Lab 7: Inter-Integrated Circuits (I2C)

Learning objectives

After completing this lab you will be able to:

- Understand the I2C communication
- Use functions from I2C library
- Perform data transfers between I2C devices and MCU

The purpose of the laboratory exercise is to understand serial synchronous communication using the I2C (Inter-Integrated Circuit) bus, as well as the structure of the address and data frame and the possibilities of communication using the internal TWI (Two Wire Interface) unit.

Table of contents

Components list

- Arduino Uno board, USB cable
- Breadboard
- DHT12 humidity/temperature sensor
- RTC DS3231 and AT24C32 EEPROM memory module
- GY-521 module with MPU-6050 microelectromechanical systems
- Jumper wires

Pre-Lab preparation

1. Use schematic of the Arduino Uno board and find out on which Arduino Uno pins the SDA and SCL signals are located.

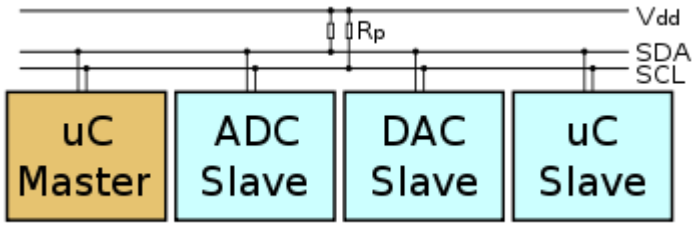
2. Remind yourself, what the general structure of I2C address and data frame is.

Part 1: I2C bus

I2C (Inter-Integrated Circuit) is a serial protocol for two-wire interface to connect low-speed devices like microcontrollers, EEPROMs, A/D and D/A converters, I/O interfaces and other similar peripherals in embedded systems. It was invented by Philips and now it is used by almost all major IC manufacturers.

I2C uses only two wires: SCL (serial clock) and SDA (serial data). Both need to be pulled up with a resistor to +Vdd. There are also I2C level shifters which can be used to connect to two I2C buses with different

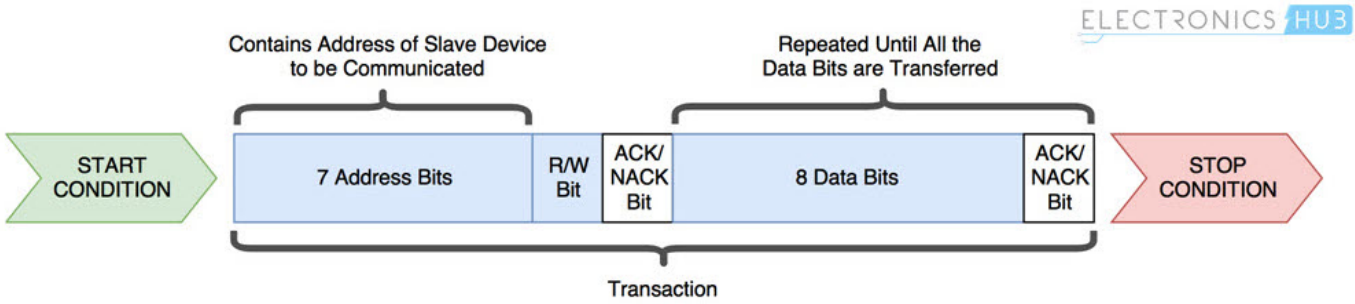
voltages. On I2C bus, there is always one Master and one or several Slave devices. Each Slave device has a unique address [2].



The initial I2C specifications defined maximum clock frequency of 100 kHz. This was later increased to 400 kHz as Fast mode. There is also a High speed mode which can go up to 3.4 MHz and there is also a 5 MHz ultra-fast mode.

In normal state both lines (SCL and SDA) are high. The communication is initiated by the master device. It generates the Start condition (S) followed by the address of the slave device (SLA). If the bit 0 of the address byte was set to 0 the master device will write to the slave device (SLA+W). Otherwise, the next byte will be read from the slave device (SLA+R). Each byte is supplemented by an ACK (low level) or NACK (high level) acknowledgment bit, which is always transmitted by the device receiving the previous byte.

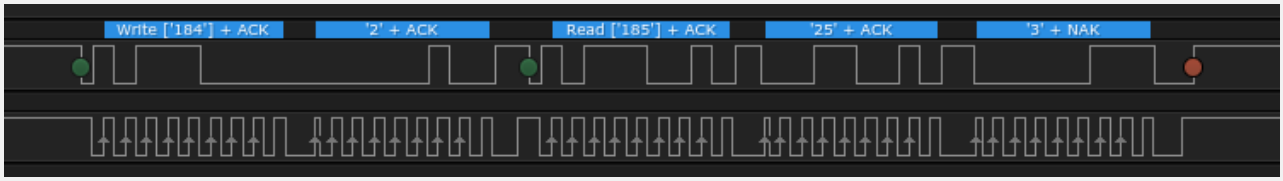
The address byte is followed by one or more data bytes, where each contains 8 bits and is again terminated by ACK/NACK. Once all bytes are read or written the master device generates Stop condition (P). This means that the master device switches the SDA line from low voltage level to high voltage level before the SCL line switches from high to low [3].



Note that, most I2C devices support repeated start condition. This means that before the communication ends with a stop condition, master device can repeat start condition with address byte and change the mode from writing to reading.

Example of I2C communication

Question: Let the following image shows several frames of I2C communication between ATmega328P and a slave device. What circuit is it and what information was sent over the bus?



Answer: This communication example contains a total of five frames. After the start condition, which is initiated by the master, the address frame is always sent. It contains a 7-bit address of the slave device, supplemented by information on whether the data will be written to the slave or read from it to the master. The ninth bit of the address frame is an acknowledgment provided by the receiving side.

Here, the address is 184 (decimal), i.e. `101_1100-0` in binary including R/W=0. The slave address is therefore 101_1100 (0x5c) and master will write data to the slave. The slave has acknowledged the address reception, so that the communication can continue.

According to the list of I2C addresses the device could be humidity/temp or pressure sensor. The signals were really recorded when communicating with the humidity and temperature sensor.

The data frame always follows the address one and contains eight data bits from the MSB to the LSB and is again terminated by an acknowledgment from the receiving side. Here, number `2` was written to the sensor. According to the DHT12 sensor manual, this is the address of register, to which the integer part of measured temperature is stored. (The following register contains its decimal part.)

Register address	Description
0x00	Humidity integer part
0x01	Humidity decimal part
0x02	Temperature integer part
0x03	Temperature decimal part
0x04	Checksum

After the repeated start, the same circuit address is sent on the I2C bus, but this time with the read bit R/W=1 (185, `1011100_1`). Subsequently, data frames are sent from the slave to the master until the last of them is confirmed by the NACK value. Then the master generates a stop condition on the bus and the communication is terminated.

The communication in the picture therefore records the temperature transfer from the sensor, when the measured temperature is 25.3 degrees Celsius.

Frame #	Description
1	Address frame with SLA+W = 184 (0x5c<<1 + 0)
2	Data frame sent to the Slave represents the ID of internal register
3	Address frame with SLA+R = 185 (0x5c<<1 + 1)
4	Data frame with integer part of temperature read from Slave
5	Data frame with decimal part of temperature read from Slave

Part 2: Synchronize repositories and create a new project

1. In your working directory, use **Source Control (Ctrl+Shift+G)** in Visual Studio Code or Git Bash (on Windows) or Terminal (on Linux) to update the local repository.

   > **Help:** Useful bash and git commands are `cd` - Change working directory. `mkdir` - Create directory. `ls` - List information about files in the current directory. `pwd` - Print the name of the current working directory. `git status` - Get state of working directory and staging area. `git pull` - Update local repository and working folder.

2. In Visual Studio Code create a new PlatformIO project `lab7-i2c` for `Arduino Uno` board and change project location to your local repository folder `Documents/digital-electronics-2`.

3. IMPORTANT: Rename `LAB7-I2C > src > main.cpp` file to `main.c`, ie change the extension to `.c`.

Part 3: I2C scanner

The goal of this task is to create a program that will verify the presence of unknown devices connected to the I2C bus by sequentially trying all address combinations.

1. Copy/paste template code to `LAB7-I2C > src > main.c` source file.

2. Use your favorite file manager and copy `timer` and `uart` libraries from the previous lab to the proper locations within the `LAB7-IC2` project.

3. In PlatformIO project, create a new folder `LAB7-I2C > lib > twi`. Within this folder, create two new files `twi.c` and `twi.h`.

   1. Copy/paste library source file to `twi.c`
   2. Copy/paste header file to `twi.h`

   The final project structure should look like this:

   ```
   LAB7-I2C            // PlatfomIO project
   ├── include         // Included file(s)
   │   └── timer.h
   ├── lib             // Libraries
   │   ├── twi         // Tomas Fryza's TWI/I2C library
   │   │   ├── twi.c
   │   │   └── twi.h
   │   └── uart        // Peter Fleury's UART library
   │       ├── uart.c
   │       └── uart.h
   ├── src             // Source file(s)
   │   └── main.c
   ├── test            // No need this
   └── platformio.ini  // Project Configuration File
   ```

4. In the lab, we are using I2C/TWI library developed by Tomas Fryza according to Microchip Atmel ATmega16 and ATmega328P manuals. Use the `twi.h` header file and add input parameters and description of the following functions.

Function name	Function parameters	Description	Example
`twi_init`	None	Initialize TWI unit, enable internal pull-up resistors, and set SCL frequency	`twi_init();`
`twi_start`			
`twi_write`			`twi_write((sla<<1) | TWI_WRITE);`
`twi_read`			
`twi_stop`			`twi_stop();`

5. Use breadboard and connect available I2C modules to Arduino Uno board, such as humidity/temperature DHT12 digital sensor, combined module with RTC DS3231 (Real Time Clock) and AT24C32 EEPROM memory, or GY-521 module (MPU-6050 Microelectromechanical systems that features a 3-axis gyroscope, a 3-axis accelerometer, a digital motion processor (DMP), and a temperature sensor). Instead of external pull-up resistors on the SDA and SCL pins, the internal ones will be used.

> **Important:** Connect the components on the breadboard only when the supply voltage/USB is disconnected!

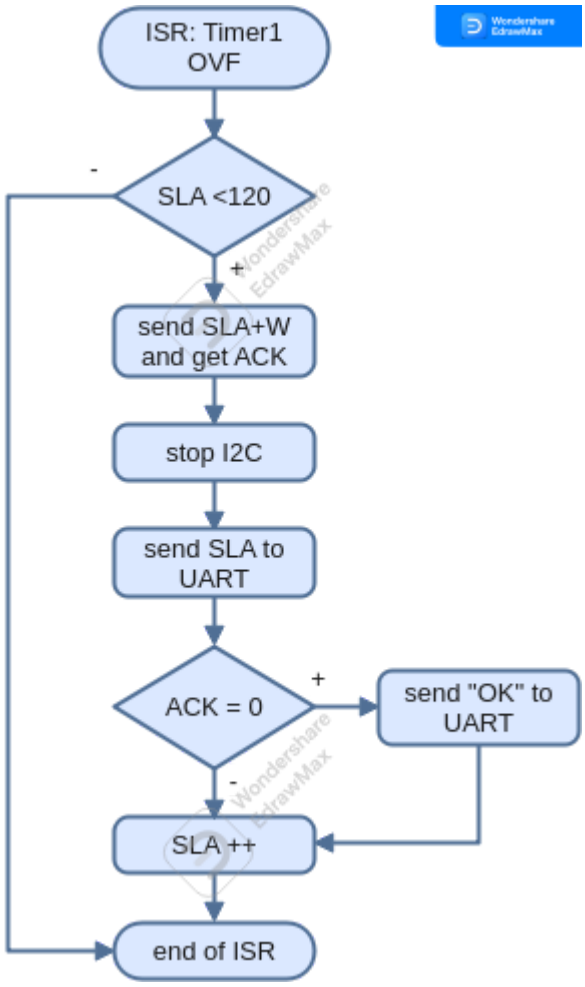
DHT12 pin	Arduino Uno pin
+	5V (or 3.3V)
SDA	SDA
-	GND
SCL	SCL

RTC+EEPROM pin	Arduino Uno pin
32K (reference clock - output)	Not connected
SQW (square-wave - output)	Not connected
SCL	SCL
SDA	SDA
VCC	5V (or 3.3V)
GND	GND

GY-521 pin	Arduino Uno pin
VCC	5V (or 3.3V)
GND	GND

GY-521 pin	Arduino Uno pin
SCL	SCL
SDA	SDA
XDA	Not connected
XCL	Not connected
ADO	Not connected
INT	Not connected

6. Go through the `main.c` file and make sure you understand each line. Build and upload the code to Arduino Uno board. Use **PlatformIO: Serial Monitor** to receive values from Arduino board. Complete the Timer1 overflow handler and test all Slave addresses from the range 8 to 119. If Slave device address is detected, send the information via UART. What Slave addresses were detected?



> **Important:** If the received characters are not displayed on the Serial Monitor, exit and restart the monitor again.

Part 4: Communication with I2C devices

1. Program an application which reads data from humidity/temperature DHT12 sensor and sends them periodically via UART to Serial Monitor or PuTTY SSH Client. Use Timer/Counter1 with a suitable

overflow time. Note that, according to the DHT12 manual, the internal DHT12 data registers have the following structure.

Register address	Description
0x00	Humidity integer part
0x01	Humidity decimal part
0x02	Temperature integer part
0x03	Temperature decimal part
0x04	Checksum

Note that a structured variable in C can be used for read values.

```
/* Global variables ---------------------------------------------------
*/
// Declaration of "dht12" variable with structure
"DHT_values_structure"
struct DHT_values_structure {
    uint8_t humInt;
    uint8_t humDec;
    uint8_t temInt;
    uint8_t temDec;
    uint8_t checksum;
} dht12;

...
dht12.humidInt = twi_read(TWI_ACK);  // Store one byte to structured
variable
```

2. (Optional) Find out how checksum byte value is calculated.

3. Program an application which reads data from RTC DS3231 chip and sends them periodically via UART to Serial Monitor or PuTTY SSH Client. Note that, according to the DS3231 manual, the internal RTC registers have the following structure.

Address	Bit 7	Bits 6:4	Bits 3:0
0x00	0	10 Seconds	Seconds
0x01	0	10 Minutes	Minutes
0x02	0	12/24 AM/PM 10 Hour	Hour
...	...	...	...

4. (Optional) Verify the I2C communication with logic analyzer.

5. (Optional) Program an application which reads data from GY-521 module. It consists of MPU-6050 Microelectromechanical systems that features a 3-axis gyroscope, a 3-axis accelerometer, a digital

motion processor (DMP), and a temperature sensor.

6. After completing your work, ensure that you synchronize the contents of your working folder with both the local and remote repository versions. This practice guarantees that none of your changes are lost. You can achieve this by using **Source Control (Ctrl+Shift+G)** in Visual Studio Code or by utilizing Git commands.

> **Help:** Useful git commands are `git status` - Get state of working directory and staging area. `git add` - Add new and modified files to the staging area. `git commit` - Record changes to the local repository. `git push` - Push changes to remote repository. `git pull` - Update local repository and working folder. Note that, a brief description of useful git commands can be found here and detailed description of all commands is here.

(Optional) Experiments on your own

1. Form the UART output of I2C scanner application to a hexadecimal table such as the following figure. Note that, the designation RA represents I2C addresses that are reserved and cannot be used for slave circuits.

```
Scan I2C-bus for slave devices:

     .0 .1 .2 .3 .4 .5 .6 .7 .8 .9 .a .b .c .d .e .f
0x0.: RA RA RA RA RA RA RA RA -- -- -- -- -- -- -- --
0x1.: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
0x2.: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
0x3.: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
0x4.: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
0x5.: -- -- -- -- -- -- -- 57 -- -- -- -- -- -- -- --
0x6.: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
0x7.: -- -- -- -- -- -- -- -- RA RA RA RA RA RA RA RA

Number of detected devices: 1
```

2. Program functions that will be able to read only one value from the RTC DS3231 at a time.

Function name	Function parameters	Description	Example
`rtc_read_seconds`	None	Read seconds from RTC	`rtc.secs = rtc_read_seconds();`
`rtc_read_minutes`	None	Read minutes from RTC	`rtc.mins = rtc_read_minutes();`
`rtc_read_hours`	None	Read hours from RTC	`rtc.hours = rtc_read_hours();`

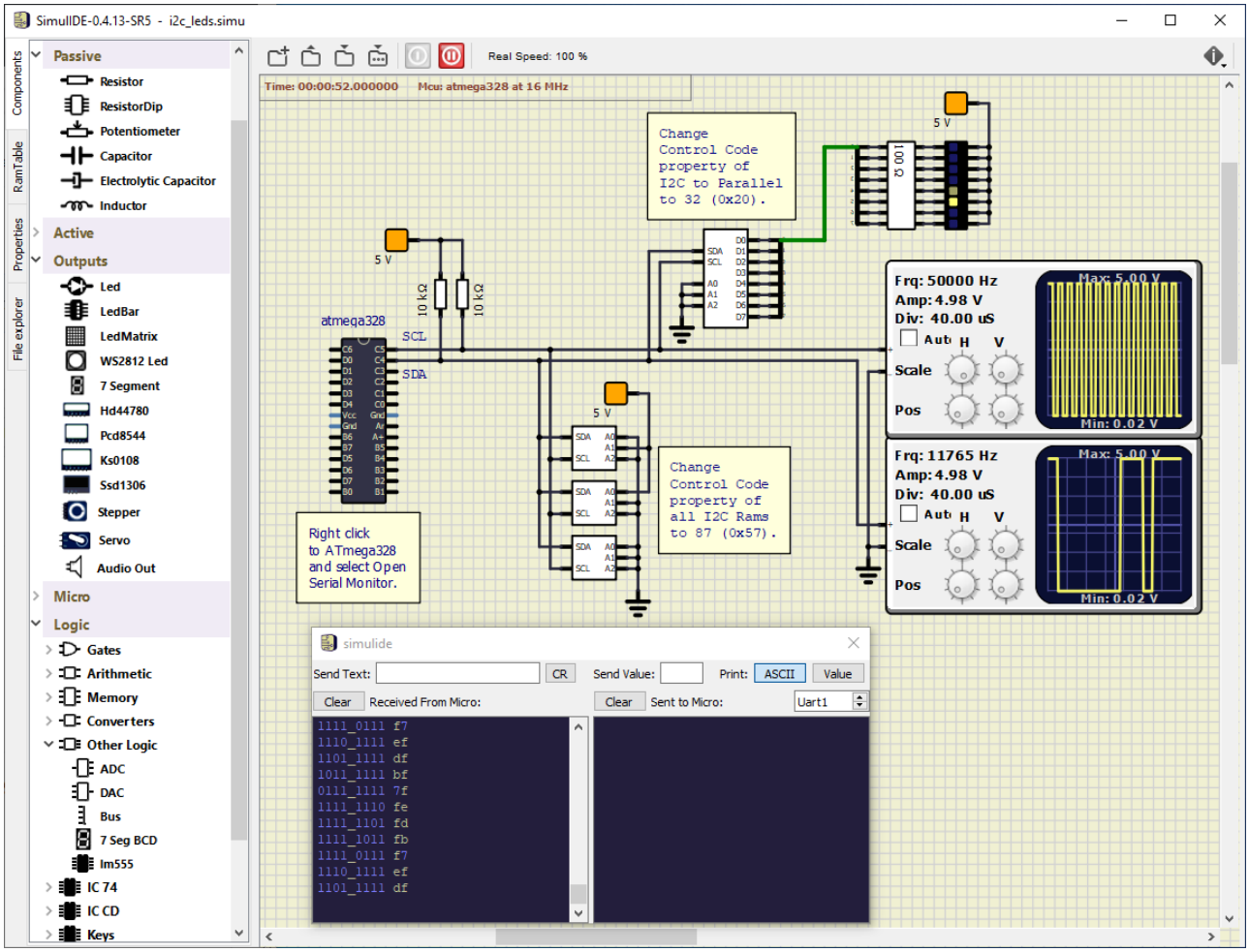
3. Program the functions that will be able to save the current time values to the RTC DS3231.

4. Consider an application for temperature and humidity measurements. Use sensor DHT12, real time clock DS3231, LCD, and one LED. Every minute, the temperature, humidity, and time is requested from Slave devices and values are displayed on LCD screen. When the temperature is above the threshold, turn on the LED.

   Draw a flowchart of `TIMER1_OVF_vect` (which overflows every 1 sec) for such Meteo station. The image can be drawn on a computer or by hand. Use clear description of individual algorithm steps.

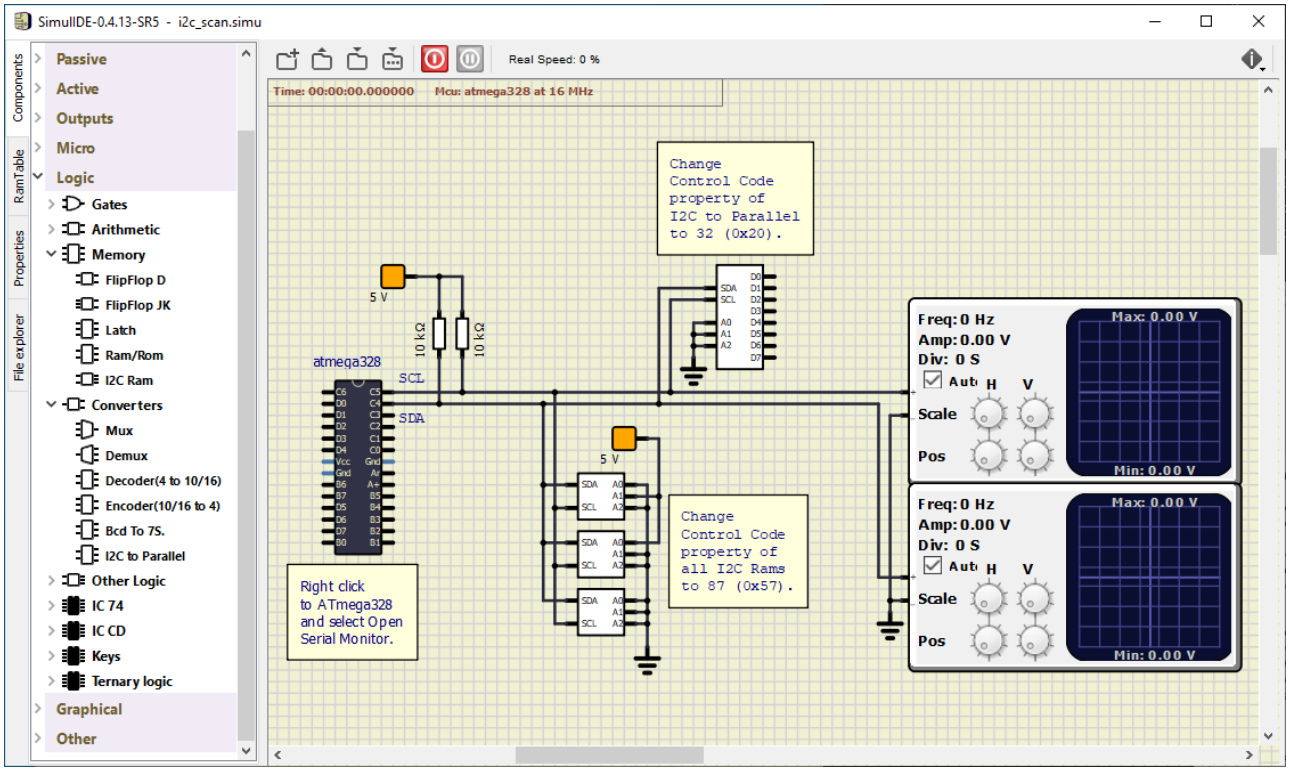
5. Draw a timing diagram of I2C signals when calling function `rtc_read_years()`. Let this function reads one byte-value from RTC DS3231 address `06h` (see RTC datasheet) in the range `00` to `99`. Specify when the SDA line is controlled by the Master device and when by the Slave device. Draw the whole request/receive process, from Start to Stop condition. The image can be drawn on a computer (by WaveDrom for example) or by hand. Name all parts of timing diagram.

6. In the SimulIDE application, create the circuit with eight active-low LEDs connected to I2C to Parallel expander. You can use individual components (ie. 8 resistors and 8 LEDs) or single **Passive > ResistorDip** and **Outputs > LedBar** according to the following figure. Several signals can form a bus **Logic > Other Logic > Bus**, as well.



Create an application that sequentially turns on one of the eight LEDs. ie first LED0, then LED1 and finally LED7, then start again from the beginning. Use Timer/Counter1 and change the value every 262 ms. Send the status of the LEDs to the UART. Try to complement the LED controls according to the Knight Rider style, ie light the LEDs in one direction and then in the opposite one.

7. In the SimulIDE application, use the following components: I2C Ram (**Components > Logic > Memory > I2C Ram**), I2C to Parallel (**Components > Logic > Converters > I2C to Parallel**) and create a schematic according to the following figure. Also, change **Control Code** property of all I2C devices. These codes represent the I2C addresses of the Slave circuits. Pins A2, A1, A0 allow you to specify part of the device address. Thus, up to 8 (2^3 = 8) identical devices can be connected and it will be possible to distinguish them. External pull-up resistors on SDA and SCL signals must be used for correct simulation.



Program an application that communicates with memory modules using the I2C bus. Store random data in the first ten address positions of the first and second memory modules. Then copy 5 values from the first memory to the third and another 5 values from the second memory to the third one. Send the first ten values from each memory module to the UART.

8. Finish all (or several) experiments, upload them to your GitHub repository, and submit the project link via BUT e-learning. The deadline for submitting the assignment is the day prior to the next lab session, which is one week from now.

References

1. Tomas Fryza. Schematic of Arduino Uno board
2. Ezoic. I2C Info - I2C Bus, Interface and Protocol
3. Electronicshub.org. Basics of I2C Communication | Hardware, Data Transfer, Configuration
4. Adafruit. List of I2C addresses
5. Aosong. Digital temperature DHT12
6. NXP. I2C-bus specification and user manual

7. Maxim Integrated. DS3231, Extremely accurate I2C-Integrated RTC/TCXO/Crystal

8. LastMinuteEngineers. Interface DS3231 Precision RTC Module with Arduino

9. Tomas Fryza. Useful Git commands