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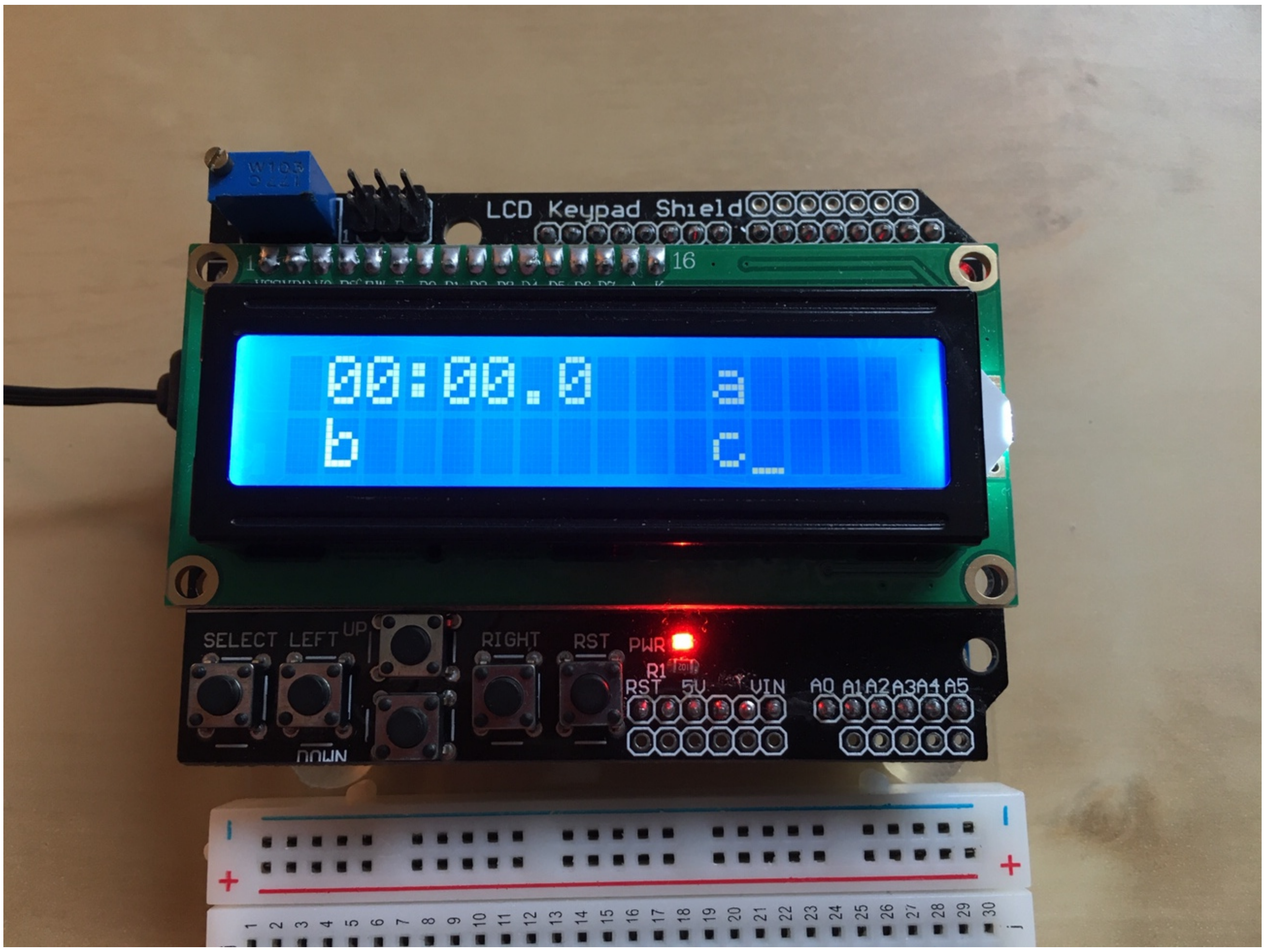
README.md

Lab 6: Display devices, LCD display

Learning objectives

The purpose of the laboratory exercise is to understand the serial control of Hitachi HD44780-based LCD character display and how to define custom characters. Another goal is to learn how to read documentation for library functions and use them in your own project.



Preparation tasks (done before the lab at home)

Use schematic of the LCD keypad shield and find out the connection of LCD display. What data and control signals are used? What is the meaning of these signals?

LCD signal(s)	AVR pin(s)	Description
RS	PB0	Register selection signal. Selection between Instruction register (RS=0) and Data register (RS=1)
R/W		

LCD signal(s)	AVR pin(s)	Description
E		
D[3:0]		
D[7:4]		

What is the ASCII table? What are the values for uppercase letters `A` to `Z`, lowercase letters `a` to `z`, and numbers `0` to `9` in this table?

Part 1: Synchronize repositories and create a new folder

Run Git Bash (Windows) of Terminal (Linux), navigate to your working directory, and update local repository. Create a new working folder `Labs/06-lcd` for this exercise.

Part 2: LCD display module

LCD (Liquid Crystal Display) is an electronic device which is used for display any ASCII text. There are many different screen sizes e.g. 16x1, 16x2, 16x4, 20x4, 40x4 characters and each character is made of 5x8 pixel dots. LCD displays have different LED backlight in yellow-green, white and blue color. LCD modules are mostly available in COB (Chip-On-Board) type. With this method, the controller IC chip or driver (here: HD44780) is directly mounted on the backside of the LCD module itself.

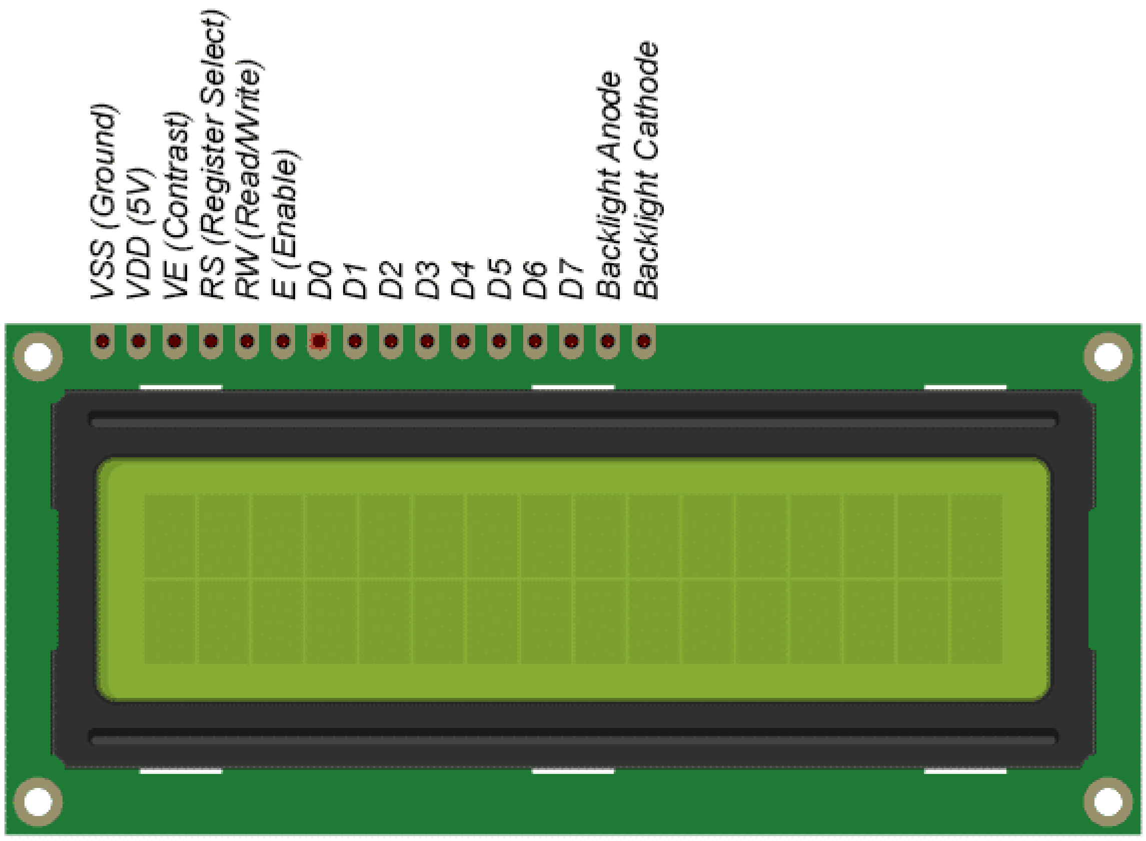
The control is based on the Hitachi HD44780 chipset (or a compatible), which is found on most text-based LCDs, and hence the driving software remains the same even for different screen sizes. The driver contains instruction set, character set, and in addition you can also generate your own characters.

The HD44780 is capable of operating in 8-bit mode i.e. faster, but that means 11 microcontroller pins are needed. Because the speed is not really that important as the amount of data needed to drive the display is low, the 4-bit mode is more appropriate for microcontrollers since only 6 (or 7) pins are needed.

In 8-bit mode we send the command/data to the LCD using eight data lines (D0-D7), while in 4-bit mode we use four data lines (D4-D7) to send commands and data. Inside the HD44780 there is still an 8-bit operation so for 4-bit mode, two writes to get 8-bit quantity inside the chip are made (first high four bits and then low four bits with an E clock pulse).

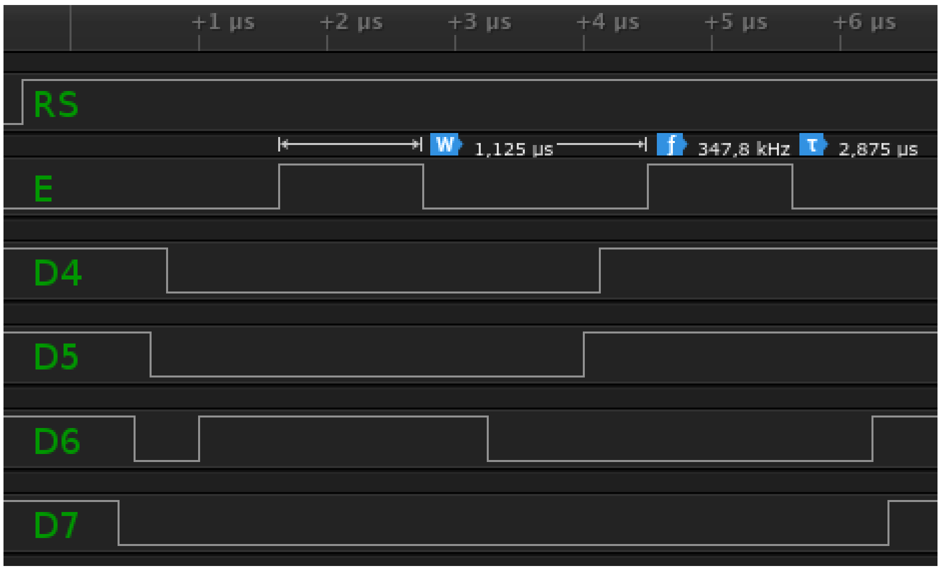
In the lab, the LCD1602 display module is used. The display consists of two rows of 16 characters each. It has an LED backlight and it communicates through a parallel interface with only 6 wires:

- RS - register select. Selects the data or instruction register inside the HD44780,
- E - enable. This loads the data into the HD44780 on the falling edge,
- D7:4 - Upper nibble used in 4-bit mode.



When a command is given on the LCD, we select the command register (RS = 0) and when data is sent to the LCD for display, we select the data register (RS = 1). A command is an instruction entered on the LCD in order to perform the required function. In order to display textual information, data is send to LCD.

> Let the following image shows the communication between ATmega328P and LCD display in 4-bit mode. How does HD44780 chipset understand the sequence of these signals?



> The following signals are read on the first falling edge of the enable: `RS = 1` (data register) and high four data bits `D7:4 = 0100`. On the second falling edge of enable, the low four data bits are `D7:4 = 0011`. The whole byte transmitted to the LCD is therefore `0100_0011` (0x43) and according to the ASCII (American Standard Code for Information Interchange) table, it represents lettre `C`.

The Hitachi HD44780 has many commands, the most useful for initialization, xy location settings, and print [1].

Table 6 Instructions

	Code											Execution Time (max) (when f_{cp} or f_{OSC} is 270 kHz)
Instruction	**RS**	**R/$\overline{W}$**	**DB7**	**DB6**	**DB5**	**DB4**	**DB3**	**DB2**	**DB1**	**DB0**	**Description**	
Clear display	0	0	0	0	0	0	0	0	0	1	Clears entire display and sets DDRAM address 0 in address counter.	
Return home	0	0	0	0	0	0	0	0	1	—	Sets DDRAM address 0 in address counter. Also returns display from being shifted to original position. DDRAM contents remain unchanged.	1.52 ms
Entry mode set	0	0	0	0	0	0	0	1	I/D	S	Sets cursor move direction and specifies display shift. These operations are performed during data write and read.	37 μs
Display on/off control	0	0	0	0	0	0	1	D	C	B	Sets entire display (D) on/off, cursor on/off (C), and blinking of cursor position character (B).	37 μs
Cursor or display shift	0	0	0	0	0	1	S/C	R/L	—	—	Moves cursor and shifts display without changing DDRAM contents.	37 μs
Function set	0	0	0	0	1	DL	N	F	—	—	Sets interface data length (DL), number of display lines (N), and character font (F).	37 μs
Set CGRAM address	0	0	0	1	ACG	ACG	ACG	ACG	ACG	ACG	Sets CGRAM address. CGRAM data is sent and received after this setting.	37 μs
Set DDRAM address	0	0	1	ADD	ADD	ADD	ADD	ADD	ADD	ADD	Sets DDRAM address. DDRAM data is sent and received after this setting.	37 μs
Read busy flag & address	0	1	BF	AC	AC	AC	AC	AC	AC	AC	Reads busy flag (BF) indicating internal operation is being performed and reads address counter contents.	0 μs

Table 6 Instructions (cont)

	Code											Execution Time (max) (when f_{cp} or f_{OSC} is 270 kHz)
Instruction	**RS**	**R/$\overline{W}$**	**DB7**	**DB6**	**DB5**	**DB4**	**DB3**	**DB2**	**DB1**	**DB0**	**Description**	
Write data to CG or DDRAM	1	0	Write data								Writes data into DDRAM or CGRAM.	37 μs t_{ADD} = 4 μs*
Read data from CG or DDRAM	1	1	Read data								Reads data from DDRAM or CGRAM.	37 μs t_{ADD} = 4 μs*
	I/D = 1: Increment I/D = 0: Decrement S = 1: Accompanies display shift S/C = 1: Display shift S/C = 0: Cursor move R/L = 1: Shift to the right R/L = 0: Shift to the left DL = 1: 8 bits, DL = 0: 4 bits N = 1: 2 lines, N = 0: 1 line F = 1: 5 × 10 dots, F = 0: 5 × 8 dots BF = 1: Internally operating BF = 0: Instructions acceptable										DDRAM: Display data RAM CGRAM: Character generator RAM ACG: CGRAM address ADD: DDRAM address (corresponds to cursor address) AC: Address counter used for both DD and CGRAM addresses	Execution time changes when frequency changes Example: When f_{cp} or f_{OSC} is 250 kHz, $37\ \mu s \times \frac{270}{250} = 40\ \mu s$

Note: — indicates no effect.

* After execution of the CGRAM/DDRAM data write or read instruction, the RAM address counter is incremented or decremented by 1. The RAM address counter is updated after the busy flag turns off. In Figure 10, t_{ADD} is the time elapsed after the busy flag turns off until the address counter is updated.

If you are an advanced programmer and would like to create your own library for interfacing your microcontroller with an LCD module then you have to understand those instructions and commands which can be found its datasheet.

Part 3: Library for HD44780 based LCDs

In the lab, we are using LCD library for HD44780 based LCDs developed by Peter Fleury. Use online manual of LCD library and add the input parameters and description of the functions to the following table.

Function name	Function parameters	Description	Exampl

`lcd_init`	`LCD_DISP_OFF`
	`LCD_DISP_ON`
	`LCD_DISP_ON_CURSOR`
	`LCD_DISP_ON_CURSOR_BLINK`
		Display off	`lcd_ini`

`lcd_clrscr`			`lcd_clr`
`lcd_gotoxy`			
`lcd_putc`			
`lcd_puts`			
`lcd_command`			
`lcd_data`			

Version: Atmel Studio 7

Create a new GCC C Executable Project for ATmega328P within `06-lcd` working folder and copy/paste template code to your `main.c` source file.

In **Solution Explorer** click on the project name, then in menu **Project**, select **Add Existing Item... Shift+Alt+A** and add LCD library files `lcd.h`, `lcd_definitions.h`, `lcd.c` from `Examples/library/include` and `Examples/library` folders and timer library `timer.h` from the previous labs.

Version: Command-line toolchain

Copy `main.c` and `Makefile` files from previous lab to `Labs/06-lcd` folder.

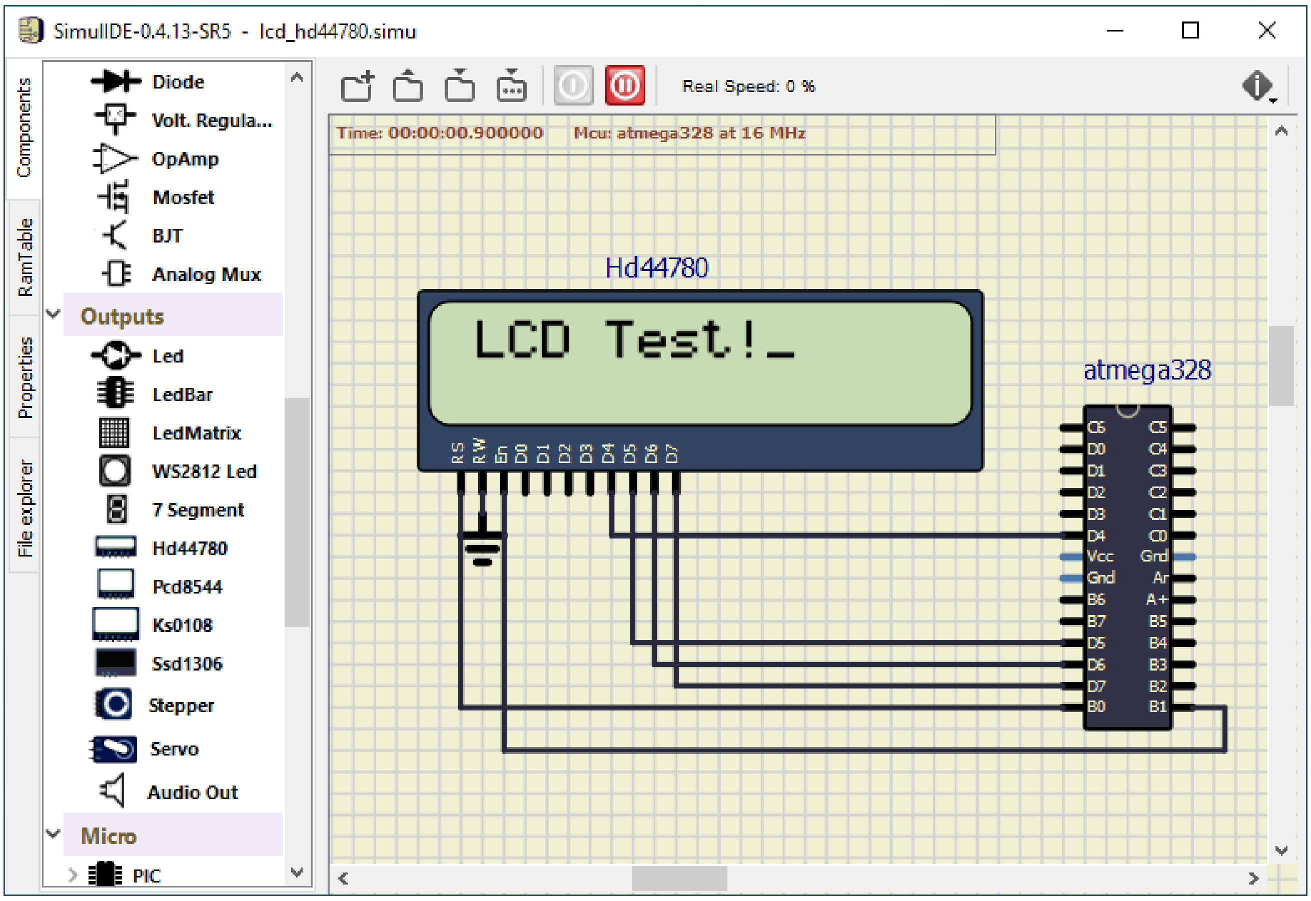
Copy/paste template code to your `06-lcd/main.c` source file.

Add the source file of LCD library between the compiled files in `06-lcd/Makefile`.

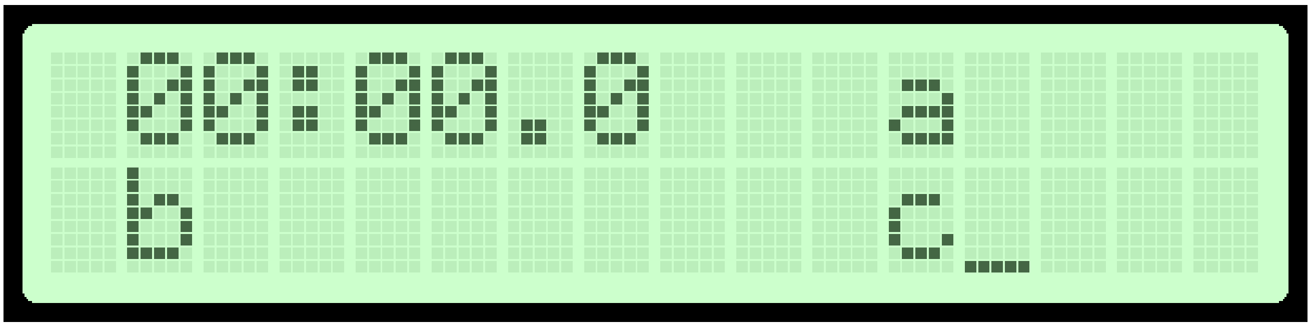
```
# Add or comment libraries you are using in the project
SRCS += $(LIBRARY_DIR)/lcd.c
#SRCS += $(LIBRARY_DIR)/uart.c
#SRCS += $(LIBRARY_DIR)/twi.c
#SRCS += $(LIBRARY_DIR)/gpio.c
#SRCS += $(LIBRARY_DIR)/segment.c
```

Both versions

Compile the code and download to Arduino Uno board or load `*.hex` firmware to SimulIDE circuit (create an identical connection to the LCD keypad shield).

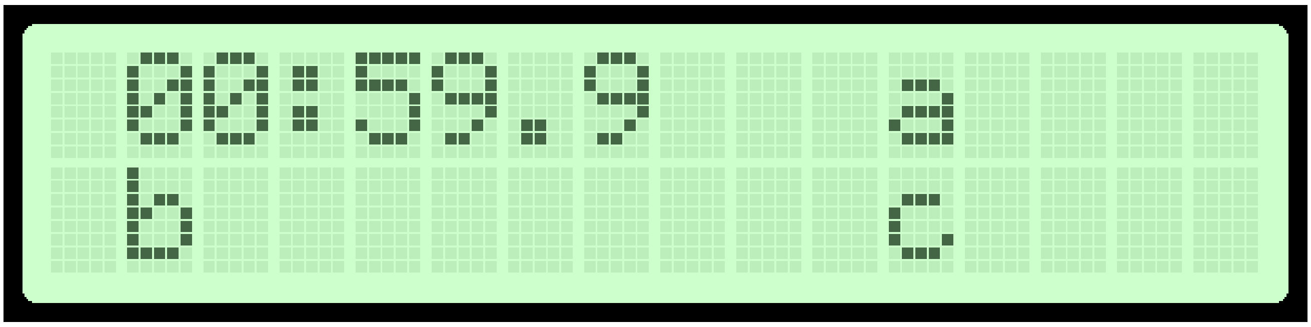


Test the functions from the table and display strings/characters on the LCD as follows [2]. Explanation: You will later display the square of seconds in position "a", the process bar in position "b", and the rotating text in position "c".



Part 4: Stopwatch

Use Timer/Counter2 and update the stopwatch value approximately every 100 ms. Display tenths of a second and seconds `00:seconds.tenths` .



```c
/* Interrupt service routines ----------------------------------------*/
/**
 * ISR starts when Timer/Counter2 overflows. Update the stopwatch on
 * LCD display every sixth overflow, ie approximately every 100 ms
 * (6 x 16 ms = 100 ms).
 */
ISR(TIMER2_OVF_vect)
{
    static uint8_t number_of_overflows = 0;
    static uint8_t tens = 0;        // Tenths of a second
    static uint8_t secs = 0;        // Seconds
    char lcd_string[2] = "  ";      // String for converting numbers by itoa()

    number_of_overflows++;
    if (number_of_overflows >= 6)
    {
        // Do this every 6 x 16 ms = 100 ms
        number_of_overflows = 0;

        // WRITE YOUR CODE HERE

    }
}
```

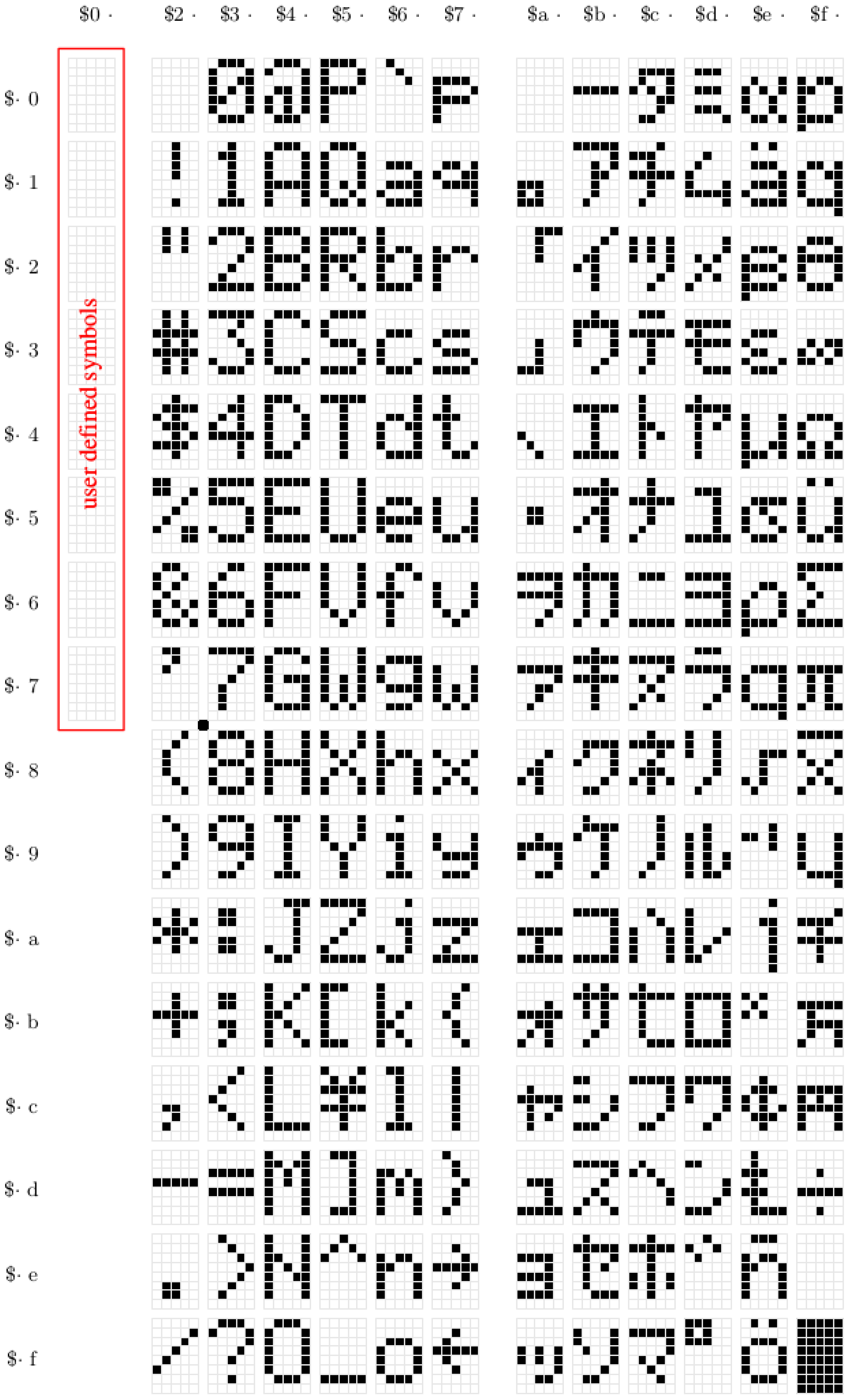
Because library functions only allow the display of strings (`lcd_puts`) or individual characters (`lcd_putc`), the current values of the variables need to be converted to these strings. To do this, use the `itoa(number, string, num_base)` function from the standard `stdlib.h` library. The `num_base` parameter allows you to display the `number` value in decimal, hexadecimal, or binary.

```
#include <stdlib.h>         // C library. Needed for conversion function
...
    itoa(tens, lcd_string, 10);     // Convert decimal value to string
    lcd_puts(lcd_string);
    ...
```

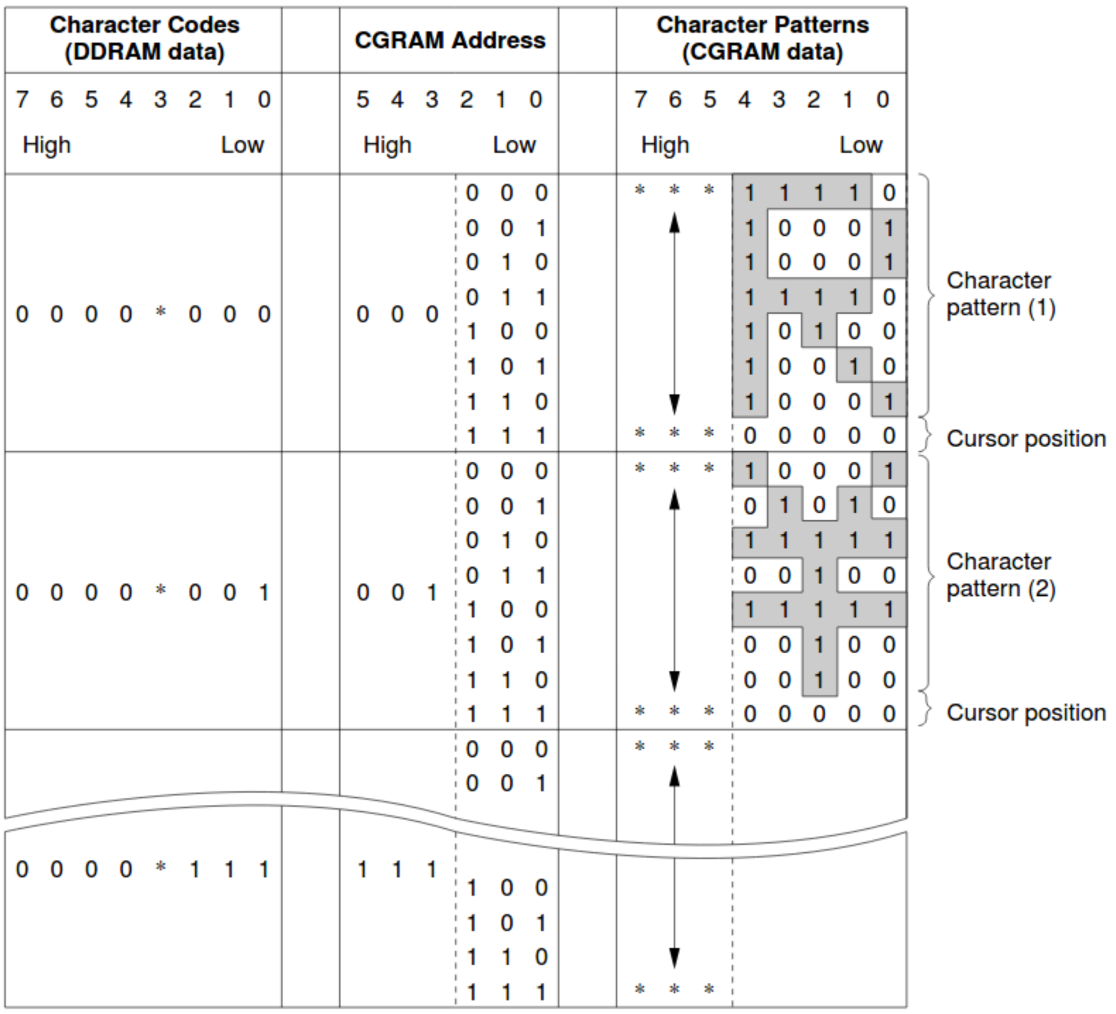
Part 5: Defined and custom characters

All LCD displays based on the Hitachi HD44780 controller have two types of memory that store defined characters: CGROM and CGRAM (Character Generator ROM & RAM). The CGROM memory is non-volatile and cannot be modified, while the CGRAM memory is volatile and can be modified at any time [3].

CGROM memory is used to store all permanent fonts that can be displayed using their ASCII code. For example, if we write 0x43, then we get the character "C" on the display. It can generate 208 5x8 character patterns.


$0 ·
$2 ·
$3 ·
$4 ·
$5 ·
$6 ·
$7 ·
$a ·
$b ·
$c ·
$d ·
$e ·
$f ·
$· 0
$· 1
$· 2
$· 3
$· 4
$· 5
$· 6
$· 7
$· 8
$· 9
$· a
$· b
$· c
$· d
$· e
$· f
user defined symbols

CGRAM is another memory that can be used for storing user defined characters. This RAM is limited to 64 bytes. Meaning, for 5x8 pixel based LCD, up to 8 user-defined characters can be stored in the CGRAM. It is useful if you want to use a character that is not part of the standard 127-character ASCII table.



Character Codes (DDRAM data)	CGRAM Address		Character Patterns (CGRAM data)		
7 6 5 4 3 2 1 0 High Low	5 4 3 2 1 0 High Low		7 6 5 4 3 2 1 0 High Low		
0 0 0 0 * 0 0 0	0 0 0	0 0 0	* * *	1 1 1 1 0	Character pattern (1)
		0 0 1		1 0 0 0 1	
		0 1 0		1 0 0 0 1	
		0 1 1		1 1 1 1 0	
		1 0 0		1 0 1 0 0	
		1 0 1		1 0 0 1 0	
		1 1 0		1 0 0 0 1	
		1 1 1	* * *	0 0 0 0 0	Cursor position
0 0 0 0 * 0 0 1	0 0 1	0 0 0	* * *	1 0 0 0 1	Character pattern (2)
		0 0 1		0 1 0 1 0	
		0 1 0		1 1 1 1 1	
		0 1 1		0 0 1 0 0	
		1 0 0		1 1 1 1 1	
		1 0 1		0 0 1 0 0	
		1 1 0		0 0 1 0 0	
		1 1 1	* * *	0 0 0 0 0	Cursor position
		0 0 0	* * *		
		0 0 1			
0 0 0 0 * 1 1 1	1 1 1	1 0 0			
		1 0 1			
		1 1 0			
		1 1 1	* * *		

Notes: 1. Character code bits 0 to 2 correspond to CGRAM address bits 3 to 5 (3 bits: 8 types).

2. CGRAM address bits 0 to 2 designate the character pattern line position. The 8th line is the cursor position and its display is formed by a logical OR with the cursor.
   Maintain the 8th line data, corresponding to the cursor display position, at 0 as the cursor display.
   If the 8th line data is 1, 1 bits will light up the 8th line regardless of the cursor presence.
3. Character pattern row positions correspond to CGRAM data bits 0 to 4 (bit 4 being at the left).
4. As shown Table 5, CGRAM character patterns are selected when character code bits 4 to 7 are all 0. However, since character code bit 3 has no effect, the R display example above can be selected by either character code 00H or 08H.
5. 1 for CGRAM data corresponds to display selection and 0 to non-selection.

* Indicates no effect.

A custom character is an array of 8 bytes. Each byte (only 5 bits are considered) in the array defines one row of the character in the 5x8 matrix. Whereas, the zeros and ones in the byte indicate which pixels in the row should be on and which ones should be off.

Design at least two custom characters, store them in CGRAM according to the following code and display them on the LCD screen.

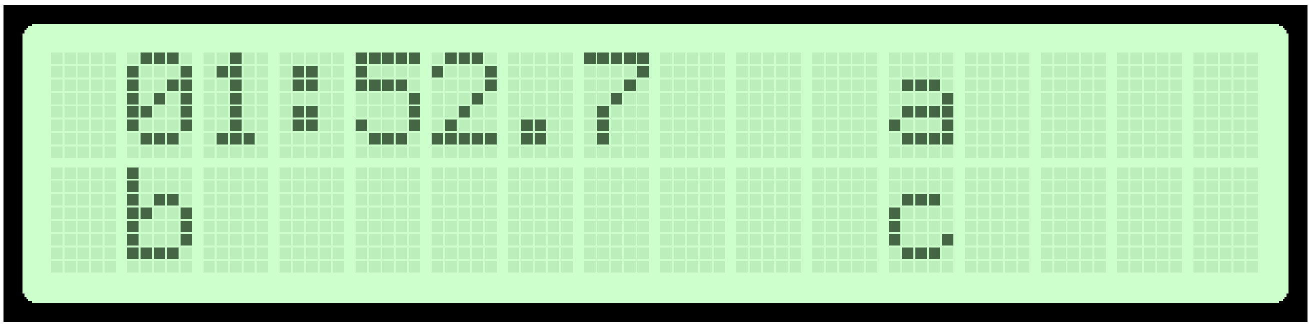
```c
/* Variables ---------------------------------------------------------*/
// Custom character definition using https://omerk.github.io/lcdchargen/
uint8_t customChar[8] = {
    0b00111,
    0b01110,
    0b11100,
    0b11000,
    0b11100,
    0b01110,
    0b00111,
    0b00011
};
...
int main(void)
{
    // Initialize LCD display
    lcd_init(LCD_DISP_ON);

    // Set pointer to beginning of CGRAM memory
    lcd_command(1 << LCD_CGRAM);
    for (uint8_t i = 0; i < 8; i++)
    {
        // Store all new chars to memory line by line
        lcd_data(customChar[i]);
    }
    // Set DDRAM address
    lcd_command(1 << LCD_DDRAM);

    // Display first custom character
    lcd_putc(0);
```

Synchronize repositories

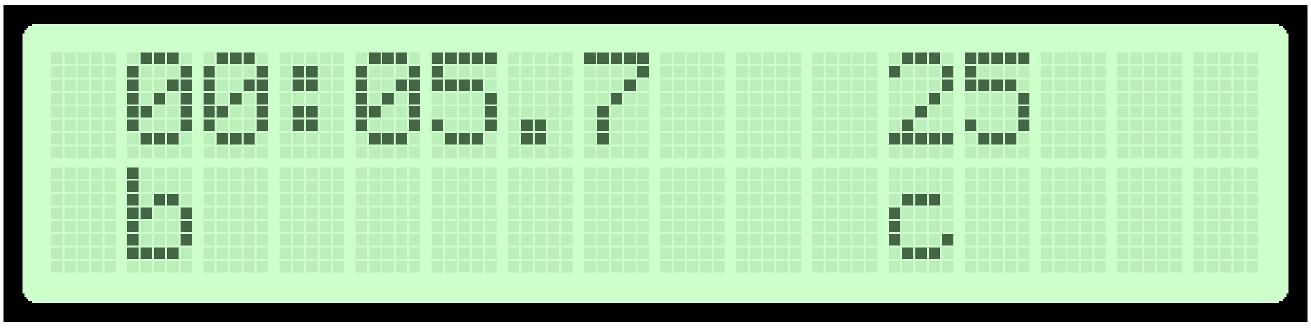
Use git commands to add, commit, and push all local changes to your remote repository. Check the repository at GitHub web page for changes.

Experiments on your own

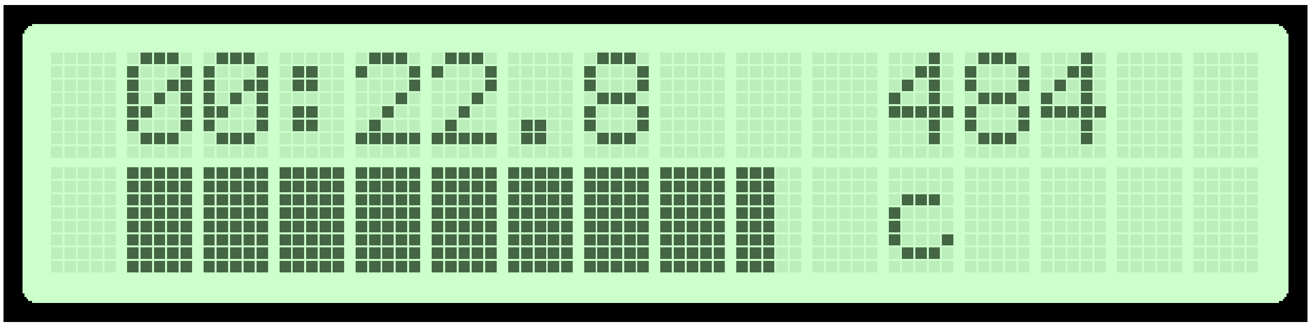
1. Complete the `TIMER2_OVF_vect` interrupt routine with stopwatch code and display `minutes:seconds.tenths`.

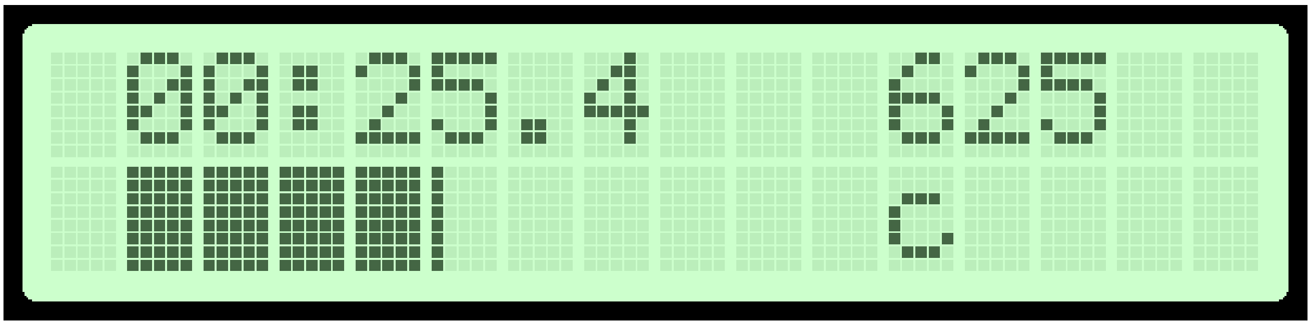


2. Display the square value of the `seconds` at LCD position "a".



3. Use new characters and create a progress bar at LCD position "b". Let the full bar state corresponds to one second.



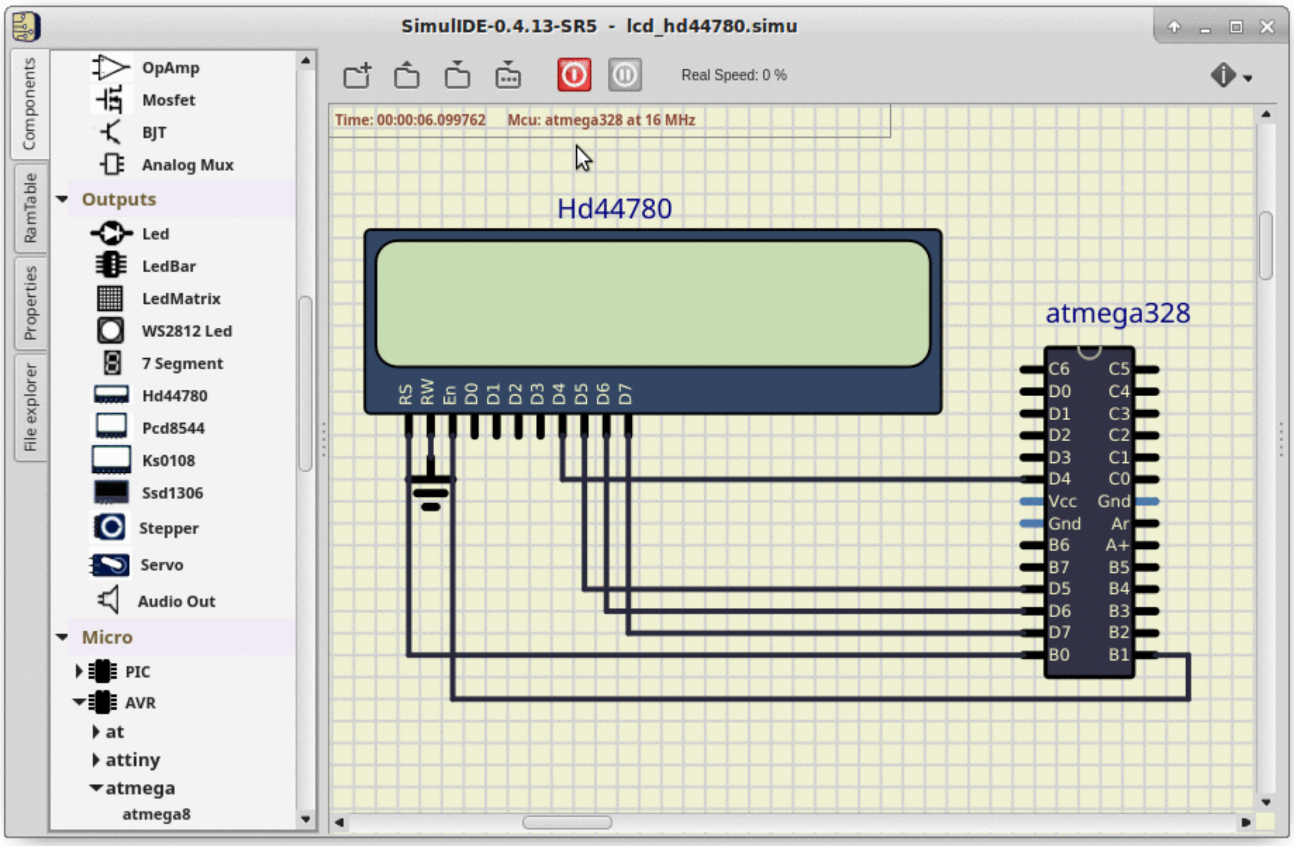


Hint: Use Timer/Counter0 with 16ms overflow and change custom characters at specific display position.

```c
/* Variables ---------------------------------------------------------*/
// Custom character definition using https://omerk.github.io/lcdchargen/
uint8_t customChar[] = {
    // addr 0: .....
    0b00000, 0b00000, 0b00000, 0b00000, 0b00000, 0b00000, 0b00000, 0b00000,
    // addr 1: |....
    0b10000, 0b10000, 0b10000, 0b10000, 0b10000, 0b10000, 0b10000, 0b10000,
    ...
};
...
/*--------------------------------------------------------------------*/
/**
 * ISR starts when Timer/Counter0 overflows. Update the progress bar on
 * LCD display every 16 ms.
 */
ISR(TIMER0_OVF_vect)
```

```
{
    static uint8_t symbol = 0;
    static uint8_t position = 0;

    lcd_gotoxy(1 + position, 1);
    lcd_putc(symbol);

    // WRITE YOUR CODE HERE
}
```

Extra. From the LCD position "c", displays running text, ie text that moves characters to the left twice per second. Hint: Use Timer/Counter1 with an 262ms prescaler and every second overflow move the auxiliary variable along the defined string, such as `uint8_t running_text[] = "   I like Digital electronics!\n";` .



Lab assignment

1. Preparation tasks (done before the lab at home). Submit:
    - Table with LCD signals,
    - ASCII values.
2. HD44780 communication. Submit:
    - (Hand-drawn) picture of time signals between ATmega328P and LCD keypad shield (HD44780) when transmitting data `DE2` .

3. Stopwatch. Submit:
   - Listing of `TIMER2_OVF_vect` interrupt routine with complete stopwatch code (`minutes:seconds.tenths`) and square value computation,
   - Screenshot of SimulIDE circuit when "Power Circuit" is applied.
4. Progress bar. Submit:
   - Listing of `TIMER0_OVF_vect` interrupt routine with a progress bar,
   - Screenshot of SimulIDE circuit when "Power Circuit" is applied.

The deadline for submitting the task is the day before the next laboratory exercise. Use BUT e-learning web page and submit a single PDF file.

References

1. https://www.sparkfun.com/datasheets/LCD/HD44780.pdf
2. https://protostack.com.au/2010/03/character-lcd-displays-part-1/
3. https://www.circuitbasics.com/
4. LCD library for HD44780 based LCDs
5. https://www.st.com/en/embedded-software/stsw-stm8063.html#documentation
6. CGRAM display memory
7. https://lastminuteengineers.com/arduino-1602-character-lcd-tutorial/