enable timer overflow, and turn on interrupts.
        sei();
}

char buffer[20];

volatile int overflow_counter = 0;

ISR(TIMER0_OVF_vect) {
        overflow_counter ++;
}

void process(void) {
        double time = ( overflow_counter * 256.0 + TCNT0 ) * PRESCALE  / FREQ;
        clear_screen();
        draw_string(0, 0, "Time = ", FG_COLOUR);
        draw_double(10, 10, time, FG_COLOUR);
        show_screen();
}

int main(void) {
        setup();

        for ( ;; ) {
                process();
        }
}
// -------------------------------------------------
// Helper functions.
// -------------------------------------------------

void draw_double(uint8_t x, uint8_t y, double value, colour_t colour) {
        snprintf(buffer, sizeof(buffer), "%f", value);
        draw_string(x, y, buffer, colour);
}
```

- In the ISR, we increment a counter to record how many times the timer has overflowed.
- In process, we multiply the counter by 256 (the number of ticks per overflow) and add the residual value of **`TCNT0`** to get the total number of elapsed ticks. This is then multiplied by the scaling factor to convert to the number of elapsed seconds since the program started.
- Note that in this implementation the counter wraps around and becomes negative when it passes 32,767. We could address this by counting with some wider numeric type.

Appendices

Appendix 1: Bit-packed boolean arrays

- Microcontrollers typically have limited RAM, so when writing complex programs we take every chance to economise on memory use.
- This subsection shows how we can use bit-level operations in an orderly way to pack multiple boolean values into simple variables, emulating a packed array of boolean.
- The key idea is as follows:
    - A variable of type **`uint8_t`** has 8 bits, so it can be used to remember up to 8 independent YES/NO values.
    - A variable of type **`uint16_t`** has 16 bits, so it can be used to remember up to 16 independent YES/NO values.
    - A variable of type **`uint32_t`** has 32 bits, so it can be used to remember up to 32 independent YES/NO

values.

- The trick is to use bitwise operators:
  - **`SET_BIT`** stores a YES value in a packed array – **`SET_BIT(collection,i)`** is analogous to **`collection[i] = true`**;
  - **`CLEAR_BIT`** stores a NO value in a packed array – **`CLEAR_BIT(collection,i)`** is analogous to **`collection[i] = false`**;
  - **`BIT_IS_SET`** asks if the value is YES – **`if (BIT_IS_SET(collection,i)) { /* do something */ }`** is analogous to **`if (collection[i]) { /* do something */ }`**;
- Practical application:
  - Remembering the state of a collection of switches.

Appendix 2: Digital I/O Cheat Sheet

Code snippets for frequently used registers:

Digital I/O	Data direction register	Detect	Turn on	Turn Off
Joystick up	`CLEAR_BIT(DDRD, 1)`	`BIT_IS_SET(PIND, 1)`	n/a	n/a
Joystick down	`CLEAR_BIT(DDRB, 7)`	`BIT_IS_SET(PINB, 7)`	n/a	n/a
Joystick left	`CLEAR_BIT(DDRB, 1)`	`BIT_IS_SET(PINB, 1)`	n/a	n/a
Joystick right	`CLEAR_BIT(DDRD, 0)`	`BIT_IS_SET(PIND, 0)`	n/a	n/a
Joystick centre	`CLEAR_BIT(DDRB, 0)`	`BIT_IS_SET(PINB, 0)`	n/a	n/a
Button left	`CLEAR_BIT(DDRF, 6)`	`BIT_IS_SET(PINF, 6)`	n/a	n/a
Button right	`CLEAR_BIT(DDRF, 5)`	`BIT_IS_SET(PINF, 5)`	n/a	n/a
LED0	`SET_BIT(DDRB, 2)`	n/a	`SET_BIT(PORTB, 2)`	`CLEAR_BIT(PORTB, 2)`
LED1	`SET_BIT(DDRB, 3)`	n/a	`SET_BIT(PORTB, 3)`	`CLEAR_BIT(PORTB, 3)`
LED2	`SET_BIT(DDRD, 6)`	n/a	`SET_BIT(PORTD, 6)`	`CLEAR_BIT(PORTD, 6)`

The End
