Namn:
Laborationen godkänd:

Computer Organization 6 hp

LUNDS TEKNISKA HÖGSKOLA
Lunds universitet

I/O handling

Purpose

The purpose of this laboratory exercise is to demonstrate how to write programs that interact with the different I/O devices available on the board. In particular, we show how to use the eight seven-segment displays and the five pushbuttons. Furthermore, we shall demonstrate a method, i.e. polling, that enables handling of external events triggered by some of the input devices.

Seven-segment displays

Seven-segment displays are composed of seven different LED segments and are used to display different patterns by lighting different segments. The common usage of seven-segment displays is to display decimal (or sometimes hexadecimal) digits by using the seven different LED segments that can be lit. One seven-segment display requires seven input signals, where each signal is responsible for one of the seven LED segments. Depending on the state of the signal, the corresponding LED segment is turned on or off. An illustration of a seven-segment display, along with its inputs (denoted with “a” to “g”), is depicted in **Figure 1**.

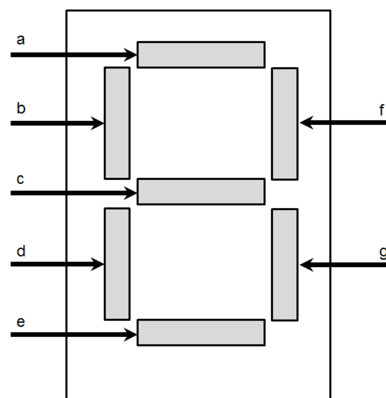


Figure 1. A seven-segment display

For example, in **Figure 1**, the input signal "a" controls the topmost horizontal LED segment. When the signal "a" drives a logic "1" the LED segment is turned on (lit up), otherwise the segment is turned off.

The Nexys 4 board is equipped with eight seven-segment displays. In the hardware platform, the eight seven-segment displays available on the Nexys 4 board are interfaced to the MicroBlaze microprocessor through one output device, i.e. *7SEGMENT DISPLAYS*, that contains eight 32-bit memory mapped data registers. Each seven-segment display on the board is controlled by one of the data registers of the *7SEGMENT DISPLAYS* device. An illustration of this device is depicted in **Figure 2**.

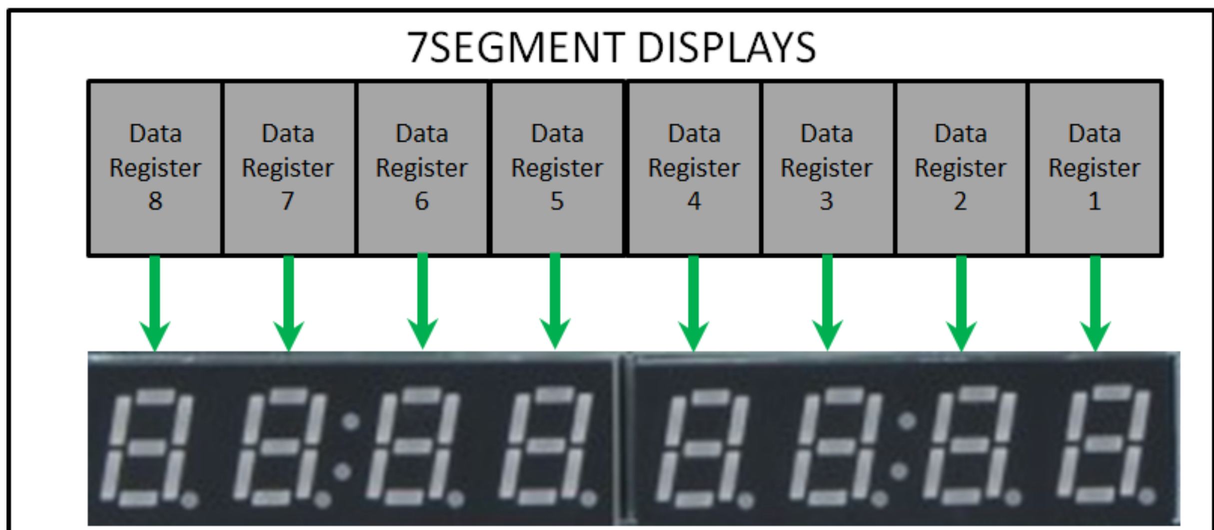


Figure 2. The output device 7SEGMENT DISPLAYS

The data registers are mapped to continuous (consecutive) memory addresses. Each data register keeps a value that is being displayed on the seven-segment display connected to it. The value is 32 bits wide, and based on the values of each of these bits different segments of the seven-segment display are turned on or off.

Assignment 1.

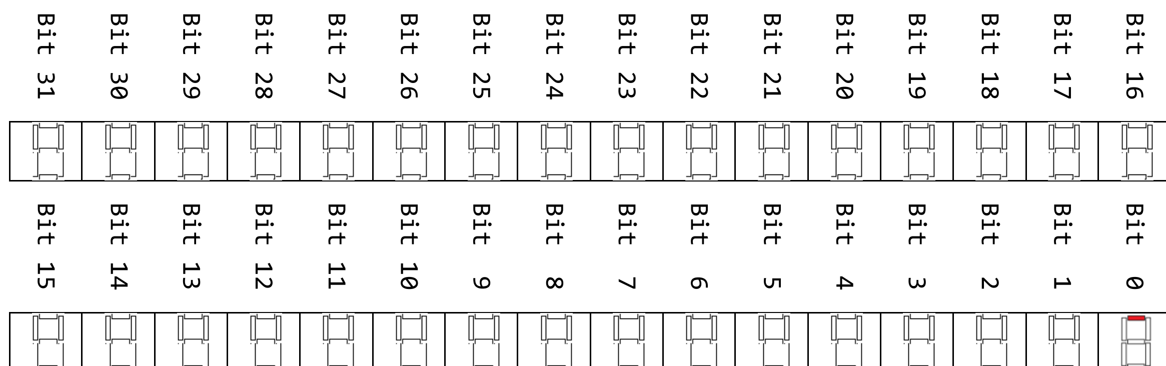
The purpose of this assignment is to identify which bit, in a given data register, is connected to which of the seven LED segments of the seven-segment display controlled by the given data register. To identify this relation, provided is a code that you can execute. The code writes to the data register that controls the right-most seven-segment display on the board. This data register is mapped to the memory address "`0x44A00000`". By observing the changes of the rightmost seven-segment display on the board, as you step through the code, you can identify the pattern.

In the current project, open the “main.c” source file, comment the code and put a note so that you can keep track to which assignment it belongs to. Repeat this step before each assignment.
Copy the following code in the “main.c” source file.

```
unsigned int *LED_1;
unsigned int value;
int i;
int main(){
	LED_1=(unsigned int *)0x44A00000;
	while (1==1){
		value=1;
		for (i=1;i<32;i++){
			*LED_1=value;
			value=value<<1;
		}
	}
}
```

Explain what this code does.

Build the project, and then debug the program. By stepping through the code, complete the following drawing based on the changes that you observe on the rightmost seven-segment display. For example, when the first value, i.e. `value=1`, is written to the data register controlling the rightmost seven-segment display the topmost horizontal segment is lit (marked with red in the drawing). This implies that the least significant bit of the data register, i.e. `Bit 0`, turns on or off the topmost horizontal segment of the seven-segment display.



Assignment 2.

The purpose of this assignment is to construct the patterns for each decimal digit. Based on the drawing in Assignment 1, construct a read-only (**const**) array of integers, where the elements of the array provide the codes for the corresponding digit, i.e. the element at index "i" in the array provides the pattern that displays the digit "i" on the seven-segment display. The template is provided bellow along with the code to display the digit "0".

```
const unsigned int display_codes[]=    {0b0111111,  // "index 0"
                                         0b_______,  // "index 1"
                                         0b_______,  // "index 2"
                                         0b_______,  // "index 3"
                                         0b_______,  // "index 4"
                                         0b_______,  // "index 5"
                                         0b_______,  // "index 6"
                                         0b_______,  // "index 7"
                                         0b_______,  // "index 8"
                                         0b       }; // "index 9"
```

Assignment 3.

The purpose of this assignment is to write a program that displays digits on the seven-segment displays.
Since displaying a digit on a seven-segment display is a functionality that we might need to exploit in other programs as well, it is better to design a function that later can be invoked from the main program. Therefore, we design a function that takes two inputs: (1) an index to a particular seven-segment display, and (2) a digit. The advantage of having such a function is that we could easily call it from the main program whenever we need to output a value on any of the seven-segment displays program, without thinking of which code should be written into which register (the function will take care of it). To index a particular seven-segment display, we use the range 0-7, where index 0 refers to the rightmost seven-segment display and index 7 refers to the leftmost seven-segment display.

For the designed system, the data registers controlling the eight seven-segment displays available on the board are mapped to consecutive memory addresses. Since the data registers are 32 bits wide (4 bytes), the difference between the addresses of two neighboring displays is equal to 4 (one byte is stored at each memory address). Utilizing the fact that the data registers controlling the displays are mapped to consecutive memory address, it is sufficient to know the base memory address (the address of the first data register) in order to obtain the memory address of the

other data registers. By having the base address, we obtain the addresses of the other data registers by adding an offset to the base address. The base address can be defined in a header file.

In the current project, create a new header file with the name "displays.h". Copy and insert the following line in the recently created header file, between the "`#define`" and "`#endif`" directives.

```
#define SEVEN_SEGMENT_DISPLAY_BASE      0x44A00000
```

The previous line defines the base address, which is as well the address of the data register controlling the rightmost seven-segment display.

In C, a function needs be declared before it is used in the "`main`" function. A common practice is to provide the declarations of the functions in header files, while the definitions of the functions are provided in source files. Therefore, next we shall add the declaration of the function, which we are about to design, in the header file "displays.h". Note that we shall use this header file to keep the declarations for all functions that deal with the seven-segment displays.

In the header file "displays.h", copy and insert the following line.

```
void displayDigitAtIndex(unsigned char index, unsigned char digit);
```

The previous line declares the function "`displayDigitAtIndex`". This function does not provide any outputs, but has two inputs, i.e. `index` and `digit`, which are both of type `unsigned char`.

So far, in the project we only had one single source file, i.e. "main.c", where the "`main`" function was defined. However, one project may contain multiple source files, where in different source files definitions of different functions are provided. These different functions can be invoked from the "`main`" function. Note that in C, the "`main`" function dictates the beginning of the program.

Following the common practice, we keep the definitions for all the functions declared in the header file "displays.h" in a separate source file, i.e. "displays.c".

Next, we provide the definition for the function "`displayDigitAtIndex`". In the current project, create a new source file with the name "displays.c", and then copy the following code:

```
#include "displays.h"
/*
*   COMMENT:
*       insert the completed definition of the array “display_codes” (Assignment 2)
*/
void displayDigitAtIndex(unsigned char index, unsigned char digit){
   if ((index<8)&&(digit<10))
     *((unsigned int *) (SEVEN_SEGMENT_DISPLAY_BASE +index*4))=display_codes[digit];
}
```

In the code that you copied, replace the commented section with the completed definition of the array “`display_codes`”. The completed definition is the result of Assignment 2.

Study the code. Explain what the code does.

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To verify that the function “`displayDigitAtIndex`” is working properly, we write a new main program. The main program invokes the “`displayDigitAtIndex`” function and its purpose is to display the digits from 0 to 9 starting from the rightmost display in a round robin fashion. As there are only eight displays and ten digits are to be displayed, the rightmost displays shall be overwritten, i.e. the digit 8 will be displayed on the display with index 0, and the digit 9 will be displayed on the display with index 1.

Open the “main.c” source file, comment the code and then copy and insert the following code.

```
#include "displays.h"
unsigned char i;
int main(){
      while (1==1){
            for (i=0;i<10;i++)
                  displayDigitAtIndex(i%8,i);
      }
}
```

Build the project and debug the code. Step through the code and verify that the correct digits are displayed on the different displays. Note that in case of incorrect representation of the digits, you will need to update the definition of the array “`display_codes`”.

Assignment 4.

The purpose of this assignment is to design a function that displays an integer number on the displays. The number is displayed such that its least significant digit is visible on the rightmost seven-segment display. However, an integer number may have more than 8 digits (more than the available number of displays). Therefore, we shall also design an auxiliary function that counts the number of digits in a given integer number.

The first step is to provide the declarations for these two functions. Copy the following lines in the "displays.h" file.

```
unsigned int numberOfDigits(unsigned int x);
void displayNumber(unsigned int x);
```

The previous two lines declare the functions "`numberOfDigits`" and "`displayNumber`". Both functions take a single input argument of type `unsigned int`. The function "`displayNumber`" does not provide any outputs, while the function "`numberOfDigits`" returns an output of type `unsigned int`.

The next step is to provide the definitions for the previously declared functions. The definitions are to be written in the "displays.c" source file. Copy the following code in the "displays.c" file.

```
unsigned int numberOfDigits(unsigned int x){
	unsigned int count=1;
	while (x/10>0){
		count++;
		x=x/10;
	}
	return count;
}

void displayNumber(unsigned int x){
	unsigned int index=0;
	if (numberOfDigits(x)<9)
		do {
			displayDigitAtIndex(index,x%10);
			index++;
			x=x/10;
		} while (x>0);
}
```

Study the codes of the two functions. Explain what each of the functions does.

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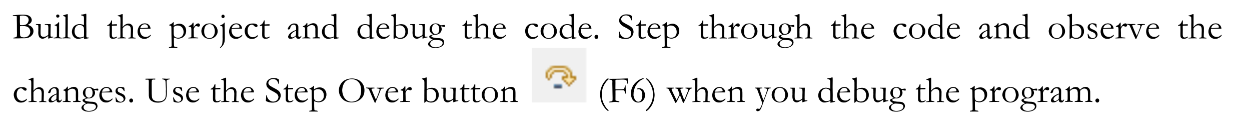
What is going to be displayed on the displays if the function "`displayNumber`" is invoked with an integer number that has at least 9 digits?____________________

Modify the "`main`" function such that you can verify the correctness of these two functions. The new program should display few different numbers on the seven-segment displays. Ensure that the numbers that are displayed don't have the same number of digits.

Open the "main.c" source file, comment its contents and write the modified code following the template provided below.

```
#include "displays.h"
int main(){
      while (1==1){
      /*
      *     COMMENT:
      *     display numbers here
      */
      }
}
```

Build the project and debug the code. Step through the code and observe the changes. Use the Step Over button  (F6) when you debug the program.

- What happens when displaying a number that has less digits than a number that has been previously displayed? ________________________________
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Assignment 5.

To ensure that each number is correctly displayed, it is important to reset the displays before displaying a new number. Design a function that resets a given display based on its index. Name this function "`resetDisplayAtIndex`". This function should have one input parameter, i.e. the index of the display that is to be reset. Add the declaration of the function in the "`displays.h`" header file, and define the function in the "`displays.c`" source file (for reference, see the previous examples).

Assignment 6.

Using the function "`resetDisplayAtIndex`", create a function that resets all displays. Name this function "`resetDisplays`". This function should not have any input parameters. Add the declaration of the function in the "`displays.h`" header file, and define the function in the "`displays.c`" source file (for reference, see the previous examples).

Assignment 7.

Write a main program that verifies that the functions you have designed in Assignment 5 and 6 work properly. Don't forget to comment the contents of the "main.c" source file before you apply the changes.

Assignment 8.

Design a function with the name "`displayNumberAtIndex`" that takes two input arguments, an index and a number, to display a number at a given index position.
The least significant digit of the number is displayed at the given index position.
If the number is too large and cannot be displayed at the given position, no action should be taken.

Write a main program so that you can verify that the function works properly. Don't forget to comment the contents of the "main.c" source file before you apply the changes.

Pushbuttons

A pushbutton produces one output signal, i.e. a logic '0' or a logic '1', based on whether the button is pressed or released. A pushbutton is illustrated in **Figure. 3**.

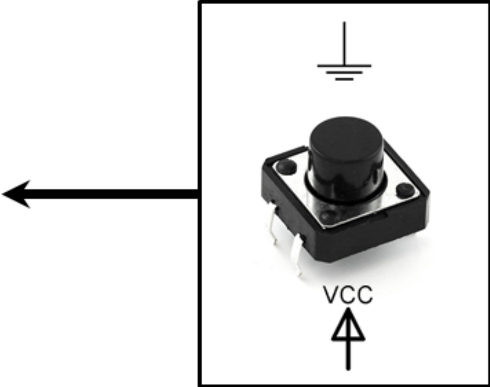


Figure. 3 A pushbutton

Five pushbuttons are available on the Nexys 4 board. In the hardware platform, these five pushbuttons are interfaced to the MicroBlaze microprocessor through one I/O device, i.e. *PUSH BUTTONS*. The *PUSH BUTTONS* device has one control and one data register. Both these registers are 32-bits wide and are mapped to known memory addresses. The control register is used to control the data flow direction for each of the bits in the data register. The outputs of the pushbuttons available on the Nexys 4 board are connected to the data register of the *PUSH BUTTONS* device, as illustrated in **Figure 4.**

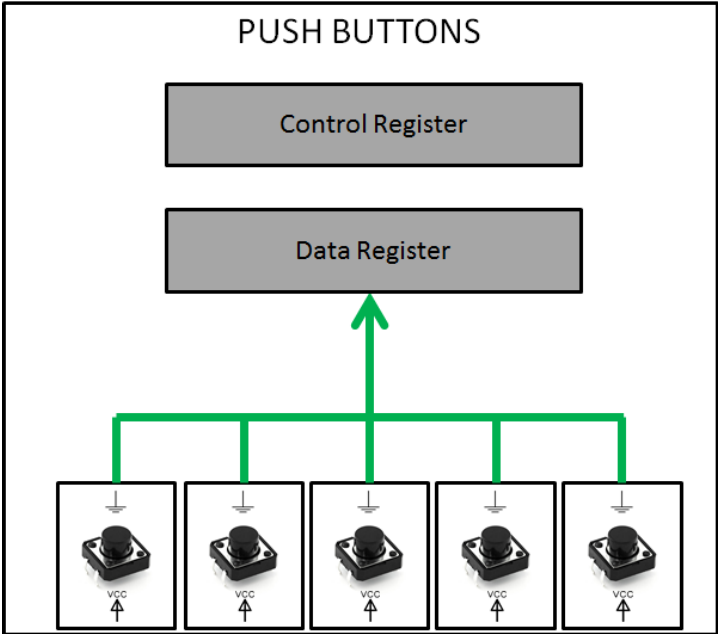


Figure 4. PUSH BUTTONS I/O device

Assignment 9.

The purpose of this assignment is to identify to which particular bits in the data register of the *PUSH BUTTONS* device are the five pushbuttons, available on the Nexys 4 board, connected. For that purpose, provided is a code that you can run on the hardware platform, and by monitoring the changes you can identify the relation.

As mentioned earlier, the *PUSH BUTTONS* device has one control and one data registers, each 32-bit wide, that are mapped to known memory addresses. For ease of reference, we define pointers which point to the memory addresses of the control and the data registers. These definitions are to be stored in a header file. Create a new header file with the name “buttons.h”, and add the following definitions:

```
#define BUTTONS_DATA    (unsigned int *) 0x40000000
#define BUTTONS_CONTROL (unsigned int *) 0x40000004
```

The *PUSH BUTTONS* device has to be configured as an input device, i.e. the data register should capture signals coming from the pushbuttons. This is done by writing “1s” in the control register of the device. The data register of this device keeps the current state of each of the buttons. Whenever a button is pressed, the particular bit of the data register to which the button is mapped to is set to 1, otherwise the bit is set to 0. Since there are five buttons, only five bits of the 32 bit long register are affected by the state of the buttons. To identify which bits are affected by each of the buttons, one can write a simple program that reads the data register of the *PUSH BUTTONS* and stores this data in a local variable.

Open the “main.c” source file, comment its contents and type the following code:

```
#include "buttons.h"
unsigned int state;
int main(){
	*BUTTONS_CONTROL=0xFFFFFFFF;
	while (1==1){
		state=*BUTTONS_DATA;
	}
}
```

The provided code, first configures the *PUSH BUTTONS* device as an input device by writing all ‘1’s in its control register, which is mapped to memory address “`0x40000004`”. Next, the program continuously reads the data register of the *PUSH BUTTONS* device, mapped at memory address “`0x40000000`”, and stores this information in the local variable “`state`”.

Build the project and debug the program. Open the "Expression" view in the debug environment, and check the contents of the variable "`state`".

What is the value of the variable "`state`" when each of the buttons is pressed? Write the values in binary format. **Hint**: Make sure that a pushbutton is pressed when the debugger reads the data register.

UP ______________________________
DOWN ______________________________
RIGHT ______________________________
LEFT ______________________________
MIDDLE ______________________________

Assignment 10.

As you observed from Assignment 9, pressing a particular pushbutton writes a logic '1' at a specific bit position in the data register of the ***PUSH BUTTONS*** device. By reading the data register of this device, a program can identify which particular button has been pressed. Instead of memorizing the different binary patterns for each of the pushbuttons, a more convenient way is to define labels. The purpose of having these labels is to refer to them in the code instead of writing the binary pattern. These labels can be stored in a header file.

Open the "buttons.h" header file, and insert the following lines.

```
#define UP        0b?????
#define DOWN      0b?????
#define MIDDLE    0b?????
#define LEFT      0b?????
#define RIGHT     0b?????
```

Complete the definitions, such that the binary patterns "0b?????" correspond to the correct patterns for each of the buttons, which you already have identified in Assignment 9.

Polling

So far, we showed how to interact with input and output devices. However, in many cases the communication with these devices is strictly defined and is usually not as straight forward as just reading or writing to data registers. Polling refers to periodically sampling the status of an external (input or output) device to determine the need to service the device. Only when a device is ready, a program (the processor or other programmable controller) can exchange data with the device. In these labs, the I/O devices that are used are not very complex. Still, for illustrative purposes we show the basic principle of polling. The polling principle can be used to sample the state of the pushbuttons. The pushbuttons can provide trigger events whenever they are pressed or released. To capture these trigger events one needs to continuously sample the state of the pushbuttons.

Assignment 11.

In this assignment, we demonstrate the polling principle for the five pushbuttons available on the Nexys 4 board.

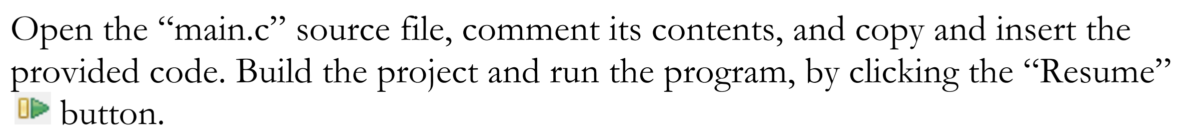
If none of the buttons is pressed, then all bits in the data register of the *PUSH BUTTONS* device are set to 0. This can be used as an indication that the device does not have any valuable input, and thus the processor should wait until the device has some data available. However, when a button is pressed, depending on which button has been pressed different actions can be taken.

The goal of the assignment is to write a program that implements the following algorithm:

1) When the program starts, a zero is displayed on the seven-segment displays.
2) If no buttons are pressed, no changes occur on the displays.
3) When the “up” button is pressed, the displayed value is incremented by one
4) When the “down” button is pressed, the value displayed is decremented by one
5) Repeat steps 2-5

The following code is one implementation of the algorithm described earlier:

```
#include "buttons.h"
#include "displays.h"
unsigned int counter;
int main(){
	*BUTTONS_CONTROL=0xFFFFFFFF;
	counter=0;
	while (1==1){
		resetDisplays();
		displayNumber(counter);
		while (*BUTTONS_DATA==0); // keep reading the data register
		if (*BUTTONS_DATA==UP)
			counter++;
		if (*BUTTONS_DATA==DOWN)
			counter--;
	}
}
```

Open the “main.c” source file, comment its contents, and copy and insert the provided code. Build the project and run the program, by clicking the “Resume”  button.

Push the “up” and the “down” buttons and observe the changes on the display.

Does the provided code work well in practice?______________________________

Why does the displayed value change much more rapidly than expected?
Hint: The MicroBlaze processor operates at 100MHz frequency

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What happens when you press and hold the “down” button?__________________

What is the explanation for this phenomena?_________________________________
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Would similar thing happen if you press and hold the “up” button?____________
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How can you solve the two problems above? ______________________________
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Assignment 12.

The purpose of this assignment is to show how to avoid the problems you have encountered in Assignment 11.

To avoid the problems, we modify the algorithm described in Assignment 11 by adding some more details. The modified algorithm is as follows:

1. When the program starts, a zero is displayed on the seven-segment displays.
2. If no buttons are pressed, no changes occur on the displays.
3. If a button is pressed, the data register of the input device is read and it is stored in a local variable.
4. Depending on the value of this variable, the displayed value is incremented if the “up” button is pressed or decremented if the “down” button is pressed.
5. Wait until a new button is pressed, or until the current button is released.
6. Repeat steps 2-6.

The following code implements the algorithm above.

```
#include "buttons.h"
#include "displays.h"
unsigned int counter;
unsigned int buttons_state;
int main(){
	*BUTTONS_CONTROL=0xFFFFFFFF;
	counter=0;
	while (1==1){
		resetDisplays();
		displayNumber(counter);
		while (*BUTTONS_DATA==0); // keep reading the data register
		buttons_state=*BUTTONS_DATA;
		if (buttons_state==UP)
			counter++;
		if (buttons_state==DOWN)
			counter--;
		while (*BUTTONS_DATA==buttons_state);
	}
}
```

Open the “main.c” source file, comment its contents and copy and insert the provided code. Build the project and run the program.

Does the provided code work well in practice?______________________________

What do you observe?____

Assignment 13.

As you observe, after implementing the algorithm in Assignment 12, in many cases when you press and hold a button, the displayed value is incremented or decremented only by one. However, sometimes it happens that when you press a button the value is incremented/decremented by more than one. The reason for this is a problem known as "bouncing". Bouncing is the tendency of any two metal contacts in an electronic device to generate multiple signals as the contacts close or open. Thus, when a button is pressed, the value of the bit to which it is connected oscillates between zero and one, before it finally stabilizes to one (when the bit is set to one, it means that the particular button is pressed). Since in the while loops, we read the data register with a very high frequency, this makes it possible to capture the non-intended transitions of the bit rendering the event of pressing the button once as multiple events. To avoid the problem of bouncing, we could add some delays between two consecutive read operations on the data register. A typical way to add some delay is by adding a for-loop that does not do anything useful.

The modified code that takes the delay into account is provided below.

```
#include "buttons.h"
#include "displays.h"
unsigned int counter;
unsigned int buttons_state;
unsigned int i;
int main(){
	*BUTTONS_CONTROL=0xFFFFFFFF;
	counter=0;
	while (1==1){
		resetDisplays();
		displayNumber(counter);
		while (*BUTTONS_DATA==0);
		for (i=0;i<20000;i++);
		buttons_state=*BUTTONS_DATA;
		if (buttons_state==UP)
			counter++;
		if (buttons_state==DOWN)
			counter--;
		while (*BUTTONS_DATA==buttons_state);
		for (i=0;i<20000;i++);
	}
}
```

Open the "main.c" source file, comment its contents and copy and insert the provided code. Build the project and run the program. Check whether this implementation fixes the problem of bouncing.

Assignment 14.

Use the code from Assignment 13. Build the project and run the program.
Press and hold the right pushbutton, and then press the up or the down button. Release the buttons. What happens with the `counter`?________________________
Press and hold the left pushbutton, and then press the up or the down button. Release the buttons. What happens with the `counter`?________________________
Press and hold the middle pushbutton, and then press the up or the down button. Release the buttons. What happens with the `counter`?________________________
Suggest a solution, such that the `counter` will be modified as long as either the up or the down button is pressed, irrespective of the state of the other pushbuttons. Modify the code and verify that it works as expected. Don't forget to comment the contents of the "main.c" source file before you apply the changes.

Assignment 15.

The code from the previous assignment does not take into account the range of values that could be presented on the displays. Modify the code such that the variable "`counter`" can only take values which are in the range that can be displayed. Apply the changes, and verify that the program works as expected. Don't forget to comment the contents of the "main.c" source file before you apply the changes.

Assignment 16.

In Assignments 11-15, the changes on the displays are only visible once any of the pushbuttons is released. Modify the code such that the changes are visible once a button is pressed. Apply the changes, build the project, and run the program so that you can verify that it works as expected. Don't forget to comment the contents of the "main.c" source file before you apply the changes.

Assignment 17.

Similar to the previous assignments, write a program that reacts to the changes of the states of the push-buttons. The "up" and the "down" buttons update the value that should be displayed on the seven-segment displays, while the "left" and the "right" buttons update the position at which the value should be displayed. The "middle" button is used as a reset. The algorithm is summarized as follows:

1. When the program starts, the value zero is displayed on the seven-segment display with index position zero (the right-most seven-segment display).
2. If the "up" button is pressed, irrespective of the state of the other buttons, the displayed value is incremented by one, as long as the displayed value is lower than the maximal value that can be displayed at the current index position. If the value displayed at the current position is the maximal value that can be displayed, then no action should be taken when the "up" button is pressed.

3. If the “down” button is pressed, irrespective of the state of the other buttons, the value is decremented by one, as long as the displayed value is larger than zero. If the displayed value is zero, no action should be taken when the “down” button is pressed.
4. If the “middle” button is pressed, irrespective of the state of the other buttons, the value zero is displayed at index position zero.
5. If the “right” button is pressed, irrespective of the state of the other buttons, the displayed value is moved one index position to the right, as long as the current index position is larger than zero. If the value is displayed at index position zero, then no action should be taken when the “right” button is pressed.
6. If the “left” button is pressed, the displayed value is moved one index position to the left, as long as it is possible to display the value at this new position. If the displayed value cannot be moved one index position to the left, then no action should be taken if the “left” button is pressed.
7. Repeat steps 2-6.

Note: A button is pressed only if the current state of the button is “1”, but the previous state has been “0”. Assume the following situation: the value “10” is displayed at index position zero (the right-most seven-segment display) and a user pushes the “up” button and holds it. This event would result in incrementing the value by one, and thus, the value “11” should be displayed at index position zero. Next, while the “up” button is pressed, the user pushes the “left” button. For this event, the value “11” should be displayed at index position one. Note that even though the current state of the “up” button is “1”, no action should be taken since it is the same press event to which the program has already reacted.