

An Introduction to Building Electronics Projects with Arduino

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Preface

The notes are structured into 6 chapters. The first chapter mainly describes basics that you likely already know from your introduction to Physics classes. Subsequently, we will discuss one chapter per workshop session. The notes are prepared as we go, and you can always find the latest version, but also solutions to the examples in the form of code examples, on [GitHub](#). If you find typos, errors, or other issues please let me know. The most recent copy of the \LaTeX files and figures can also be found on [GitHub](#).

The lecture notes contain clickable links in [dark blue](#). Furthermore, boxes throughout the text discuss are used for the following contents:



Background information on topics that do not necessarily fit into the text but are important to keep in mind will be given in a box like this.



Think about it more! These boxes will challenge you to think a problem through for yourself and go into more detail.

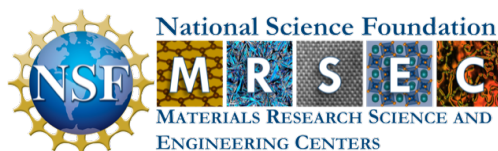


Exercise 0 Exercises are given in these boxes. Flex your coding muscles and practice what you've learned.



Question 0 Questions will be given in these boxes. They should solidify your background knowledge.

This workshop was first designed for interested students at the [Materials Research Science and Engineering Center \(MRSEC\)](#) at Brandeis University in fall 2021. Support is provided by the Brandeis NSF MRSEC, DMR-2011486.



Acronyms

AC alternating current

ADC analog-to-digital converter

AWG american wire gauge

BOM bill of materials

CSV comma separated values

DAC digital-to-analog converter

DC direct current

I²C inter-integrated circuits

I/O input / output

IDE integrated development environment

LED light-emitting diode

MOSFET metal-oxide-semiconductor field-effect transistor

MRSEC Materials Research Science and Engineering Center

PCB printed circuit board

PWM pulse width modulation

SQUID Simplifying Quantitive Imaging Development and Deployment

TEC thermoelectric cooler

0. Introduction

Scientific research that focuses on experiments and measurements has rapidly grown in the recent past, mainly thanks to significant improvements in engineering, instrument availability, and computing power. While many companies provide state-of-the-art research instrumentation and setups, cutting-edge scientific discovery often still thrives from home-built setups.

In addition to scientific instrument development and availability, the consumer / hobby market has seen a huge increase in home-made electronics.¹ This development has especially been facilitated by products such as [Arduinos](#) and [Raspberry Pis](#), as well as the huge maker community. Automation of research experiments can often benefit from such existing, low-cost products in order to significantly enhance an experiment or measurement. Furthermore, complete low-cost instruments enabling frugal research have also been developed based on such platforms, see, e.g., the [Simplifying Quantitative Imaging Development and Deployment \(SQUID\)](#) project.

In this workshop, we will develop a temperature regulation system in order to cool a sample. We will read the temperature using a thermistor, use buttons to control the set point, use a display to show the displayed and set temperature, and finally drive a thermoelectric cooler in order to achieve sample cooling.

0.1. Basic Physics to Remember

Building electronics is not just fun because you can hold your final product in your hand and play with it, but also since it is a direct application of basic physics. Remember your introductory classes!

Ohm's law Throughout this workshop, you will encounter Ohm's law very frequently. This law states the current I through a conductor with resistivity R is directly proportional to the voltage U across the conductor. We can write this as:

$$I = \frac{U}{R} \tag{0.1}$$

$$U = RI \tag{0.2}$$

¹For example, have a look at [this](#) article in the New York Times. Looking at the images clearly shows a 3D printed case as well as a standard Arduino cloud interface.

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Remember this relationship for when you design your circuits.



Maximum current Arduino pins, as we will discover later, can supply 5 V to, e.g., an light-emitting diode ([LED](#)). Since an [LED](#) is a diode, it's resistance (if connected properly) is close to zero (see also [Wikipedia](#)). Therefore, applying a 5 V voltage would result in an infinite current across this component. How would you add a resistor to limit the potential current to a maximum of 10 mA?

Electric power If a current flows through a resistor, electric energy is transferred. The energy per time that is used in this resistor is the electric power P , which can be calculated as

$$P = UI. \quad (0.3)$$

Often, electric power is dissipated as heat. For example, an [incandescent light bulb](#) creates light (and heat!) by applying a voltage to a filament that is generally made of tungsten. The filament heats up and emits light. All electronic components have a maximum power rating, also often expressed as a maximum current rating.



Maximum power versus maximum current Assume you have a component that consumes at most 5 W of power at a current of 1 A. What is the maximum voltage that you can apply? What is the resistance of this element at the maximum voltage?



Electronic components and symbols You are probably already familiar with basic electronic components such as resistors, capacitors, etc., and their symbols. We will discuss various components during this workshop. A good overview of components to refresh your memories can be found [here on Wikipedia](#). Standard electronic symbols, which are really useful for drawing circuit diagrams, can be found [here](#).

0.2. Analog and Digital

If you turn on a radio, and it is too loud, you can use the volume knob, which is nothing else than an adjustable potentiometer, in order to regulate the volume of the sound. This volume can be adjusted over a whole range of settings. The potentiometer adopts linearly depending on its position, giving you an analog control over the volume. Mapping the volume from 0 (quiet) to 1 (loud), you can reach any value in between. Digital signals on the other hand are either on or off. An Arduino generally has many digital input / output (I/O) pins which can be either high (5 V) or low (grounded). If

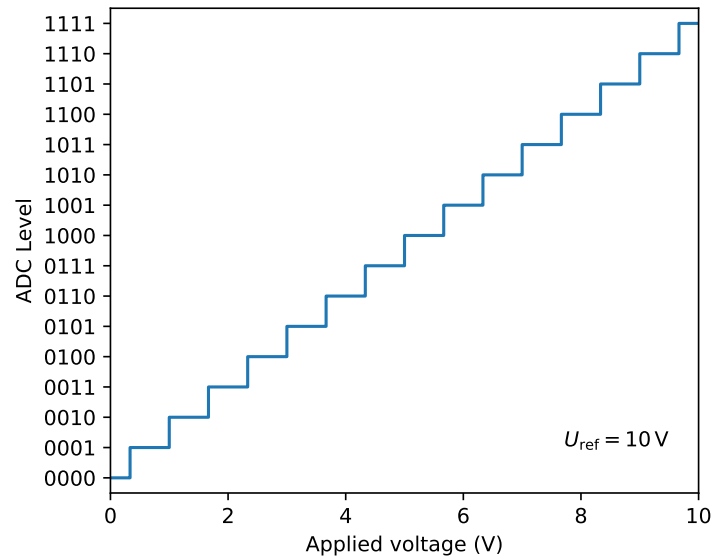


Figure 0.1.: A 4 bit *ADC* with given levels. The reference voltage is 10 V.

you connect a 3.3 V battery to an input pin, of course via a resistor in order to not exceed the current maximum, the switch would either tell you that it is high or low, depending on the threshold that are actually set in order to determine this. Any kind of microprocessor *only* understands digital signals.

0.2.1. Analog-to-Digital Conversion

In order to measure as signal from a sensor, e.g., a photodetector or a temperature sensor as we will use later, a device called an analog-to-digital converter (*ADC*) can be used. Above we mentioned that any kind of microprocessor only understands digital signals. The same is also true for an *ADC*. While a digital I/O pin has two levels (high / on or low / off), an *ADC* generally has many more levels in between. The resolution of an *ADC* is generally expressed in bits.



Bit For any microprocessor, the two possible states (high and low) can be expressed as 1 and 0. Binary numbers (base 2) are therefore the ideal representation to express different states. A digital I/O pin has 1 bit resolution, which means it can either be 1 or 0. Higher resolution means that more bits are available to set states. For two bits, i.e., a binary number with with two digits, the possible states are 00, 01, 10, 11. This means that 2 bit resolution has a total of four steps. For n bits, the number of available steps are 2^n .

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Figure 0.1 shows the levels of a 4 bit ADC in binary as a function of the voltage that would be measured. The reference voltage here is $U_{\text{ref}} = 10 \text{ V}$. This reference voltage is the voltage that the ADC can measure at most, i.e., the voltage that it will return when the ADC level is 1111.

Knowing the resolution n of an ADC, we can easily calculate the minimum voltage difference that can be determined as

$$\Delta U = \frac{U_{\text{ref}}}{n}. \quad (0.4)$$

For the given example above in Figure 0.1, the minimum voltage would thus be $\Delta U = 0.625 \text{ V}$. Anything smaller voltage difference requires a higher resolution ADC.

0.2.2. Digital-to-Analog Conversion

Of course, we sometimes require the opposite of an ADC and need to convert digital signal into the analog world. The device that allows for this transformation is a digital-to-analog converter (DAC). A true DAC takes a digital signal and returns an analog voltage by dividing a reference voltage as many times as necessary. The same resolution limitations as for an ADC also apply to a DAC. For example, a 4 bit DAC with a reference voltage of 10 V can only increase the analog output in steps of 0.625 V.

Pulse width modulation (PWM) An interesting way to have a pseudo DAC is to use a process called pulse width modulation (PWM). Figure 0.2 shows a schematic of this process for a 5 V pin. The digital pin is rapidly turned on and off. If it is at 5 V for 50% of the time, a 50% duty cycle, the effective, smoothed-out voltage that can be seen by a “slow” component would be 2.5 V. Depending on the duty cycle, a pseudo-analog output can therefore be created. A great example to use PWM is to have a dimmable LED. LEDs generally have only two states, on and off, i.e., is the voltage is high enough to light them, they are bright and otherwise dark. Using PWM however, we can turn an LED on and off in rapid succession such that it looks to the human eye as if the light source itself was dimmed.



Analog output with PWM Can you come up with a way to create a smooth analog output from a PWM pin? Think about how your cellphone charger turns alternating current (AC) into direct current (DC).

0.3. Arduino

For this class, we will be using an Arduino Micro. You can find more information and various alternative Arduino boards for all kinds of projects on the [Arduino website](#).

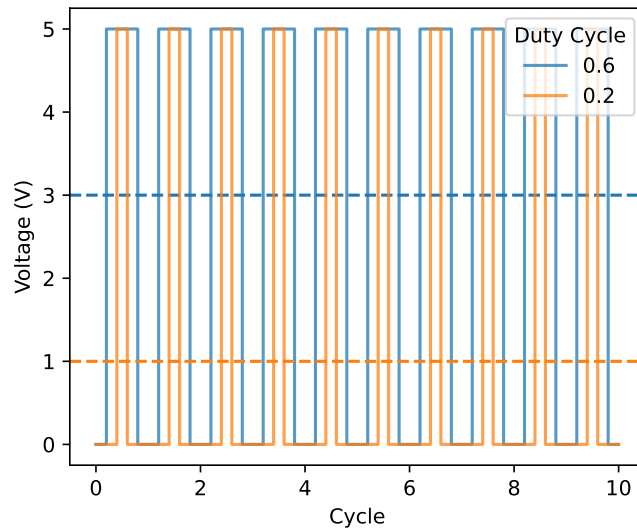


Figure 0.2.: *PWM cycles and average voltage for two different duty cycles.*

In Appendix A, a schematic of the Arduino Micro board is given. This pinout diagram specifies what all the various pins on the board mean and what they are used for. It is a very handy reference for when you develop your project.

0.3.1. Programming an Arduino

The easiest way to program an Arduino is by using the integrated development environment (IDE) for Arduino that can be found [here](#). The website also has installation guides on how to install the IDE and Arduino driver on your computer, depending on your operating system. Please see this documentation or look at it at least briefly, since it will help you with troubleshooting in case your computer does not find the Arduino board.

The Arduino IDE is very useful when you are starting to learn how to program your Arduino. Under “File”, “Examples” you can find eleven categories that give you many well-explained example snippets of code for various applications. We will make a lot of use of these examples, especially during the first few chapters of this workshop. The IDE also allows you to verify your code, i.e., check if it contains any errors (check button in the toolbar) and to upload your code to the Arduino itself (right arrow button in the toolbar). In order to upload your code to the Arduino board, make sure that you have the correct board selected. Go to “Tools”, “Board” to select “Arduino Micro”. Furthermore, you need to select the port on which your board is connected to the computer. To do

0. Introduction

so, go to “Tools”, “Port” to select the correct one. Now you are ready to begin uploading example code or your own code.

Programming language overview To program your Arduino, the code must be written in C++. There are many great introductions online that can help you to get started, see also the background information box below. Therefore, we will only discuss very briefly the most important rules here. These will help you to avoid the most common mistakes.

- Commands and instructions are case sensitive
- Variables must be declared. If you need an integer for example and assign it the value three, you can do this by declaring the variable as `int myVar = 3;`
- All command lines must be terminated by a semi colon ;
- Functions, loops, etc. get surrounded by curly brackets
- It is up to the user to make the code look readable. If you want, you can write everything into one line since line endings and function endings are defined by the above stated rules.
- Line comments are preceeded with `//` while block comments use the following structure:

```
/*  
    My comments in a block...  
*/
```

In general, the minimum file structure for your Arduino code should look similar to the following.

```
// variable declarations, load libraries  
  
void setup() {  
    // setup code  
}  
  
void loop() {  
    // main code that repeats  
}
```

On the very top of your code, put variable declaration and initialization if required and load the necessary libraries. The `setup` function is the part that runs once when you boot up your Arduino. The `loop` function will then run repeatedly and, ideally, until you unplug or reset the Arduino. We will see later how to fill these standard functions. In addition, you can of course write your own functions with any names of your choosing, just make sure they do not collide in naming with these default functions.



Numbers To understand variable declarations in C++ better, we need to remind ourselves how numbers are stored in a computer's / microprocessor's memory. One of the most important types of numbers are integers, declared in C++ as `int`. In the Arduino Micro, an integer is 16 bit in size. This means that 16 positions are available in binary. Integers with a sign can therefore go from -2^{15} to $2^{15} - 1$; the first bit is reserved for the sign. An `unsigned int` on the other hand goes from 0 to $2^{16} - 1$. Integers of type `long` have 32 bit available.

Decimal point numbers are represented by `floats`, which can take values from $-3.4028235 \times 10^{38}$ to 3.4028235×10^{38} . They require 32 bits of memory to be stored.

You can find more information on different variable types in the [respective Arduino reference section](#).

Debugging When code does not do the thing we expect it to, it is often difficult to exactly see why it does not work. While the Arduino IDE catches many bugs, it cannot catch logic errors. If you simply code a script on your computer, you might debug it by printing out values to the screen. The same can be done with the Arduino. Unless you have a screen connected to the Arduino, you have to send the values to print via the serial connection to your computer for displaying. The statement `Serial.begin(9600);` should go into your setup routine. This begins the serial communication to your computer with a `baud rate` of 9600. Inside your main loop, you can then use the following print statements to write to your computer:

- `Serial.print("Hello");` prints "Hello " without a line break.
- `Serial.println("World!");` prints "World!" on the same line as the print before and then starts a new line.

To see these printed values, click in the Arduino IDE on “Tools” and then select “Serial Monitor”. Note that you can also send commands from the computer to the Arduino via Serial. More information can be found [here](#).



Help with programming your Arduino To find further information on how to program for Arduino and get yourself started with C++, see the following links:

- [Starters guide for programming for Arduino](#)
- [Programming reference specifically for Arduino](#)
- [Libraries in Arduino](#)
- [Glossary of commonly used terms](#)
- [User forum](#)

Note that many components that we use come with detailed instructions and guides. For example, if you buy components from [Adafruit](#), these parts generally come with a guide for Arduino, etc.

More Help As with so many things in life these days, more help is generally just one [search on the internet](#) away. There are many forums, articles, etc., on the web that discuss building electronics with Arduino. The hope is that this workshop helps you to discover the vast possibilities and gives you the right keywords to search your way through.

0.3.2. TinkerCAD

If you want to play with a virtual Arduino, give [TinkerCAD](#) a try. On its website you can simulate an Arduino, add components, write code, and then run the setup like in real life. It is a great tool to plan a project and start experimenting with setups, e.g., while you are waiting for components to ship.

1. Blink

Like programming tutorials start with a “Hello World!” program, electronics tutorials generally start with a blink example. In this chapter you will learn how to write to and read from digital I/O pins.

1.1. LEDs

1.1.1. Internal LED

Arduinos with a built-in LED allow the user to program and use this LED. Therefore, all the hardware you need is the Arduino and a USB cable in order to connect it to your computer. Feel free to plug the Arduino into a breadboard as shown in Figure 1.1. The internal LED in Figure 1.1 can be seen just on the right side of the label that says

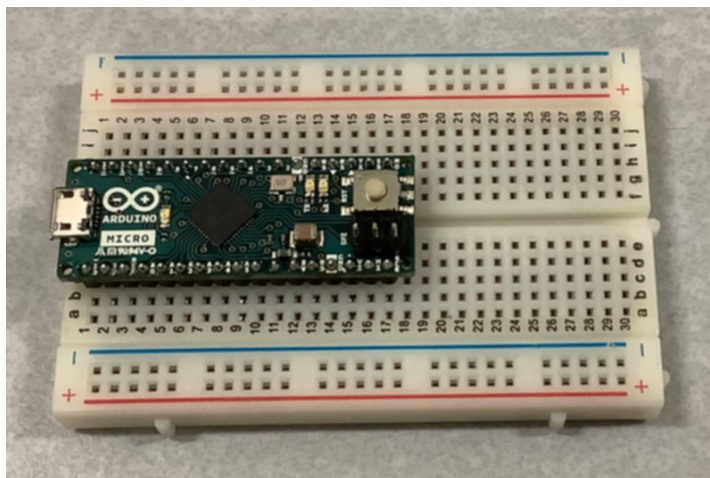


Figure 1.1.: Arduino micro plugged into a breadboard. On the left the USB connection is visible. On the right of the label where it says “Arduino”, the internal LED can be seen.

“Arduino”. In addition, you can see a button on the right-hand side of the board (the reset button) as well as two more LEDs on the left side of this button. These additional LEDs cannot be accessed by the user and are reserved for the system.

1. Blink

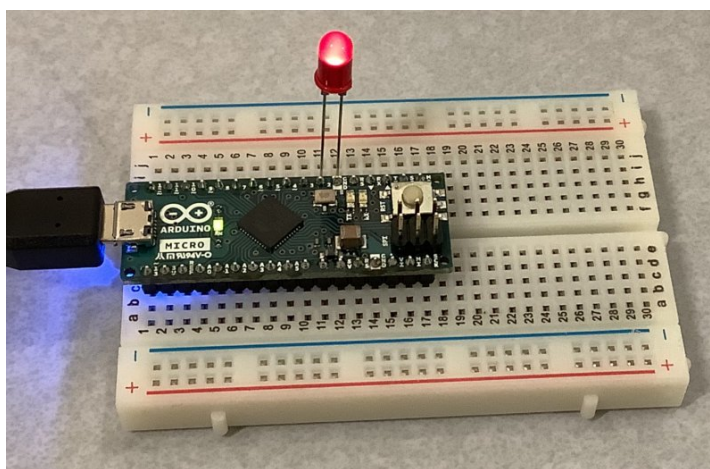
If you start the **IDE** and load the basic example “Blink”, you will get some code that will control the **LED**. The following exercises will use this simple example and slowly extend it.



Exercise 0 Open the example blink file and read the comments. What is done in the setup? What does the variable `LED_BUILTIN` stand for? Study the loop: What will happen when you upload the code to your Arduino? Do so and see if your assumptions were correct. Modify the timings of the program such that the **LED** blinks at a different rate.

1.1.2. External LED

We can also connect an external **LED** to a digital I/O pin. To use a pin as an output pin, i.e., to set its level by software, we have to define the `pinMode` to be in **OUTPUT** mode. Furthermore, connecting an **LED** to a pin and simply driving it can be bad for the **LED**, since it has, by itself, no resistance. Looking at equation (0.2) we can see that in such a case the current should become infinity, which might destroy the I/O pin. Fortunately, Arduinos have an internal resistor that prevent this from happening. However, the **LED** might still get too much current, which might significantly reduce its lifetime. You can either add a resistor or use an LED with an internal one, as we are doing here (Figure 1.2).



*Figure 1.2.: Arduino with one **LED** connected.*

1. Blink



Exercise 1 Draw a wiring diagram to connect your own **LED** to a Arduino output pin. Where do the anode and cathode of the **LED** connect to? Attach your **LED** to the arduino and modify the simple blink experiment to use your **LED** instead of the built-in one. If you have trouble figuring out how to connect the **LED**, study Figure 1.2 and remember that every electric circuit must be completed.

1.1.3. Dimming an LED

As we have discussed above, **LEDs** cannot be dimmed in the traditional way, i.e., by using a potentiometer to lower the voltage. However, we can use a **PWM** output in order to only have the **LED** on for a certain amount of time. This will result in our brain perceiving the **LED** as dimmed. We have already described the **PWM** outputs above in Section 0.2.2, see also Figure 0.2. In order to identify a **PWM** output, look at the pinout (Appendix A). Digital pins indicated with \sim are the ones that can be used in this fashion, e.g., pin 3.



Exercise 2 Connect your **LED** to a **PWM** output pin. From the Arduino IDE, load the basic example named “Fade”.

1. Read the setup and loop functions. How is the pin output set and what is different from how the pin was set in the previous exercise?
2. Modify the fade amount to 7 and run it again. At the brightest point, the **LED** briefly blinks. Why?
3. Can you rewrite the routine in order to prevent it from blinking at the highest point? An **if** statement might be useful.

The **void** `loop()` function acts as an endless loop. The most commonly used looping structures are **while** and **for** loops. In fact, the loop function itself underneath is a **while(true)** loop.



Exercise 3 Inside the **void** `loop()` function, write a **for** loop to replace the ramp. Ensure that your loop does not blink, even if you select various fade amounts.

1. Blink

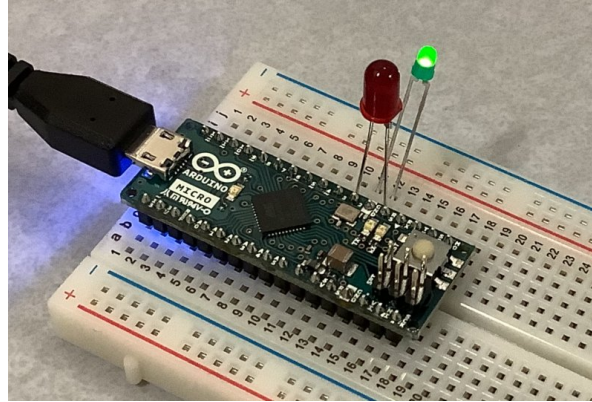


Figure 1.3.: An Arduino with two LEDs connected.



Question 0

- How does integer division in C++ work?
- How can you do a division in C++ and round the result to the nearest integer?
- What is a boolean variable and how do you compare two booleans, e.g., in an `if` statement?
- How would you flip the state of a boolean variable?

1.1.4. Multiple LEDs

Since you have more than one pin available, multiple LEDs can be set up. An example of a test setup is shown in Figure 1.3 This can be especially useful if you want to display the status of your setup using different colored LEDs.

Subfunctions in C++ Sometimes it is useful to put some of your code into external functions, i.e., not to write them into the main loop. For example, you can write a function as following:

```
void myFunction(bool toggle) {  
    // your code here...  
}
```

You can then call this function from the main loop by calling `myFunction(true)`; if you want to assign the value `true` to the variable `toggle`.

1. Blink

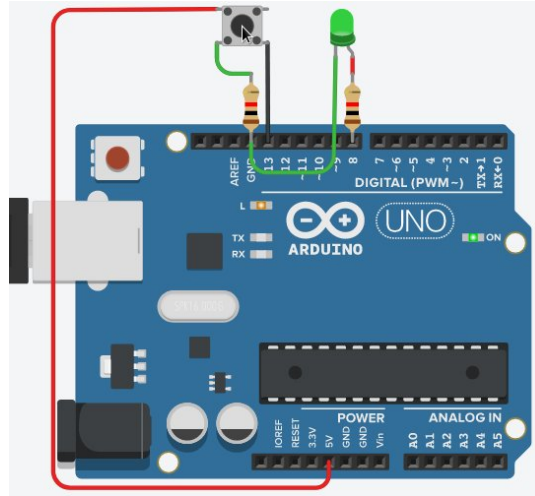


Figure 1.4.: TinkerCAD simulation of Arduino with a button and LED connected.



Exercise 4 Setup two LEDs, a red and a green one. Write a program that switches between blinking the red and green LEDs. Write a subroutine that takes a boolean variable as an input and, depending on the value of this input variable, turns either the red or the green LED on (and the other one off).

1.2. Buttons

Most devices that allow for user interactions contain some buttons. We can use the digital I/O pins in order to connect a button. Figure 1.4 shows a TinkerCAD simulation of an Arduino with a button and an LED connected. Here, we connect the button on one side to the 5 V output of the Arduino and the other side via a 1 k Ω resistor to ground and simultaneously to a digital I/O pin. The resistor limits the current to 5 mA, see equation (0.2). In the setup routine, we need to set the `pinMode` to `INPUT`, since we want to read the value that is connected to the pin. If the button is unpressed, the pin is on the same electrical potential as ground and therefore in a low state. If the button is pressed however, the pin is at 5 V and thus in a high state. In the loop you can, e.g., read the state of the button connected to `buttonPin` as:

```
int buttonState = digitalRead(buttonPin);
if (buttonState == HIGH) {
    // the button is pressed
} else {
    // the button is not pressed
}
```

1. Blink



Exercise 5 Connect a button and an **LED** to your Arduino and write a program that turns the **LED** on while the button is pressed. Then adjust your routine such that, whenever you press the button, the **LED** is turned on for 3 s and then turns off after the time has elapsed.



Adding time In the second part of the above exercise, you have (most likely) written your program such that if the button is pressed while the **LED** is on, nothing happens. The light will still turn off once the set time elapses after the initial button press. Can you come up with code that would allow you to reset the countdown when pressing the button again, i.e., add time to the timer?

2. Display

In order to display the temperature of our sample cooling setup, we will connect a display to our Arduino. Displays come in many shapes and forms, from the monitor you might be reading this on to simple [LED](#) seven-segment displays. An overview of various displays that are ready to be deployed on Arduino can, e.g., be found [here](#). For our specific case, a simple seven-segment display will do the trick to display the temperature.

2.1. Seven-segment displays

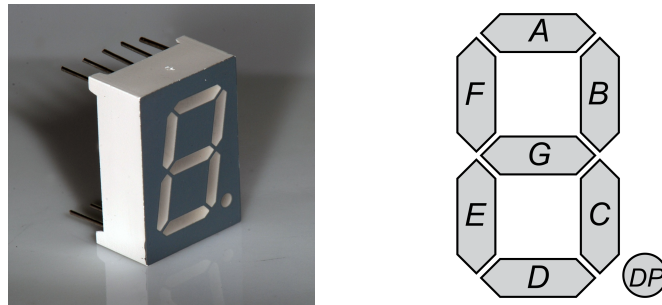


Figure 2.1.: Seven-segment display: photo (left) and schematic (right). Credit: *Peter Halasz* (left) and *Uln2003* (right) via Wikipedia. License: CC by SA-3.0 (left), Public domain – CC0 (right)

As displayed in Figure 2.1, seven-segment displays contain seven individual segments that allow us to display any number and even some letters. In addition, they usually contain a decimal point. The right-hand figure shows the schematic and typical labeling of a seven-segment display. Each segment is its own [LED](#) and we could drive these [LEDs](#) by using multiple [I/O](#) pins. However, in order display multiple numbers, the number of [I/O](#) pins that we would use up would very fast become too extensive. Figure 2.1 shows that the seven-segment display has five pins on top and, not shown here, also five connectors on the bottom. For each seven-segment display you could look up the wiring diagram and notice that each segment has its own connection and that they have a total of two common grounds.

Chips such as a 74HC595 that allow us to convert serial into parallel data allow us to effectively control multiple outputs, as required for such a display, while only using

2. Display

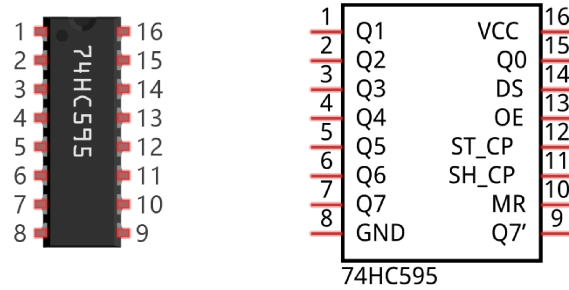


Figure 2.2.: Schematic and pin names of a 74HC595 chip. Credit: [Freenove](#), License: CC BY-NC-SA 3.0

a a few pins. Figure 2.2 shows a schematic and pin names of such a chip. Note the notch on the top of the schematic that each chip contains in order to provide you with a reference on the pin assignments. You can in fact find various versions of this chip from different manufacturers, e.g., the data sheet for the Texas Instruments version can be found [here](#). Generally, the pins have the following purposes:

Pin name	Pin number	Description
Q0 - Q7	1-7, 15	Parallel data output
GND	8	Ground
Q7'	9	Serial data output
MR	10	Remove shift register
SH_CP	11	Serial shift clock
ST_CP	12	Parallel update output
OE	13	Enable output
DS	14	Serial data input

As indicated by the names, the parallel data output pins are the eight pins that can be connected to the individual LEDs of a seven-segment system. The GND pin provides the ground connection of the chip. The serial data output (Q7') can be used to connect another 74HC595 chip in series. The MR and SH_CP take care of clearing the shift register and timing when a shift happens. The ST_CP triggers an update in the parallel output and the OE pin enables this output. Finally, the DS pin is where the serial input is given.



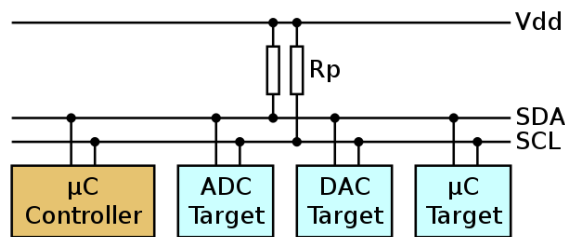
Want do build your own seven segment display driver? Detailed instructions on how to use a 74HC595 chip to drive a seven segment display can be found online, e.g., on in chapter 15 of [this tutorial](#). Building such a driver is outside the scope of our workshop, however, it might be useful for you to read and understand the shifting itself and how it works. Please have a look at the mentioned tutorial.

2.2. Adafruit four-digit, seven-segment display with backpack

As described above, we could build our own driver for a seven-segment display. However, it seems to be fairly cumbersome to develop such a driver, especially since low-cost, pre-fabricated displays with communication “backpacks” exist. Here, we will use an [Adafruit four-digit, seven-segment display](#) that communicates with the Arduino via the inter-integrated circuits (I²C) communications protocol.



I²C protocol I²C is a single ended, synchronous, multi-controller/multi-target, single bus communication protocol and is ideally suited for integrated microelectronics. The following figure shows the configuration with one microcontroller and three selected devices. (Credit: [Tim Mathias](#), License: CC BY-SA 4.0)



The microcontroller connects to each device via a data (SDA) and a clock line (SCL). Furthermore, power (Vdd) and ground (GND) are connected as well; to light our [LEDs](#) we need power. The clock defines the timing of commands, i.e., triggers sending / receiving and the data line sends the required commands. More details on the I²C communication protocol can be found on [Wikipedia](#).

2.2.1. Assembly

The four-digit, seven-segment display package requires assembly by soldering. Figure 2.3 shows the individual components of the display that need to be soldered together. On the top left is the display itself. The backpack is shown on the bottom and the header pins, which allow us to connect the display to the breadboard, are shown on the top right. If you have never soldered before, please review the [this video](#) that will show you some best practices. Generally, remember to:

- Avoid excessive amounts of solder
- Ensure good contact between your component and the printed circuit board (PCB)

2. Display

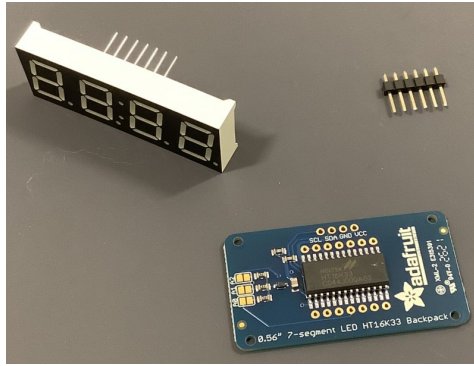


Figure 2.3.: Parts of the four-digit, seven-segment display.

- Double check your parts orientation



Types of soldering The two types of soldering generally referred to are through hole and surface mount soldering. In this workshop we will only perform through-hole soldering, i.e., we will stick the leads / pins through the PCB and solder from the other side in order to ensure a connection. Surface mount soldering mounts components on top of PCBs. A great tutorial video for this type can be found [here](#).

One of the great features when using components and kits from Adafruit is that they have very detailed instructions. All instructions for the four-digit, seven-segment display can be found [here](#).



Exercise 6 Assemble the display kit by following the [Adafruit assembly instructions](#). Double, then triple check the orientation of the display prior to soldering; it is difficult to remove the display after soldering and resolder it in the correct orientation. (In fact, I experienced this last part the hard way. Right after I wrote

→ make sure of display orientation!

I soldered the display onto the PCB the wrong way around...)

2.2.2. Controlling the display from Arduino

As for the assembly, Adafruit has detailed instructions on how to connect and control the display. In fact, they even provide an Arduino library that allows us to easily control the display (this was one of the reasons for choosing this display to start with). [This tutorial](#) goes in detail through the setup for Arduino, including a how-to for installing

2. Display

the libraries. For reference, Figure 2.4 shows an image of the display connected to the Arduino.

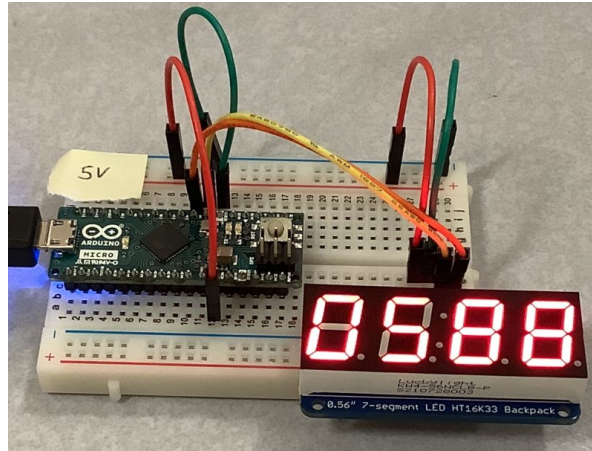


Figure 2.4.: The display connected to the Arduino Micro on a breadboard.



Exercise 7 Go through the [Adafruit tutorial](#) to connect the display to your Arduino. Then ensure that it works as expected by running the example script that Adafruit provides. Various different ways are given in the tutorial. Make sure you understand the different ways of controlling the display. Feel free to modify the example and display your own values.



Exercise 8 For our final setup we want the display to display the current temperature (2 digits plus +/- sign) and the set point if this is changed by pressing a button. Write a subroutine that takes two input arguments and allows you display the following values: " \square -9", " \square 20", "**s**-10". The last example is for displaying the setpoint with an additional **s** in front of it (which is equal to 5). *Hint:* Your subroutine might start with something like this:

```
void dispTemp(int temperature, bool setPoint) {...}
```


3. Temperature sensor

Temperature is generally measured with a thermocouple. In these devices, two metals are brought together that, due to the [Seebeck effect](#), create a temperature-dependent voltage between them. The voltages produced generally are very low and therefore require amplification before they can be read in by an [ADC](#). Such an amplifier for a K-type thermocouple can, e.g., be found [here](#). In this specific case, the amplification circuit would allow us to read temperatures from -250°C to $+750^{\circ}\text{C}$, i.e., a total range of 1000°C .



Question 1 The Arduino Micro that we are using contains eight 10 bit ADCs. Why is it very difficult to get a precise reading of the thermocouple described above using such an [ADC](#)? What would you need to implement / improve the precision?

3.1. Thermistor

While regular thermocouples have a very wide range, this range is not required for our setup. Here we are therefore using a thermistor, which is simply a resistor that is highly temperature dependent.

3.1.1. Voltage divider

In order to understand how we can determine the value of a thermistor with an Arduino, we first need to review how voltage dividers work. Figure 3.1 shows a schematic of a voltage divider built of two resistors with values R_1 and R_2 . The current flows from V_{in}

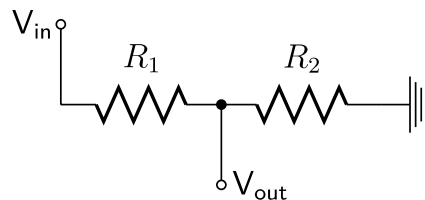


Figure 3.1.: A resistive voltage divider. After [Krishnavedala via Wikipedia, CC0](#).

3. Temperature sensor

to ground. We can calculate the voltage measured between V_{out} and ground as following.

$$R_{\text{tot}} = R_1 + R_2 \quad (3.1)$$

$$I_{\text{tot}} = \frac{V_{\text{in}}}{R_{\text{tot}}} \quad (3.2)$$

$$V_{\text{out}} = R_2 I_{\text{tot}} \quad (3.3)$$

$$V_{\text{out}} = V_{\text{in}} \frac{R_2}{R_1 + R_2} \quad (3.4)$$

In equation (3.1) we first calculate the total resistance of the setup. Plugging this result into equation (0.2), we can calculate the total current flowing, equation (3.2). Since V_{out} is measured over R_2 , we can simply calculate the voltage over this element as in equation (3.3), which when simplified results in equation (3.4). More details, as well as more general voltage divider setups, can be found on [Wikipedia](#).

3.1.2. Using a thermistor with an ADC

In order to determine the resistance of a thermistor and thus to determine the temperature, we can use above described voltage divider setup. For example, we could use a reference resistance R_{ref} instead of R_1 in Figure 3.1 and replace R_2 with the thermistor that has a resistance R_{therm} . Connecting V_{out} to an [ADC](#), we can then determine the thermistor resistance by solving equation 3.4 for $R_2 \equiv R_{\text{therm}}$. We can thus write

$$R_{\text{therm}} = \frac{R_{\text{ref}}}{\frac{V_{\text{in}}}{V_{\text{out}}} - 1}. \quad (3.5)$$

For an [ADC](#) with n bit resolution, we furthermore know that the measured value x relates to the voltage as

$$V_{\text{out}} = \frac{x \cdot V_{\text{ref,ADC}}}{2^n - 1}, \quad (3.6)$$

where $V_{\text{ref,ADC}}$ is the reference voltage of the [ADC](#). Plugging equation (3.6) into (3.5) results in

$$R_{\text{therm}} = \frac{R_{\text{ref}}}{\frac{(2^n - 1) \cdot V_{\text{in}}}{x \cdot V_{\text{ref,ADC}}} - 1}. \quad (3.7)$$

If the reference voltage of the [ADC](#) and the reference voltage of our voltage divider setup are the same, we can further simplify the equation to

$$R_{\text{therm}} = \frac{R_{\text{ref}}}{\frac{2^n - 1}{x} - 1}. \quad (3.8)$$

3.1.3. Determining the temperature

Knowing the resistance R_{therm} of the resistor, we can determine the temperature by looking up the correct value in a lookup table, see the comma separated values (CSV) file on [GitHub](#).

The temperature can also be calculated using the [Steinhart-Hall](#) equation, which is a model for the resistance of a semiconductor at different temperatures. This model states that the temperature T and resistance R_{therm} depend on each other as

$$\frac{1}{T} = a + b \ln R + c (\ln R)^3. \quad (3.9)$$

Here, a , b , and c are constants. Doing a curve fit of this equation to the lookup table for the thermistor, we can determine the constants as $a = 2.78522 \times 10^{-3} \text{ K}^{-1}$, $b = 2.41846 \times 10^{-4} \ln(\text{k}\Omega)^{-1}$, and $c = 8.31227 \times 10^{-7} \ln(\text{k}\Omega)^{-3}$.

A simplified version of above equation, the so-called B-parameter equation (see [Wikipedia](#)) assumes that the constants are $a = 1/T_0 - (1/B) \ln R_0$, $b = 1/B$, and $c = 0$. We can therefore rewrite equation (3.9) as

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B} \ln \left(\frac{R}{R_0} \right). \quad (3.10)$$

Here, $T_0 = 298.15 \text{ K}$ is room temperature and $R_0 = 10 \text{ k}\Omega$ the resistance at T_0 . The parameter B for our thermistor is $B = 3950 \text{ K}$.

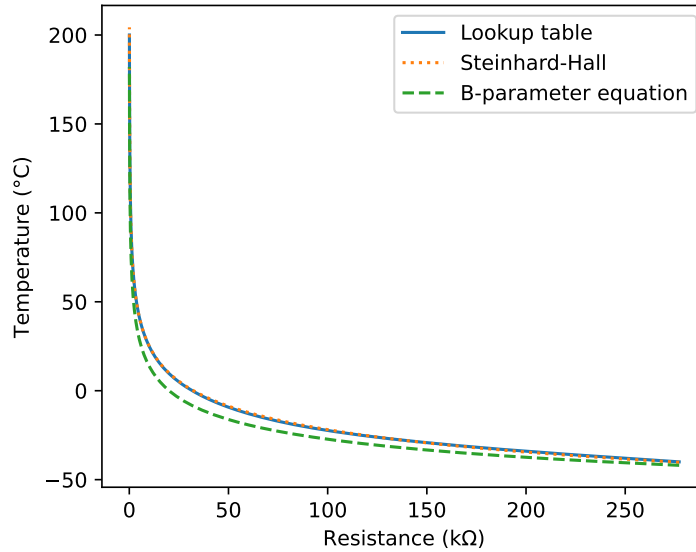


Figure 3.2.: Temperature as a function of resistance for [Adafruit 3950 NTC thermistor](#)

3. Temperature sensor

Figure 3.2 shows the temperature determined using the lookup table in comparison with fitting the Steinhart-Hall equation (3.9) and the B-parameter equation (3.10) results. While the B-parameter equation gets close to the real values, it still has a significant offset. The Steinhart-Hall fit to the lookup table on the other hand seems to be a fairly good match.



Question 2 How will you determine the temperature? The lookup table has the most precision, however, what would you do with a resistance that is in between two values in the table? Our setup will have an actual temperature range between around 25°C and -20°C. How well do the methods compare in this range?



Question 3 The Arduino Micro has a 10 bit ADC on board. Assuming a reference resistor $R_{\text{ref}} = 10 \text{ k}\Omega$, calculate the smallest temperature difference that you would be able to determine with this ADC in the above defined temperature range.

3.2. Reading the temperature with the Arduino

We will now use the thermistor in order to measure the room temperature. With above introduction, you should be ready to build the setup by yourself. However, there are also detailed instructions available on [Adafruit's website](#) on how to set this up correctly. Note however the uncertainties in the different approaches for determining the temperature shown in Figure 3.2.



Exercise 9 Connect the thermistor using the provided reference resistor to your Arduino and measure the voltage on any of the analog input pins (ADC[0] through ADC[7] in Figure A). If you connect your input to `sensorPin = A0;`, you can read the ADC value by calling `sensorValue = analogRead(sensorPin);`. Read the resistance value out using the serial monitor. If you have trouble reading from the ADC, check out the Arduino example under “Analog”, “AnalogInput”. *Note:* Make sure that the reference voltage of the ADC is the same voltage as the one you are using for V_{in} .



`int sensorPin = A0;` In above exercise, the ADC pin was initialized as an integer with the value A0. Why does this not throw an error?

3. Temperature sensor

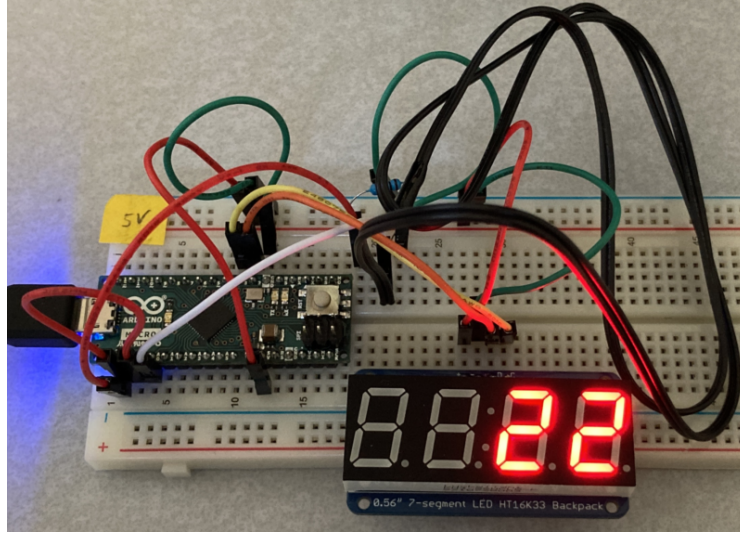


Figure 3.3.: Temperature reading via thermistor and shown using the the four-digit, seven-segment display.



Exercise 10 In Section 3.1.3 we have discussed various approaches of determining the temperature. Implement your solution from above's question in order to calculate the temperature and print it out using the serial monitor. How precise are your readings? Does your room temperature measurement make sense?



Exercise 11 Instead of printing the temperature via the serial monitor, display the temperature on the four-digit, seven-segment display that you have controlled in Chapter 2. Be conscious about the environment and recycle – even your code!

Figure 3.3 shows the final setup after the last exercise. Note that your setup might of course look slightly different.

Your temperature readings might be varying a lot from measurement to measurement. The reason for this is electronic noise. There are two ways of reducing the effects of such noise: (1) For your result use the average of several measurements. (2) The 5 V line of the Arduino is fairly unfiltered and depends on the power supply you are using. The 3.3 V Arduino line (see Figure A) on the other hand is fairly stable, and it would therefore be advantageous to use this line for ADC measurements. To do so, switch your V_{in} to use the 3.3 V line. You can provide this line to the ADC as a reference voltage. To do so, also connect the AREF pin to the same 3.3 V line.

3. Temperature sensor



Exercise 12 Using above methods of averaging and using the 3.3 V as your measurement and reference voltage, determine if your temperature measurements improve.

Finally, as Physicists we know that an ice-water mixture at standard pressure and temperature (we are close to the ocean, so let's assume that's given) is by definition at 0°C. The thermistor that you have is waterproof, and you can therefore submerge in such a “calibration solution”.



Exercise 13 Determine the temperature of an ice-water mixture using your code. How precise is your determination of the temperature? If you are off by several degrees, there might be an error in your temperature measurement capability and your code might need correction.

4. Thermoelectric cooling element

The final part that we need to implement in order to build a sample cooling system is the actual cooling element. As a cooling element, we will use a Peltier cooler from [Adafruit](#), which is mounted onto a heat sink and fan assembly.

4.1. Components and their Physics

4.1.1. The Peltier effect

Thermoelectric coolers make use of the so-called Peltier effect in order to create a heat flux between two different types of materials. This means that heat flows from one element to the other, i.e., that one side gets cold and the other one hot. The Peltier effect was discovered in 1834 by French Physicist [Jean Charles Athanase Peltier](#). In principle, it works similar to a thermocouple, which we discussed above. Figure 4.1 shows a schematic on how the Peltier effect is used to create a thermoelectric cooler. Here, an n- and a p-doped semiconductor are brought together. If we simply measure the voltage across the two metals, we can use the setup as a thermocouple. (Note that this is different from a thermistor, see introduction to Chapter 3.) If we power the setup

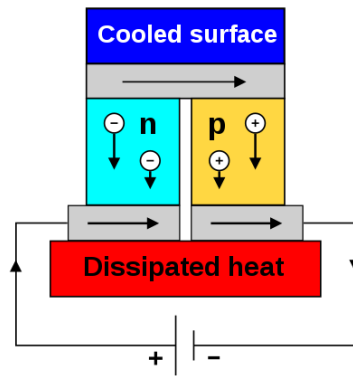


Figure 4.1.: The Peltier effect acting on a thermoelectric cooler. Credit: [Ken Brazier](#) via [Wikipedia](#), License: [CC BY-SA 4.0](#)

4. Thermoelectric cooling element

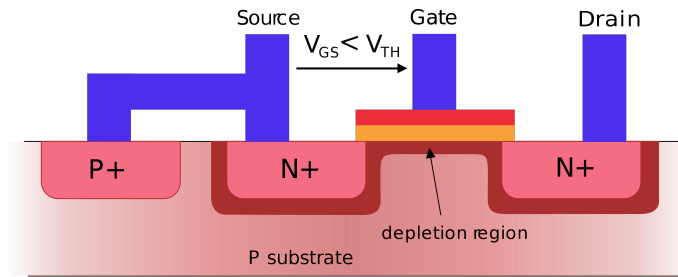


Figure 4.2.: A cross-section through an *nMOSFET*. See text for a detailed description. Credit: Wikipedia, License: CC BY-SA 3.0.

with a DC voltage, a heat flow is generated. The heat flow per unit time is given as

$$\dot{Q} = (\Pi_m - \Pi_n)I. \quad (4.1)$$

Here, Π_m and Π_n are the Peltier coefficients of the two semiconductors and I is the current. Not that the amount of heat flow is directly proportional to the current.

A typical thermoelectric cooler contains many semiconductor junctions added together in series. Furthermore, in order to achieve efficient cooling on one side, the heat from the hot side needs to be removed. This is generally done by mounting the hot side on a heat sink. In our case, the heat sink is connected to a fan which helps to remove heat faster.

4.1.2. MOSFET

The Peltier cooler that we will be using draws 5 A of current at 12 V. The voltage and especially the current are too high for any Arduino pin. We therefore need to implement a switch that we can turn on and off via an Arduino pin and that can handle high currents in order to drive the cooling element. One type of switch that can drive our circuit is a metal-oxide-semiconductor field-effect transistor ([MOSFET](#)).



Question 4 One issue of driving the cooler directly from the Arduino is the that the pins only put out 5 V. At this voltage, what current would be drawn by the Peltier cooler? Compare this current with the maximum current that an Arduino pin can supply. What would happen if you try to drive the cooler off a 5 V pin?

MOSFETs are ideal devices to use as high-current switches that can be rapidly turned on and off by simply using an Arduino pin. Figure 4.2 shows the inner workings of

4. Thermoelectric cooling element

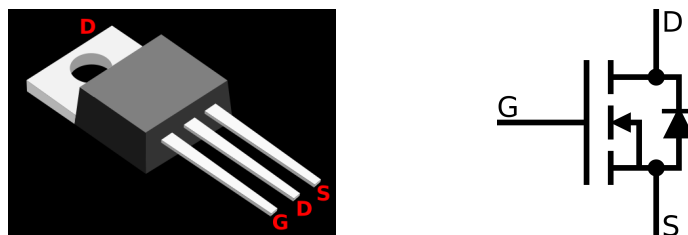


Figure 4.3.: Schematic with pin assignments of the *nMOSFET* we are using here (left) and electrical symbol of a *nMOSFET* (right). Note the diode connecting the source (S) to the drain (D). The gate is labeled G. (Right image credit: *ErikBuer* via *Wikipedia*, license: *CC BY-SA 4.0*.)

an n-type MOSFET, also often referred to as an NMOS. The source and drain on an *nMOSFET* are n-type materials, i.e., they contain a surplus of electrons and are therefore electron donors. These two channels are inside a p-type substrate which lacks electrons and is therefore an electron acceptor. When simply applying a voltage in between source and drain, the p-type material in between does not allow a current to flow. However, by applying a positive voltage to the gate, electrons are attracted to the gate area, which creates a conductive band allowing current to flow in between the source and the drain.

MOSFETs can have wildly different specifications. For Arduino electronics, we want to utilize the ones for which the gate switches when applying a low voltage of only 5 V. Furthermore, we need a MOSFET that can at least handle 5 A of current. At high currents, MOSFETs can get hot and might need to be mounted to a cooling element themselves. In our case however, the MOSFET can be air-cooled up to a current of ~ 15 A, therefore, a cooling element will not be necessary at the 5 A used here.

Since MOSFETs allow for rapid switching, they can also be driven from PWM pins. This allows you to regulate the current to the cooler and therefore to cool it more and less efficiently.



Some applications for MOSFETs Using MOSFETs allows you to rapidly switch various voltages and work with high currents. Furthermore, the high-frequency switching allows you to control the current by connecting the gate to a PWM pin. For example, MOSFETs are frequently used as motor drivers. In order to have a motor run backwards it is often required to have a setup that can switch polarities. To enable this, an H-bridge can be used.

4.2. Implementing a MOSFET controlled Peltier cooler

Figure 4.3 shows a schematic (left) and the electrical symbol (right) of the nMOSFET that we are using here. The data sheet can be found [here](#). As shown in the electrical symbol, this nMOSFET has an additional diode in between the source and the drain. This means that current can flow between the source and then drain even when we do not apply a gate voltage. For the nMOSFET to actually work as a switch, we need to set it up such that, when switched, the current flows from the drain to the source.



Question 5 With above mentioned considerations in mind, draw a circuit diagram that allows you to control the 12 V power supply to drive the thermoelectric cooler from a 5 V Arduino pin. In which part of your circuit diagram will the full 5 A current flow when the gate is activated? Make sure that the 5 V from the gate is connected to ground via a 10 k Ω resistor, such that it is not floating when turned off (remember that an Arduino I/O pin configured as an output cannot be used as a voltage sink).

If you are having trouble with this exercise, a mock setup can be found on [TinkerCAD](#). The thermoelectric cooler is here represented by a 2.4 Ω resistor. If you run the simulation, it will slowly increase the voltage every three seconds. The voltage and current applied to the “cooler” are displayed on a volt and ampere meter, respectively.



Exercise 14 Now implement the above wiring diagram in real life. Before you connect the 12 V to the actual power supply, make sure that:

- You did not connect 12 V to any Arduino I/O pins
- The full 5 A current does not flow through the breadboard at any point

Double check this carefully since, if not connected properly, you might destroy the Arduino and / or the breadboard. Also connect the fan of the thermoelectric cooler to the 12 V, however, connect it such that it is permanently on when the 12 V are connected.

As mentioned above, the breadboard cannot handle 5 A of current since the leads are too small. Small wires have a higher resistance per unit length compared to wires with larger diameters and therefore get hotter when a given amount of current flows through them. We thus have to use appropriate wiring. In the US, wire sizes are standardized and given in units of american wire gauge (AWG). The lower the number in AWG, the thicker is the wire we are dealing with. Tables such as [these ones](#) show how much

4. Thermoelectric cooling element

current can be carried by any given wire. As you can see, a 20 AWG wire can carry 5 A and would therefore be sufficient to be used for the Peltier cooler.



Exercise 15 Turn on the thermoelectric cooler with different PWM outputs on the gate and verify (1) that the cooler actually gets cold and (2) that the voltage applied across the cooler is what you would expect from your PWM output level. Control the cooler from a subroutine that allows you to easily set the power level from the main loop.



Exercise 16 Using Kapton tape, stick the thermistor on the surface of the thermoelectric cooler. First measure the room temperature and then the lowest temperature that the Peltier element can reach for varying control levels. To record the temperature you can either display it on the seven-segment display or print it out via serial.



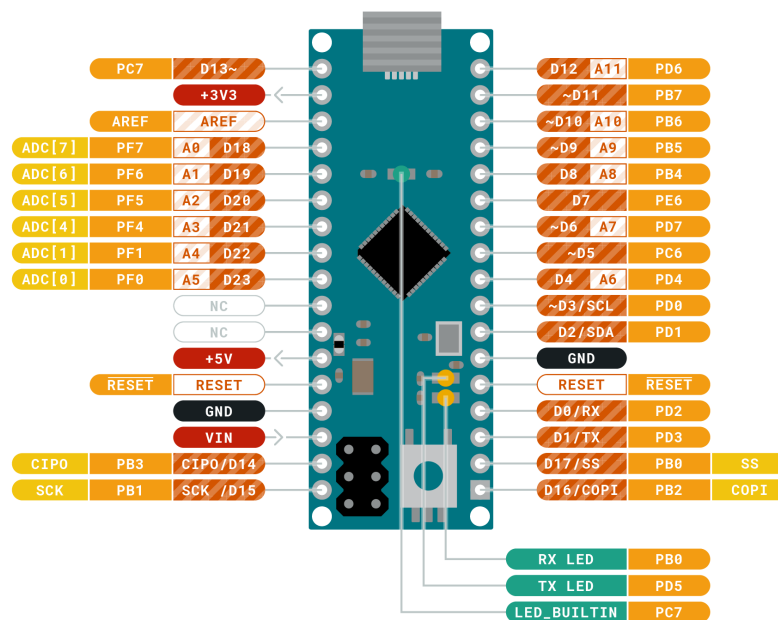
Exercise 17 Now that you have an idea on how cool the Peltier element can get, set it to maximum cooling and turn off the cooling fan. What happens to the temperature and why?

Appendices

A. Arduino Micro Pinout



**ARDUINO
MICRO**



	Ground		Internal Pin		Digital Pin		Microcontroller's Port
	Power		SWD Pin		Analog Pin		
	LED		Other Pin		Default		

ARDUINO.CC



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B. Bill of materials (BOM)

The following table states all components used in this workshop. It assumed that soldering stations and supplies are provided.

Component	Supplier	Article #	Amount	Cost total
Arduino Micro	Digikey	A000053	1	\$20.70
USB Cable	Digikey	102-5943-ND	1	\$2.55
Breadboard	Adafruit	239	1	\$5.95
Breadboard wires	Adafruit	153	1	\$4.95
LED red	Digikey	516-1339-ND	1	\$0.81
LED green	Digikey	516-1334-ND	1	\$0.78
Buttons	Adafruit	367	1	\$2.50
Resistors 1 k Ω	Adafruit	4294	1	\$0.75
Resistors 10 k Ω	Adafruit	2784	1	\$0.75
Display	Adafruit	1002	1	\$10.95
Thermistor	Adafruit	372	1	\$4.00
thermoelectric coolers (TECs)	Adafruit	1335	1	\$34.95
MOSFET	Adafruit	355	1	\$1.75
12 V power supply	Adafruit	352	1	\$24.95
Power jack adapter	Adafruit	368	1	\$2.00
Total cost:				\$118.34

C. Open source design tools

C.1. Calculators

- **Heat sink calculator** to determine if you need a heat sink or not. <https://daycounter.com/Calculators/Heat-Sink-Temperature-Calculator.phtml>

C.2. Designing

- **Fritzing** Makes electronics design accessible. Easy and simple interface to draw some of your own setups, quick to get started with. Suppliers such as Adafruit have Fritzing libraries with components that you can import. <https://fritzing.org/>
- **KiCad** Cross-platform electronics design suite. <https://www.kicad.org/>

C.3. Virtual Hardware

- **TinkerCAD** Electronic playground from Autodesk. Allows you to virtually set up electronic components and write / test code for them. <https://www.tinkercad.com/>