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Variations on a Theme: Physical Computing

by Ralph P. Lano, 1. Edition

For whom

This book is intended for Bachelor students in their first or second semester. It should be used as part of a lecture, since it is probably not suited for self-study. If you are interested to learn about Arduinos and if you would like to understand how to build circuits that work together with those Arduinos, then this book should be useful to you. Very little to no previous knowledge is required.

From whom

Since 2011, I have been Professor of Internet Programming and Multimedia Applications in the MediaEngineering program at the Nuremberg Institute of Technology. From 2003 to 2010 I was Professor of Software Engineering and Multimedia Applications at the University of Applied Sciences Hof, and from 2010 to 2011 Professor of Media and Computing at HTW Berlin. I received my doctorate in 1996 from the University of Iowa on the subject 'Quantum Gravity: Variations on a Theme'. From 1996 to 1997 I was Postdoctoral Research Associate at the Centre for Theoretical Studies of the Indian Institute of Science. From 1997 to 2003 I worked at Pearson Education and later at Siemens AG in software development and project management.

About what

Physical Computing is all around us. Our smartphones, our cars, our washing machines, all are examples of physical computing. Even our toaster has become smart these days. Smart meaning controlled by a micro-controller, and physical computing meaning some electronic components controlled by a micro-controller. If these electronic components are electric motors, magnets or other actuators, then the electronic becomes physical, meaning something moves. But physical also means measuring things like temperature, sound, and light. We want to learn about all these, about electronics, about electronic components, and about micro-controllers.

We start with a little bit of history, not because usually that's what one does, but because many of the concepts and components become really easy to grasp and understand. After having seen some of the origins, we then learn about simple electric circuits and simple electronic components. We get to know batteries, switches, resistors, capacitors and inductors. And we will briefly hear about Ohms law and Kirchhoff's circuit laws. We also get to learn how to use the circuit simulator. Then the active electronic components follow, such as diodes, LEDs, and transistors. We learn about the different type of diodes that there are and what they are used for. We get to know transistors, bipolar and field-effect, and how to use them as switches and as amplifiers. We get to see the multivibrators, especially the astable and the bistable, and learn why they are so important for computers. After these introductory chapters, we have enough of a foundation to do some real physical computing. We will use an Arduino and connect it with the different electronic components we learned about in the previous chapters.

How

does one learn to play the piano? Not by watching or listening. It's the same with everything else: you have to practice a lot! And the more you practice, the better you become at it. That is why, after a brief introduction to the core material we have lab-section, which are all about trying things out, doing experiments. The course as I teach it, consists of three components: the lecture, the labs and assignments. The lecture is two hours per week and corresponds to the first part of each chapter in the book. We complete one chapter in about two to three weeks. In the labs, which also last two hours a week, we then devote ourselves to the experiments. We manage between two or three of the experiments per lab. In the labs, the students work in teams, usually in pairs, to help each other. Before being allowed to take part in the labs, the students have to show that they prepared the labs through their assignments.

Where

can I find the examples? You can find them on the website of the book: www.VariationsOnATheme.eu. Also updates, links to the development environment, and the book in electronic form can be found there. The book in printed form is available on Amazon, in black and white.

May I

use the examples, or copy the book? This material is licensed under Creative Commons Attribution - Non-commercial - Distribution under Equal Terms 4.0 International (CC-BY-NC-SA 4.0). That is, you may reproduce and redistribute the material in any format or medium, remix the material, modify it, and build upon it. However, you must provide appropriate copyright and other proprietary notices, include a link to the license, and indicate whether any changes have been made. This information may be provided in any reasonable manner, but not in such a way as to create the impression that the Licensor is specifically endorsing you or your use. You may not use the material for commercial purposes. And if you remix, modify, or otherwise directly build upon the material, you may distribute your submissions only under the same license as the original, and you may not use any additional clauses or technical procedures that legally prohibit others from doing anything that the license permits. To view a copy of this license, visit <http://creativecommons.org/licenses/by-nc-sa/4.0/>.

Why

The Physical Computing class consists of a 2h lecture and a 2h lab. Hence we needed to focus on the essentials. There are many books out there, most of them either have too much on electronics, or focus only on the Arduino. I wanted a small book, that has the minimum of what is needed to understand the Arduino circuits in the last chapter, assuming next to no previous knowledge. And, I wanted the students to record their experiments like it would be done in a real industrial laboratory notebook. I think this is an important lesson.

Who helped?

I would like to thank Paul Falstad for the Electronic Circuit Simulator which he graciously put under an opensource license. Without his simulator this book would not exist. I would also like to thank the Wikipedia and its thousands of authors. It makes it so incredibly easy to access and use information. In addition, I would like to thank Johannes Brendel and Daniel Baer for their patience and support during the first iteration of this class. Their invaluable feedback made this project orders of magnitude better, than what it would have been. The book should not, but most likely will contain errors. If you find one, please let me know. Be warned that this is only the second iteration, hence I assume it will contain quite a few inconsistencies. I am not very proud of it, because it was created in a hurry, it had to get out there by October 10th, to be used for the fall term. So it did.

References

- [1] Erik Bartmann, Die elektronische Welt mit Arduino entdecken, O'Reilly Verlag, 2011
- [2] Electronics All-in-One For Dummies, For Dummies, by Doug Lowe
- [3] Arduino Cookbook: Recipes to Begin, Expand, and Enhance Your Projects, O'Reilly, by M. Margolis, B. Jepsen, N.R. Waldin
- [4] ITP Physical Computing, <https://itp.nyu.edu/physcomp/>
- [5] Elektronik Kompendium, <https://www.elektronik-kompendium.de/>

Labs and Safety

I am a strong believer in learning by doing. However, doing is sometimes a little more dangerous than not doing. That is why we have to talk about lab safety before we start. We are only dealing with batteries and some static electricity, nothing that you have not encountered before. But shortcircuiting a battery can cause a fire, or touching your precious iPhone or laptop, while statically charged, might be the end of it. That is why we need to be aware of lab safety.

Safety

Safety comes first. Some of the experiments can be dangerous or harmful, they are marked with the label "Instructor". Those are potentially harmful experiments, that should only be done by your instructor or under the direct supervision of your instructor. Especially, people with a heart condition, should be extremely careful. Please let your instructor know if you have or suspect a heart condition.

We will only be working with 9 volt batteries, and those are completely safe, if used properly. Dangerous is anything that has to do with regular electric outlets of 110 or 220 volts: even currents as small as 50 to 100 mA can trigger cardiac arrest [1]. Also dangerous could be static electricity [3]. So again, any of those experiments marked with "Instructor" should be done by your instructor. If through your actions you put others or yourself in danger, disciplinary measures will be administrated. Never perform any unauthorized experiments.

Although a 9V battery may seem pretty harmless, if used in the wrong way, it can cause a fire or even explode. Hence, always follow these simple rules:

- if it starts smelling, disconnect the battery!
- if it starts smoking, disconnect the battery!
- if the battery gets hot, disconnect the battery!
- never leave electric circuits unattended, always make sure you disconnect the battery, before leaving the table or the room.

If any of the above occurs, recheck your circuit. Have somebody else take a look at. If you don't find a mistake, totally disassemble it and start anew.

In addition being harmful to people, electricity can also be harmful to equipment. We expect you to perform all experiments in a serious and professional manner. Some of the equipment is rather sensitive. You are expected to treat all the equipment provided with care.

Preparations

In the labs you will work in teams of two students. You will perform experiments and write down the results of these experiments in your laboratory notebook. Labs will require preparations beforehand, usually given as an assignment. In case you have not done the preparation, you are not permitted to perform the lab. Your instructor will check that you made the necessary preparations before you are allowed to perform any of the experiments. At the end of the labs, your instructor will witness and sign your entries, like it would be done in a real industrial laboratory. Your laboratory notebook is the only proof that you performed the labs, hence do not lose it.

Before attempting to perform any of the experiments in this lab, you need to have done the following preparations beforehand:

- You should know what to do in case of an emergency [2].
- You should know about the dangers of static electricity to people and equipment. (Look for "dangers of electrostatics" on Google.)
- You should know what a short-circuit is, and why it is dangerous.

In addition you should familiarize yourself with the laboratory notebook how to set it up, how to use it, and why it is important. For this please read [4,5].

Laboratory Notebook

You are expected to keep notes of all the experiments you perform in your laboratory notebook. To see examples on how this is done properly, you should read reference [4]. We want to follow reference [7] for the outline of our experiments, which means, all experiments should include:

1. **Title:** The title should be short and descriptive.
2. **Hypothesis:** Briefly describe the intended experiment and what you expect the outcome to be.
3. **Materials:** List the materials needed to perform this experiment.
4. **Procedure:** In the procedure you describe the experiment in a step by step fashion. This should be brief, but contain enough information, such that somebody else, with your knowledge, can repeat the experiment and verify it.
5. **Observations & Results:** What did you observe and what were the results of the experiment? Not all experiments work perfectly, sometimes they don't work at all. Truthfully describe your observations.
6. **Conclusion:** You started out with a hypothesis, in the conclusion section you either verify or falsify your hypothesis. In the scientific method [8], both are equally important.

In case you are interested to learn how laboratory notebooks are used in industry, we refer you to references [5,6].

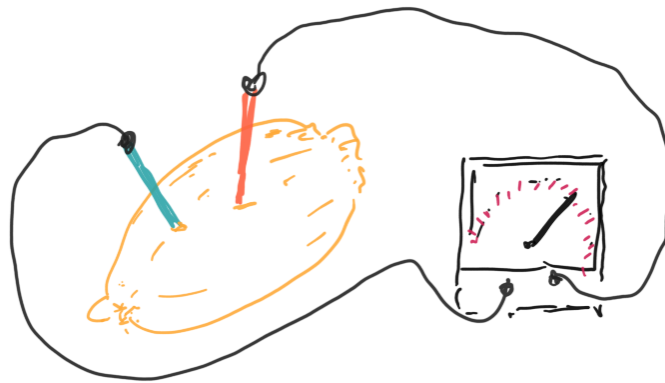
Further Reading

You first *must* read reference [1] on "Electrical cardiac injuries". Even currents as small as 50 to 100 mA can trigger cardiac arrest. Also take a look at table 1 in this reference. In addition, it is required that you read reference [2] on what to do in case of an emergency. If you care about your equipment, like your smartphone and your laptop, then reading the article on "Static electricity and people" [3] might be very enlightening. For German readers the question why the Wikipedia has no German article for the scientific method [8] should be interesting to ponder about.

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- [1] Electrical cardiac injuries: current concepts and management, Victor Waldmann, Kumar Narayanan, Nicolas Combes, Daniel Jost, Xavier Jouven, Eloi Marijon, European Heart Journal, Volume 39, Issue 16, 21 April 2018, Pages 1459–1465, <https://academic.oup.com/eurheartj/article/39/16/1459/3746021>
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- [3] Static electricity and people, Niels Jonassen, <https://incompliancemag.com/article/static-electricity-and-people/>
- [4] Instructions for Using Your Laboratory Notebook, IW Hunter and BJ Hughey, web.mit.edu/me-goffice/communication/labnotebooks.pdf
- [5] How to Start—and Keep—a Laboratory Notebook, www.iphandbook.org/handbook/ch08/p02/
- [6] Guidelines for Keeping a Laboratory Record, David R. Caprette, abacus.bates.edu/~ganderso/biology/resources/Lab_notebook_guidelines_DR_Caprette.pdf
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- [8] Scientific method, https://en.wikipedia.org/wiki/Scientific_method

Introduction



Physical Computing [1] is all around us. Our smartphones, our cars, our washing machines, all are examples of physical computing. Even our toaster has become *smart* these days. Smart meaning controlled by a microcontroller [2], and physical computing meaning some electronic components controlled by a microcontroller. If these electronic components are electric motors, magnets or other actuators, then the electronic becomes physical, meaning something moves [3]. But physical also means measuring things like temperature, sound, and light. We want to learn about all these, about electronics, about electronic components, and about microcontrollers.

A Brief History of Electricity

Electricity was known to humans for a long time [4]. The first one's were the ancient Egyptians, already in 2750 BCE they were writing about shocks from electric fish. The ancient Arabs were the first to make the connection between electric fish and lightning. Ancient Mediterranean cultures knew that rubbing amber with a cat's fur can attract small objects such as feathers.

Then in the 17th century things started to get interesting. In 1663 Otto von Guericke invented the *friction machine*, which produced static electricity [5]. About eighty years later, in 1745, Ewald Georg von Kleist, and independently Pieter van Musschenbroek, invented what is now called the *Leyden jar*, which could store static electricity [6]. Another fifty years later, in 1791, Luigi Galvani connected metal cable to the nerves and muscles of a frog, and was startled when they moved [7]. Alessandro Volta repeated Galvani's experiments, and by refining them invented the *Voltaic pile* [8]. This was the first battery providing constant current. And the rest is history as they say [9].



L'Électrisée, [25]

What is Electricity?

From this brief history lesson we learn, that electricity has fascinated people for thousands of years. Over those years people tried to get an understanding, and they came up with analogies, but also new concepts and ideas. The most important ones are *charge*, *current* and *voltage*. First people identified *charges*. There are two kinds: negative and positive [10]. Electrons, for instance carry negative charge, and protons carry positive charge. Then people realized that these charges can move. And that is what we call a *current*: a current is moving charges, like water currents are moving water. If there are no charges moving, then there is no current. And finally, what makes these charges move? That is what *voltage* is. Only if there is a voltage then charges will move. That is similar to water will move only downhill, if it is flat, water will not move.

Simple Analogy

If you want an analogy, then think of a toy wooden railroad track. The little cars are like the charges. If you put a car on a track, and the track is flat, the car will just sit there. No current flowing. But if the track is inclined, then the little cars will move down the track. Hence we have a current. And the height, is the potential, in this case the gravitational potential, in the case of electrons the electric potential. And another name for electric potential is voltage. By the way, the track for our cars, is like a piece of cooper wire for the charges.



With analogies we always have to be a little careful: it is true, that having more cars, is equivalent to having a higher current. However, if in our train example, we make the slope steeper, then the cars will move faster. Well, for electrons there is no faster. They always move pretty much with the same speed (about half the speed of light). Therefore analogies are helpful, but one needs to know their limits. For most of what we do, the railroad track analogy will work fine.

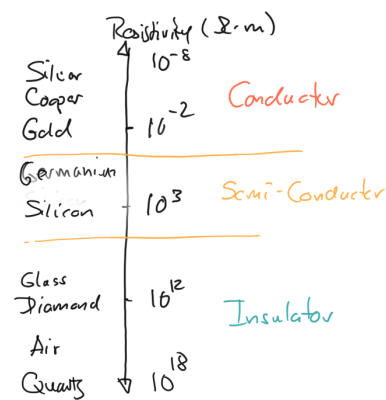
Conductors of Electricity

One more thing we need to talk about, and that is *conductors* [11]. Like in classical music, there are good conductors and bad conductors. Usually metals are good conductors, whereas glass, ceramics, wood, and plastic are bad conductors of electricity. Bad conductors are also called *insulators*. Also air, tends to be a poor conductor. For water it depends: distilled water is not a good conductor, but add some salt and it becomes a decent conductor.

There is one more type of conductor, the *semi-conductor* [12]. Silicon and germanium are semi-conductors. As their name suggests, they are kind of in between conductors and insulators.

How can we distinguish conductors from semi-conductors? Well, there is an interesting temperature dependence of the conductivity: the conductivity of conductors reduces as temperature increases, whereas for semi-conductors it is the opposite way. This may seem pretty useless, but if you consider what the difference the invention of the transistor made, you might think differently about this seemingly useless property.

There is also something called super-conductors, but it is forbidden to talk about those [13].



Review

We took a very brief look at the history of electricity, we learned about charge, current and voltage, and we learned about conductors. We saw that there are analogies, but also noticed, that we have to be a little careful with analogies. In the next section, the labs, we will repeat some of those historic experiments with simple household items.

Labs

Before we start with our first lab section, we need to talk about safety. In case you haven't, you *must* read the chapter on Labs and Safety before proceeding. You will have to sign a statement, stating that you obey by the rules set forth therein.

In the labs you will work in teams of two students. You will perform experiments and write down the results of these experiments in your laboratory notebook. At the end of the labs, your instructor will sign and witness your entries. Laboratory notebooks are used in industrial labs as a primary record of research. It can have an essential role in protecting any intellectual property that comes from the research [17].

Preparations

Labs will require preparations beforehand, usually given as an assignment. In case you have not done the preparation, you are not permitted to perform the lab.

Before attempting to perform any of the experiments in this lab, you need to have done the following preparations beforehand:

- You should know what to do in case of an emergency [14].
- You should know about the dangers of static electricity to people and equipment. (Look for "dangers of electrostatics" on Google.)
- You should know what a short-circuit is, and why it is dangerous.

In addition you should familiarize yourself with the laboratory notebook, how to set it up, how to use it, and why it is important. For this please read [15,16].

Note to Instructors

Equipment needed for the labs in this chapter: alligator clips, aluminum foil, balloons, batteries (1.5V and 9V), coil, copper wire, electroscope, graphite, hot water, ice cubes, iron nails, Leyden jar, lighter, multi-meter, potato/lemon, saran wrap, silicon, small iron nail or needle, small magnet, small solar cell, thread, PVC pipe, towel, blue LED, resistor, anti-slug copper strip.

Experiments

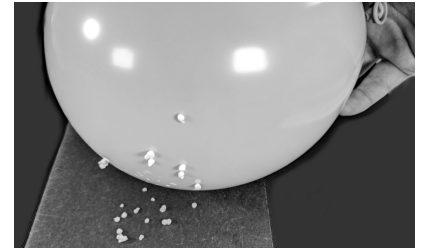
In this lab we will learn some of the physical principles behind electric components. We actually build a whole bunch ourselves: we learn how to make our own resistor (graphite), capacitor (alu+saran), and inductor (wire+nail). We also learn how to use a multi-meter to measure voltage, current, resistance, capacitance, and inductance.

1. Balloons

Equipment: children's balloons, t-shirt.

One of the simplest demonstration of static electricity is with children's balloons. Simply rub the balloon on a synthetic cloth, like a t-shirt for instance, and then hold it to the wall. The balloon should stick to the wall for a little while. If you have feathers, small Styrofoam pieces or small pieces of paper, they should be attracted to the balloon.

Question: Why is that?



2. PVC Pipe (Instructor)

Equipment: PVC pipe, towel.

IMPORTANT: No computers, smart phones, smart watches or any other electronic devices should be near static electricity!

Since most of us do not have cat fur and/or amber at our disposal, nowadays we use towels and PVC pipes instead. Basically the same idea as with the balloon, but a little more effective is the PVC pipe. You need a PVC pipe and a towel. Rub the PVC pipe with the towel for a few times. Some techniques are more efficient than others. You will notice that small pieces of paper get attracted or repelled by the PVC pipe.



3. Electroscope (Instructor)

Equipment: electroscope, balloons, PVC pipe, battery, towel.

IMPORTANT: No computers, smart phones, smart watches or any other electronic devices should be near static electricity!

In our first two experiments we saw how to create static electricity. But how do we measure electricity [18]? Well, you can use little pieces of paper and see if they get attracted. Or you could touch the electric fish, or touch the PVC pipe and get an electric shock, not recommended. That is at the minimum unpleasant, and depending on the voltage even dangerous. You could also use frog legs, if you happen to have them handy.

Alternatively, we can use an electroscope. With simple household items, we can actually build our own. Use the balloon or the towel and PVC pipe to generate static electricity. Try to connect a battery to the electroscope. Which of the three methods creates the most static electricity?



4. Leyden Jar

Equipment: electroscope, Leyden jar.

A Leyden jar [6] is basically a capacitor. Like the electroscope, it is really easy to build our own Leyden jar. Take an empty plastic bottle, fill it with water, add a little salt and close it. Through the lid you stick a nail, and finally wrap aluminum foil around it. Once build, we can use the multi-meter to measure the capacitance of our Leyden jar.



5. Ground (Instructor)

Equipment: electroscope, Leyden jar, anti-slug copper strip.

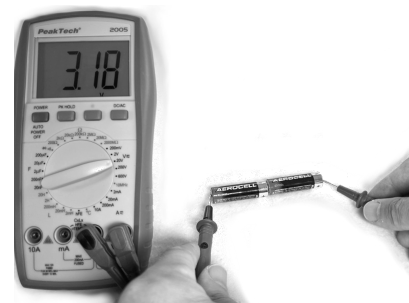
It is time to learn about what electrical engineers refer to as "ground" [24]. You may want to watch video [19] to learn a little more about ground. If you repeat the above experiments with the PVC pipe, the Leyden jar (and later the capacitor), with the aluminum foil being connected to ground, you will notice that all the effects are significantly stronger.

I hope it is clear, that Mehdi Sadaghdar, also known on YouTube as ElectroBOOM [19], is an electrical engineer. That means he knows what he is doing. You should not attempt to repeat any of his experiments! Still they are very entertaining and instructional.

6. Measuring Voltage

Equipment: multi-meter, two 1.5V batteries.

Another way to measure electricity is with a voltmeter, or in our case a multi-meter. To get started we want to measure the voltages of batteries. First, just measure the voltages individually, then connect two 1.5V batteries in series, that means the plus of one 1.5V battery connected to the minus of the other 1.5V battery. You can look at reference [20] if you need additional help.

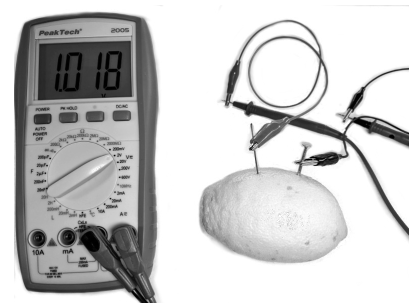


7. Homemade Battery

Equipment: multi-meter, potato/lemon, aluminum foil, copper wire, alligator clips, iron nail.

First, take aluminum and connect it to the multi-meter using alligator clips. Then moisten your fingers, touch the aluminum and the other lead of the multi-meter, and measure the voltage. Try this with different metals like iron or copper. [21]

Second, stick a piece of copper wire and an iron nail into a potato or lemon. Measure the voltage using the multi-meter. Again use different metals, and for each combination measure the voltage difference. Does it make a difference if you use a potato or a lemon?



Questions:

1. What other ways are there to create electricity?
 2. How do you know if a battery is full or empty?
 3. Assume you want to create a battery with a voltage of 1.1 volts. Which metals would you use?
- [22]

Another interesting experiment is the Aluminum Air Battery [23].

Introduction

8. Resistance

Equipment: multi-meter, two hands.

Set your multi-meter to measure resistance (Ohm). Then hold the two leads between your fingers, and see what resistance your body has. Now moisten your fingers and repeat the experiment. You should notice that the resistance is less now.



9. Conductance

Equipment: multi-meter, copper wire, coil, graphite, alligator clips.

Use your multi-meter to measure resistance. First, start with a piece of copper wire. Take a short piece and measure it. Then use the coil and measure its resistance. According to Amazon, it is 280 meters long (all eight or only one wire?).

Second, use graphite pencil leads. Take the following measurements:

- full length pencil leads 0.5mm
- full length pencil leads 0.7mm
- half length pencil leads 0.5mm
- two half length pencil leads 0.5mm connected in series
- two half length pencil leads 0.5mm connected in parallel

Record their respective conductance. Conductance is the inverse of resistivity.

Question: What are the units of conductance? How could you estimate the length of the above wire via its resistance?



10. Resistor

Equipment: multi-meter, graphite, alligator clips.

Make your own resistor out of graphite pencil leads. First, measure the resistance of the graphite in ohm. Then make your own resistor that has the resistance of exactly 4 ohms. This is basically how a carbon film resistor works.

Question: Could you also create a variable resistor?

11. Capacitor

Equipment: multi-meter, aluminum foil, saran wrap, blue LED, alligator clips, 9V battery.

Another way to build a capacitor is with aluminum foil and saran wrap. Make a sandwich, starting with a layer of saran wrap, followed by aluminum foil, another layer of saran wrap, and another layer of aluminum foil. Have two thin pieces of additional aluminum foil stick out perpendicular for contacts to the two different layers of aluminum foil. Roll the whole thing up like a burrito, but make sure that the two different aluminum foils don't touch each other. You may want to add a third saran wrap layer, just to make sure.

1. Use the multi-meter to measure capacitance of your "burrito".
2. Charge your "burrito" with a 9V battery. Connect the blue LED. If connected in the right way, it should light up briefly.



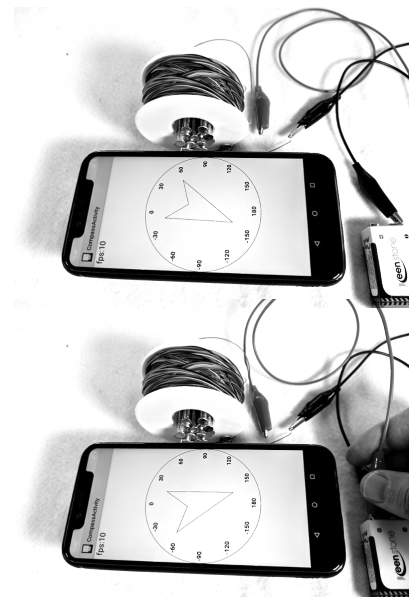
12. Coil

Equipment: multi-meter, coil, iron nails, compass.

A current flowing through a coil will generate a magnetic field. Use the multi-meter to measure the inductance of the coil in Henry. Now place some iron nails in the inside of the coil and measure the inductance again. The coil consists of eight wires. Instead of using just one wire, use two and then three wires, in series. Each time measure the inductance.

If you connect the coil to the 9V battery, you can create a measurable magnetic field. If your smartphone has a magnetic sensor, you can use a compass app to measure it. You can also use an old school compass instead.

Question: How does the inductance depend on the number of turns?



13. Homemade Ammeter (Instructor)

Equipment: coil, iron nails, thread, small iron nail or needle, small magnet.

Use the coil and add some nails in the inside. Connect to 9V battery only briefly! Measure the magnetic field with your smartphone (in case your phone has a magnetic sensor). Build your own ammeter by suspending a nail or a magnet from a tripod just in front of the coil. The nail should move, when the coil is connected to the battery. The more current the more it will move. This is basically how an analog ammeter works. Next, your instructor should use the multi-meter to measure the current flowing through the coil (should be about 1 ampere, which is a lot).

Questions:

1. If your battery is rated 800mAh, how long will it take to drain your battery (assuming 1 ampere of current is drawn)?
2. Why do we add nails to the coil?

Challenges

1. Conductor vs Semi-Conductor (Instructor)

Equipment: multi-meter, copper wire, graphite, silicon, hot water, ice cubes, lighter.

We have learned about conductors, semi-conductors and insulators. There is an interesting temperature dependence for the different materials, which we can measure.

First, we look at a conductor, graphite (pencil lead). Measure its resistance using a multi-meter. Next, use a lighter or a candle to heat it up a little, while still measuring the resistance. Notice that the resistance changes. (You could also use any metal wire, just the effect is smaller).

Next, use silicon, a semi-conductor. Put it in hot, distilled water and measure the resistance. Then add ice cubes (made from distilled water) to the water and observe what happens to the resistance.

Questions

1. Name three ways to generate electricity.
2. Which one has the higher resistance?
 - pencil lead of 0.7 mm thickness
 - pencil lead of 0.5 mm thickness.

Introduction

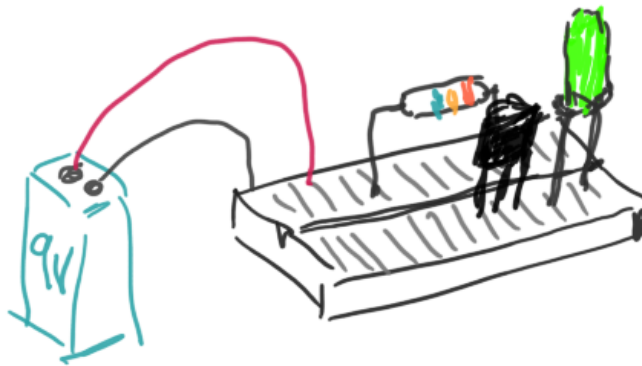
3. The galvanic cell corresponds to a
 - capacitor
 - resistor
 - transistor
 - battery.
 4. Give an example each for a conductor, a semiconductor and an insulator.
 5. Describe how you can build your own capacitor out of aluminum foil and saran wrap.
-

References

If you never heard about any of the things we talked about today, it may make sense to read the Wikipedia articles [1-5]. The textbook "Lessons in Electric Circuits" has a decent introduction into static electricity. You may want to read chapter 1 [7]. There is also the German "Elektronik Kompendium" website and book, and you may want to read the first four chapters under the "Elektrotechnische Physik" heading ("Atome, Elektronen und Ionen", "Elektrische Ladung", "Elektrische Spannung", "Elektrischer Strom / Elektrische Stromstärke") [8]. Finally, there is the "Electronics" Wikibook [9]. It is o.k., but very brief.

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- [2] Microcontroller, <https://en.wikipedia.org/wiki/Microcontroller>
- [3] Actuator, <https://en.wikipedia.org/wiki/Actuator>
- [4] Electricity history, <https://en.wikipedia.org/wiki/Electricity#History>
- [5] Electrostatic Generator, https://en.wikipedia.org/wiki/Electrostatic_generator#History
- [6] Leyden jar, https://en.wikipedia.org/wiki/Leyden_jar
- [7] Luigi Galvani, https://en.wikipedia.org/wiki/Luigi_Galvani#Galvani_vs._Volta
- [8] Voltaic pile, https://en.wikipedia.org/wiki/Luigi_Galvani#Galvani_vs._Volta
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- [10] Discovery of two kinds of charges, https://en.wikipedia.org/wiki/Electron#Discovery_of_two_kinds_of_charges
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- [25] Hubert-François Gravelot: Die Elektrizierete, Wikipedia, the original uploader was Rainer Zenz at German Wikipedia. / Public domain, <https://commons.wikimedia.org/wiki/File:Elektrisiertmaschine.jpg>

Electronic Components



In this chapter we learn about simple electric circuits and simple electronic components. We get to know batteries, switches, resistors, capacitors and inductors. And we will hear about Ohms law and Kirchhoff's circuit laws. Towards the end we will also see logic gates for the first, but not the last time. We also need to learn how to use the circuit simulator.

Electronic Components

In the labs of the last chapters we met and made our first electronic components: resistors, capacitors and coils. In general, one distinguishes between:

- active components: such as batteries, transistors and diodes,
- passive components: as there are resistors, capacitors and coils, among many others, and
- electromechanical components: switches, motors, or fuses, for instance.

In this chapter we will learn mostly about passive components. In what follows, we get to know all kinds of electronic components [1], what they do and how they work, and how to connect them together to all kinds of different circuits.

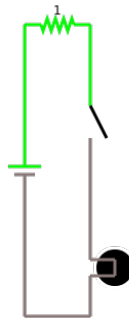
AC/DC

The Wikipedia says "AC/DC are an Australian rock band formed in Sydney in 1973 by Scottish-born brothers Malcolm and Angus Young." [2]. You may never have heard of AC/DC (probably a good thing), but you will hear a lot about DC in this class, and a little about AC. DC stands for *direct current*, the type of current that comes out of batteries. AC stands for *alternating current*, the type that comes out of the electrical outlets in your walls. DC is a lot simpler and somewhat less dangerous than AC. For now, we will only deal with DC.

Electric Circuits

According to the thesaurus, the word *circuit* is a synonym for circle or cycle [3]. In electronics it refers to a bunch of electronic components, such as batteries, switches and lamps connected together with wires, such that they form a cycle, i.e., there are no loose ends.

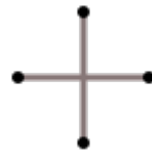
As an example, consider what happens when you turn on your light at home. We can represent this in a circuit diagram, which would look something like the following:



battery, switch and lamp

In a circuit diagram we represent each circuit by its circuit symbol, and wires are depicted as lines connecting those symbols. Usually, there is a circuit where the electricity comes from: here it is a battery, at home it is AC coming from the electric outlet. Then there is a light bulb and a switch. Each has its diagram. They are all connected by wires. And once you close the switch, the light goes on.

Something we should be aware of is how crossings of wires are depicted in our diagrams. The subtle difference is the dot in the center of the diagram below. It means that in the diagram to the left the wires are not connected, whereas on the right they are.



wires not crossing



wires crossing

We can simulate the behavior of electric circuits in a simulator, before we attempt to build the real thing. This is usually a good idea, just to make sure it is working. We will learn about the simulator in the labs.

Battery

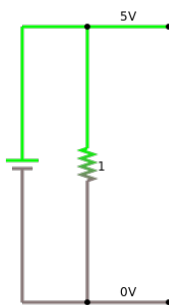
Let's first start with the battery. There is all different kinds, with all kinds of voltages. But they all have two things in common: they produce DC, and they have a plus and a minus pole.



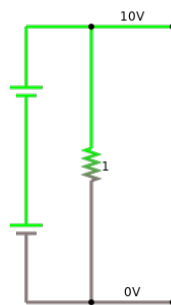
Now let's briefly talk about them electrons. They are negatively charged, and they are all located at the minus pole of the battery. That is why it is minus. Now there is lots of electrons there (really lots). And electrons don't like each other very much, that is why they repel each other. And if they have a chance to get away, they will. So, if we happen to take a piece of wire and connect the minus pole of the battery to the plus pole, all those electrons will just start running. And since there are so many of them, it gets hot. We call this a "short circuit". Generally, short circuits are bad, so usually we want to slow the electrons down a little. That's why we need resistors.

But before talking about resistors, let's talk a little more about batteries. Basically, most batteries are voltaic cells (named after Alessandro Volta). The most common one's have 1.5 volts, but there is also the 9 volt kind, that we will be using a lot. In the examples here, we will use 5 volt batteries. You can't buy those, but you can take three 1.5 volt batteries, connect them in series and you get 4.5 volts, close enough.

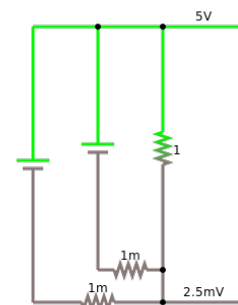
What did I mean, when I just said "we connect them in series"? Well, if we have two (or more) batteries, then we can connect them in several different ways, and the two important one's are to connect them "in series" and "in parallel":



single battery



batteries in series



batteries in parallel

When we connect batteries

- in series, the voltage doubles,
- in parallel, the voltage stays the same.

Notice, how the plus pole and minus pole of the batteries are connected. It is not a good idea, to connect them in any other way.

Short Circuit

Short circuiting [4] a battery is very dangerous! It can cause a fire or even an explosion! That is why we need to know about short circuits and how to recognize them. A short circuit is whenever you directly connect the plus pole and minus pole of a battery. This can happen directly or indirectly, as depicted in the following two diagrams:



short circuit of a single battery



short circuit of two batteries

Although a 9V battery may seem pretty harmless, if used in the wrong way, it can cause a fire, or in extreme cases they even might explode. Just search for "lithium ion explosion" on YouTube, and you will know what I am talking about.

There are several steps to make sure you do not have a short circuit:

1. double check your setup before connecting the battery,
2. have somebody else double check your setup (four-eyes principle [5]),
3. run your setup in a simulator, most simulators check for short circuits,
4. use an ohm-meter in place of the battery, before connecting the battery. If the ohm-meter reads zero ohms, you have a short circuit, and you should not connect the battery.

Despite taking all these precautionary measures, it might still happen that you have a short circuit. How do you know that you have a short circuit? Any of the following are signs that you have a short circuit:

- if it starts smelling,
- if it starts smoking,
- if it gets hot.

Any one of those is a sign that you have a short circuit! In case that happens:

Disconnect the battery!

This is also, why you should never leave an electric circuit unattended. Even for a short toilet break, disconnect the battery! Never leave an electric circuit unattended!

Direction of Current

Historically, people were thinking that the carriers of charge were positively charged. They did not know that electrons were negatively charged. So for them, the current was flowing from the plus pole of the battery to the minus pole. Only after J. J. Thomson discovered the electron, did we know [6]. But nobody ever had the guts to change that convention, and hence we are still stuck with this stupid convention. Although we know now it is the electrons that are the charge carriers, and it is the electrons that do the moving, and they really move from the minus pole to the plus pole, the convention still is to say that the current flows from plus to minus. Sorry. Interesting enough it makes no difference.

Resistor

Resistors restrict the flow of current. Too much current, like too much alcohol, is not good. That's why we need resistors. Resistance is measured in *Ohms*. Right, that is the Georg-Simon guy our university is named after.

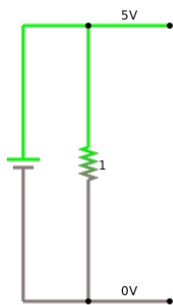


$$I = \frac{V}{R}$$

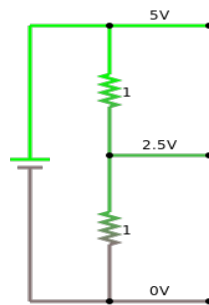
For resistors, there is an interesting relation between current and voltage, which is called Ohm's law [7]:

It says that if you have a voltage of 1 volt [V] and a resistance of 1 Ohm [Ω], then a current of 1 ampere [A] is flowing. If you increase the resistance, the current goes down, if you decrease resistance, current goes up. If the resistance is zero, you have a problem: we call this a "short circuit".

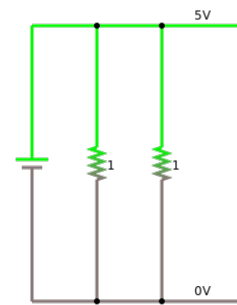
Like with batteries, once we have more than one resistor, we can place them in series or in parallel:



single resistor



resistors in series



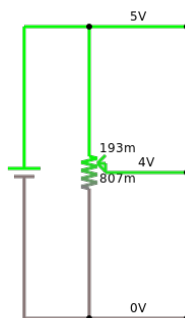
resistors in parallel

Resistors have two very important applications:

- Protector, i.e. resistors limit the current flowing through components, hence protecting them, an LED for instance.
- Voltage divider: i.e., resistors can be used to divide a voltage, which is to say, allow us to create an arbitrary voltage between zero and the voltage of the battery.

Variable Resistor

Normal resistors are constant, meaning their resistance does not change. However, there are also resistors whose resistance changes. The simplest one being the potentiometer, sometimes also called trimmer. You can change its resistance by either moving a lever (old style, several hundred years ago) or turn a knob (new style, only a hundred years old):



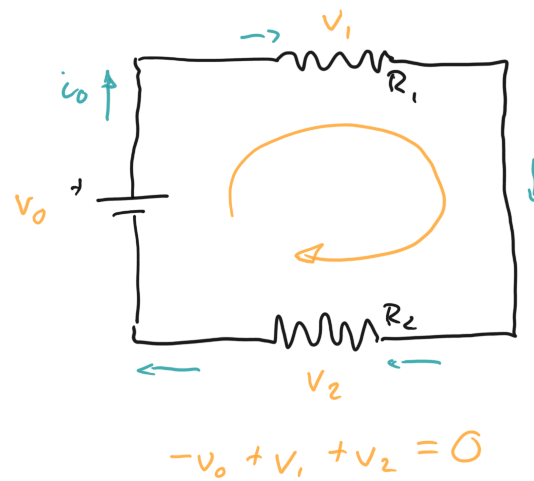
potentiometer

There are also variable resistors that change their resistance depending on temperature, and others that change their resistance depending on light intensity. Others change their resistivity when stretched, others when shouted at, called microphone.

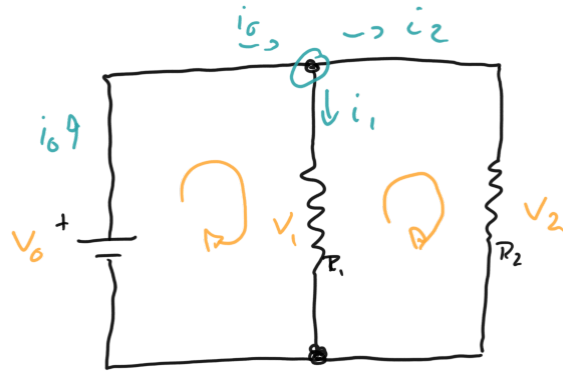
Kirchhoff's Circuit Laws

Some people like to play computer games, other people like to do Sudokus, others do cross-word puzzles. Electrical engineers, however, love to calculate what the voltages and currents are at different locations in a given electrical circuit. Since you decided to become an engineer (it was not my decision, mind you!), you got to change habits (no more computer games), meaning you got to learn about them Kirchhoff Laws [8]. Lucky for you, there is only two of them.

We start with the second one, Kirchhoff's Voltage Law: all voltages in a closed circuit add up to zero. The tricky part in the second law is the sign of the voltage. Basically, the direction of the current, gives the sign of the voltage. Except for batteries, there it is reverse. So basically we look for loops, and for every component we have, we write down a voltage. In the example below, that is for the battery, v_0 , for the first resistor, v_1 , and for the second resistor, v_2 . Since those three components form a loop, these voltages have to add up to zero. And since v_0 is a battery, it gets a minus sign. Easy.



The other Kirchhoff law, the first one, is also called the Current Law: all the currents coming in and out of a *node* add up to zero. A node is where a bunch of wires come together. And usually currents going into a node get a plus sign, and currents going out, get a minus sign. In the diagram below there are two nodes. We just worry about the upper one (in this case the lower one gives the same result). As you can see, there is i_0 coming into the node, and i_1 and i_2 are coming out of the node. Hence, i_0 gets a plus sign, and i_1 and i_2 each get a minus sign. These three currents all must add up to zero.



In addition, you see that in this example, there are also two loops. So from Kirchhoff's second law we get two more equations. And turns out, if you are good at math-gymnastics, that is enough to calculate all the voltages and currents in this circuit.

$$\begin{aligned} -v_0 + v_1 &= 0 \\ -v_1 + v_2 &= 0 \\ i_0 - i_2 - i_1 &= 0 \end{aligned}$$

Conservation Laws

Now once in a while it is good idea to stop for a moment, and appreciate the philosophical deepness of certain statements. We will do this a couple of times in these lectures, this one being the first time. We call this enlightenment, and at least in my opinion, we still live in the age of enlightenment [9], one of the few great contributions of Europe to the World (although most of the world does not know about it).

Kirchhoff's first law, is nothing but the conservation of charge. Kirchhoff's second law, is simply conservation of energy put in another form. So both of them are conservation laws. Where do conservation laws come from? Well, since we mentioned Georg-Simon Ohm's name, let us also mention another person's name, of local origin: Emmy Noether [10]. Emmy Noether proved that:

"If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time."

American physicists Leon M. Lederman and Christopher T. Hill argue in their book *Symmetry and the Beautiful Universe* [11] that Noether's theorem is "certainly one of the most important mathematical theorems ever proved in guiding the development of modern physics, possibly on a par with the Pythagorean theorem". Albert Einstein described her as the most important woman in the history of mathematics [12].

Just to emphasize this a little more: there is not a single physical theory that is not a consequence of Noether's theorem. All of modern physics, that is QED, QCD, electroweak theory and Einstein's theory of gravity are all a consequence of Emmy Noether's theorem! If that does not impress you, nothing will.

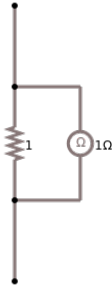
Measurement

So how do we know that the Kirchhoff laws actually are correct? Well, we check, meaning we measure. For measuring DC we usually use a multi-meter device, that can measure voltage, current and resistance. For now we do not need to understand the internal workings of a multi-meter, but we need to be aware that depending on what we want to measure, we have to use the multi-meter in slightly different ways:

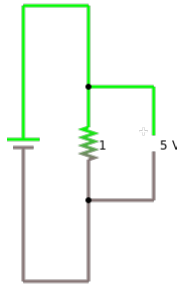
Electronic Components

- Resistance: when measuring resistance, the component is *not connected* to the battery, and we simply connect it to the multi-meter.
- Voltage: we measure voltage across a component, while it is connected to the battery.
- Current: we measure current that goes through a component by inserting the multi-meter in front or after the component, also while it is connected to the battery.

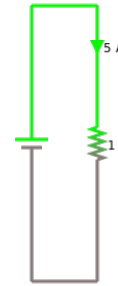
And the multi-meter has to be set to the respective settings, sometimes you also have to use different terminals, depending on the IQ of your multi-meter. Most multi-meters are stupid, so you have to be smart. Below are the diagrams depicting the different ways these measurements are done:



measuring resistance



measuring voltage



measuring current

When measuring current, you have to be careful not to break the multi-meter. Please use the four-eye principle before trying to measure current. On average, about half of the multi-meters in our labs get "fried", because students have not been careful when trying to measure current!

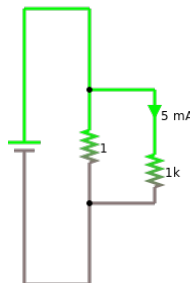
Voltmeter

We learned how to measure charge (electroscope) and how to measure current (ammeter = coil + needle). But how do we measure voltage? From what we just learned, the way we measure voltage is by connecting the voltmeter parallel to the component we want to measure. Now if we remember Ohm's law,



$$I = \frac{V}{R}.$$

we can calculate the voltage, if we know the resistance R and the current I . So we build our voltmeter out of our ammeter and a known resistor (1 kOhm, for instance). Then instead of measuring voltage, we measure current, and multiply by the resistance (times 1000, for 1 kOhm) to get the voltage. Pretty smart, or?



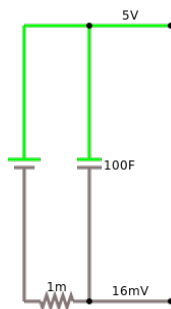
voltmeter

Capacitor

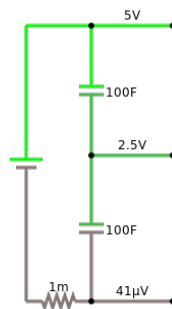
There are two more components we need to talk about and that is capacitors and inductors. A capacitor is basically two metal plates separated by air or some insulator. The Leyden jar is a capacitor and our burrito is a capacitor. By themselves capacitors are pretty useless, except for energy storage. But together with other components, and especially when dealing with AC, they become really useful.



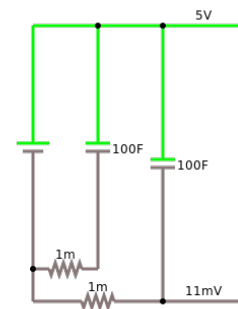
Like resistors, capacitors can be placed in series and in parallel:



single capacitor



capacitors in series



capacitors in parallel

Capacitors have three very important applications:

- Energy store: a capacitor stores "energy" like a battery (in the electric field).
- Gate: a capacitor will not let DC pass, but it will let AC pass.
- Timer: since it takes some time for a capacitor to charge (or discharge), they are very often used for "timing".

Inductor

When an electric current runs through a wire, it creates a magnetic field. Turns out that when you wind the wire up in a coil, the magnetic field gets stronger, the more turns the stronger the field. Such a coil is called an *inductor* and has a couple of useful properties. We need to learn about inductors, because motors, relays and servos are inductors. As such they have the property to *induce* current into our circuits (hence the name). This inducing of current sounds pretty innocent, but not to our Arduinos: they tend to get killed by those induced currents. So to protect our Arduinos, we need to learn about inductors.



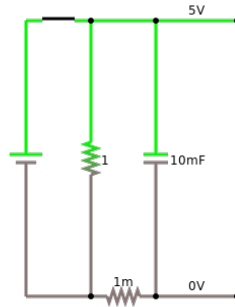
Inductors have four important applications:

- Energy store: an inductor can store energy (in the magnetic field).
- Magnet: an inductor always has a magnetic field, which can be used to lift or move things (electromagnet, motor, servo, relays).
- multi-meter: basically all analog multi-meters use a coil to move their needle.
- Transformer: out of two inductors you can make a transformer, but only with AC.

And last but not least, almost all loudspeakers use coils.

Kirchhoff and Ohm Revisited

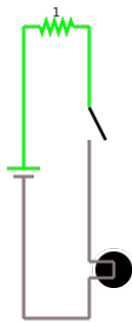
Kirchhoff's laws are conservation laws, and therefore they are always valid. Ohm's law on the other hand is only true for resistors. So if we are dealing with capacitors, inductors or any other electronic components other than resistors, then Kirchhoff's laws still hold true, but Ohm's law is not valid. To see this, let us consider the following circuit in detail:



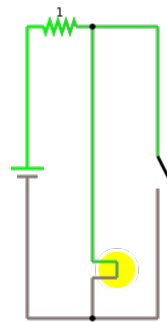
Kirchhoff's laws

Switch and Logic Gates

Let's return to the switch for a moment: it seems to be the most trivial of all components. Which is kind of true. Still it has some nice surprises for us. We start simple, and take a look at the following two circuits:



switch and lamp

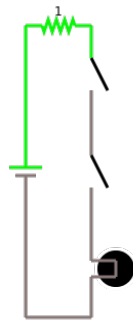


NOT gate

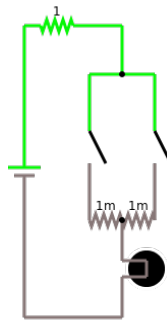
The first is really trivial: you turn on the switch, the light goes on, you turn the switch off, the light goes off. But, in the second circuit it is the reverse. That's kind of cool. What we have is a logic NOT gate: if the switch is on, the light is off, and vice versa. We can write this down in what mathematicians call a truth table:

Switch	Light
off	on
on	off

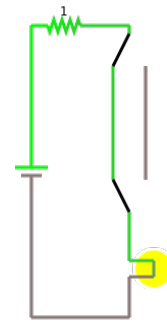
It turns out that using switches, we can build all the logic gates mathematicians know about. Here are examples for the AND, the OR and the XOR gates:



AND gate

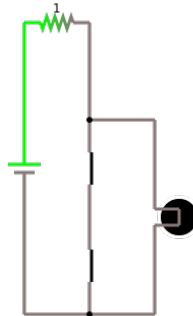


OR gate



XOR gate

And finally, there is one very special logic gate, the NAND gate:



NAND gate

There will be another philosophical comment on the NAND gate, but that will have to wait a little.

Review

This chapter introduced us to electric circuits and electronic components such as batteries, resistors, all kinds of variable resistors, capacitors and inductors. We briefly heard about AC and DC, as well as the direction of current. We talked about short circuits and their potential dangers. We saw how to measure resistance, voltage and current, and got to know Ohm's and Kirchhoff's laws. We now know what the difference is between putting things in series or in parallel. At the end we even met the logic gates. I would call this an intellectual tour de force.

Labs

In this lab we will learn about simple circuits and passive electronic components such as resistors, variable resistors, capacitors, and inductors. We will also use Ohm's law, and verify Kirchhoff's circuit laws.

Preparations

Before attempting to perform any of the experiments in this lab, you need to have done the following preparations beforehand:

- you must have read the article on short circuits [4],
- you must be able to identify plus and minus pole of a battery,
- you must know how to measure voltage vs current,
- you must know the color codes of resistors,
- you must know the difference between putting components in series and in parallel.

You should also draw all the needed circuit diagrams for the different experiments below, before you come to lab. If something is unclear, please ask one of the instructors before attempting the experiment!

Note to Instructors

Equipment needed for the labs in this chapter: Arduino box, alligator clips, multi-meter, 9V battery, inductors. Mark the Arduino boxes with the students names, so that every group gets the same box again.

0. Circuit Simulator

Before you start with the experiments, make sure you make yourself familiar with the circuit simulator, appendix C. You should make sure that you try out the simulations of each experiment first. Because, if the simulation does not work, the real experiment will definitely not work!

1. Resistor

Equipment: Arduino box, multi-meter.

Familiarize yourself with the color code of resistors [13]. Important is the third ring, and the important colors are black (=0), brown (=1), red (=2), orange (=3), yellow (=4). Also notice red-red-red is 2.2 kOhm, also denoted as 2K2.

Take a couple of different resistors from the Arduino box, try to predict their resistance using the color code. Then use the multi-meter to verify your prediction.

Question: what would you guess is the next color after yellow?

2. Resistors in Series and in Parallel

Equipment: Arduino box, multi-meter.

When you put resistors in series, their values simply add up:

$$R_{total} = R_1 + R_2.$$

If you put them in parallel, their inverses add up:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2}.$$

Verify this by putting two 10 kOhm resistors first in series and then in parallel. Use the multi-meter to measure the total resistance in each case.

3. Protector

Equipment: Arduino box, multi-meter, 9V battery, LED.

One of the most important applications of the resistor is that of the protector. Let's consider an LED. The current going through an LED should be around 20 mA. If the current is much higher, the LED will die.

If you recall Ohm's law:

$$I = \frac{V}{R}.$$

We can find the required resistance for a given voltage and current:

$$R = \frac{V}{I}.$$

We have a 9V battery, and the current flowing should be 20 mA. With this you can calculate the required resistance to protect the LED. Most of the time, you will not find exactly the right resistor. In that case, you pick the closest one, that is a little higher than the calculated one.

Build the circuit consisting of the battery and the resistor. Do not add the LED yet. Now measure that the current through that circuit is less than 20 mA. Once you verified that, add the LED. (Make sure LED and resistor are in series! And, LEDs only work in one direction, its cathode should be connected to minus.)

4. Voltage Divider

NOTE: use resistors with high resistance, like the 1kOhm, 4.7kOhm and 10kOhm!

Equipment: Arduino box, multi-meter, 9V battery.

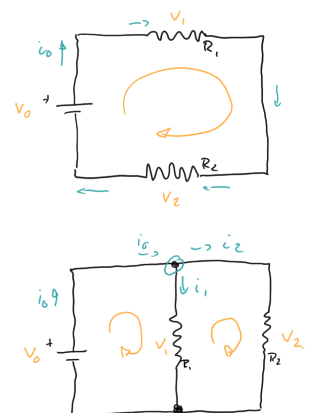
Another important applications of resistors is that of the voltage divider. Assume, you need a voltage of something like 3 volts. How do you do that? You put two resistors in series and use Kirchhoff's law to calculate the value of the voltage in the middle. Draw a circuit with a 9 volt battery and the two resistors, and write down all the voltages. Then build the circuit, and verify your calculation. Maybe use the 4.7 kOhm and the 10 kOhm for a first try.

5. Kirchhoff's Circuit Laws

Equipment: Arduino box, multi-meter, 9V battery.

Important: Before attempting to do this experiment, make sure you understand how to measure current! If you are not certain, please ask your instructor.

In class we learned about Kirchhoff's circuit laws. We want to verify them by building the two circuits to the right. Use two resistors of more than 1kOhm for R_1 and R_2 , but make sure they are different. Then first calculate all the voltages and currents in these circuits. Finally, verify this, by measuring the voltages and currents with the multi-meter.



6. Potentiometer

Equipment: Arduino box, multi-meter, 9V battery.

The simplest variable resistor is the potentiometer. Basically, our simple graphite pencil lead resistor already was a variable resistor. They are very practical. A very common application is to use them as a continuous voltage divider. Build the circuit example from class, using a 9V battery, and show that you can create any voltage between 0 and 9 volts this way.

First, use multi-meter in ohm setting, to see which pins of the potentiometer you need to connect to where.

7. Variable Resistors

Equipment: Arduino box, multi-meter.

There are also other variable resistors. In our Arduino box, there are two: one for light and one for temperature.

The light depending resistor (LDR) (also called photoresistor or phototransistors [14]) changes its resistance depending on the amount of light entering it. The one in our Arduino box looks like a transparent LED. Simply connect the two leads to our multi-meter and measure resistance. You will notice that the resistance changes depending on the light entering the LDR. Also notice, that it makes a difference which way you connect the LDR. For now, we don't have to worry about this.

Our Arduino box also contains a temperature sensor, the TMP36 to be exact [15]. The TMP36 looks like a transistor. We connect the two outer terminals to our multi-meter and we measure resistance. You can warm up the TMP36 by holding it in your hands. You will notice how the resistance changes, depending on temperature. Again, it seems to make a difference which way you connect the TMP36.

8. Capacitor

Equipment: Arduino box, multi-meter, 9V battery, blue LED.

First, take one of the electrolytic capacitor from the Arduino box and measure its capacitance with the multi-meter.

Second, connect the big electrolytic capacitor (100 uF) with the 9V battery. Be careful about the polarity, i.e. connect the minus of the capacitor to the minus of the battery. Then connect the capacitor to one of the blue LEDs. If you connect it correctly, the LED should light up briefly. (Don't do this too often, or with a very strong capacitor, it might destroy your LED.)

Third, we want to put capacitors in series and in parallel. Theoretically, when two capacitors are put in series, their inverses add up:

$$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2}.$$

However, if they are put in parallel, their values simply add up:

$$C_{total} = C_1 + C_2.$$

This is very different from the way resistors behave. Verify this by putting two capacitors first in series and then in parallel. Use the multi-meter to measure the total capacitance in each case [16,17].

Fourth, we want to measure the voltage over time. To do this, you measure the voltage a) while charging the capacitor and b) while discharging the capacitor. Make a measurement like once a second, write your observations down in a table, and then use the table to draw a graph using the graph paper provided.

9. Generator

Almost all electric motors can also be used as electric generators. Connect the motor to the multi-meter, which should be set to measure volts. Depending on how fast you turn the motor, you may want to select the AC setting. However, if you turn your motor slowly, the DC setting should work fine. Turn the motor and notice that there is a voltage.

Because electric motors also are generators, they are potentially dangerous for our Arduino, because if they generate more than 3.3 volts, and very often they do, it will kill our Arduino, unless we know how to protect it (next chapter).

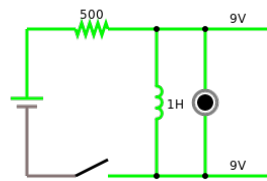
10. Inductor

Equipment: Arduino box, multi-meter, inductor. Could also use motor for this!

For this experiment, you should use one of the inductors or the coil might also work.

First, take one of the inductors provided and measure its inductance with the multi-meter.

Second, we should also be able to use inductors to store some energy. For this, build the following circuit:



inductor

As long as you keep the switch closed, the current flows through the inductor, creating a magnetic field. The moment you release the switch, no more current is coming out of the battery. But now, the magnetic field creates a current, and that is why the LED should light up briefly.

Third, inductors too can be put in series and in parallel. Find out how the formulas go for inductors in series and in parallel, and verify them [18].

Challenges

1. Challenge - Logic Gates

Equipment: Arduino box, multi-meter.

With the switches from the Arduino box, build some of the logic circuits we talked about in class:

- NOT
- AND
- OR
- XOR
- NAND

2. Solar Cells

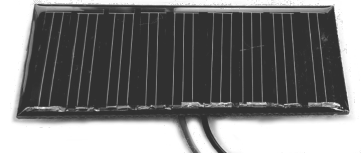
Equipment: multi-meter, small solar cell.

Measure the voltage and amperage of a small solar cell. Change the light, sun light would be ideal. Make different measurements with different light settings. Calculate the power production. How much power does a 100 watt incandescent light bulb use? A hair dryer? An electric car? For more details see reference [19].

Remember that power (P), which is measured in Watt [W], is simply voltage times current, i.e.,

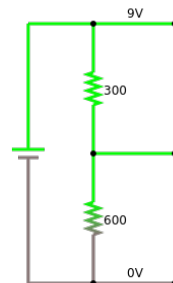
$$P = V \cdot I.$$

On a clear day, the sun's energy reaching the Earth's surface is about 1000 Watts per square meter (W/m^2). How efficient is your solar cell?



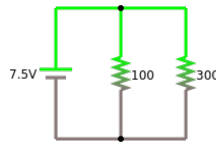
Questions

1. Is a resistance of 100 ohms a high resistance, or rather a small one?
2. What is the color code of a 2.2 kOhm resistor?
3. You can connect batteries in series or parallel. How high is the total voltage in one or the other case?
4. We have worked with different variable resistors. Name three different types of variable resistors.
5. What can go wrong when you try to measure current?
6. How to measure current, how to measure voltage, and how to measure resistance? Sketch one circuit diagram each.
7. Name the two Kirchhoff laws.
8. Consider the following voltage divider. The battery supplies 9 volts, one resistor is 300 Ohm, the other 600 Ohm. What is the voltage in the middle, between the two resistors? Which law do you use to calculate this?



9. Why should you use resistors with high resistances in a voltage divider?

10. Consider the following circuit. It consists of a 7.5 volt battery, a resistor R_1 of 100 Ohm and a resistor R_2 of 300 Ohm. Calculate the currents I_1 and I_2 that flow through the resistors R_1 and R_2 .



11. Name two important applications of capacitors.
12. First connect an electrolytic capacitor to a 9V battery. Then connect the capacitor to an LED. What happens?
13. Most LEDs die when the current through them is more than 20mA (for humans it is a little more, but not much). You only have a 9V battery, but you also have a lot of resistors. What do you do to get some light without killing the LED?

References

We learned a lot in this chapter. Although we do not have the time to go into some of the historical details, it is still interesting to read about the people involved. So in case you are looking for some light reading, just read the Wikipedia articles about Ohm, Kirchhoff or Faraday. If you never heard about Emmy Noether, then you should read about her. And in case you happen to not take our warnings about exploding batteries seriously, search for "lithium ion explosion" on Youtube.

- [1] Electronic component, https://en.wikipedia.org/wiki/Electronic_component
- [2] AC/DC, <https://en.wikipedia.org/wiki/AC/DC>
- [3] Thesaurus.com, <https://www.thesaurus.com/browse/circuit>
- [4] Short circuit, https://en.wikipedia.org/wiki/Short_circuit
- [5] Four Eyes Principle, https://www.openriskmanual.org/wiki/Four_Eyes_Principle
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- [7] Ohm's law, https://en.wikipedia.org/wiki/Ohm%27s_law
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- [10] Emmy Noether, https://en.wikipedia.org/wiki/Emmy_Noether#cite_note-FOOTNOTELedermanHill200473-7
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- [13] Electronic color code, https://en.wikipedia.org/wiki/Electronic_color_code#Resistor_color-coding
- [14] Photoresistor, en.wikipedia.org/wiki/Photoresistor
- [15] TMP36 Temperature Sensor, learn.adafruit.com/tmp36-temperature-sensor/overview
- [16] Kennzeichnung von Kondensatoren, www.elektronik-kompodium.de/sites/bau/1109061.htm
- [17] How To Check Capacitor (Very easy), www.youtube.com/watch?v=4_jtub0lyJI
- [18] Introduction to the electronics inductor component explained and demonstrated with LED circuit, www.youtube.com/watch?v=kvHTgAQ8FcM
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www.leifiphysik.de/elektronik/halbleiterdiode/versuche/kennlinie-einer-silizium-solarzelle

[21] Michael Faraday, https://en.wikipedia.org/wiki/Michael_Faraday

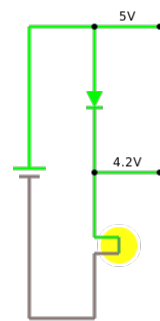
Active Components



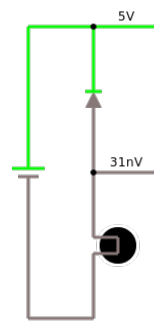
This chapter is about active electronic components, such as diodes, LEDs, and transistors. We learn about the different type of diodes that there are and what they are used for. We get to know transistors, bipolar and field-effect, and how to use them as switches and as amplifiers. We get to see the multivibrators, especially the astable and the bistable, and learn why they are so important for computers.

Diode

The diode [1] is the most basic active component. It is made out of a semiconductor material with what is called a p-n junction [2]. Diodes have the nice property, that they let current only go one way, from anode to cathode. Let's take a look at this in our simulator:



diode forward



diode blocking

You may notice this interesting voltage drop of 0.7 volts across the diode. This is also known as the "forward bias" [1]. This is typical for a silicon semiconductor, and we will see this a few more times in the future. Germanium diodes have a voltage drop of about 0.3 volts.

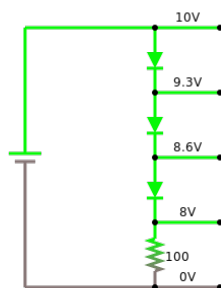
Diodes have many uses, such as

- constant voltage source,
- current steering,
- over-voltage protection,
- temperature sensor and
- rectifier.

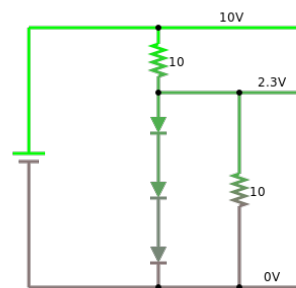
We will not talk about the rectifier, since that has to do with AC, but we will see examples for all the other usages.

Constant Voltage Source

We just learned that a silicon diode has a voltage drop of 0.7 volts. This can actually be used to create a constant voltage source. If we connect three diodes in series, the voltage drop will be three times 0.7 volts, that is 2.1 volts. Depending on whether we have the diodes before or after the resistor, we can use them in two different ways:



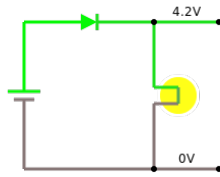
diodes before a resistor



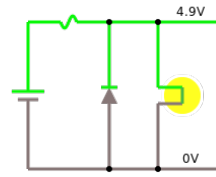
diodes after a resistor

Current Steering

Diodes are also very useful in protecting sensitive electric circuits from somebody accidentally switching plus and minus, i.e. they can be used to allow current to flow only in one, the intended, direction:



diode protection series

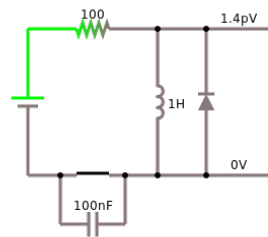


diode protection parallel with fuse

Just so that you know, this last circuit, protects our multi-meters when you happen to measure current in the wrong way. Meaning the way that "breaks" the multi-meter. Lucky for you, most multi-meters are protected by this circuit, and all you have to do is to replace the fuse, and you are good to go.

Over-Voltage Protection

They also can be used for over-voltage protection, especially when dealing with motors or relays (fly-back diode):



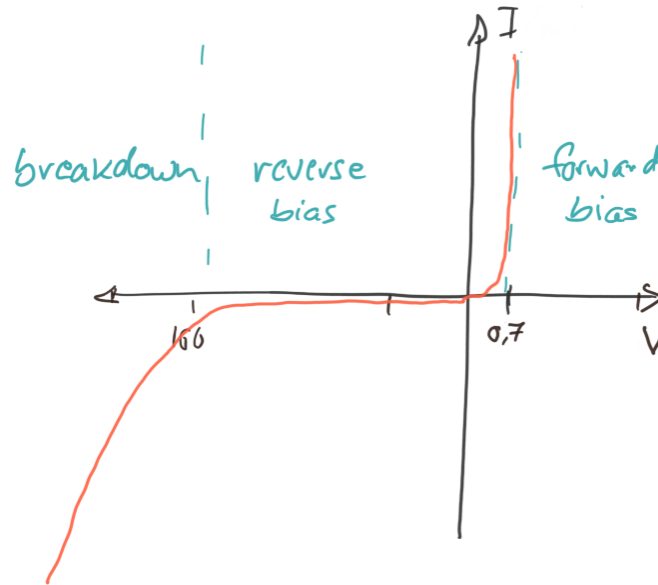
diode protecting motor

Temperature Measurement

The voltage drop of 0.7 volts that we already heard about, actually depends a little on temperature for most diodes. For silicon diodes it is usually $-2 \text{ mV}/^\circ\text{C}$. So if we very carefully measure this voltage drop, we can measure the temperature.

Current-Voltage Characteristic

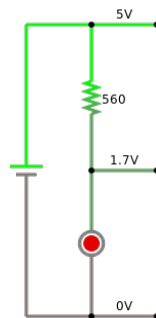
At this stage it is time to learn about what is called the current-voltage diagram, also called the "I-V characteristic". Basically, we change the value of the voltage going through our diode from some negative voltage to some positive voltage, and measure the current. (Naturally, the current should not be too high, or our diode will start to go up in smoke.) When plotting the result in a graph, we will get something like the diagram below.



Usually, we will not measure these diagrams ourselves, but look them up in so-called data-sheets [4]. The manufacturers of the components usually provide them.

Light Emitting Diode (LED)

LEDs are diodes that emit light [5], however, only if connected in the right direction, because like diodes, they let current only pass in one direction.

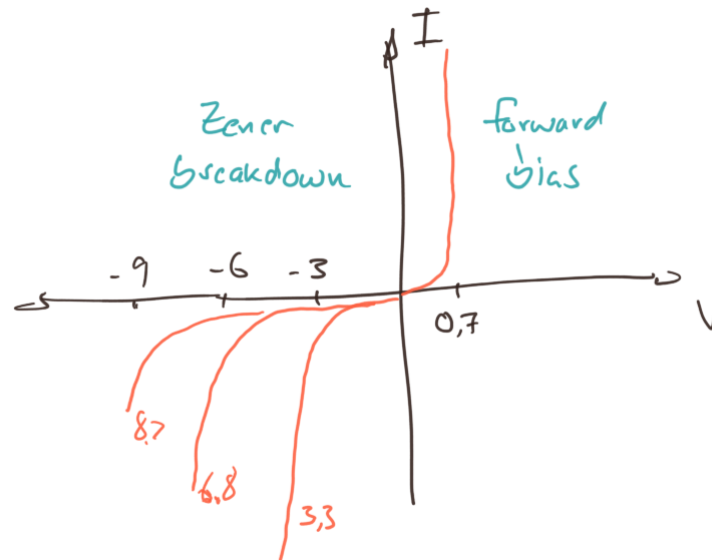


led with current-limiting resistor

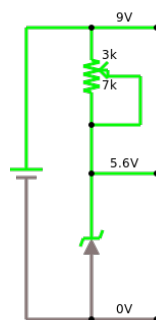
Most LEDs need to be protected, if the current through them gets too high, they break. This is why we usually use a current-limiting resistor to protect them.

Zener Diode

We already saw how to use a normal diode to create a source of constant voltage. Only, that voltage wasn't quite as constant as we would have wanted it to be. That is why there is a special diode called the Zener diode [6]: its only purpose is to create a constant voltage. It is based on the Zener effect. Normal diodes will block any current, that goes in the wrong direction, i.e. from cathode to anode. But a Zener diode will block it only to a certain voltage, if the voltage increases above that value, it will no longer block. The diagram below shows the current-voltage diagram for three different Zener diodes.



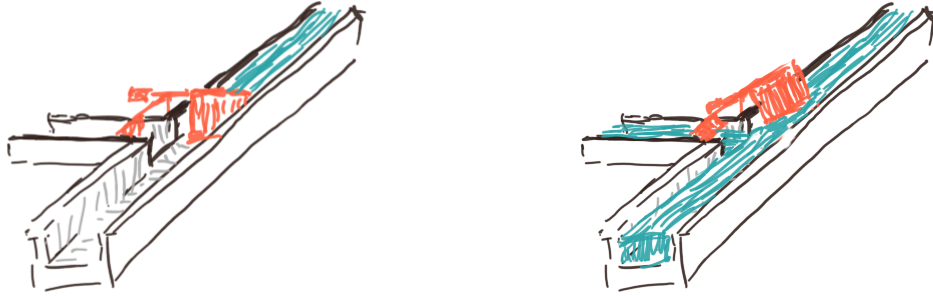
For us, Zener diodes are important, because our Arduino, the MKR1000, only likes 3.3 volts as its voltage. Most USB power supplies, however, produce 5 volts. So with a Zener diode, we can turn 5 volts into 3.3 volts. There are Zener diodes available for all kinds of voltages [7].



Zener diode

Transistors

Although diodes are already pretty neat, transistors are what we really want to learn about. Transistors can act as switches and as amplifiers. The simple diagram below, visualizes how they work: a small current of water, the pipe coming in from the left, controls the flow of the water in the big pipe. If there is no flow coming in from the left, the main water pipe is blocked. Only if water flows in from the left, will the gate open, and release the main stream. This is a very crude analogy, but a very helpful one.



Bipolar Transistor

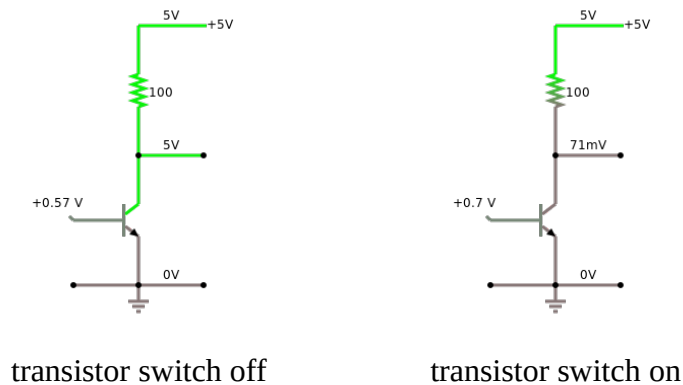
The bipolar transistor was invented in 1947 by American physicists John Bardeen, Walter Brattain, and William Shockley at Bell Labs [9]. It has transformed our lives like no other electronic device, and probably is on par with the invention of the fire and the wheel. It is surprisingly simple, made up of two semiconductor junctions (npn or pnp).



A transistor has three terminals, called base (B), collector (C) and emitter (E). The defining feature of a transistor is that a small current flowing into the base terminal, can control a much larger current flowing from the collector to the emitter terminal. Hence it can be used either as a switch or as an amplifier.

Transistor as Switch

If you want to use the transistor as a switch, all you have to do put a small voltage on the base terminal, usually a little more than 0.7 volts for a silicon transistor:



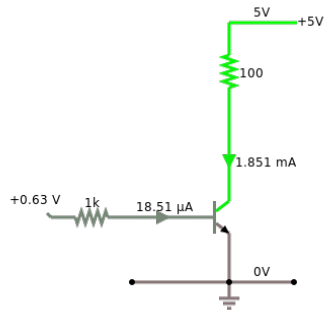
If the base voltage is less than these 0.7 volts, the transistor is off, meaning no current is flowing between collector and emitter. However, if the base voltage is higher than about 0.7 volts, then the transistor is on, meaning a high current is flowing between collector and emitter.

Transistor as Current Amplifier

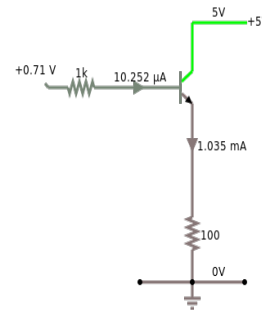
In addition, a transistor can be used as an amplifier, which is its most important application. There are three configuration to do that, and they are called

- common base,
- common emitter, and
- common collector.

Since the first one is hardly used, we will not talk about it. The second one is the most common one, and the last one is also used quite often.



common emitter



common collector

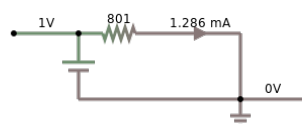
You can remember which is which, by looking at the emitter of the transistor: if the emitter is connected to (common) ground, then it is common emitter. Although the diagrams look almost the same, the two amplifiers have somewhat different properties. We put those differences together in one table [10]:

	common emitter	common collector
input impedance	medium	high
output impedance	high	low
voltage gain	medium	low
current gain	medium	high
power gain	very high	medium
phase shift	180°	0°
typical use	switch, amplifier	impedance matching

So depending on what you need, you pick one or the other. If you are not sure, go for the common emitter.

Transistor as Voltage Amplifier

First and foremost, bipolar transistors amplify *current*. But what if we want to amplify voltage? Well, with a resistor and Ohm's law we can turn voltages into currents:

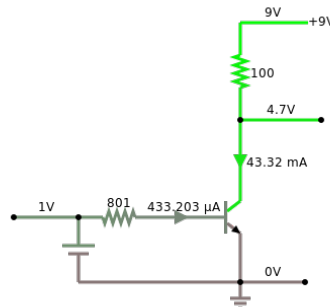


turn voltage into current

Active Components

But, in addition we need to remember, that the voltage drop between base and emitter has to be around 0.7 volts. We can do this by adding something like 0.5 volts to our input signal with a voltage divider (that is two resistors).

Once we have that, we can amplify voltages. In the example below, we amplify an input voltage with a range of 0 to 0.9 volts to an output voltage of 0 to 9 volts, that is an amplification by a factor of 10.

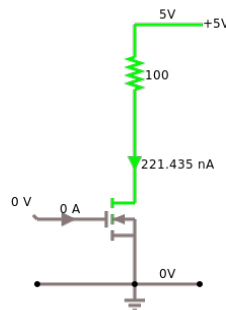
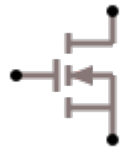


voltage amplifier

You may notice the phase shift of the common emitter circuit: the 0V input voltage is turned into a 9V output voltage and the 0.9V input voltage is turned into the 0V output voltage.

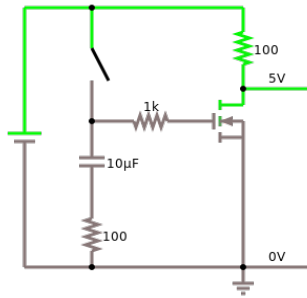
Field-Effect Transistor (FET)

Besides the bipolar transistors, there are also the field-effect transistors (FET) [11]. In principle, they are quite similar. The main differences are, that one, the terminals of FETs are called source, drain, and gate (corresponding to emitter, collector, and base, respectively), and two, they are triggered by voltage and not by current. Meaning no current has to flow through the gate for the transistor to switch. It basically turns voltage into current:



FET transistor

This has an interesting consequence that you should be aware of: the bipolar transistor will only be "on", when a current is flowing. Not so the FET. To see this, consider the following circuit:



FET as switch

If you replace the FET in the circuit above with a bipolar transistor, you will notice the difference. To see the effect in practice, watch video [12] starting at position 5:00 minutes. Also notice the different voltage it needs to be turned on and off.

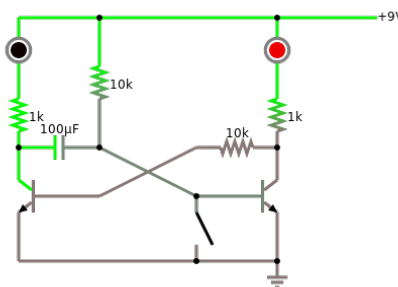
Why are FETs, especially MOSFETs, so important? Because they can be fabricated much smaller than bipolar transistors, and therefore basically all integrated circuits are made with FETs.

Multivibrators

Three very interesting circuits that we can build out of transistors, resistors and capacitors are the *multivibrators* [13]. They are interesting because we need them to build a computer. The astable multivibrator generates the clock cycles for our computer, and the bistable multivibrator is the basic unit that stores the bits in the memory of our computer, i.e. the RAM.

Monostable Multivibrator

We start with the simplest, but also most useless of the multivibrators, the monostable multivibrator. When you close the switch in the circuit below, the dark LED will lighten up, but after a while, the other LED will turn on again, and stay on. So one of the two LEDs (two states) is the stable state, hence monostable. It is not totally useless, and it's usually used to turn a rather short signal, into a longer signal of a fixed time interval.

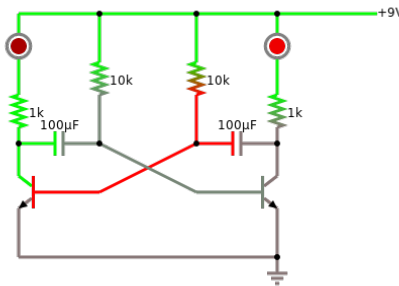


monostable multivibrator

Active Components

Astable Multivibrator

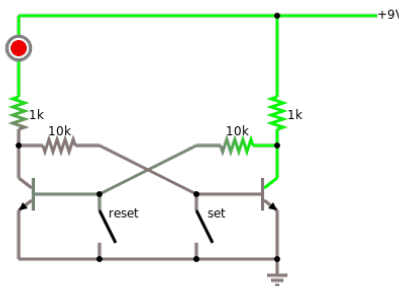
Next up is the astable multivibrator. Again, it has two states (or LEDs), but the interesting thing is, that it keeps on switching back and forth between the two states, i.e., none of the states is stable, that is astable. This is a frequency generator. It can be used to generate the clock-cycles for our computer. Depending on the values for the resistors and capacitors, basically any frequency can be generated. We can also use it to create a blinker or we can use it to create sound, if the frequency is high enough.



astable multivibrator

Bistable Multivibrator

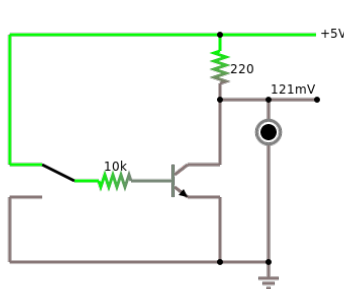
Finally we come to the bistable multivibrator, also called *flip-flop*. Again, it has two states (LED on or off). But this time, both of the states are stable. When we close the "reset" switch, the LED is off. When we close the "set" switch, the LED turns on. And stays on, until the "reset" is closed again. And this is the type of circuit that your computer uses to store information, one bit to be exact.



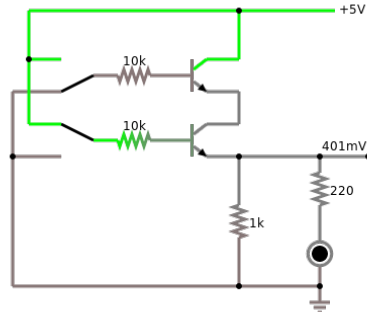
bistable multivibrator

Logic Gates

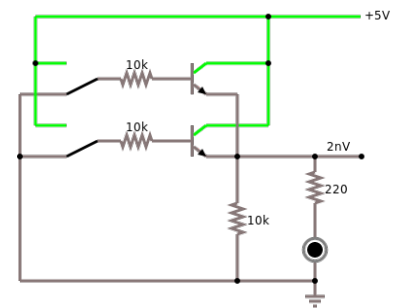
The other important application of transistors are the logic gates [14]. In the second chapter, we have seen how to build them out of switches. Since transistors can act as switches, it is not surprising that we can build them also out of transistors. Below you see all the logic gates build with transistors, we start with NOT, AND and OR,



NOT gate

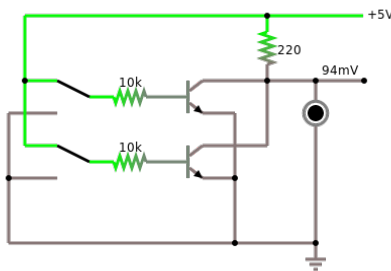


AND gate

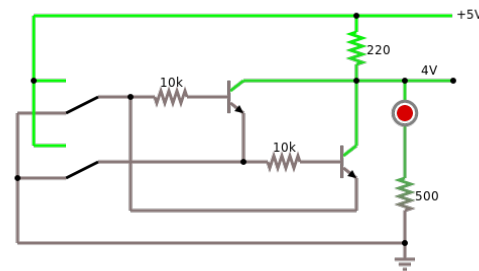


OR gate

continue with NAND and the NOR,

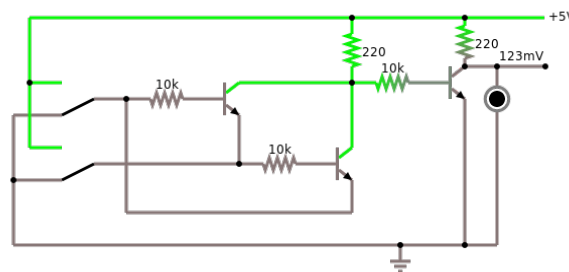


NAND gate



NOT-XOR gate

and notice, that we can turn the NOT-XOR into an XOR by inverting its output with a NOT gate:



XOR gate

In the research section, we will talk a little more about the NAND gate and its profound philosophical implications.

Review

In the lines above, we focused on active components, such as diodes and transistors. To be more exact, we saw silicon diodes, LEDs and Zener diodes, as well as bipolar and field-effect transistors. We learned that diodes can be used as constant voltage source, for current steering and over-voltage protection, even temperature measurement. We now know how to use transistors as switches and as amplifiers, with the common emitter and common collector circuits. Finally we learned about the multivibrators, and towards the end build all the logic gates out of transistors. Again, pretty amazing what we accomplished.

Labs

In today's lab we will learn about active electronic components such as diodes, LEDs and transistors.

Preparations

Before attempting to perform any of the experiments in this lab, you need to have done the following preparations beforehand. You have to be able to

- measure current with a multi-meter,
- find the direction of a diode and an LED,
- identify B, E, and C on a bipolar transistor.

Note to Instructors

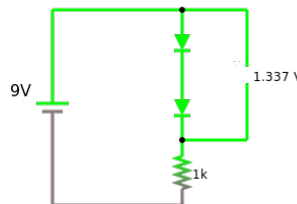
Equipment: Alligator clips, Arduino box, multi-meter, engineering paper, Zener diode 1N5226, bipolar transistor BC547. Experiment 2 should be done in groups of four students since two multi-meter are needed.

1. Diode

Equipment: Arduino box, multi-meter.

First, take a diode and measure its resistance. Notice, that a diode has an anode and a cathode. Identify each, and measure the resistance in both directions.

Second, diodes can be used to create a source of constant voltage. Use two diodes and a resistor (!) to create a voltage source of 1.4 volts.



diode constant voltage source

Third, use a diode for current steering: build the circuit "diode protection series" from class. Instead of the light bulb use a motor. You should notice, that no current is flowing when you switch the poles of the battery.

2. Current-Voltage Characteristic of a Diode

NOTE: this experiment should be done in groups of four students.

Equipment: Arduino box, multi-meter, engineering paper.

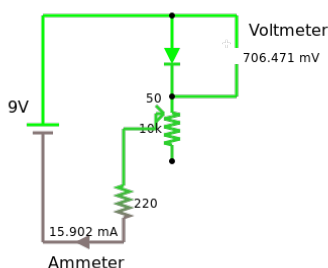
Important: If you destroyed a multi-meter in the last lab, because you did not understand how to measure current, you should not attempt this experiment.

First take a look at the data sheet for the 1N4007 diode [16]. Notice that on the 3rd page it shows several diagrams for the current-voltage characteristic of that diode. We want to repeat one of those measurements.

Before starting make sure you read reference [17]. You need to be able to create voltages between +9 volts and -9 volts. In experiment 6 in lab 2, we created a continuous voltage source that can give us voltages between 0 and 9 volts.

Before attempting to do this experiment with a diode, we can do it with a simple resistor. Use maybe a 10 kOhm resistor. Change the voltage from +9 to -9 volts, in one volt increments, and measure the current flowing. Write down your measurements in a table, and then graph the table. You should get a straight line.

Next, use the diode instead of the resistor. Again modify the voltage, but this time, in the forward direction we need voltages between 0 and 1.0 volts, ideally in 0.1 volt increments, and in the blocking direction we need voltages between 0 and 9 volts, ideally in 1 volt increments. Again, write down your measurements in a table, and then graph it. You should get a graph like the one we saw in class.



current voltage characteristic diode

3. Light Emitting Diode (LED)

Equipment: Arduino box, multi-meter.

An LED is a diode that emits light. Most LEDs (at least the ones we are using) need protection through a resistor. In experiment 3 of Lab 2 we calculated how much resistance is needed for a given voltage. In general, the current flowing through a LED should be less than 20 mA.

First, connect a red LED to the 9V battery in series with its protective resistor. The LED should light up. It will do this, only if connected in the correct way (cathode should be connected to minus). Next, use the multi-meter to measure the voltage drop across the LED (should be something like 1.9 volts). Finally, replace the LED with a different color LED. Notice that the voltage drop depends on the color of the LED.

Second, LEDs can also act as light detectors. Measure the resistance of an LED in the forward direction. Now shine on it with a bright light (smartphone flashlight). You will notice, that the resistance increases, depending on the brightness of the light.

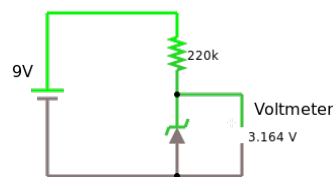
As an interesting side note, it is possible to measure Planck's constant measuring voltages and currents of differently colored LEDs [21].

4. Zener Diode

Equipment: Arduino box, multi-meter, Zener diode 1N5226.

The Arduino we are using, uses 3.3V for its power. Most power supplies for Arduinos (like USB power supplies), and also many of the other Arduinos use 5V. As long as we stay in one world things are fine. But once we start connecting other Arduinos or sources to our Arduino, things might get problematic or rather deadly for our Arduino. Also, sometimes you find circuit diagrams on the internet that you might want to use with your Arduino. But before you do that, make sure you understand for which Arduino this circuit diagram was intended.

However, not all is lost. Because we can use a Zener diode to protect our Arduino. For example, the 1N5226 is a common 3.3V Zener diode which we can use to protect our Arduino. Check out reference [22] and read the "Level Shifting With a Zener Diode" paragraph. Then build the following circuit, and test if it works.



Zener diode voltage characteristic

What you want to measure is the voltage across the Zener diode. You should change the value of the resistor (maybe 220 Ohm, 1kOhm, 10kOhm) and measure the voltage for each. You should notice that the voltage stays close to the 3.3 volts. Our Arduino input is protected!

5. Bipolar Transistor

Equipment: Arduino box, multi-meter, transistor BC546, 1.5V and 9V batteries.

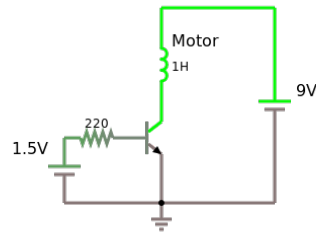
First, you need to find the transistor's data sheet [23]. Use it to identify base, emitter and collector of your transistor.

Second, make sure to always protect the base with a protective resistor. If you don't, your transistor goes ka-boom.

Third, find out how to use the multi-meter to test if a transistor is NPN or PNP. In addition, you can test this way if your transistor is fine or already broken. Note the hFE your multi-meter displays. Find what the hFE should be for your transistor in the data sheet.

Fourth, to get started, connect the motor directly to the 1.5 volt battery. Notice, that it moves rather slowly. Then connect it directly to the 9 volt battery. It is going quite a bit faster.

Finally, build the circuit below. Notice, that the motor turns pretty fast. Change the resistor to 100 Ohms (put two 220 Ohms in parallel). The motor now should turn as fast as if it were directly connected to the 9 volt battery. **DO NOT MAKE THE RESISTOR SMALLER THAN 100 OHM!**



transistor as switch motor

If you are good at using the ammeter (i.e. you haven't broken one yet), you can measure the current going through the motor (use the 10A setting). You can compare that to the current going into the base of the transistor (use the 200mA setting). I measured a current of 140mA going through the motor and of 1.3mA going into the base of the transistor. Hence the amplification is about:

$$\text{amplification} = \frac{140mA}{1.3mA} = 107.$$

Looking at the hFE we measured (or looked up) we would expect a little more, but close enough.

Question: What is the hFE of the Darlington transistor TIP120 [24]?

6. FET as Switch

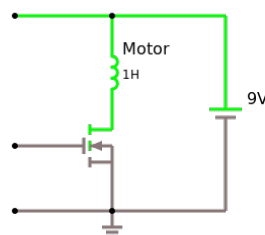
Equipment: Arduino box, multi-meter, FET IRF520

FETs are more robust than bipolar transistors, since they do not react to current but voltage instead. This means we can directly connect the gate to 9 volts of the battery without destroying it (a bipolar transistor would not survive this).

First, check out the datasheet [25,26] and use it to identify the gate, drain and source terminals of your FET. Then find out what the "Gate-Source Threshold Voltage" is. You need to apply at least this voltage for the FET to switch.

Second, find out if you can use the multi-meter to test a FET transistor. It probably will not work. Is there another way?

Third, build the "fet switch" example below. Notice, what happens when you connect the gate to 9 volt, and what happens when you connect it to 0 volt, i.e. the minus pole of the battery.



FET as switch motor

Active Components

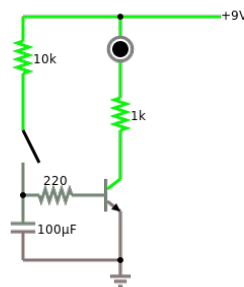
Finally, try the following: using the circuit above, make sure the motor is turned off. Now rub your feet on the floor, and then touch the gate terminal of your FET. With some luck, the motor will turn, because the static electricity generated by your feet is high enough to turn on the FET. (Nowadays, FETs are usually protected against static electricity. If they weren't you would have just killed it...).

Question: What are the advantages of a bipolar transistor, and what are the advantages of a FET transistor?

7. Multivibrators

Equipment: Arduino box, multi-meter, transistor BC546.

First, recall how capacitors work. When you charge them, and then discharge them, the voltage decreases slowly, following an exponential decay. Then build the circuit below. You will notice that when you close the switch, the LED goes on (use a yellow LED for best results). As you release the switch, you will notice that after some time, the LED gets dimmer slowly, until it goes off. Depending on the 220 Ohm resistor and the capacitance, this will take a different amount of time. This is the basis for the multivibrators.



multivibrator

Now we are ready for the real thing. Make sure you understand the difference between the different multivibrators. Although they sound and look almost the same, they have very different applications. Then build the astable and the bistable multivibrator. You can use the FETs instead of the bipolar transistor, they work as well. As for the astable, notice what happens when you change the values of the capacitors or the charging resistors (10kOhm). (Don't change the protective resistor or your LED will say bye-bye!)

Challenges

1. Current-Voltage Characteristic LEDs

Like with diodes, you can also measure the current-voltage characteristics for LEDs. Interesting enough, you will notice a dependence on the color of the LED. And even more interesting, you can use this to measure Planck's constant [21]. Explaining this effect is what got Albert Einstein his Nobel Prize.

2. Current-Voltage Characteristic Transistors

Like diodes, transistors too have current-voltage characteristics. We will take a brief look at those in the references [27,23,26]. But you can actually measure them yourself.

Research

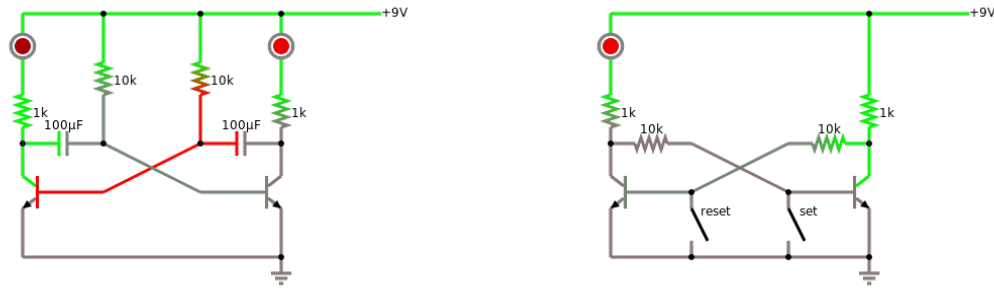
Sheffer Stroke

A few pages ago we mentioned that the NAND gate is very special [29]. Mathematicians actually call it the Sheffer stroke [28]. Why is it so special? It turns out that all other logic circuits, that is the NOT, the AND, the OR, even the XOR and the NOR can be build out of NANDs. This is totally unexpected. Interesting enough, the Sheffer stroke is what Mathematicians call funcionally complete [30]. Knowing this and having heard about the Principia Mathematica [31], one may marvel at the simplicity of the creation.

Questions

1. How can you determine whether a diode is a silicon or germanium diode? What do you have to measure?
2. Can an LED be used as a detector for light?
 - yes
 - no.
3. Suppose you are color blind. How could you find out the color of an LED by measuring something?
4. Sketch a current-voltage characteristic curve for a diode.
5. Does a bipolar transistor amplify current or voltage by default?
6. Which one breaks more easily, a bipolar transistor or a FET?
7. Please draw the diagram of a bipolar transistor and label base (B), collector (C) and emitter (E).
8. Transistors are typically used in the common emitter or common collector configuration. Draw the schematic for one of the two.

9. Identify which multivibrator is which.



10. Connect the component on the left side with its function on the right side:

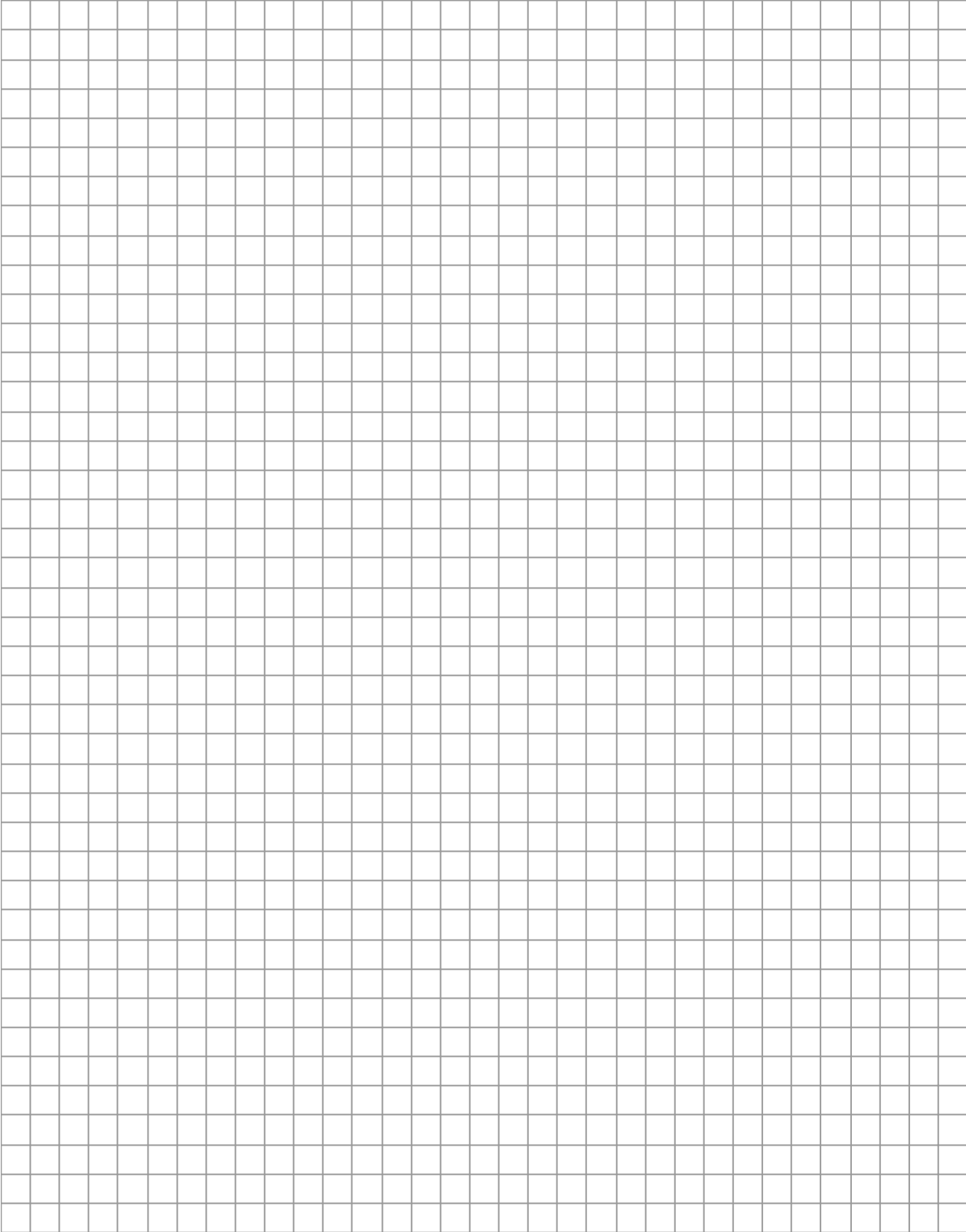
TMP36		diode
BC546		CPU
IRF520		FET transistor
1N4004		bipolar transistor
741		operational amplifier
6502		temperature sensor

References

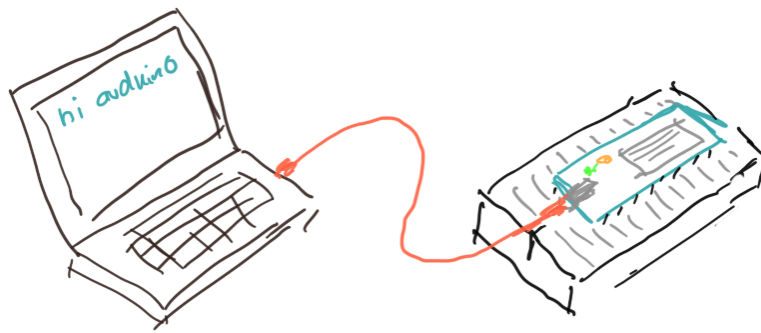
There are a few things that might be worthwhile your time. If you want to know more about how transistors work, you should read up on the p–n junction in the Wikipedia [2]. If you want to watch a good Youtube video on how to design a transistor circuit, watch reference [32] by Ben Krasnow. The difference between bipolar transistors and field-effect transistors is really nicely depicted in video [12] by Jeff Feddersen on Vimeo. Of more general interest is the video by Manu Prakash, Computing with fluids [33]. This reemphasizes the importance of the NAND gate. And because we have been talking about people in the previous chapters, you may want to read up on John Bardeen, one of the inventors of the transistor. And while at it, you might be interested to find out who else won two Nobel Prizes (and which family won six Nobel Prizes).

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- [2] p–n junction, https://en.wikipedia.org/wiki/P–n_junction
- [3] Datei:Kennlinie Diode 1N914.svg, de.wikipedia.org/wiki/Datei:Kennlinie_Diode_1N914.svg
- [4] Datasheet, <https://en.wikipedia.org/wiki/Datasheet>
- [5] Light-emitting diode, https://en.wikipedia.org/wiki/Light-emitting_diode
- [6] Zener diode, https://en.wikipedia.org/wiki/Zener_diode
- [7] Zener Diode Reference, [web.archive.org/web/20090216233625/http://www.logwell.com/tech/components/zener.html](http://www.logwell.com/tech/components/zener.html)
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- [10] Grundsaltungen des Transistors, www.elektronik-kompodium.de/sites/slt/0203111.htm
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- [21] Classroom fundamentals: measuring the Planck constant, www.scienceinschool.org/2014/issue28/planck
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- [23] BC546 - ON Semiconductor, <https://www.onsemi.com/pub/Collateral/BC546-D.PDF>
- [24] TIP120, <https://www.onsemi.com/products/discretes-drivers/darlington-transistors/tip120>
- [25] MOSFET IRF520, itp.nyu.edu/physcomp/lessons/electronics/transistors-relays-and-controlling-high-current-loads/
- [26] IRF520, <https://www.vishay.com/docs/91017/91017.pdf>
- [27] Transistor-Kennlinienfelder, www.elektronik-kompodium.de/sites/bau/0203112.htm
- [28] Sheffer stroke, https://en.wikipedia.org/wiki/Sheffer_stroke
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- [31] Principia Mathematica, https://en.wikipedia.org/wiki/Principia_Mathematica
- [32] Ben Krasnow, Applied Science, How to design a transistor circuit that controls low-power devices, www.youtube.com/watch?v=8DMZSxS-xVc
- [33] NAND gate is universal, can simulate any other logic gate (Computing with fluids | Manu Prakash, <https://www.youtube.com/watch?v=OhroLzvW-JI>)

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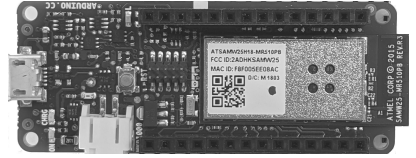
Arduino



We have arrived at the final chapter, we are ready to do some physical computing [1]. We will use an Arduino board and connect it with the different electronic components we learned about in the previous chapters.

Hardware

The first Arduino was introduced in 2005. Since then it has become extremely popular with hobbyists all over the world. The main reason being its ease of use, price and support. The simplest one is the Arduino Uno. We will be using the Arduino MKR1000 [2], which has a few very nice additional features. Besides those, there are many other Arduinos available.



MKR1000 Board Specifications

The MKR1000 has the following features:

- regular USB (5V) can act as power supply (VIN),
- operating voltage is 3.3V,
- it has 8 digital I/O pins,
- it has 12 PWM pins (0,1,2,3,4,5,6,7,8,10,A3 or 18,A4 or 19),
- it has 7 analog input pins (ADC 8/10/12 bit),
- it has one analog output pin (DAC 10 bit),
- the build in LED is at pin 6, and
- it supports Wi-Fi .

Its CPU is a 32-bit ARM CPU running at 48 MHz. It has 32 KB of SRAM and 256 KB of flash memory.

To keep our Arduino healthy, we need to be aware of two things: the voltage applied to any pins should always be less than 3.3V and the current we draw from any of the I/O pins must be less than 7 mA. If we keep these limits, than our Arduino will be fine. If not, it will be dead.

A very good reference into the foundations of Arduino hardware and software is reference [4]. It is a very good idea to printout reference [3], the pinout of the MKR1000.

Software and IDE

To program the Arduino, we need a computer. That can be a Windows PC, Mac or Linux computer. All the computer needs is a USB port. Arduino comes with software to program it, the Arduino IDE [3]. It is very easy to install and use. Basically, the Arduino uses the C programming language, but to us it will almost look like Java.

Any Arduino program starts in the *setup()* method. This method is called only once, at the start of the program.

```
void setup() {
  // executed only once at start
}

void loop() {
  // executed repeatedly
}
```

After the *setup*, the *loop()* method is called. It is called again and again, until you turn of the Arduino or upload a new program.



Before you can run your programs, you need to compile them. This is done either through the menu (Sketch->Verify/Compile), a shortcut (Ctrl-R) or a button. If the compiler is happy with your code, you can upload it to your Arduino. This can be done through the menu (Sketch->Upload), a shortcut (Ctrl-U) or a button. Once a program is uploaded to the Arduino, it will start executing immediately. You can only run one program at a time.

The IDE comes with really many examples, you can find them under File->Examples.

Serial

The Arduino board can send messages to our PC via the serial port. With serial port we mean the USB port. For this you need to setup a serial connection in the setup() method,

```
void setup() {
  Serial.begin(9600);
}

void loop() {
  Serial.println("Hello from your Arduino");
  delay(1000);
}
```

Then use the Serial.println() method to print to the *Serial Monitor*. The Serial Monitor (Ctrl-Shift-M) is part of the IDE. It shows us the messages that come from the Arduino board.

The communication is two way, meaning we can also send messages from the Serial Monitor to the Arduino. Again, we need to setup a serial connection in the setup() method,

```
void setup() {
  Serial.begin(9600);
}

void loop() {
  if (Serial.available() > 0) {
    char c = Serial.read();
    Serial.println(c);
  }
}
```

Then in the loop() method, we wait for incoming characters. If one is available, we can read it. We can only read one character at a time. Strings are quite different in C as compared to Java [5].

Digital I/O

Our Arduino has a whole bunch of digital pins (0,1,2,3,4,5,6,7,8,10) We can write to and read from them. First, we must specify, if we want to use a pin as input or output pin. We do this in the setup using the pinMode() method. We specify the pin (here it is pin 6) and whether to use it as INPUT or OUTPUT:

```
int ledPin = 6;

void setup() {
  pinMode(ledPin, OUTPUT);
}

void loop() {
  digitalWrite(ledPin, HIGH);
  delay(1500);
  digitalWrite(ledPin, LOW);
  delay(500);
}
```

Arduino

Once we specified that, we can use the `digitalWrite()` method to write to that pin. A digital pin can have two states, either LOW, which is 0 volts, or HIGH, which for our Arduino is 3.3 volts. Interesting enough, there is an internal LED connected to pin 6, so when running the above program that LED should blink.

Reading works completely analogous. You must declare the pin as INPUT pin using the `pinMode()` method,

```
int ledPin = 6;
int inPin = 0;

void setup() {
  pinMode(ledPin, OUTPUT);
  pinMode(inPin, INPUT);
}

void loop() {
  int val = digitalRead(inPin);
  digitalWrite(ledPin, val);
}
```

and then use the `digitalRead()` method to read from that pin.

Analog I/O

In addition to digital I/O, there is also analog I/O. All Arduinos can read analog voltages using the `analogRead()` method. Again, we first need to say that we want to use a pin as INPUT or OUTPUT. Then we need to specify the resolution of the converter, using the `analogReadResolution()` method. Here 8 stands for 8-bit, resulting in values between 0 and 255. We can also use 10-bit or 12-bit resolutions.

```
void setup() {
  Serial.begin(9600);
  pinMode(A1, INPUT);
  analogReadResolution(8);
}

void loop() {
  Serial.println( analogRead(A1) );
  delay(2);
}
```

You can see the readings either in the Serial Monitor, or if it is numbers, then you can also use the Serial Plotter (Ctrl-Shift-L), to visualize the data in a graph. Arduino uses an analog to digital converter, also called ADC, to do the conversion from input voltages to digital numbers. Our Arduino has seven analog input pins (A0-A6). The two millisecond delay gives the ADC a little time. It is not the fastest.

Some Arduinos also have analog output pins. Our Arduino (MKR1000) has one, the DAC0 pin. On that pin we can create arbitrary output voltages, between 0 and 3.3 volts in our case. To do this, it uses a digital to analog converter, called DAC. It is on pin A0 for the MKR1000. We do need to specify its resolution, which for the MKR1000 can only be 8-bit or 10-bit. However, for some strange reason, we should not set the pin as output pin, but rather not specify it at all.

```

int val = 0;

void setup() {
  Serial.begin(9600);
  pinMode(A1, INPUT);
  analogReadResolution(8);
  // do not do this: pinMode(A0, OUTPUT);
  analogWriteResolution(8);
}

void loop() {
  val += 1;
  val %= 256;
  analogWrite(A0, val);
  Serial.println(analogRead(A1));
  delay(2);
}

```

This means, we can actually use our Arduino to generate arbitrary wave forms, i.e. become a function generator.

PWM

Another form of analog output is Pulse Width Modulation (PWM). In PWM we do not modulate the voltage. The voltage is either 0 or 3.3 volts. But we generate a square wave, where we modulate the width of the pulse. If you average that, it then looks almost like an analog voltage. PWM is available on all Arduinos, even if they do not have a DAC.

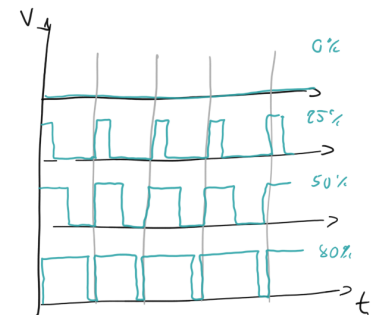
```

int val = 0;

void setup() {
  Serial.begin(9600);
  pinMode(A2, OUTPUT);
}

void loop() {
  val += 1;
  val %= 256;
  analogWrite(A2, val);
  delay(2);
}

```



The value can be any value between 0 and 255.

Review

In this chapter we introduced the Arduino physical computing platform. Among the many different kinds of Arduinos, we focused on the MKR1000, mostly because it comes in such a beautiful box. We had a brief introduction to the Arduino IDE and how to write simple Arduino software sketches with it. In the ensuing examples we saw how to communicate between Arduino and PC, how to use the digital and analog inputs and outputs, and what PWM stands for. We have now enough knowledge under our belts to become really dangerous!

Labs

Today we will use our Arduino for the first time. We will learn how to connect it to our laptop, install the required software, upload and execute programs on the Arduino, and how to connect different electronic components such as diodes, LEDs and transistors to it. Many of the examples here are inspired from Programming in Arduino [3].

Before you can start with any of the experiments in this chapter, you need to install the Arduino IDE first, see the appendix for details.

Preparations

Before attempting to perform any of the experiments in this lab, you need to have done the following preparations beforehand. You have to be able to

- bring your laptop, and ideally have installed the Arduino IDE on it [6],
- you have read the Arduino MKR1000 FAQ [7],
- know about static electricity, and
- why you should not connect the Arduino directly to your laptop, but always connect it using a USB hub.

Note to Instructors

Equipment: Arduino box, bipolar transistor BC547.

Before you Start

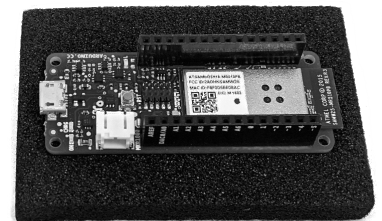
Equipment: Arduino box.

Although quite robust, the Arduino has to be handled carefully. Try to avoid any static electricity. When not needed, put the Arduino back on its conductive foam and inside its anti-static bag. The image on the side shows the Arduino on its conductive foam (black).

Before using the Arduino, remove the conductive foam that protects the pins and place it on the breadboard. Do this very carefully, and make sure not to bend any of its legs. If you have difficulty, ask your instructor to help you.

Connect the Arduino through the USB hub with your computer. There has been irreparable damage to laptops, so to avoid that use a hub.

The Arduino is powered through the USB hub. So before building circuits, disconnect your Arduino from the USB hub. Before connecting it, please let an instructor check your circuit.



Make sure you understand the different voltages on the Arduino board, Vin, 5V and VCC:

- **Vin:** This pin can be used to power the board with a 5 volts source. **WE WILL NOT USE THIS.**
- **5V:** This pin outputs 5 volts powered from the USB connector. **WE SHOULD NEVER USE THIS.**
- **VCC:** This pin outputs 3.3V through the on-board voltage regulator.

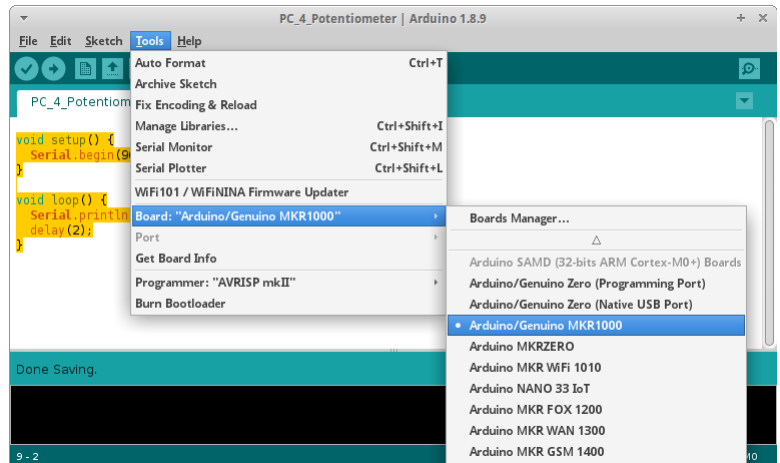
You should always use **VCC**, i.e., the 3.3 volts. Connecting any of the pins to 5 volts (or more) will destroy your Arduino. Not a good thing.

Preparing the IDE

Equipment: Laptop, Arduino box.

After installation of the IDE, you need to select the proper Arduino board. There are many Arduinos, we are using the MKR1000. So under Tools->Board select the proper board.

Also make sure you selected the correct serial or USB port your Arduino is connected to. On Mac and Linux everything should work out of the box. On Windows you most likely have to install a driver, follow the instructions in [9].



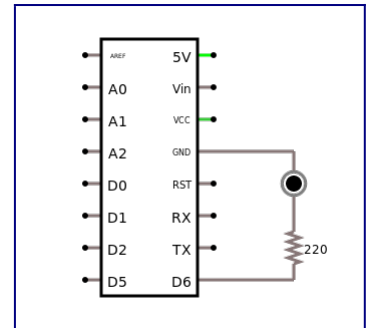
1. Blink

Getting the LED "L" to blink is actually quite easy: simply type the following code into the Arduino Software (or load the "Blink" sketch from File>Examples>Basics). Verify it (Ctrl-R) and Upload it (Ctrl-U) to the Arduino board. The LED should start blinking [10].

```
int ledPin = 6;

void setup() {
  pinMode(ledPin, OUTPUT);
}

void loop() {
  digitalWrite(ledPin, HIGH);
  delay(1500);
  digitalWrite(ledPin, LOW);
  delay(500);
}
```



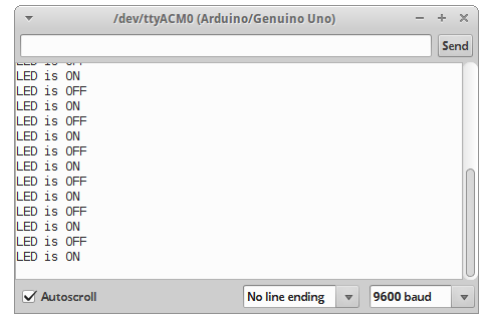
2. Blink and Serial

In this sketch we learn how the Arduino board can send messages to our PC via the USB serial port.

```
int ledPin = 6;

void setup() {
  Serial.begin(9600);
  pinMode(ledPin, OUTPUT);
}

void loop() {
  digitalWrite(ledPin, HIGH);
  Serial.println("LED is ON");
  delay(1500);
  digitalWrite(ledPin, LOW);
  Serial.println("LED is OFF");
  delay(500);
}
```



The LED should blink again, but if we look at the Serial Monitor (Ctrl-Shift-M), we see messages that come from the Arduino board.

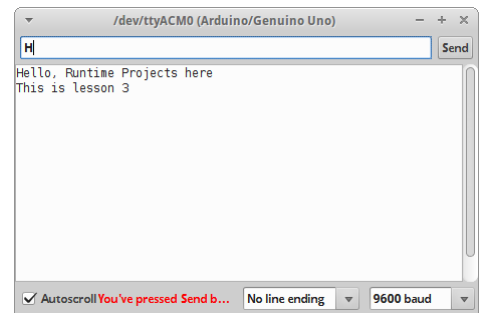
3. Serial-2-Way

We can also use the Serial Monitor to send commands or strings to the Arduino via the serial port.

```
int ledPin = 6;

void setup() {
  Serial.begin(9600);
  pinMode(ledPin, OUTPUT);
  Serial.println("Greetings from your
Arduino!");
}

void loop() {
  if (Serial.available() > 0) {
    char incomingMessage = Serial.read();
    if (incomingMessage == 'H') {
      digitalWrite(ledPin, HIGH);
    } else if (incomingMessage == 'L') {
      digitalWrite(ledPin, LOW);
    }
  }
}
```



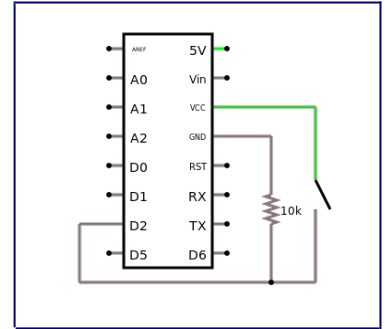
Run the above program, open the Serial Monitor, type an 'H' in the text field, and click on the "Send" button. The LED on the Arduino should turn on. If you send the 'L' command, the LED should switch off.

4. Button and Tilt Switch

To read the state of a button we use the `digitalRead()` method. We connect the button to the digital pin 2.

```
void setup() {
  Serial.begin(9600);
  pinMode(2, INPUT);
}

void loop() {
  int switchState = digitalRead(2);
  if (switchState == LOW) {
    Serial.println("Button is OFF");
  } else {
    Serial.println("Button is ON");
  }
  delay(500);
}
```



The program checks the value of the digital pin 2, and prints the state of the button to the Serial Monitor (Ctrl-Shift-M).

Instead of the button, you may also use the tilt switch that comes with the Arduino box.

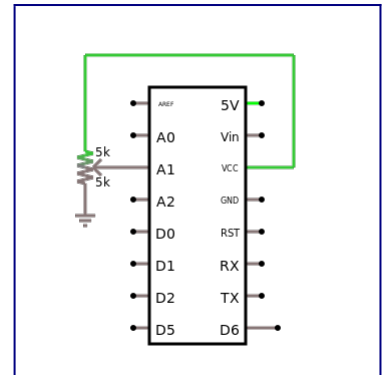
You can also modify the program such that the LED on the board goes on, if the button is pressed and off otherwise [11,12].

5. Potentiometer

Next, let us read analog input from the analog pin A1. For this we need to connect a potentiometer to the Arduino in the way shown to the right.

```
void setup() {
  Serial.begin(9600);
  pinMode(A1, INPUT);
  analogReadResolution(8);
}

void loop() {
  Serial.println(analogRead(A1));
  delay(2);
}
```

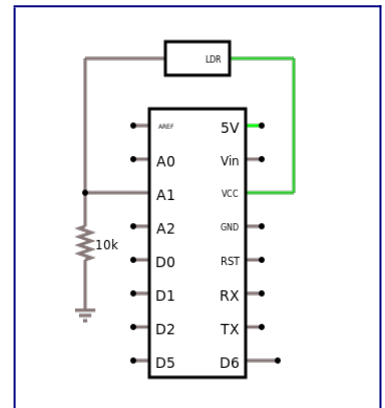


To visualize the data being read, we can use the Serial Plotter (Ctrl-Shift-L). The method `analogRead()` converts the voltage applied to pin A1 to a value between 0 and 1023 [14,15].

6. LDR

A photo sensor or light dependent resistors (LDR) will change its resistance depending on the amount of incident light.

```
void setup() {
  Serial.begin(9600);
  pinMode(A1, INPUT);
}
```



```
void loop() {
  int sensorValue = analogRead(A1);
  delay(5);
  Serial.print("Raw Sensor Value \t .");
  Serial.print(sensorValue);
}
```

Here we also see, how to output sensor values to the Serial Monitor in a nice looking way [16,17].

7. Temperature

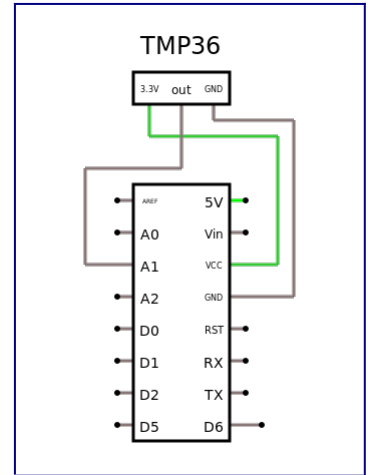
We can use the analog input together with our temperature sensor to measure temperature [18,19].

```
void setup() {
  Serial.begin(9600);
  pinMode(A1, INPUT);
}

void loop() {
  int sensorVal = analogRead(A1);
  delay(5);
  Serial.print("Raw Sensor Value: ");
  Serial.print(sensorVal);

  // convert raw ADC value to voltage
  float voltage = (sensorVal / 1024.0) * 3.3;
  Serial.print(", Volts: ");
  Serial.print(voltage);

  // sensor changes 10 mV per degree C
  // the datasheet says
  // temp = ((voltage - 500mV) times 100)
  Serial.print(", Degrees C: ");
  float temperature = (voltage - 0.5) * 100;
  Serial.println(temperature);
}
```



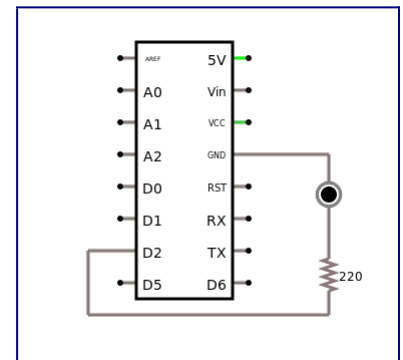
8. PWM

We can use Pulse Width Modulation to change the brightness of an LED.

```
const int greenLEDPin = 2;
int greenValue = 0;

void setup() {
  pinMode(greenLEDPin, OUTPUT);
}

void loop() {
  greenValue++;
  greenValue %= 256;
  analogWrite(greenLEDPin, greenValue);
  delay(20);
}
```



The green LED should get brighter until its brightness goes down to zero. The period should be about 5 seconds [13].

9. Melody

To see an example where we use the digital pin as output, look at the built-in examples 02.Digital > toneMelody. You first need to connect an 8-ohm speaker (buzzer) to GND and digital pin 2.

```
#include "pitches.h"

const int tonePin = 2;

int melody[] = {
  NOTE_C4, NOTE_G3, NOTE_G3, NOTE_A3, NOTE_G3,
  0, NOTE_B3, NOTE_C4
};

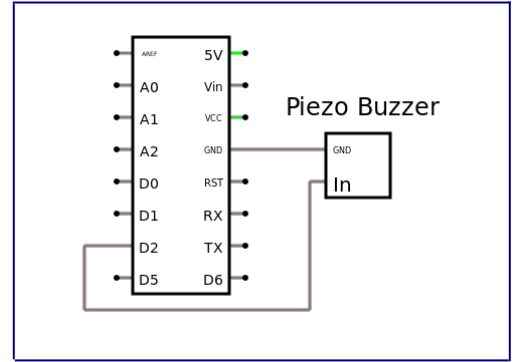
// note durations: 4 = quarter note, 8 = eighth note, etc.:
int noteDurations[] = {
  4, 8, 8, 4, 4, 4, 4, 4
};

void setup() {
  // iterate over the notes of the melody:
  for (int thisNote = 0; thisNote < 8; thisNote++) {

    // to calculate the note duration, take one second divided by the
    note type.
    //e.g. quarter note = 1000 / 4, eighth note = 1000/8, etc.
    int noteDuration = 1000 / noteDurations[thisNote];
    tone(tonePin, melody[thisNote], noteDuration);

    // to distinguish the notes, set a minimum time between them.
    // the note's duration + 30% seems to work well:
    int pauseBetweenNotes = noteDuration * 1.30;
    delay(pauseBetweenNotes);
    // stop the tone playing:
    noTone(tonePin);
  }
}

void loop() {
  // no need to repeat the melody.
}
```

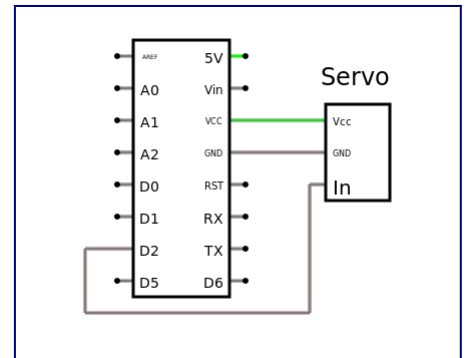


This example also teaches how to use arrays with the Arduino. Try adding a capacitor between the D2 output of the Arduino and the input of the speaker [20-22].

10. ServoMotor

As an example for an actuator, let us consider the ServoMotor example. You need to connect the servo in the way indicated to the right. The orange cable (yellow in the diagram) should be connected to digital pin 2. The brown cable should be connected to GND, the red cable to +3.3V.

Executing the following code, will result in the servo turning slowly from 0 to 180 degrees.



```
#include <Servo.h>

Servo myServo;

void setup() {
  myServo.attach(2); // attach servo to pin 2
  Serial.begin(9600);
}

void loop() {
  for (int angle = 0; angle < 180; angle++) {
    Serial.println(angle);
    myServo.write(angle);
    delay(15);
  }
}
```

If you open the Serial Monitor, you can see the current angle the servo is set to. This example also teaches how to import libraries and how to use an object [23].

Challenges

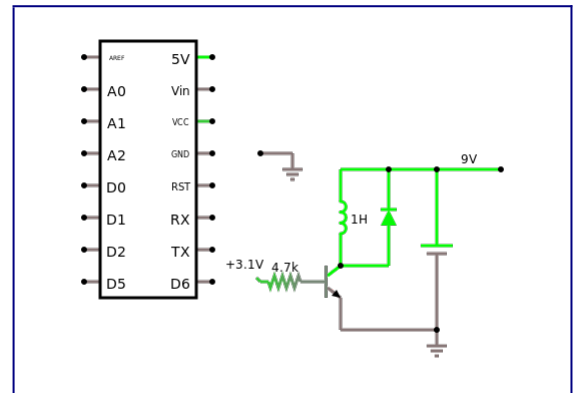
1. Motor

Running a motor requires a little more current than our Arduino can deliver. We have to use a transistor. To the right you see the circuit using a bipolar transistor.

```
const int motorPin = 8;

void setup() {
  Serial.begin(9600);
  pinMode(motorPin, OUTPUT);
}

void loop() {
  if (Serial.available() > 0) {
    char incomingMessage = Serial.read();
    if (incomingMessage == 'H') {
      digitalWrite(motorPin, HIGH);
    } else if (incomingMessage == 'L') {
      digitalWrite(motorPin, LOW);
    }
  }
}
```

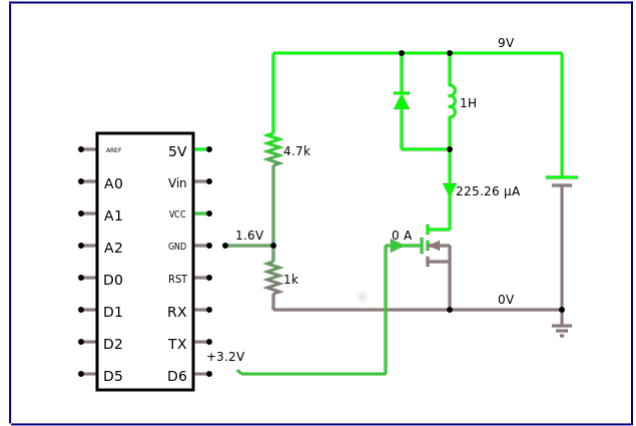


You can use the Serial Monitor to turn the motor on and off.

NOTE: BE VERY CAREFUL WHEN BUILDING THIS CIRCUIT. IT IS VERY LIKELY THAT YOUR ARDUINO WILL BE DEAD IF YOU GET SOMETHING WRONG!

We can also use a FET. The tricky part here is, that for the FET to switch, it needs a little more than 4 volts. But our Arduino only gives 3.3 volts. So what do we do? One solution is to use another bipolar transistor [26], but that is kind of stupid, because then we can drive the motor with the bipolar, no need for the FET.

But we can use a voltage divider and do a little level shifting! If you look at the schematic to the right, we use the 4.7kOhm and 1kOhm resistors as a voltage divider. We then connect the middle of that divider to the ground (GND) pin of the Arduino. That has the effect, that the 1.6 volts of the voltage divider is added to the 3.3 volts of the Arduino pin, hence shifting us above the 4 volts needed to switch the FET [24-28].



Idea: we may want to improve this circuit using a diode and/or a capacitor.

2. Function Generator

Using the analog output pin A0 and the DAC, we can write a little function generator that might come in handy when investigating AC voltages and currents.

```

const int step = 10;
int outputValue = 0;

void setup() {
  Serial.begin(9600);
  // do not do this: pinMode(A0, OUTPUT);
  analogWriteResolution(8);
}

void loop() {
  outputValue += step;
  outputValue %= 256;
  analogWrite(A0, outputValue);

  Serial.print("X: "); Serial.print(outputValue); Serial.print(" ");
  Serial.println("uT");

  delay(10); // 256 ms = 1/4 Hz
}

```

Use a real oscilloscope, connect it to GND and pin A0 to see the output. Change the frequency and the waveform generated.

We can also generate sound this way, we just need to make sure it generates frequencies in the audible spectrum. And we may need to amplify them with a transistor and a 9 volt battery [29-30].

3. Software Oscilloscope

Experiment 5, the potentiometer can also be used as a software oscilloscope. Try to estimate its time resolution. Use one Arduino as a function generator, and another as a software oscilloscope.

4. Pressure Sensor

Just to get you thinking, take a look at reference [31]. It basically describes how to turn the anti-static foam that protects your Arduino from static electricity into a pressure sensor [32,33].

5. LCD Display

If you are interested in using the LCD display that comes with the Arduino box, check out reference [34].

6. Other Projects

Now you basically know how the Arduino works. There are many cool projects you can do at this stage [35]. However, you should be aware of the fact, that most projects on the internet assume your Arduino uses 5 volts. Since ours does not, you should first learn about level shifting [36]. Also, there are many sensor kits, with easy to use sensors, check out references [37-39]. And once in a while there are other projects you find on the internet [40].

Questions

1. What does a digital-to-analog converter (DAC) do?
2. Normally the input pins of an Arduino can be connected to 5 volts. Applies this also for the MKR1000, the Arduino we used?

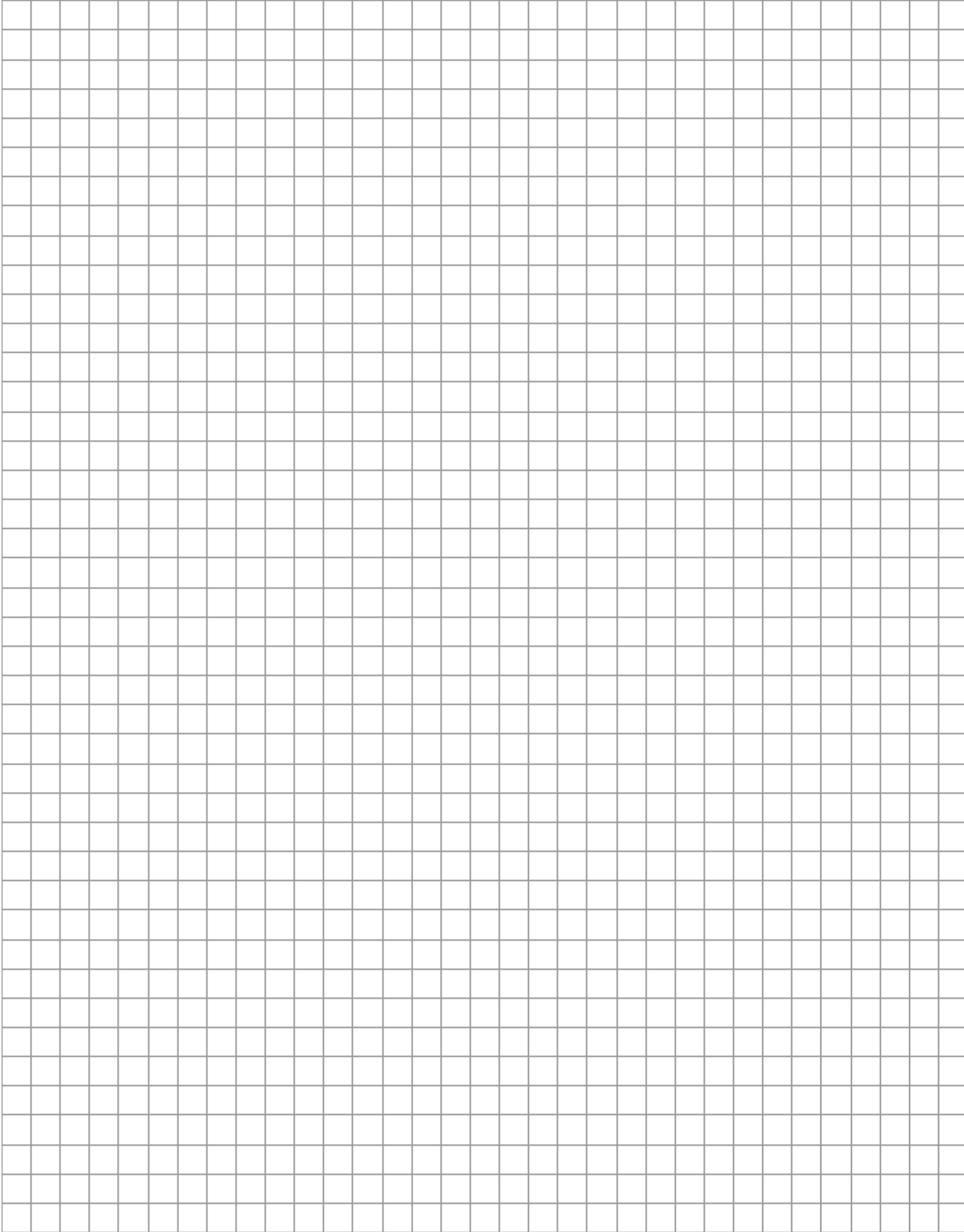
References

You should read a little about the history of the Arduino, it is quite interesting, especially considering the revolution (IoT) it has caused.

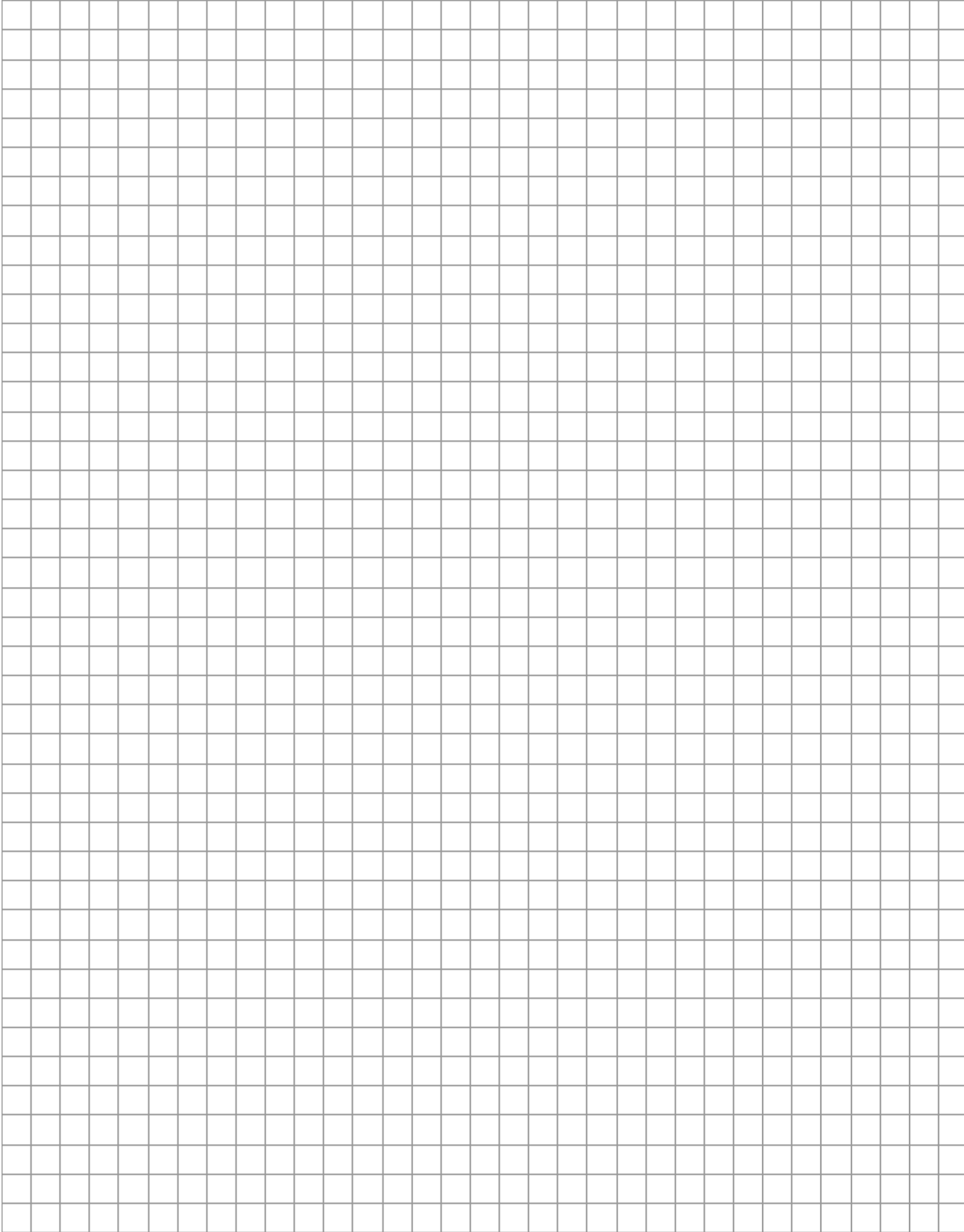
- [1] What Is Physical Computing?, <https://itp.nyu.edu/physcomp/>
- [2] Arduino MKR1000, <https://store.arduino.cc/arduino-mkr1000-wifi-with-headers-mounted>
- [3] MKR1000 Pinout, https://www.arduino.cc/en/uploads/Main/MKR1000_pinout.png
- [4] Foundations, <https://www.arduino.cc/en/Tutorial/Foundations>
- [5] string, <https://www.arduino.cc/reference/tr/language/variables/data-types/string/>
- [6] Download the Arduino IDE, <https://www.arduino.cc/en/main/software>
- [7] FAQ - READ THIS, thread in the MKR1000 section of the Arduino forum: <https://forum.arduino.cc/index.php?topic=449441.0>
- [8] Programming in Arduino, <https://programminginarduino.wordpress.com/author/programminginarduino/>
- [9] Getting started with the Arduino MKR1000, <https://www.arduino.cc/en/Guide/MKR1000>
- [10] Blink, <https://www.arduino.cc/en/Tutorial/Blink>
- [11] Project 02: Spaceship Interface, <https://programminginarduino.wordpress.com/2016/02/29/project-2/>
- [12] Project 08: Digital Hourglass, <https://programminginarduino.wordpress.com/2016/03/03/project-08-digital-hourglass/>
- [13] Project 04: Mixing color lamp, <https://programminginarduino.wordpress.com/2016/03/01/project-04/>
- [14] AD Wandler, <https://www.arduino.cc/en/Tutorial/ReadAnalogVoltage>
- [15] Serial Plotter tool, <http://randomnerdtutorials.com/arduino-serial-plotter-new-tool/>
- [16] Project 04: Mixing color lamp, <https://programminginarduino.wordpress.com/2016/03/01/project-04/>

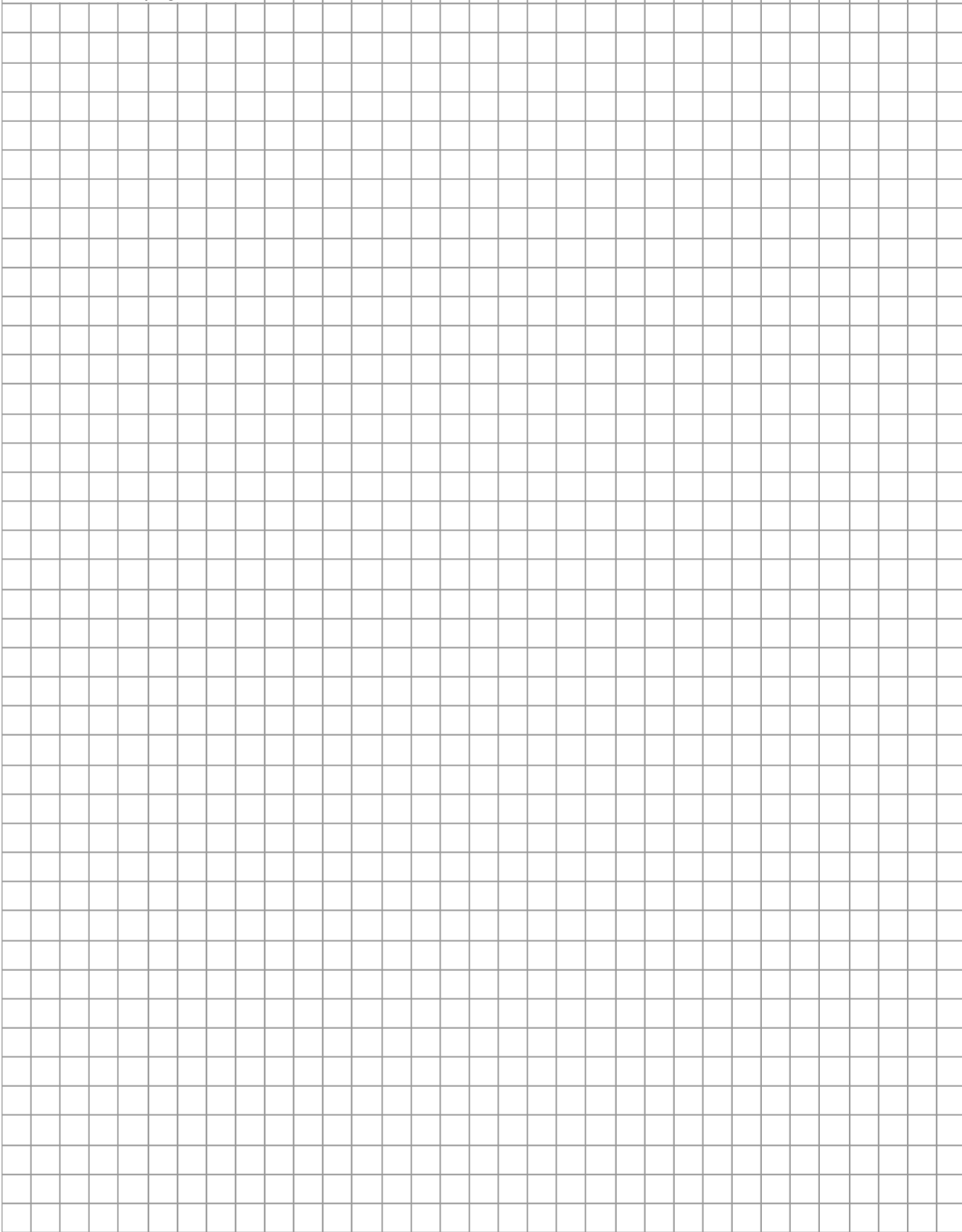
- [17] Project 06: Light Theremin, <https://programminginarduino.wordpress.com/2016/03/02/project-06/>
- [18] Project 03: Love-o-meter, <https://programminginarduino.wordpress.com/2016/02/29/projecte-3/>
- [19] Using a Temp Sensor, <https://learn.adafruit.com/tmp36-temperature-sensor/using-a-temp-sensor>
- [20] Play a Melody using the tone() function, <https://www.arduino.cc/en/Tutorial/toneMelody>
- [21] Project 06: Light Theremin, <https://programminginarduino.wordpress.com/2016/03/02/project-06/>
- [22] Project 07: Piano (musical keyboard),
<https://programminginarduino.wordpress.com/2016/03/02/project-07/>
- [23] Project 05: Mood Cue, <https://programminginarduino.wordpress.com/2016/03/01/project-05/>
- [24] Project 09: Motorized Pinwheel, <https://programminginarduino.wordpress.com/2016/03/04/project-10-2/>
- [25] Driving motors: Darlingtons and MOSFETs, <https://vimeo.com/107917397>
- [26] Big Loads with MKR1000, https://create.arduino.cc/projecthub/Arduino_Genuino/big-loads-with-mkr1000-eee4cc
- [27] Project 10: Zoetrope, <https://programminginarduino.wordpress.com/2016/03/05/project-11/>
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- [38] 001310302-an-01-en-ARDUINO_MEGA2560_R3_STARTER_KIT.pdf
- [39] More sensors are described in 001359118-an-01-de-KURZ_ALLNET_4DUINO_SENSOR_KIT_37_IN_1.pdf
- [40] Feinstaubsensor, <https://luftdaten.info/feinstaubsensor-bauen/>

Arduino

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Arduino

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A. Hardware

We use the Arduino MKR IoT Bundle [1], mostly because it comes in such a beautiful box. In case you are not familiar with the different electronic components, I took some photos for you:

			
Battery	Switch	Tilt Sensor	Bread Board
			
Resistor	Potentiometer	Capacitor	Inductor
			
Diode	LED	Zener	
			
Bipolar Transistor	FET	Temperature Sensor	Photoresistor
			
Piezo Buzzer	Motor	Servo Motor	

In addition, we add a few components to the kits:

<ul style="list-style-type: none"> • 9 volt battery • copper wire, iron nails • alligator clips • graphite pencil lead, 2x0.5 and 1x0.7mm (must be real graphite, kind of hard to get) • jumper cable 	<ul style="list-style-type: none"> • potentiometers (ones included are no good) • Zener diode • inductor • BC547 (box includes 2 FETs, but they switch at 4 volts, not at 3.3 volts) • hub (to protect your laptop)
--	--

You will also need a multi-meter, ideally one that can measure capacitance and inductance. It should have a replaceable fuse, because there is a high likelihood, that it gets blown at least once per semester.

The instructor also needs in addition:

- balloons
- PVC pipe and towel
- electroscope
- Leyden jar
- saran wrap and aluminum foil
- lemon
- coil and nails
- a piece of real silicon
- a small solar cell

Hope I did not forget anything.

Arduino MKR IoT Bundle

Currently the "Arduino MKR IoT Bundle" [1] is sold out. In case that stays that way (likely because of the FET issue), here is a list of the ingredients of that bundle:

- 1 Arduino MKR1000 board, with header soldered.
- 1 micro USB cable,
- 1 400-point breadboard,
- 70 solid-core jumper wires,
- 1 9V battery snap,
- 1 stranded jumper wire
- 1 stranded jumper wire,
- 6 phototransistors,
- 3 potentiometers (10 kilohm),
- 10 pushbuttons,
- 1 temperature sensor (TMP36),
- 1 tilt sensor,
- 1 alphanumeric LCD (16 x 2 characters),
- 1 bright white,
- 34 LEDs (6 ldr bright white, 1 RGB, 8 red, 8 green, 8 yellow, 3 blue),
- 1 small DC motor (6/9V),
- 1 small servo motor,
- 1 piezo capsule (PKM17EPP-4001-B0),
- 1 H-bridge motor driver (L293D),
- 1 octocouplers (4NE5),
- 2 MOSFET transistors (IRF520),
- 5 capacitors (100uF),
- 5 diodes (1N4007),
- 3 transparent gels (R,G,B)
- 1 male pin strip (40 x 1),
- 20 resistors (220 ohm),
- 5 resistors (560 ohm),
- 5 resistors (1 kilohm),
- 5 resistors (4.7 kilohm),
- 20 resistors (10 kilohm),
- 5 resistors (1 megohm),
- 5 resistors (10 megohm)

References

[1] Arduino MKR IoT Bundle, <https://store.arduino.cc/arduino-mkr-iot-bundle>

B. Multi-meter

In our experiments we will need to measure resistance, capacitance, voltage, and current. We will be using a digital multi-meter for this. Here we describe how to use a multi-meter, and what setup is required for each of the different measurements. Multi-meter come in all kinds of forms: analog and digital, cheap and expensive, but their usage is all very similar. If you know how to use one, you know how to use all of them.



Digital Multi-meter

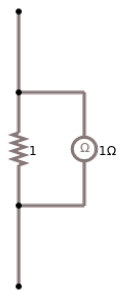
If we look at any digital multi-meter, two things are noticeable immediately: the display with big digits and the round dial with all kinds of different settings. In addition there are two cables, one black and one red, with pointed ends, the multi-meters test leads. Most multi-meters have a fuse, that protects them in case they are used in the wrong way. Hence, when your multi-meter doesn't seem to work anymore, don't throw it away: most of the time, all you need to do is replace the fuse, which costs only a couple of cents.

Also, most multi-meters have only one way to connect the black cable, but there are several plugs for the red cable. You want to avoid the plugs that say "A" or "mA" (for ampere, that is current) on them, because those are the ones that cause trouble (more below). Hence, it is a good habit, if not sure, to connect the plug that says volts or ohms.

Another thing to notice, especially with our multi-meter, that by default it tries to measure AC. But we are only doing DC. So, if you measure the voltage of a 1.5 volt battery, and it does not read around 1.5 volts, but something more like 0, then it is not because your multi-meter is broken, but because you have it in the AC setting. Simply switch it to the DC setting by pressing the DC/AC button.

Resistance

Measuring resistance is the easiest: first, you need to turn on the multi-meter, most of the time by simply turning the dial. Second, you set the dial to the resistance setting, usually indicated by an Omega for Ohm. Here you start with the highest possible setting, usually some mega-ohm, like 100MOhm. Then you take the two pointed leads and connect them to the resistor you want to measure. Make sure the resistor is not connected to anything else. This is very important.



measuring resistance

Let's say the resistor you want to measure is some kilo-ohms. Then if you measure it with the mega-ohm setting we selected first, it will read all zeros. Because compared to mega-ohms, kilo-ohms is basically nothing. So what you do then, you gradually adjust the dial, wait a little for the reading to stabilize, and continue this process until your reading starts to make sense. Now if you have something that has no resistance, either because it has none (like a wire or a superconductor), or because it has a short circuit, then continuing this process to the lowest setting of your device, it will always read zero. If it does that, then you know you have a short circuit.

Short Circuit

We can measure the resistance of just one component, like a resistor, or we can measure the resistance of a whole circuit. So before we connect the battery to our circuit, we can connect our multi-meter instead of the battery. If the resistance we measure is zero, then our circuit contains a short. That means our circuit is a short circuit, and we should not connect the battery. Instead we should find the short, fix it, make sure it is fixed, by again measuring the resistance of the whole circuit. Only after being certain that we do not have a short, should we connect the battery!

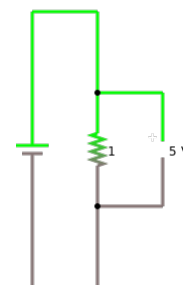
Capacitance

Measuring capacitance is completely analogous to resistance. You set your multi-meter to the highest capacitance setting it has, usually indicated by a C for capacitance or something like nF for nano-Farad, or uF for micro-Farad. Again start with the highest setting. Then connect the capacitor to your multi-meter.

A couple of remarks on measuring capacitance: first, not all multi-meters can measure capacitance. Actually most of the cheaper ones, can not measure capacitance. Second, when measuring capacitance, you should do this only for the small capacitors that we have. Large capacitors (like the ones inside washing machines) are very dangerous. Quite often they might still be charged, and a shock from a large capacitor, that was connected to 220 volts, and still holds some rest-charge, could be lethal!

Voltage

Measuring voltage is a little more complicated: you measure voltage while your circuit is connected to the battery, that is on a "live" circuit. When measuring anything on a live circuit, one has to be quite careful not to accidentally cause a short circuit. So make sure you only touch the pieces you intend to touch! The diagram on the side depicts how you measure voltage.



measuring voltage

First, you select whether you want to measure DC or AC type voltage. We will only measure DC, hence select the DC setting. Second, pick the voltage setting that is slightly higher than your batteries voltage. So if you have a 9 volt battery, select the 10V or 20V setting on your multi-meter. Finally, connect the black lead first, usually on the side of the resistor that is connected to the negative pole of the battery, and then connect the red lead to the other side of the resistor, usually the one that is connected to the positive pole of the battery. If you happen to switch the poles, you will get a negative reading for the voltage. That is fine.

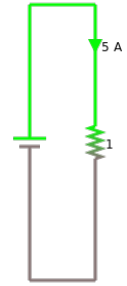
B. Multi-meter

Current

Measuring current is the most complicated, and should be done with care. Many multi-meter (or better fuses) have not survived a wrong current measurement! The reason being, when measuring current, actually current is flowing through your multi-meter, and too much current is just deadly for anything. But that is what fuses are for: in your multi-meter, they protect the multi-meter, in your house, they protect you.

For most multi-meters, you will have to not only change the dial setting to measuring current (A), but you also have to reconnect the red (positive) lead to a different output terminal. Most multi-meters actually have two different ones: one for lots of current, like 10 amperes (10A), and one for smaller currents like milli-amperes (mA). We only work with batteries, so the milli-ampere setting is what we want. Again, we start with the highest values our multi-meter allows for, maybe something like 500mA. And we need to tell it, if we intend to measure DC or AC: we will only measure DC, hence select the DC setting.

Next, we connect the multi-meter to our circuit. If you look at the circuit for measuring current on the side, you will notice, that the multi-meter is part of the circuit. So we kind of have to "break" our circuit: we need to find a spot where we can integrate our multi-meter into the circuit. The easiest way to do this, simply remove one of the connecting wires, and replace it by the multi-meter.



measuring current

Transistors

Some modern digital multi-meters actually allow for the checking of transistors and diodes. They can check, if the transistor is still working, if it is a npn- or pnp-type, and usually can measure the transistors hFE value. For the details on how to do this, you should check your multi-meters manual.

Inductance

Measuring inductance is exactly like measuring resistance or capacitance. However, only few multi-meters can measure inductance.

References

[1] multi-meter, <https://en.wikipedia.org/wiki/multi-meter>

[2] Multi-meters current, isaac.exploratorium.edu/~pauld/summer_institute/summer_day15current/meters_current.html

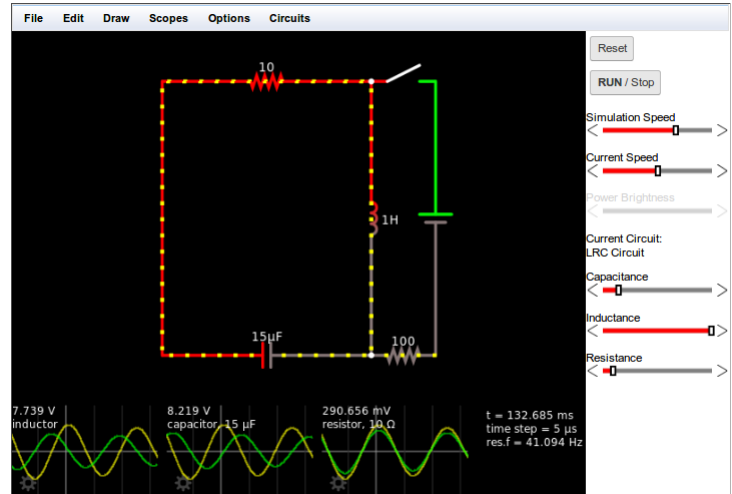
C. Simulator

We will be using the Circuit Simulator, developed by Paul Falstad [1], who graciously put this incredible project under an open source license. The Simulator can be integrated in web pages, but there is also a desktop version available.

Overview

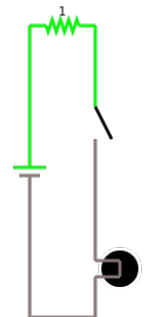
Since it runs in a browser, no installation is necessary. Using the *File* menu you can import and export circuit files. They are basically text files describing the circuit. Under the *Circuits* menu you will find quite an incredible number of example circuits. Additional ones can be found on the website [2]. The examples from the lectures are to be found in the file "pc_004.zip" on the Google drive.

Finally, if you want to modify existing circuits or create your own from scratch, you find all available electronic components in the *Draw* menu. You simply select which component you want to use, and click somewhere on the diagram to place it. You can then drag it around, change its size and direction and add it to the circuit as you like. By clicking on the "Run/Stop" button you can then start the simulation.



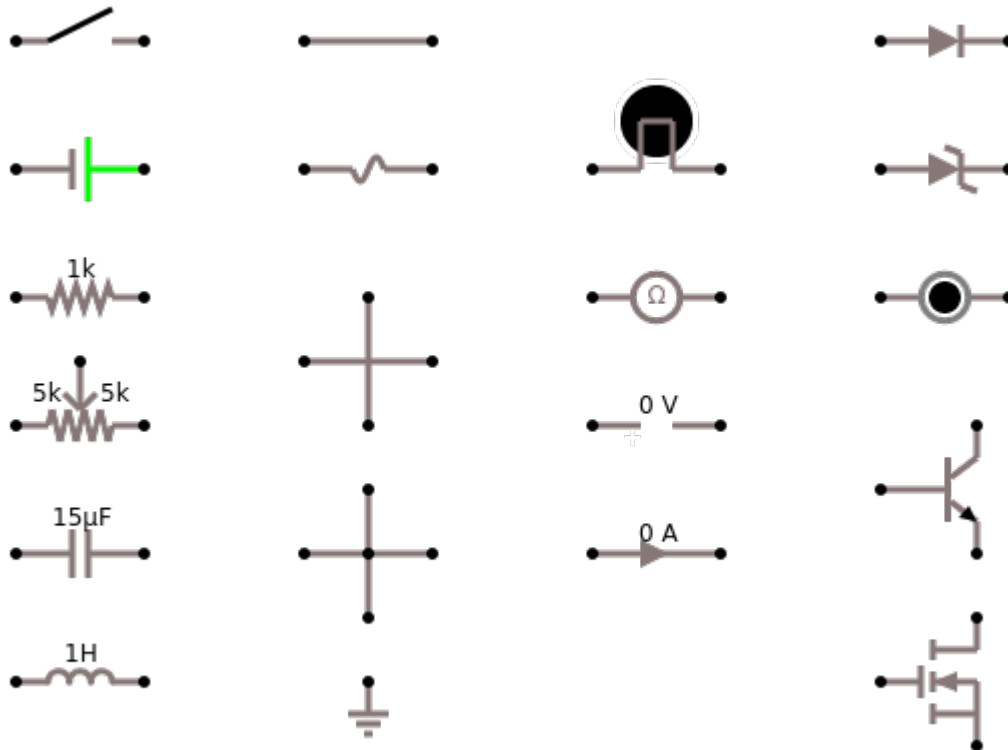
Get Started

To get started, it is probably a good idea to start simple. For this draw a battery ('v'), then a resistor ('r'), a switch ('s') and a lamp (l), and connect them with wires ('w'). If you want a real lamp, instead of an LED, you find that under the Draw menu (Outputs and Labels > Add Lamp). Now test your first circuit by turning the switch on and off.



Circuit Diagrams

Below are all the circuit diagrams that we will be needing:



Of Interest

As you will see, the Circuit Simulator is pretty amazing. Towards to end of the class we will need the fact that it is possible to create and use sub-circuits [3]. Also, helpful might be the fact that one can import circuits through the URL:

```
http://falstad.com/circuit/circuitjs.html?cct=
$
+1+0.000005+10.20027730826997+53+5+50%0Aw+304+64+304+128+0%0Ad+304+128+36
8+192+2+
default%0Ad+304+256+368+192+2+default%0Ad+240+192+304+128+2+default
%0Ad+240+192+304+256+2+
default
%0Aw+304+256+304+352+0%0Aw+368+192+416+192+0%0A207+304+64+304+16+4+
+in%5Cp%0A207+304+352+304+400+4+++in-%0A207+416+192+480+192+4+
+out%5Cp%0A207+240+192+160+192+4+++out-%0A
```

References

- [1] Circuit Simulator, <http://falstad.com/circuit/>
- [2] Electronics Demonstrations, falstad.com/circuit-java/e-index.html
- [3] How to create sub-circuits: <http://falstad.com/circuit/subcircuits.html>

D. Arduino IDE


Before we can use our Arduino, we need to install the Arduino IDE on our computer.

Installation of Arduino Software

Depending on your operating system, the installation may be slightly different.

Linux

- download IDE from Arduino website [1]
- unzip and install running `./install.sh`
- connect Arduino board through USB
- you need to add your username to the tty and dialout groups:
 `sudo usermod -a -G tty yourUserName`
 `sudo usermod -a -G dialout yourUserName`
- logout and log back in, for changes to take effect
- start IDE, make sure to select your Arduino board under Tools>Board
- select serial port under Tools>Serial Port
- change language in File>Preferences
- load the "Blink" scetch from File>Examples>Basics
- run your first scetch



The screenshot shows the Arduino IDE window titled "Blink | Arduino 1.0". The menu bar includes "File", "Edit", "Sketch", "Tools", and "Help". Below the menu bar is a toolbar with icons for file operations and a search icon. The main text area contains the following code:

```
/*
 * Blink
 * Turns on an LED on for one second, then off for one second, repeatedly.
 *
 * This example code is in the public domain.
 */

void setup() {
  // initialize the digital pin as an output.
  // Pin 13 has an LED connected on most Arduino boards:
  pinMode(13, OUTPUT);
}

void loop() {
  digitalWrite(13, HIGH); // set the LED on
  delay(1000);           // wait for a second
  digitalWrite(13, LOW); // set the LED off
  delay(1000);           // wait for a second
}
```

At the bottom of the window, a status bar indicates "1" and "Arduino Uno on /dev/ttyACM1".

Mac [4]

- download IDE from Arduino website [1]
- you may have to unzip the software
- to install it, copy the Arduino application in the Applications folder
- connect Arduino board through USB
- start IDE, make sure to select your Arduino board under Tools>Board
- select serial port under Tools>Serial Port
- change language in File>Preferences
- load the "Blink" scetch from File>Examples>Basics
- run your first scetch

Windows

- download IDE from Arduino website [1]
- install software
- connect Arduino board through USB
- install drivers
- start IDE, make sure to select your Arduino board under Tools>Board
- select serial port under Tools>Serial Port
- change language in File>Preferences
- load the "Blink" scetch from File>Examples>Basics
- run your first scetch

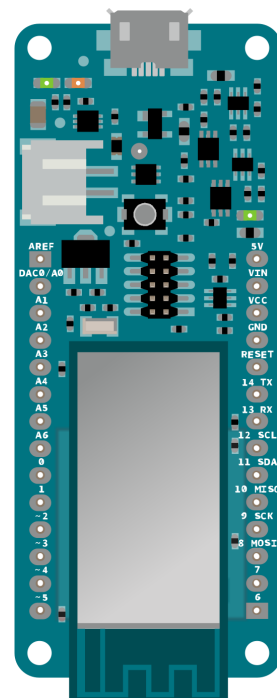
Shortcuts

The following shortcuts will become handy, when doing a lot of Arduino coding:

- Ctrl-S: Save
- Ctrl-R: Verify
- Ctrl-U: Upload
- Ctrl-T: Pretty Print

Arduino Board MKR1000

The schematic on the side shows the layout of the Arduino MKR1000. We see the USB and power connectors. Usually the Arduino gets its power through the USB port. In addition we see two sets of pins: on the right there are pins for power and for digital inputs/outputs (D6-D14). On the left we see the analog output DAC0, the analog inputs A1-A6, and some more digital inputs and outputs (D0-D5). There are also a few LEDs: the power LED, the TX and RX (for communication) and the "L" LED, the one we will be using a lot.



Test: Blink

Getting the LED "L" to blink is actually quite easy: simply type the following code into the Arduino Software (or simply load the "Blink" scetch from File>Examples>Basics). Verify it (Ctrl-R) and Upload it (Ctrl-U) to the Arduino board. The LED should start blinking.

```
void setup() {
  pinMode(6, OUTPUT);
}

void loop() {
  digitalWrite(6, HIGH);
  delay(1000);
  digitalWrite(6, LOW);
  delay(1000);
}
```

(see: <https://www.arduino.cc/en/Tutorial/Blink>)

References

- [1] Download the Arduino IDE, <https://www.arduino.cc/en/Main/Software>
- [2] Arduino Beginner's Course, <http://runtimeprojects.com/2016/03/arduino-beginners-course-introduction-to-arduino/>
- [3] ESP8266 Remote Controlled Sockets, <http://randomnerdtutorials.com/esp8266-remote-controlled-sockets/>
- [4] Install the Arduino Software (IDE) on OS X, <https://www.arduino.cc/en/Guide/MacOSX>

E. Definitions

A couple of definitions of terms. It might come in handy, but personally, I believe the formulas in the next appendix are more useful.

Ampere (A): Is the SI unit for current I. It is defined in terms of the charge of an electron via $1 \text{ C} = 1 \text{ A}\cdot\text{s}$.

Capacitor: An electronic component that stores energy in the form of an electric field. It resists a sudden change in voltage.

Conductance (S): The inverse of resistance. Measured in Siemens, which are the inverse of Ohms, $1 \text{ S} = 1/\Omega$.

Coulomb (C): The elementary charge e of the electron is defined to be $-1.602\,176\,634 \times 10^{-19}$ Coulomb.

Current (I): The movement of charge carriers, usually electrons, in an electric field. It is measured in Amperes.

Henry (H): The SI unit for inductance.

Impedance (Ω): A more generalized form of resistance, also valid for AC type current. The impedance of a device can vary with the frequency of the electricity applied. A perfect resistor will have a constant impedance for all frequencies. Capacitors and inductors have varying impedances at different frequencies. It is measured in Ohms.

Inductor: An inductor is a device that stores energy in a magnetic field. It opposes a sudden change in the flow of current.

Joule (J): The work required to exert a force of one newton (1 N) for one meter (1 m), $1 \text{ J} = 1 \text{ N}\cdot\text{m}$.

Ohm (Ω): A measure of resistance or impedance, $1 \Omega = 1 \text{ V/A}$.

Power (P): Voltage times current, measured in watts. The amount of work being done per unit time.

Resistance (Ω): Properties of a circuit that impede the flow of electrons. Resistance converts electrical energy into phonons that are given off as waste heat. Resistance is measured in Ohms.

Volt (V): A potential due to an electric field. One volt is defined as one joule of work per one coulomb of charge, $1 \text{ V} = 1 \text{ J/C}$.

Voltage: Is the difference in electric potential between two points in an electric field. It is measured in volts.

Watt (W): A measure of power (P). A watt is a joule (1 J) of work done in a second (1 s). $1 \text{ W} = 1 \text{ J/s}$.

F. Formulas

It is helpful to briefly review some formulas from school. First, it gets us into the formula mode of thinking, and second, it might help us to get a better feeling for the electrical units.

Mechanics and Gravity

As a starter, let's remember what we learned in school about mechanics and gravity.

Force

According to Newton, force (F) is defined as mass (m) times acceleration (a):

$$F = m \cdot a.$$

Now when we talk about gravitation, then the acceleration, a, becomes the Earth's acceleration, which we call g and Newton formula becomes

$$F = m \cdot g,$$

where the g is the famous 9.81 [m/s²]. The force is measured in Newtons, [N], and mass is measured in [kg].

Energy

Energy, or to be more precise, potential energy in a gravitational field, is defined as

$$W = F \cdot x = m \cdot g \cdot x.$$

Here, W stands for work, and x is the distance that we move something in a gravitational field. The higher we lift something, there more energy is needed. Energy or work is measured in Joule [J] and distance is measured in meters [m].

Power

Finally, there is something called power (P) and that is defined as work per unit time, i.e.,

$$P = \frac{W}{t}.$$

Power is measured in Watts [W] or in the old units horsepower. It is pretty useless, unless when you buy a car or a battery, then you want to know.

Electrostatics

After remembering these basic formulas from mechanics, we can see the equivalence in the electrical world.

Force

In gravitation, we talked about a gravitational field (g), and a particle of mass (m) will experience a force (F) by its effect. Similarly, a charge (q) will experience a force (F) in an electric field (E)

$$F = q \cdot E.$$

Now, force is still measured in Newton [N], but charge is measured in Coulomb [C], and the electric field has units of volt per meter [V/m].

Energy

Energy is still defined as force times distance,

$$W = F \cdot x = q \cdot E \cdot x.$$

This is electric potential energy, i.e., if we want to move a charge q in an electric field of strength E by a distance x , then the above equation gives us the energy needed to do that.

Analogy

What you hopefully noticed was that there is an analogy between gravitation and electricity. In gravitation we talk about a mass m , in electricity we talk about a charge q . In gravitation there is a gravitational field, g , and in electricity there is an electric field, E . Gravitational fields exert a force on masses, and electric fields exert forces on charges. And to move a mass in a gravitational field costs energy, and to move a charge in an electric field, also costs energy.

Voltage, Current and Resistance

Life would have been easy, if the story ended here. But turns out, when we deal with electric circuits, it is very hard to measure an electric field, and even harder to measure a charge. But it is really easy to measure voltage and current. That is why the story continues, because we want to measure stuff.

Voltage

The voltage is defined as work done divided by the amount of charge being moved,

$$V = \frac{W}{q}.$$

Voltage is measured in volts [V] and as above, work in Joule [J] and charge in Coulomb [C].

As you see, voltage is like the electric potential energy (W) per charge (q). This is why voltage is sometimes also called the electric potential. So voltage has to do with energy.

Current

The current is defined as amount of charge being moved over a given period of time,

$$I = \frac{q}{t}.$$

Current is measured in ampere [A], charge is still measured in Coulomb [C], and time is measure in seconds [s].

Think of a little piece of wire, and imagine all the little electrons in there as they move. You count the number of electrons that move in a short piece of this wire over the time period of one second. That is current.

E. Formulas

Power

Remember that power (P) was defined as work per unit time, i.e.,

$$P = \frac{W}{t},$$

and using the definitions for voltage and current above, you might see after some math-gymnastics that

$$P = V \cdot I.$$

Power is still measured in Watt [W], voltage in volts [V] and current in ampere [A].

Resistance

Now there is one last thing missing and that is electrical resistance (R). It is defined as voltage divided by current,

$$R = \frac{V}{I}.$$

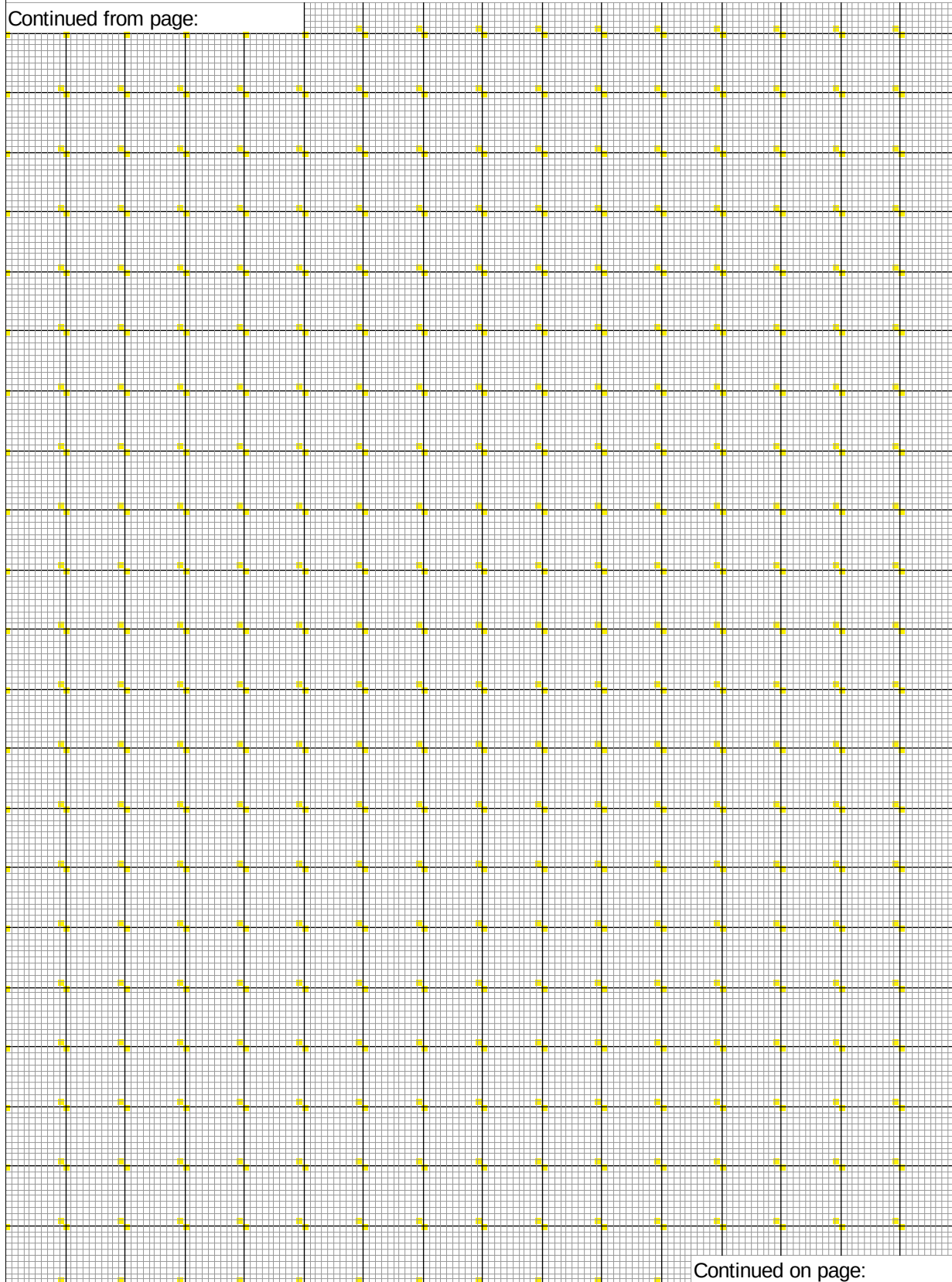
Resistance is measured in Ohm [Ω], voltage in volts [V] and current in ampere [A].

As an interesting side note, there is no real mechanical equivalent to the idea of electrical resistance. It's something new. It's Ohm's law.

G. Graphpaper

Project:

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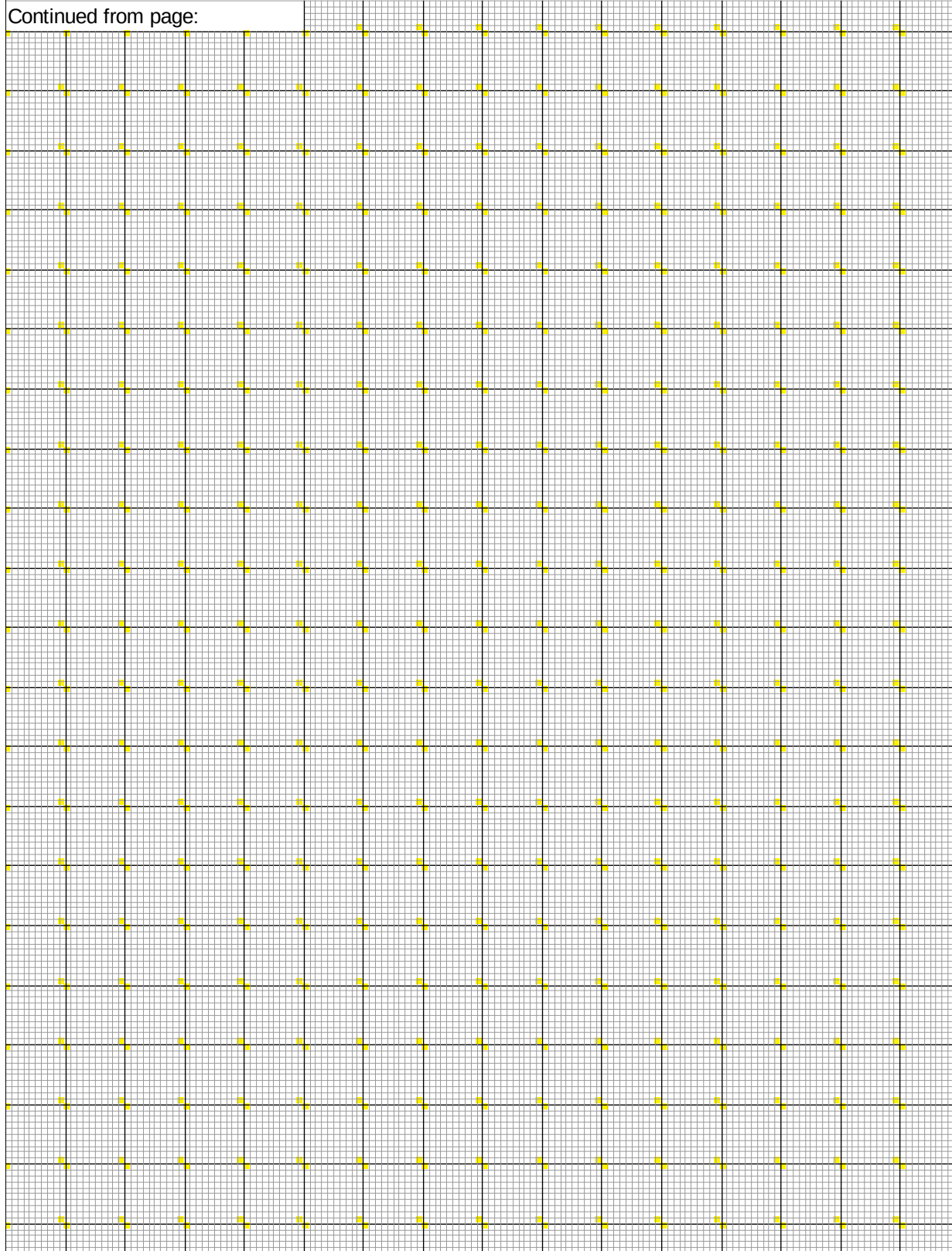
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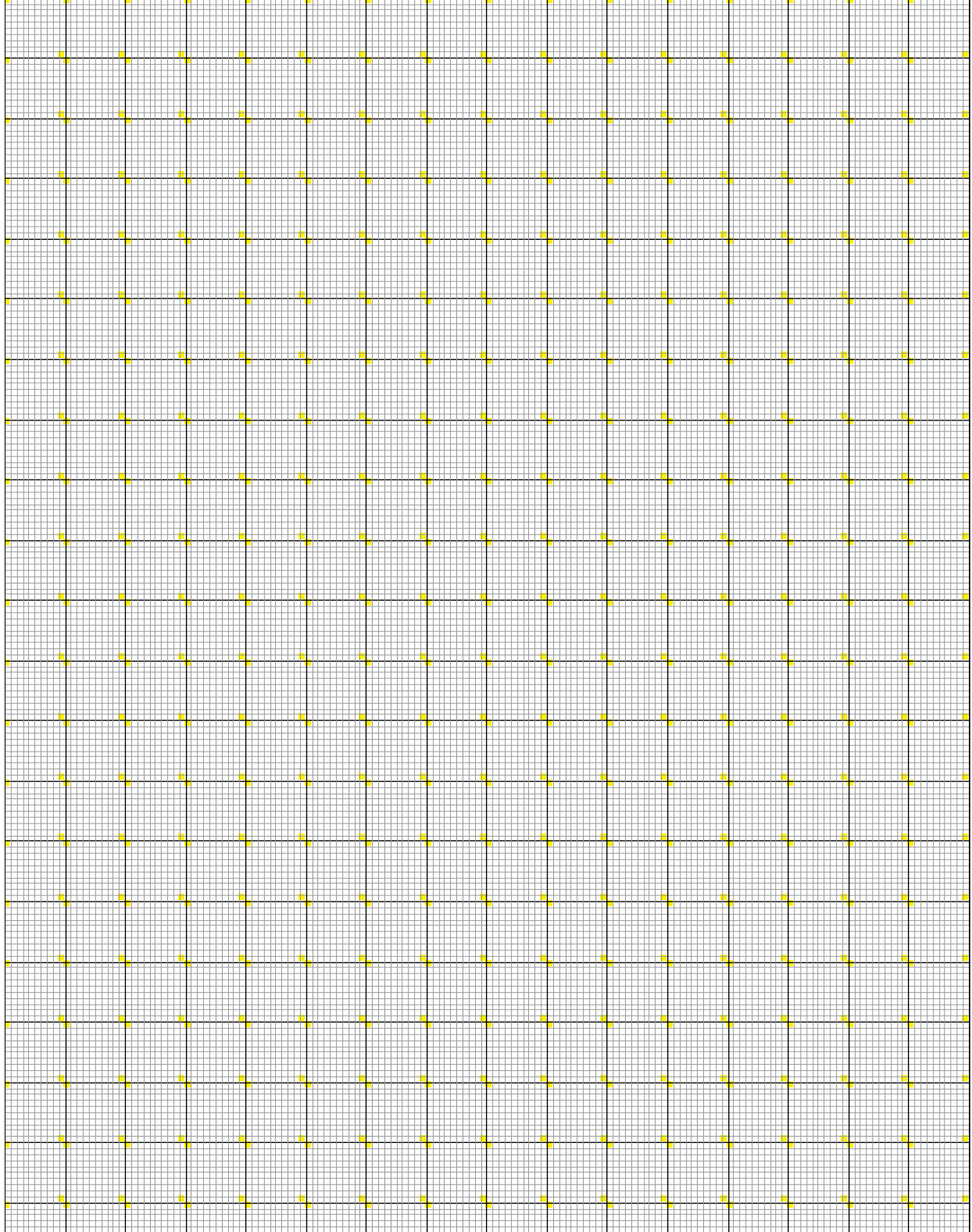
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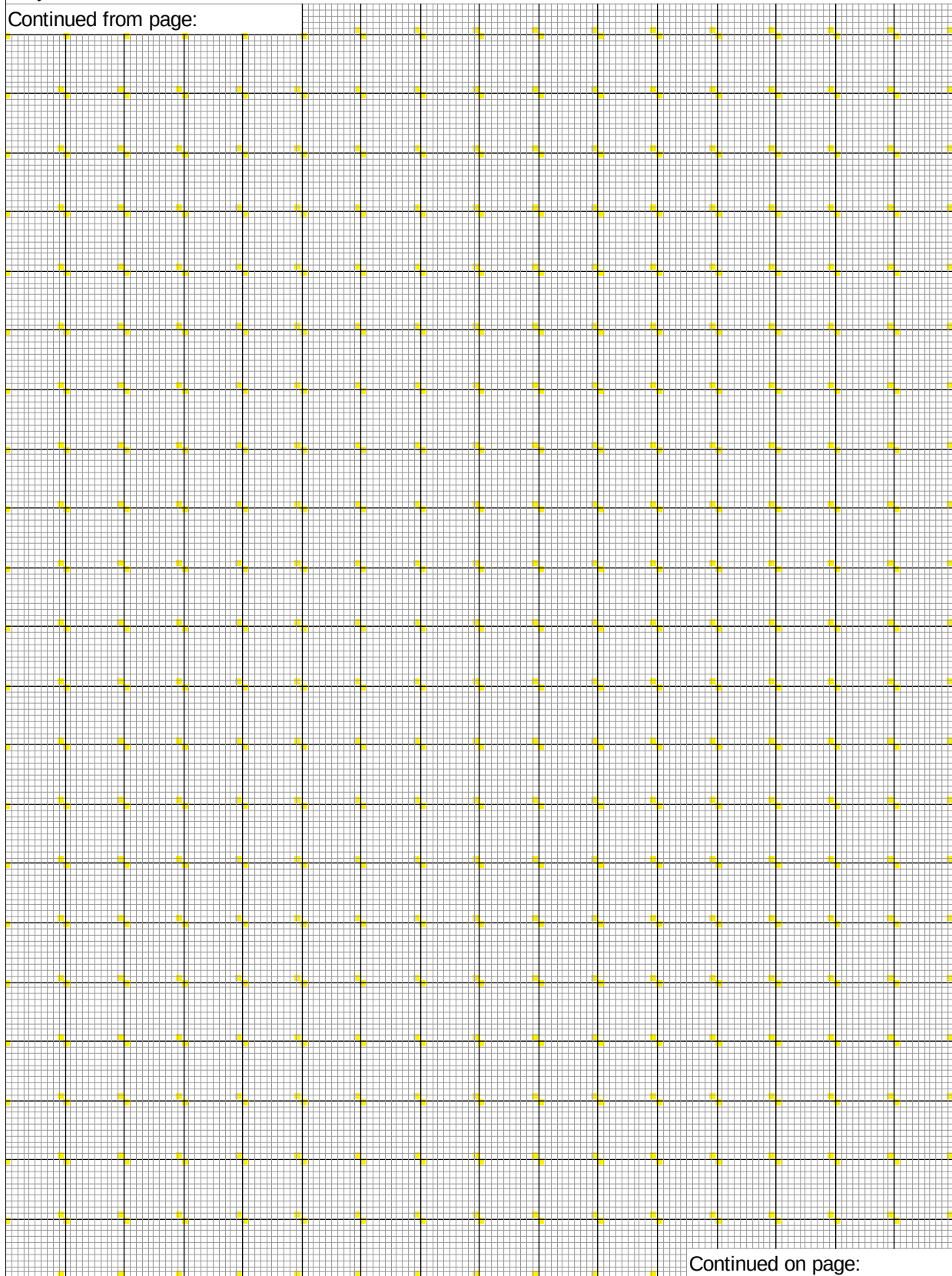
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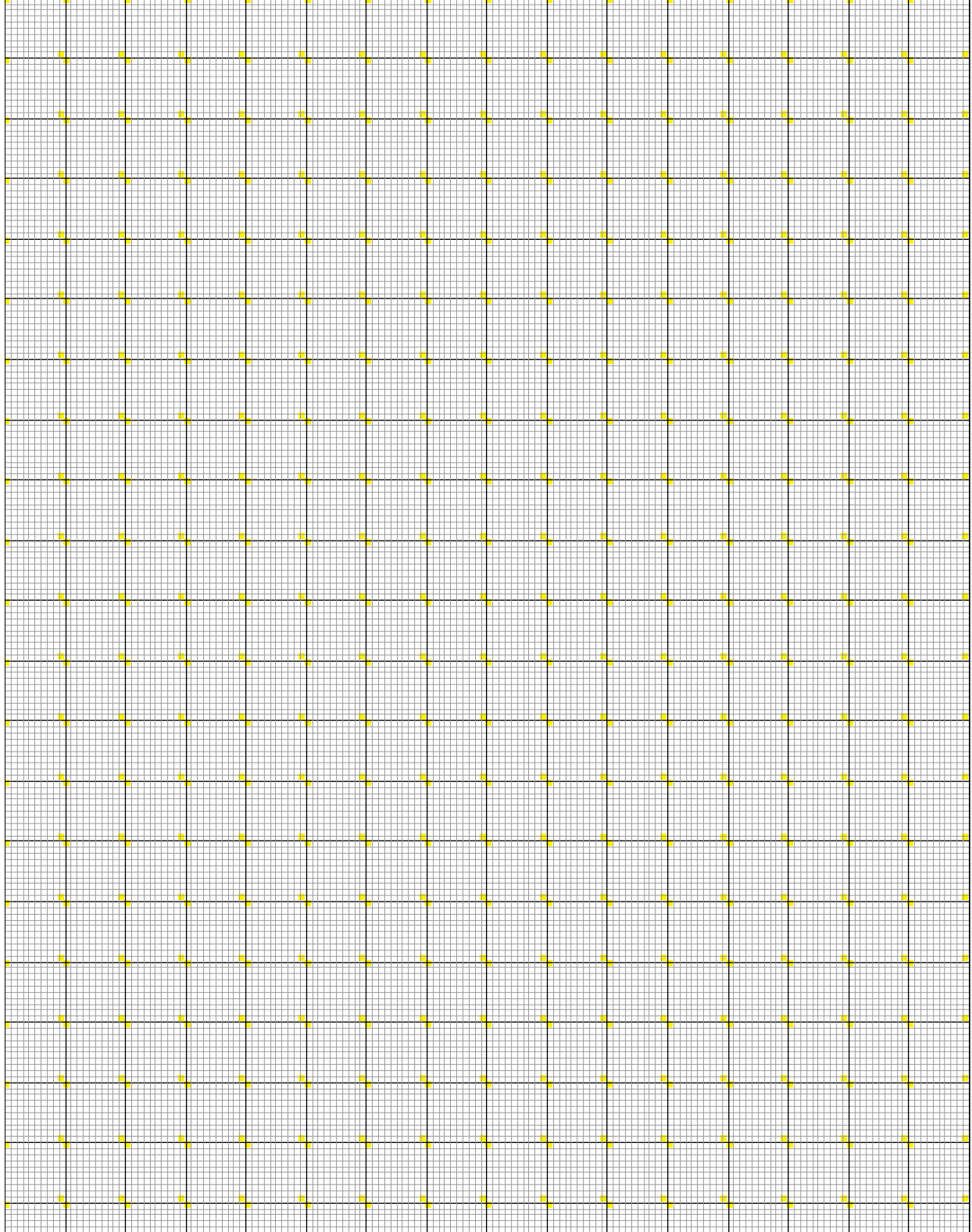
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