Manual ARM Microcontroller Course E.T.S.V. Scintilla

Cursuscommissie

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1 Introduction

Welcome to the ARM microcontroller course 2015 of ETSV Scintilla. In this course we hope to teach you some of the basics of programming a microcontroller, the common caveats and the fun of getting a mixed hardware and software project to work. We've chosen for an ARM microcontroller as these are more and more common, with a lot of chip manufacturers having their own implementations. The goal is to build a function generator using a Nucleo-F411RE board, made by ST, and a the shield. In order to build that, we'll talk about using digital input and outputs, analog peripherals, timers and SPI. Using that and a little background information on Direct Digital Synthesis, you should be able to have a function generator running on the last evening.

1.1 Preliminary Schedule

Day 0 Install the software on your laptop. See section 2 for a guide.

Day 1 C for microcontrollers, using GPIO and event handling. Sections 4 to 8.

Day 2 Using Timers and analog peripherals. Sections 9 to 10.

Day 3 The Serial Peripheral Interface. Section 11.

Day 4 Direct Digital Synthesis and building a function generator. Section **??**.

All necessary material, including reference manuals, datasheets, are available at `http://www.scintilla.utwente.nl/docs/cursus`.

1.2 Acknowledgments

We would like to thanks our sponsor ST Microelectronics for supplying the Nucleo-F411RE development board, Eurocircuits for supplying the shield PCB and Analog Devices for the DAC.

2 Setup Eclipse and Toolchain

In this course Eclipse is used as the IDE, as it's cross-platform and highly customizable. It is recommended to use a clean install of **Eclipse 4.4 Luna** for C/C++. Besides Eclipse you'll need to install some Eclipse plugins and drivers for STLink, the device that connects to your Nucleo board. The guide is written with Windows and GNU/Linux in mind, but it should work as well on OSX.

2.1 Windows

This guide assumes that you've a recent version of Java Runtime Environment installed. If needed you can download JRE from `http://www.oracle.com/technetwork/java/javase/downloads/jre8-downloads-2133155.html`.

2.1.1 Eclipse

1. Go to `http://www.eclipse.org/downloads/` and download **Eclipse IDE for C/C++ Developers**
2. Unpack and install.
3. Go to Help → Install New Software
4. click on Add..., fill in Name: *GNU ARM Eclipse Plug-ins*. Location: `http://gnuarmeclipse.sourceforge.net/updates` and press OK
5. select all but the Freescale Project Templates, click Next and install.

2.1.2 Toolchain

1. Get the toolchain from `https://launchpad.net/gcc-arm-embedded`. (gcc-arm-none-eabi***-win32.exe)[1]
2. Install the toolchain, but in the final window disable "Add path to the environment variable".
3. Download the latest build tools (gnuarmeclipse-build-tools-win32-2.*-*-setup.exe) from `http://sourceforge.net/projects/gnuarmeclipse/files/BuildTools/`
4. Run the installer, remember the path of the Build Tools.
5. In Eclipse, go to Window → Preferences. C/C++ → Build → Global Tools Paths
6. Locate the installed Build tools, enter the path in Build Tools folder.
7. Select *GNU Tools for ARM Embedded Processors*, locate the toolchain and enter the path in Toolchain folder, and click Apply.

[1] On 2/5/2015: `https://launchpad.net/gcc-arm-embedded/4.9/4.9-2015-q1-update/+download/gcc-arm-none-eabi-4_9-2015q1-20150306-win32.exe`

2.1.3 STLink v2

1. Download the latest STLink v2 driver from http://www.st.com/web/catalog/tools/FM147/SC1887/PF260218
2. Extract files and run stlink_winusb_install
3. Install driver.
4. Download STLink Utility from http://www.st.com/web/en/catalog/tools/PF258168, install.

2.1.4 Debugger - OpenOCD

This is optional, but a debugger might help you a lot. We're using OpenOCD as it's available for all platforms, and easily integrates with the Eclipse plugins we installed.

1. Download the latest development (0.9.*) version of OpenOCD for your architecture from http://sourceforge.net/projects/gnuarmeclipse/files/OpenOCD/Windows/.
2. Follow the installation procedure.
3. In Eclipse go to Window → Preferences → Run/Debug → String Substitutions
4. Fill in the path to the bin directory of OpenOCD in the Value field of *openocd_path*, then click OK.
5. The next steps only apply after making a project, see section 3.3.

2.1.5 Packs - Device Support

1. In Eclipse, open the Packs perspective.
2. Click on the Refresh button. It will now load all available packs from Keil.
3. Select the device menu, locate the STM32F4 series and install the package.

2.2 Linux

This guide assumes a working Java runtime environment. It was tested using OpenJDK 1.8, and should work equally well with a recent version of Oracle JRE.

2.2.1 Toolchain and Eclipse

1. Get the toolchain from https://launchpad.net/gcc-arm-embedded (gcc-arm-none-eabi***-linux.tar.bz2)
2. Extract to a directory of your liking.
3. Install Eclipse Luna for C/C++ development, if you haven't already.[2]

[2]Either via your package manager, or by downloading from http://www.eclipse.org/downloads/

4. open Eclipse, set a workspace and click on Help → Install New software.

5. click on Add..., fill in Name: GNU ARM Eclipse Plug-ins. Location: http://gnuarmeclipse.sourceforge.net/updates and press OK

6. select all but the Freescale Project Templates, click Next and install.

7. In Eclipse, go to Window → Preferences. C/C++ → Build → Global Tools Paths

8. Select GNU Tools for ARM Embedded Processors, locate the toolchain and enter the path in Toolchain folder.

2.2.2 STLink flasher for Linux

The STLink Utility provided by STMicroelectronics is Windows only, but an open source alternative is available on GitHub.

1. Go to http://github.com/texane/stlink, download the Zip file

2. Extract the zip file to a preferred location.

3. In a terminal cd to the directory the files are in, and build stlink using:
```
./autogen.sh
./configure
make
sudo make install
```

4. get the path of st-flash using:
```
whereis st-flash
```

5. In Eclipse, click Run → External Tools → External Tools Configurations

6. Click on Program, and then on New. Name the new configuration *st-linkv2 flash*, and paste the path to st-flash in the Location field.
   Working directory: ${project_loc}/Release
   Arguments: write ${project_name}.bin 0x8000000

7. Click Apply and close.

2.2.3 Debugger - OpenOCD

This is optional, but a debugger might help you a lot. We're using OpenOCD as it's available for all platforms, and easily integrates with the Eclipse plugins we installed.

1. Download the latest development (0.9.*) version of OpenOCD for your architecture from http://sourceforge.net/projects/gnuarmeclipse/files/OpenOCD/GNULinux/.

2. Extract the package to a directory.

3. In Eclipse go to Window → Preferences → Run/Debug → String Substitutions

4. Fill in the path to the bin directory of OpenOCD in the Value field of *openocd_path*, then click OK.

5. The next steps only apply after making a project, see section 3.3.

2.2.4 Packs - Device Support

1. In Eclipse, open the Packs perspective.

2. Click on the Refresh button. It will now load all available packs from Keil.

3. Select the device menu, locate the STM32F4 series and install the package.

3 Starting a Project

To accompany this guide there is a video walk-through available on https://www.youtube.com/watch?v=HxGEBEWRyy8
In Eclipse go to **File** → **New C Project**. Enter a name for the project, and select *STM32F4xx C/C++ Project* from the project type dropdown. From Toolchains choose the *Cross ARM GCC*.
In the next menu, for the Nucleo-F411 in the Target processor needs to be changed to Cortex-M4, the flash size to 512KB, and Content: Empty.
Keep the suggested settings in the Folders menu and Select Configurations menu.
In the Cross GNU ARM Toolchain make sure to select the Toolchain **GNU Tools for ARM Embedded Processors**, and if necessary locate the *bin* folder of the toolchain. Click Finish. Now a simple project is set up with an empty `main()` function.
To make optimal use of our Eclipse installation, right-click on the project, and select Properties. Browse to **C/C++ Build** → **Settings** → **Devices**. Locate the STM32F411RE, select it and click Okay. You can now test the installation by pressing the **Build** icon.

3.1 Clock Configuration

The default clock configuration in the file *_initialize_hardware.c*, in the *src* directory of the project does not work for our Nucleo board. As a start here is a little bit of code that does. Replace the function `configure_system_clock()` on the bottom of the page with the code in snippet 1, which lets the board run on the external oscillator, with a system frequency of 84MHz.[3]

3.2 Flashing the Program Memory

To load the binary onto the microcontroller, the STLink Utility can be used, as well as a debugger.

3.2.1 STLink Utility under Windows

1. Open the STLink Utility
2. Connect to the device by clicking Target → Connect
3. Open the binary *projectname.elf* and click Burn.

3.2.2 STLink Flash under Linux

1. In Eclipse, go to Project Properties → C/C++ Build → Settings → Build Steps
2. Add the command to Post-build steps, and give it a description *Create Binary*:
```
arm-none-eabi-objcopy -S -O binary "${ProjName}.elf""${ProjName}.bin
"
```

[3] Try the calculation for yourself using the given formulas in paragraph 6.3.2 of the datasheet.

Snippet 1 84MHz system clock configuration for Nucleo-F411RE

```
/** System Clock Configuration
*/
void configure_system_clock(void)
{

  RCC_OscInitTypeDef RCC_OscInitStruct;
  RCC_ClkInitTypeDef RCC_ClkInitStruct;

  __PWR_CLK_ENABLE();

  __HAL_PWR_VOLTAGESCALING_CONFIG(PWR_REGULATOR_VOLTAGE_SCALE2);

  RCC_OscInitStruct.OscillatorType = RCC_OSCILLATORTYPE_HSI;
  RCC_OscInitStruct.HSIState = RCC_HSI_ON;
  RCC_OscInitStruct.HSICalibrationValue = 16;
  RCC_OscInitStruct.PLL.PLLState = RCC_PLL_ON;
  RCC_OscInitStruct.PLL.PLLSource = RCC_PLLSOURCE_HSI;
  RCC_OscInitStruct.PLL.PLLM = 16;
  RCC_OscInitStruct.PLL.PLLN = 336;
  RCC_OscInitStruct.PLL.PLLP = RCC_PLLP_DIV4;
  RCC_OscInitStruct.PLL.PLLQ = 4;
  HAL_RCC_OscConfig(&RCC_OscInitStruct);

  RCC_ClkInitStruct.ClockType = RCC_CLOCKTYPE_SYSCLK|
      RCC_CLOCKTYPE_PCLK1;
  RCC_ClkInitStruct.SYSCLKSource = RCC_SYSCLKSOURCE_PLLCLK;
  RCC_ClkInitStruct.AHBCLKDivider = RCC_SYSCLK_DIV1;
  RCC_ClkInitStruct.APB1CLKDivider = RCC_HCLK_DIV2;
  RCC_ClkInitStruct.APB2CLKDivider = RCC_HCLK_DIV1;
  HAL_RCC_ClockConfig(&RCC_ClkInitStruct, FLASH_LATENCY_2);

}
```

3. Now you can run st-flash by clicking Run → External Tools → stlinkv2

3.3 Debugging

This part assumes you installed OpenOCD, as in section 2.1.4 for Windows or 2.2.3 for GNU/Linux.

1. Build the project and make sure the executable file exist.
2. Go to Run → Debug Configurations...
3. Select the **GDB OpenOCD Debugging** group and click New.
4. In the new configuration, the Main tab should already be filled in. Click on the Debugger tab.
5. Add the following line to the Config Options
   -f board/st_nucleo_f4.cfg
6. Click on the Common tab, and select *Shared file*
7. Click Apply and Close.

4 Programming C

Due to its low level description, C is a relatively simple language to get started with: it features only a minimum of possible operations, so there is not that much to learn.

4.1 Data Types

Every operation needs at least one variable. There are two types of variables: integer type variables (for integer numbers) and floating point variables (for non-integer numbers). In ARM microcontrollers it is strongly advised to use unsigned integer type variable with a size of 32 bits or less standard. Longer data types or floating point variables take more time to perform operations on and thus decrease performance and increase power consumption. Keep in mind that an ARM has 32 bit registers: using data types smaller than this will not save memory, but will just leave the rest of the bits in the register unused.

4.1.1 Integer Data types

The integer type variables can be found in table 1. This table shows that there is no Boolean type variable. To be able to process operations which require a true/false input, any other integer data type can be used. Giving the value “0” as the argument of a function will execute the same as a logic “false” and any other value will be processed as a logic “true”. The code snippet in Snippet 2 will thus switch on an LED. The LED will switch on for every value of x, as long as it not 0.

In microcontrollers it is very common to use an integer as an array of bits. For example a 16 bits unsigned integer (uint16_t) can not only be used to store a 16 bit number, but could also be used to store 16 bits. For this we have to know how unsigned integers are stored. This type of integers is stored as a binary number. If we consider the decimal number “1234”, this can be stored in binary as “0b0000010011010010”. The “0b” is a marking which determines that a number is given in binary and the zeros at the beginning are added to show this is a 16 bit number. Microcontrollers often have setting registers where one bit e.g. determines if a hardware peripheral is switched on. To alter this specific bit one can use bitwise operators, which will be discussed later in this manual.

Apart from the binary “0b” notation, hexadecimal notation is very common as well. Instead of base 10 (decimal) or base 2 (binary) we now use base 16. This notation can be considered to be a short form of binary notation which groups four bits in one digit. The star of a hexadecimal number is indicated with “0x”. In hexadecimal notation one can now count 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F. In this base 16, 0x0 is the same as 0b0000, 0x5 is the same as 0b0101 and 0xE is the same as 0b1110. The longer decimal number 1234 can be converted to hexadecimal by separating the binary number in groups of four digits and rewriting these groups to hexadecimal. “0b0000 0100 1101 0010” in hexadecimal notation will become “0x04D2”. Hexadecimal numbers have the advantages of both binary and decimal notation: it is grouped per bit, but the notation is still short.

Snippet 2 Example of an integer as a Boolean

```
uint16_t x = 1615;
if(x){
        setLED();
}else{
        resetLED();
}
```

Table 1 Integer data types in C

Name	Syntax	Range	Size (bits)
Boolean	Non-existent	There are no Booleans in standard C	1
Signed character	`int8_t`	-128 to 127	8
Unsigned character	`uint8_t`	0 to 255	8
Signed integer	`int16_t`	$-32,768$ to $32,767$	16
Unsigned integer	`uint16_t`	0 to $65,535$	16
Signed long integer	`int32_t`	-2^{31} to $2^{31}-1$	32
Unsigned long integer	`uint32_t`	0 to $2^{32}-1$	32
Signed long long integer	`int64_t`	-2^{63} to $2^{63}-1$	64
Unsigned long long integer	`uint64_t`	0 to $2^{64}-1$	64

4.1.2 Floating point data types

Apart from the integer data types, non-integer or "floating point" data types can be used as well. Floating point operations are generally harder for a microcontroller to process. For example, it is harder to perform $1.23456 \cdot 10^1 + 9.87654 \cdot 10^{-2}$ than to perform $12345678 + 98765432$. This implies that floating point operations take longer to calculate and thus decrease performance. It can be concluded that it is unwise to use floating point numbers when this is not necessary. The possible floating point types can be found in Table 2. The long double indicated here is specified according to the "IEEE 754 quadruple-precision binary floating-point format", but implementations of the long double may differ per system.

Table 2 Floating point data types in C

Name	Syntax	Sign bit	Exponent bits	Fraction bits	Size (bits)
Floating point	`float`	1	8	23	32
Double floating point	`double`	1	11	52	64
Long double floating point	`long double`	1	15	112	128

4.1.3 Arrays

An array is an indexed lists of a certain data type. These arrays can e.g. be used to store lists of variables, as we will do later to map an output sample number to an output value. As in every properly thought out programming language, the first entry in the array is numbered "0". As an example, the example code

in code snippet 3 generates a list of squares of the first 8 integer numbers and returns the value of the fifth square. This should be 25.

Snippet 3 Example code for reading and writing of an array

```
//generate a list of 8 signed numbers of 16 bits named "y"
uint16_t y[8];

//fill the list with the squares of the index numbers
for(uint16_t i=0; i<8; i++){
        y[i] = i*i;
}

//return the value of the fifth square
return y[5];
```

4.1.4 Structs

C is no object oriented language, but has a feature which comes close to object oriented storing of variables. This can be done by defining a so called "struct" type variable. A struct can be considered to be an object with several variables in it. Structs are used often where there is a clear repetition in data sets. As an example, a microcontroller has several sets of input and output pins (or "general purpose input and output (GPIO) ports", more about this later). Each GPIO port has (amongst others) a setting for pin modes. Data could be organized in a very convenient way if we could make an object "GPIO port" with as one of its internal variables a value for the pin mode for that port. In code snippet 4 the type definition (similar to a class) for the GPIO ports is given, a struct (similar to an object) *"GPIOA"* is created, and one of its variables is changed and returned.

Snippet 4 Example of defining and working with a struct

```
//give a type definition for the GPIO structs
typedef struct
{
  uint32_t MODER;    //GPIO port mode register
  uint32_t OTYPER;   //GPIO port output type register
  uint32_t OSPEEDR;  //GPIO port output speed register
  uint32_t PUPDR;    //GPIO port pull-up/pull-down register
  uint32_t IDR;      //GPIO port input data register
  uint32_t ODR;      //GPIO port output data register
  uint32_t BSRR;     //GPIO port bit set/reset register
  uint32_t LCKR;     //GPIO port configuration lock register
  uint32_t AFR[2];   //GPIO alternate function registers
} GPIO_TypeDef;

//initialize GPIO port "GPIOA"
GPIO_TypeDef GPIOA;

//Set the variable "MODER" in the struct "GPIOA" to "0x0001"
GPIOA->MODER = 0x0001;

//return the variable "MODER" of struct "GPIOA"
return GPIOA->MODER;
```

4.1.5 Enumerated type

An enumerated type is a limited list of keywords, using symbolic names to make a program clearer to the programmer. This data type will be useful when you want to implement a state machine, as in code snippet 5. The defined keywords can be used directly in code.

Snippet 5 Example of a state machine using enumerated type

```
//define the enumerated type States with three possible values
typedef enum
{
        startState,
        waitState,
        processState
} States;

//declare and initialize mystate to startState.
States mystate = startState;
```

4.2 Operators

To perform operations on variables, operators can be used. These operators can be categorized into 4 main categories:

1. Mathematical (arithmetic) operators
2. Comparison operators
3. Logical operators
4. Bitwise operators

This section gives a brief overview of these operators.

4.2.1 Standard Operators

A list of standard mathematical operators in C can be found at: http://en.wikipedia.org/wiki/Operators_in_C_and_C%2B%2B#Arithmetic_operators
A list of standard comparison operators can be found at: http://en.wikipedia.org/wiki/Operators_in_C_and_C%2B%2B#Comparison_operators.2Frelational_operators

4.2.2 Logical Operators

Logical operator do operations on word. This means That a variable is processed as a logical "false" if its value is 0 and is processed as a logical "true" if it has any other value. A list of the possible logical operators is given in Table 3.

Table 4 shows how the operation `0b1100 && 0b0110` is performed.

These operators base their input on a whole word. There are also operations which perform logical operations based in each individual bit in a word. These are called bitwise operators

Table 3 List of logical operators on words

Name	Syntax	Application
Logical NOT	!a	Returns the logical inverse of a
Logical OR	a || b	Returns "true" if a, b or both are true
Logical AND	a && b	Returns "true" if a and b are both true

Table 4 Processing of a logical operation on a word

a	1	1	0	0	→	TRUE	
b	0	1	1	0	→	TRUE	&&
					return value:	TRUE	

4.2.3 Bitwise operators

A bitwise operator performs the logical operation not per word, but per bit. A list of possible bitwise operators is given in table 5

Table 6 shows how the operation `0b1100 & 0b0110` is performed. This shows that the logical and operation is performed for every column and not for the whole word. This will later prove very useful for reading, setting and clearing specific bits.

4.2.4 Compound assignment operators

It is very common to perform bitwise operation where a certain variable is both one of the arguments, as well as the location to store the result of the operation. For this a shortened form called a "compound assignment operator" can be used. This allows to for shorter code over which the programmer has a better overview. For example the logical operations in code snippet 6 perform exactly the same operation. A full list of these operators can be found at http://en.wikipedia.org/wiki/Operators_in_C_and_C%2B%2B#Compound_assignment_operators

Snippet 6 Example of compound statements

```
//initializing the variables
uint8_t x = 0b01010101;
uint8_t y = 0b00001111;

//performing a bitwise operation on variable x
x = x & y;

//performing the same operation again using a compound assignment
    operator
X &= y;
```

An example which uses a lot of these bitwise operators is the resetting of a specific bit. It might sound simple to set a single "1" to a "0", but takes quite some steps to clear bit 5 as is Table 7. To perform this operation, the code in code snippet 7 is used. This code is explained step by step in table 8.

Table 5 List of bitwise operators

Name	Syntax	Application
Bitwise NOT	~a	Flips all bits in a
Bitwise OR	a | b	ORs the first bit of a with the first bit of b, etc.
Bitwise AND	a & b	ANDs the first bit of a with the first bit of b, etc.
Bitwise exclusive OR	a ^ b	XORs the first bit of a with the first bit of b, etc.
Bitwise left shift	a << b	Shifts the bits in a b places to the left
Bitwise right shift	a >> b	Shifts the bits in a b places to the right

Table 6 Processing of a bitwise operator

a	1	1	0	0	
b	0	1	1	0	&
return value:	0	1	0	0	

Snippet 7 Example of the clearing of a single bit in a register

```
//initializing the variables
uint8_t x = 0b10101010;
uint8_t bitToClear = 5;

//clearing the bit to clear
x &= ~(1<<bitToClear);
```

Table 7 Example of clearing of a single bit

Bit number	7	6	5	4	3	2	1	0
Current value of x	1	0	1	0	1	0	1	0
Desired value of x	1	0	0	0	1	0	1	0

Table 8 Step by step explanation of the code in snippet 7

#	Description	Substituted code
1	Original statement	`x &= ~(1 << bitToClear);`
2	Rewriting &= to the full form	`x = x & ~(1 << bitToClear);`
3	Substituting x and bitToClear	`x = 0b10101010 & ~(1 << 5);`
4	Rewriting 1 to binary	`x = 0b10101010 & ~(0b00000001 << 5);`
5	Performing the bitshift between brackets	`x = 0b10101010 & ~(0b00100000);`
6	Performing the bitwise NOT operation	`x = 0b10101010 & 0b11011111;`
7	Performing the AND operation	`x = 0b10001010;`

4.3 Statements in C

To build logical blocks with these operators, statements are added to determine when and how to perform the logical operations. This can be done using control statements. This section will cover some basic control statements.

4.3.1 Conditional Statements

There are two types of conditional statements: if statements and switch cases. In this manual we assume you are familiar with if statements. The syntax for a C if statement is as given in code snippet 8, both with or without the "else" statement.

Snippet 8 Example of an if statement with and without an else clause

```
int16_t x = -3;
int16_t y;

//set y as the absolute value of x
if(x > 0){
        y = x;
}else{
        y = -x;
}

//set x to its absolute value
if(x < 0){
        x = -x;
}
```

Alternative to the if statement, a switch statement can be used. The given argument determines to which line in the statement the program will jump. In code snippet 9 an example of a morning routine is given. If you wake up on time, there is time to take a shower and have breakfast, if there is little time left, you will skip some steps and if your wake up very early or too late you will go back to sleep.
The same routine could be realized using if statements, but in many cases the switch statement is more insightful and convenient. Switch statements are extremely useful to implement state machines and execute some code depending on a state variable.

Snippet 9 Example of a switch statement

```
//variable for time until your lecture starts in quarters of an hour
int16_t timeToLecture = 2;

//choose what to skip depending on how much time you have
switch(timeToLecture){
        case 4:
                //just do the same routine as when you had 3 quarters
                    of an hour
        case 3:
                //if you have 3 quarters of an hour start by taking a
                    shower
                takeAShower();
                //then continue with the next step of your morning
                    routine
        case 2:
                //if you have 2 quarters of an hour have some breakfast
```

```
                haveBreakfast();
                //then continue with the next step of your morning
                    routine
        case 1:
                //leave directly if there is only on 1 quarter of an
                    hour left
                leaveForLecture();

                //and end your morning routine (jump out of switch
                    statement)
                break();
        default:
//in the case that the time until the lecture is more than 4 quarters
    of an hour or less than 1 (0 or negative), go back to sleep.
                goBackToSleep();

                //end of the default routine
                break;
}
```

4.3.2 Iteration Statements

C knows two types of iterations: for loops and while loops. It is assumed that the reader knows how to work with these loops. The syntax for these loops is given in code snippet 10 and code snippet 11.

Snippet 10 Example of a for loop

```
//perform a piece of code 10 times
for(uint16_t i=0; i<10; i++){
        //write the code to loop here
}
```

Snippet 11 Example of a while loop

```
//blink an LED as long as a button is pushed
while(readButton()){
        blinkLED();
}
```

4.4 Functions

If code is to be used multiple places, it is advised to make functions of these blocks of code. This manual assumes you know what functions are. The C syntax for functions is as given in code snippet 12. Use a reference to the function inside the `main()` scope and the code in the function block will be executed. The declaration of a function needs to be before the first call of the function. To do that you can use function prototypes, where you specify the name, return type and number and types of the arguments.

Snippet 12 Example of a function

```
//function prototype of the function multiply
int16_t multiply(int16_t, int16_t);

int main(){
        //define some variables
        int16_t a = 4;
        int16_t b = 5;

        //calculate the value for c using the multiply function
        int16_t c = multiply(a, b);
}

//definition of the function multiply
int16_t multiply (int16_t x, int16_t y){
return x * y;
}
```

5 Microcontroller Settings

5.1 Registers

The memory of a microcontroller is divided into words of 32 bits. These are called "registers". These registers can contain e.g. the stored value of a variable in your process. Apart from the memory for variables, there are also registers which have special functions. The values in these registers are connected to in hardware to specific blocks with specific functions, such as settings for a hardware component. Writing to those special registers allow the user to change the settings of the microcontroller.

5.2 Libraries with "typedef"s

The special registers mentioned above are physical places in the memory of the microcontroller. These registers are numbered. For example, the least significant bit in the register with memory location 0x40023830 controls if the clock to GPIO port A is enabled (this register will soon be explained in detail). These hexagonal numbers are not the most practical reference, as it will soon be unclear which number means. In larger projects where dozens of these registers are used it is too confusing to use this notation.
For more clarity, libraries with type definitions can be used. These tables function as a table which links a practical name to a register location. The library with this table for the registers which have to do with the "reset and clock control" (RCC) settings is *"stm32f4xx.h"*. This library sets a variable name for a certain memory address in the form of a struct. A struct is an object with multiple variables in it. For the RCC the struct is called `RCC` and the component needed enable clocks to GPIO ports is called "AHB1ENR". In the case we want to enable the clock to GPIO port A the typedef library has defined that the value for variable `RCC->AHB1ENR` ought to be stored in register 0x40023830. If we now want to enable the clock to GPIO port A, the programmer can use the command

```
RCC->AHB1ENR = RCC->AHB1ENR | 0x0001;
```

Or in shorter notation:

```
RCC->AHB1ENR |= 0x0001;
```

Each module of the chip, e.g. GPIO, timers and ADCs, has its own library with those memory location references. Include this library and the reading and writing to these registers becomes much more convenient.

6 ARM clock design

The architecture of ARM microcontrollers is designed to make the user do a tradeoff between performance and energy consumption. Especially in mobile applications, this is an important aspect which can save battery life. As the ARM microcontrollers are implemented in CMOS technology, the energy consumption is more or less proportional to the amount of clock ticks of the system clock. To reduce power consumption there are two possible options:

1. Reduce the clock speed
2. Disable parts of the system

Both these options can be configured in the system settings of an ARM. After a reset or power down, the ARM reboots and sets a 16MHz internal RC oscillator as system clock and disables all hardware peripherals. This means that to use any subsystem of the chip, e.g. GPIO pins, DACs and timers, the clock to this module has to be enabled first.
If clock frequencies higher than 16MHz are required (which it will be near the end of the course), the internal phase locked loop (PLL) has to be used. This PLL uses the 16MHz RC oscillator as an input and multiplies this frequency to generate a high frequency clock. If this PLL output is then set to function as the system clock, higher performance can achieved at the cost of a higher power consumption.

7 GPIO

GPIO is an abbreviation for “General Purpose Input and Output” and allows the programmer to read or set the voltages on the pins of the microcontroller to a high (3.3V) or low (0V) value. In ARM microcontrollers, the input and output pins can be read and written to similar to a memory address. Input pins are connected to a (read only) input data register which can be read in the same way any other register is read. Output pins are connected to an output data register. This is a register just like any other, except this memory cell is connected to pins, so the bits in this register determine the voltages on the pins of the chip. This principle of interacting with GPIO pins in the same way as with memory addresses is called “memory mapped input and output” or “memory mapped IO”.
The GPIO pins are grouped in functional units called ports. The microcontroller used for this course features six ports: port A, B, C, D, E and F. Each port has multiple registers to change the settings for the pins in it. The rest of this chapter will use a small x to indicate a register, this x can be replaced by the letters A, B, C, D, E and F to function for this specific port. E.g. the mode register (GPIOx_MODER) for port B is “GPIOB_MODER”. The registers with the possible settings for GPIO pins are given in table 11.

Exercise 1

Turn on the LED on the Nucleo board. To do this follow the following steps:

1. Find out to which microcontroller pin the user LED is connected (refer to chapter 5.4 and table 15 of the Nucleo user manual)
2. Enable the clock to this pin.
3. Initialize this pin
4. Switch on the LED

8 Polling and Interrupts

There are three ways of writing a microcontroller program. The first way is write a program which executes all lines of code from top to bottom and then finishes,

Table 9 List of possible GPIO settings in ARM microcontrollers

Register	CH.	Full name	Function
GPIOx_MODER	8.4.1	Mode register	Sets a pin as input or output pin
GPIOx_OTYPER	8.4.2	Output type register	Sets an output pin as push pull or open drain mode
GPIOx_OSPEEDR	8.4.3	Output speed register	Sets the maximum speed of an output pin to 2MHz, 10MHz or 50MHz
GPIOx_PUPDR	8.4.4	Pull-up/pull-down register	Allows to add a pull-up or pull-down register
GPIOx_IDR	8.4.5	Input data register	Allows to read the digital value of an input pin
GPIOx_ODR	8.4.6	Output data register	Sets the digital value to output to a pin
GPIOx_BSRR	8.4.7	Bit set/reset register	Allows to set or clear a bit in the output data register in one step.
GPIOx_LCKR	8.4.8	Lock register	Allows locking of the settings above
GPIOx_AFRL GPIOx_AFRH	8.4.9 8.4.10	Alternate function register (64-bits long)	Allows to set alternative functions for a pin

similar to e.g. a MATLAB calculation. This is what you have done in exercise 1. In virtually all practical cases a microcontroller executes a continuous task and is never finished with its program. This leaves us the other two options.

8.1 Polling

A way to program a microcontroller program to run until the end of times is with the use of a `while(1){}` loop. As the argument for the loop will be true forever, the microcontroller will loop the code within the braces forever. Your code can now be split up in two parts: first an initialization to be performed once, followed by a loop with the code which should be run continuously. An example project which turns on an LED when a button is pressed could be as in code example 13. Keep in mind that this example refers to a library (*buttonLED.h*) to call functions from, so this example code alone is not enough to switch the LED on and off. This approach, the microcontroller will check the state of the button every time the loop is performed. Processes in which the processor checks for input, such as the LED example in code example 13 are called "polling". Polling is easy to implement and gives programmer complete control over the order of the performed instructions, but it does have some downsides.

Snippet 13 Example of using a while(1) loop and polling

```
//include a libraries here
#include buttonLED.h

int main(){
        //run the initialization code here
        initPins();

        while(1){
                //the code to loop continuously goes here

                //check if the button is pushed
                if(readButton()){
                        //switch on LED if the button is pushed
                        setLED();
                }else{
                        //switch off LED if button is not pushed
                        resetLED();
                }
        }
}
```

Exercise 2

Switch on the LED when the user button is pushed. To do this follow the following steps:

1. Find out to which microcontroller pin the user button is connected (refer to chapter 5.5 of the Nucleo user manual)
2. Enable the clock to this pin and the LED pin.
3. Initialize these pins
4. Read the button input (the electrical connection of the button to the microcontroller can be found in figure 25 of the Nucleo user manual).
5. Switch on the LED when the button is pushed using polling.

Exercise 3

A problem occurring often is that buttons physically bounce when pushed. The effect of this is that instead of switching on neatly, the button input might flicker a few times before staying on. You can compensate for this by letting your code check if the button input is stable over a longer period. Toggle the LED state when you press the user button: switch the LED on when the user button is pushed and off when it is pushed again. If the button seems to "fail" sometimes when you press it, you are experiencing bouncing.

8.2 Interrupts

Alternative to polling, event based interrupts can be used. In this way of designing a process, the processor does not check for input, but a set event will trigger the processor to jump to a certain part of your code. In the case of the switching

of the LED it would be more convenient if we could write a program which executes the function `setLED()` when the button input becomes high, and performs the function `resetLED()` when the button input becomes low. This means we only have to execute code when the button input changes. In your code you can program at which events you want the microcontroller to generate an interrupt and how to handle this when this happens. Some examples of things which can generate interrupts are changing levels on input pins (pin change interrupts), periodic interrupts (timer interrupts) or input on communication busses (e.g. SPI interrupts).
To enable an interrupt for a specific function, you first have to enable the Nested Vector Interrupt Controller (NVIC), for the specific interrupt vector. After an event occurs for which you enabled the interrupt, the program pointer automatically switches to a callback function, called the interrupt service routine (ISR) or interrupt handler. In this function you *must* clear the interrupt flag. An example for enabling an interrupt and an interrupt handler is given in snippet 14. All interrupt registers can be found in chapter 10 of the reference manual.

Snippet 14 Example of enabling an interrupt and ISR

```
// for button at PC0
// EXTI0, bit 2 (SYSCFG->EXTICR[0], bit 2)
NVIC_EnableIRQ(EXTI0_IRQn); // enable IRQ for ext signals on EXTI0_IRQn
NVIC_SetPriority(EXTI0_IRQn, 13); // set the priority
SYSCFG->EXTICR[0] = SYSCFG_EXTICR1_EXTI0_PC;
EXTI->RTSR |= 0x00000001;   // set EXTI line 0 (EXTI0) to rising
    trigger enabled
EXTI->IMR |= 0x00000001;   // enable interrupt for EXTI0

// the ISR:
void EXTI0_IRQHandler(void)
{
     if(EXTI->PR & 1) {
        // do some fancy stuff
     }
    EXTI->PR |= 1; //clear interrupt flag of EXTI0 by writing a 1.
}
```

Exercise 4

In exercise 3 polling was used to read out the button. A good exercise before going on to timers would be to try it with an interrupt. Enable the interrupt for the user button, then write an interrupt service routine in which you toggle the LED.

8.3 Polling vs. Interrupts

Polling and interrupts both have their advantages and disadvantages, but in the general case polling is easier and interrupts are faster and more efficient.

Table 10 Comparison of polling and interrupts

	Polling	Interrupts
Principle	Let the processor check if inputs have changed	Execute code immediately at an event
Implementation	A `while(1){}` loop (very easy)	Event triggers and event handlers (less simple)
Robustness	Code is always executed in the same order without interruption	Interrupts can cause delays at unwanted moments, causing errors.
Reaction time	Every time the loop is executed	Immediately
Processor time costs	The processor wastes clock ticks on checking variables which are the same most of the time.	The processor only executes code when an event takes place.
Power consumption	Processor always runs at 100% : energy consumption is always maximum.	Processor can run slower when there is no event, saving power.

9 Timers

A peripheral found in all microcontrollers is the timer. Timers is a counter fed by a clock. It can be considered to be a register which increments or decrements (depending on the timer settings) by one on every tick of a clock connected to it.

The microcontroller on the Nucleo has seven general purpose timers: TIM2 -TIM5 and TIM9 - TIM11 of which the latter only count upwards. The timers can be fed with different clock sources, internally or externally. This clock source is fed through a programmable 16-bit clock divider called "prescaler" to generate a clock signal for the timer. If the counter *TIMx_ CNT* reaches a so called auto-reload value *TIMx_ ARR* it resets the counter to zero and throws a event.

The counter is connected to four input capture/ output compare channels *TIMx_ OC*. These channels can be connected to a output pin and can work in different modes ranging from measuring the pulse length on a input to toggle a output. In figure 1 a simplified sketch is made to give insight in the purpose of the auto-reload and the output compare registers. Of course is this only one of the possible modes of operation. Look in the reference manual in chapter 13 or 14 for more in depth information about which registers to use.

There are also timers with more specific task: The main purpose of a watch-dog is to check whether or not the code not hangs, it does this by being set periodically to an initial value, if for some reason this does not happen, then the device gets reset or an event is thrown.
Another timer is the Systick timer. This timer runs on the background and is used to generate so called ticks which are used by a realtime operating system to schedule slots for the different task.

Exercise 5.a

Make Timer 2 run at a period of 1 Hz. To do this, follow the following steps.

1. Enable the clock to timer 2.
2. Initialize the timer by setting the prescaler and auto reload value.
3. Start the timer.

To check whether the timer runs, you can check the counter value. If the counter value is above half the auto reload value, switch on an LED, if it is below this value, switch off the LED.

Exercise 5.b

It is possible to set a certain status bit if a timer update (reload) occurs. This status bit will be used to generate timer interrupts in the next exercise. To do this, enable the update interrupt flag. To check whether the flag is set, you can poll it in your process loop. If the flag is set, toggle an LED. Do not forget to reset the flag once you have handled it.

Exercise 5.c

For clearly defined timing (for example, in a function generator), you do not want to wait untill the while(1) loop has detected that the update flag has been set. In this case, use an interrupt. to do this, follow the following steps:

1. Initialize and start the timer such that it updates every second.
2. Initialize the interrupt controller to generate interrupts on Timer 2 flags. Hint: use the NVIC_EnableIRQ function.
3. Write an interrupt handler which checks if the correct interrupt flag has been set, toggles an LED and clears the interrupt flag afterwards.

Table 11 List of possible GPIO settings in ARM microcontrollers

Register	CH.	Full name	Function
TIMx_CR1	13.4.1	Control register one	Main control register, used for enabling the counter and setting the counter mode
TIMx_CR2	13.4.2	Control register two	Second control register, used for setting DMA and other triggering
TIMx_SMCR	13.4.3	Slave mode control register	Settings used for using the timer in slave mode
TIMx_DIER	13.4.4	DMA / interupt enable register	Used for enabling the different interupt/ dma events
TIMx_SR	13.4.5	Status register	Houses all the interrupt flags
TIMx_EGR	13.4.6	Event generation register	Settings for generating DMA events
TIMx_CCMR1	13.4.7	Capture/ Compare mode register 1	Mode selection of the different channels
TIMx_CCER	13.4.9	Capture/ Compare enable register	Setting for the polarity of the channels and enabling them
TIMx_CNT	13.4.10	Counter register	The register containing the counter value
TIMx_PSC	13.4.11	Prescaler register	Prescaler used for dividing the clock
TIMx_ARR	13.4.12	Auto-reload register	The register containing the auto-reload value
TIMx_CCR1	13.4.13	Capture/ Compare register channel 1	The register containing the capture/ compare value of channel one
TIMx_DCR	13.4.17	DMA control register	Settings for the DMA
TIMx_DMAR	13.4.18	DMA adress register for full transfer	The register containing the adress for burst DMA
TIM2_OR	13.4.19	TIM2 option register	Extra options

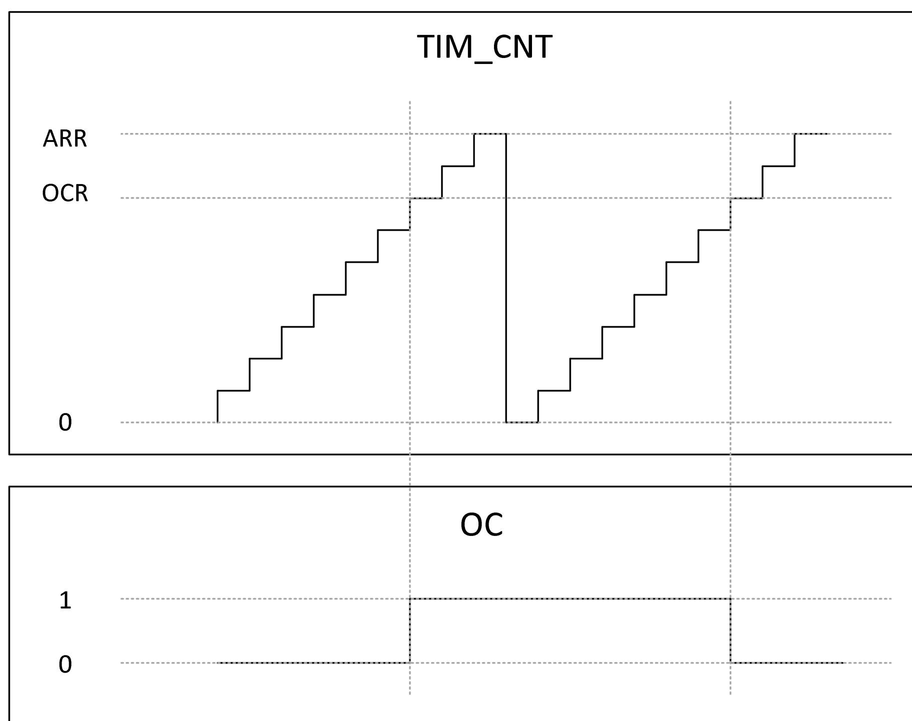


Figure 1: Simplified timing diagram

10 Analog Peripherals

Like most microcontrollers, the used STM32F411 microcontroller has an internal analog to digital converter (ADC). There are 19 input channels to select: 16 GPIO channels, an internal reference voltage, an internal temperature sensor and a battery voltage monitoring feature, connected via an internal voltage divider. To function properly, the ADC requires a proper ADCCLK clock, from the ADC prescaler. An overview of this can be seen in figure 2, from the STM32F411 reference manual.

The ADC can be started from various triggers, both internal and external, and can generate interrupts when done. It also supports several modes: single conversion mode, free running mode (convert a single channel continuously), and group conversion (convert a group of channels in sequence, in arbitrary order). When reading the reference manual, the difference between injected and regular channels can be a bit unclear, so for clarity: the injected channels can have a higher priority than the regular ones, making it possible to interrupt a regular conversion group for an injected conversion.

Exercise 6

Use the ADC to read the output voltage of the potentiometer on the custom shield and use it to alter the LED blinking frequency. To do this, follow the following steps:

1. Find the right ADCCLK frequency from the datasheet, and set (and enable it).
2. Find, from the reference manual, what has to be done to use the ADC.
3. Set the ADC to continuously running mode, on the channel for the right IO pin.
4. Find out what bit is set when the ADC is done.
5. Implement polling for this bit in your main loop from the timer example. Set the blinking frequency for the LED when required.
6. Replace the polling routine by an interrupt for faster code, by enabling the ADC interrupt. (Or continue to the next exercise).

Exercise 7

Polling the ADC to check whether it has finished yet cost processor clock ticks, and results in a false answer most of the time. It thus is a waste of processor resources to do this using polling. A more elegant and processor efficient approach to execute a routine when the ADC has finished would be by having the ADC generate an interrupt when it has finished. To do this, replace the polling routine by an interrupt by enabling the ADC interrupt.

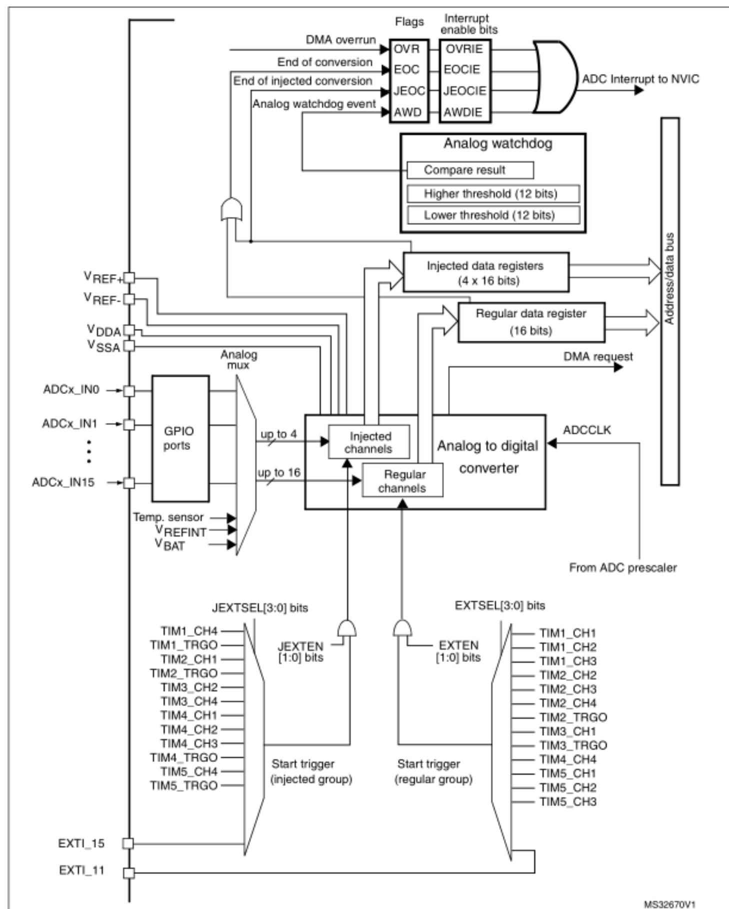


Figure 2: ADC block diagram

11 SPI

For communicating with other chips several standards have been devised. The simplest to implement is the Serial Peripheral Interface (SPI). SPI is a 4-wire master-slave serial interface with signals for clock (SCK), master out slave in (MOSI), master in slave out (MISO) and chip select (CS, sometimes slave select called). The master device controls sets the clock and the chip select. Because SPI is a loose standard the polarity of the clock (rising or falling edge) and chip select are not set in stone. Below in figure 3 is a timing diagram of the interface.

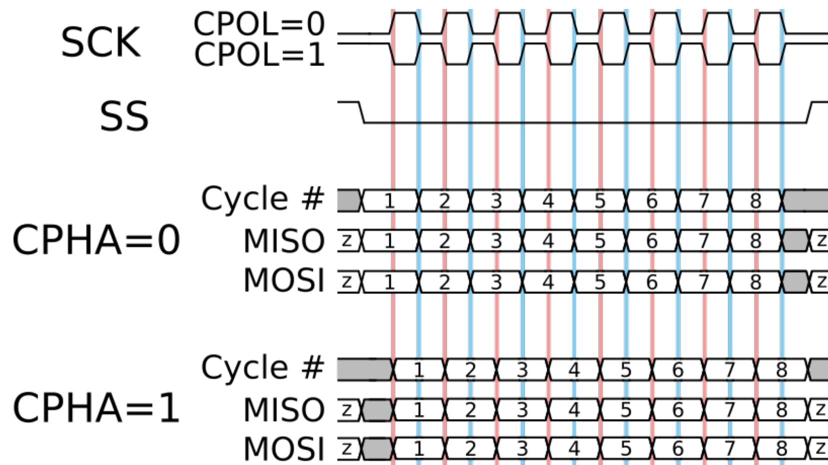


Figure 3: SPI timing diagram

11.1 Talking to the DAC

For the final assignment the goal is to make a function generator. To translate the digital domain to the real world an Analog Devices AD5611 SPI DAC is used. The dac can be found on the underside of the shield in a tiny 6 pin package. Check the Nucleo manual to know which peripheral is used on on which port it is connected. The DAC used does not have a MISO output.

Exercise 8

1. Look in the datasheet of the AD5611 to see how many bits need to be transmitted, and on which bits the data needs to be present.
2. Find the needed clock polarity (CPOL) and clock edge (CKE).
3. Calculate the maximum SPI speed for the DAC and the used system clock.
4. Set up SPI1 for the correct SPI Mode, framesize and frequency.[4]
5. *Optional* Try to send the value of the potentiometer to the DAC, to make sure the settings are correct.

[4]See chapter 20 of the STM32F411RE datasheet.

12 Direct Digital Synthesis

An elegant way to build a function generator with a microcontroller is by using Direct Digital Synthesis. In a DDS system, a sawtooth wave with a variable frequency is generated using only additions. The goal of these additions is to make a phase accumulator.

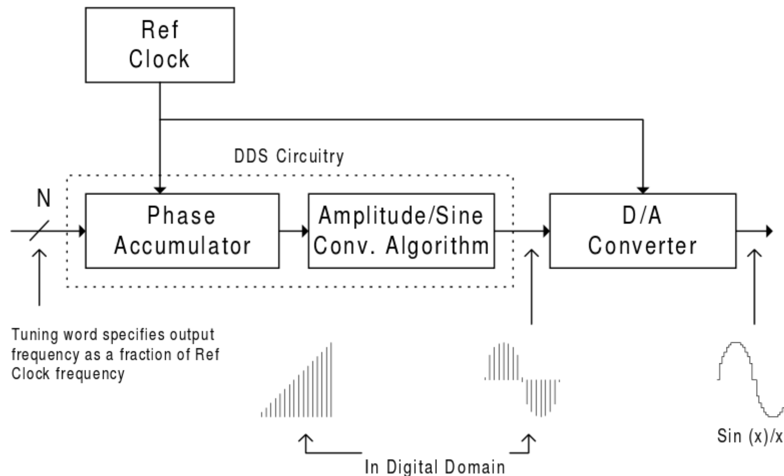


Figure 4: An overview of a DDS system. With a reference clock, (magic) tuning word, phase accumulator and phase to sine conversion.

12.1 Phase accumulator

The theory of a phase-accumulator is that through constantly adding a value to, for instance, a 16 bit integer, the value increases up to the moment that it overflows. This moment can be considered the moment when the phase changes from 2π to 0π. See figure 5. One can use this entire number, or any amount of the most significant digits as the phase of the signal to be generated (For the figures we chose to use the upper 8 bits). One can clearly see that the value of this sawtooth-wave is linearly related to the phase. (i.e. Divide the sawtooth by its maximum amplitude, and multiply with $2\ \pi$ to get the phase).

Using the example with a phase of just 8 bits, one can see that choosing a value for the speed register that is larger than 0x00FF, will result in oversampling, there will be moments that the phase will jump by more than the least significant digit, in this case the system is sub-sampling. When there is a value chosen for the speed register that is smaller than 0x00FF, the phase will not change during every clock-tick. This is called oversampling. The most significant digits, which are used as a phase, can be directly sent to a DAC to generate a sawtooth. They can also be used as an index in a lookup table, in which other waveforms are stored as a list of samples(sines cardiac-pulses, triangle-waves, etc.)

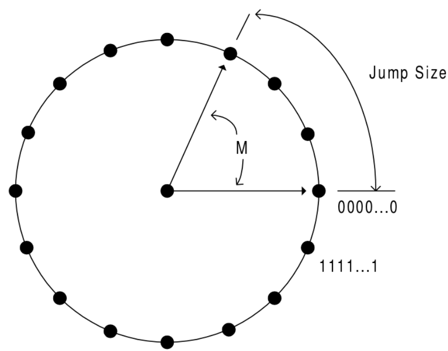


Figure 5: The phasewheel, this describes how an integer changes its phase when it overflow

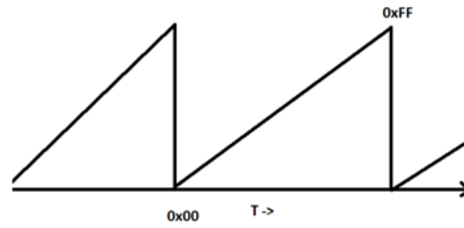


Figure 6: Sawtoothwave as produced by the 8 most significant bits of a phase accumulator

The frequency of the output signal is related to the speed register with the following relation:

$$f_0 = \frac{M \cdot f_s}{2^n}$$

In which:
f_0 is the output frequency.
f_s is the sampling frequency.
M is the value for the speed register (the magic number).
N is the word length used for the phase-accumulator.

Exercise 9

Build a function generator using DDS.

1. Choose an appropriate size of the phase accumulator
2. Make a reference clock with a known frequency
3. Calculate a magic number M for a target frequency
4. Implement the DDS algorithm
5. Send the sawtooth wave to the DAC over SPI
6. Now change M to be variable with potentiometer, or buttons, or whatever you like!
7. Implement a sawtooth to sine wave converter
8. Optimize the design

A Nucleo Board Hints

This appendix will contain some hints we've collected for the Nucleo F411RE board.

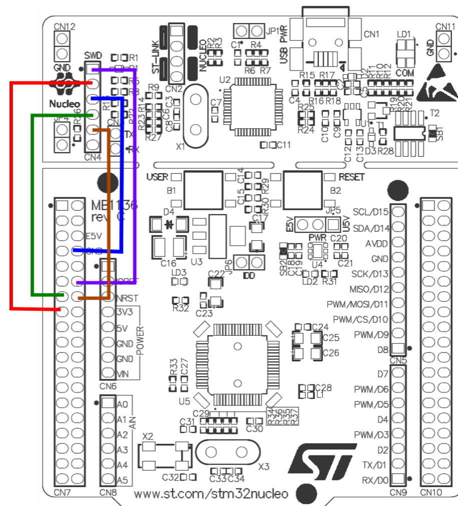
A.1 Breaking the board

It's possible to use the Nucleo without the attached STLink programmer. So you might as well put some action in your life and start breaking the board. You'll have to connect an external power supply, as explained in paragraph 5.3.2 of the Nucleo User Manual. Then you'll have to connect a few wires from the STLink CN4 connector to the Morpho connector CN7 of the Nucleo, check table 12 and figure 7.

Table 12 STLink connections for a cut Nucleo board.

Name	STLink CN4 pin	Morpho CN7 pin	Colour (fig 7)
VDD Target	1	12	Purple
SWCLK	2	15	Red
GND	3	8	Blue
SWDIO	4	13	Green
NRST	5	14	Brown

Figure 7: Connection diagram for STLink to cut Nucleo board.



B Function Generator Shield

In table 13 the connections of the Shield components to the Arduino header and STM32F411RE microcontroller can be found. LEDx are the LEDs, BUTx the three buttons, POT is the analog input of the potentiometer and CS, MOSI and SCK are connected to the DAC. Although you can use the capacitive touch buttons, P1 to P4, on the shield, it requires some additional programming.

Table 13 Pin connections of the shield to the Arduino header and STM32F411RE microcontroller.

Component	Arduino Pin	STM32 Pin	Alternate function
LED0	D3	PB3	
LED1	D5	PB4	
LED2	D6	PB10	
BUT0	D7	PA8	
BUT1	D8	PA9	
BUT2	D9	PC7	
CS	D10	PB6	SPI1_CS
MOSI	D11	PA7	SPI1_MOSI
SCK	D13	PA5	SPI1_SCK
POT	AD4	PC1	ADC1_11
P1	AD3	PB0	ADC1_8
P2	AD2	PA4	ADC1_4
P3	AD1	PA1	ADC1_1
P4	AD0	PA0	ADC1_0

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