POLYTECH
Peter the Great
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Course

«Introduction to Biomedical Engineering»

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Section 1: Basic electronics
Lecture 1.1: Diodes and Transistors

Contents

Introduction to Electronics

This section is designed to introduce basic concepts of electronics to a person who never dealt with such concepts before. The section is split onto 3 sub-sections. We will start with introducing the basic components, we will describe its functions and behavior, and then we will continue with more applied concepts such as amplifiers and filters.

First, let's talk about the electronics from a prospective of a lay person. On the screen, you can see a Figure of 2 people. Can you spot an electronics engineer?

Figure 1 - Spot the electronic engineer….

Right, the person on your right you all recognize, it is famous Steve Jobs, the founder and spiritual leader of Apple Inc. The person on your left however is less known, this is Steve Wozniak, the Principle Electrical Engineer of Apple, and the actual creator of all early Apple products.

However, you can see what I mean; it takes a specific kind of person to be an electronics engineer. You have to read and understand very complicated impenetrable diagrams, you gotta spend almost all of your time in a workshop with no natural light, surrounded by the massive amount of quite complicated equipment, and you gotta speak a specific language which is only spoken by geeks like you.

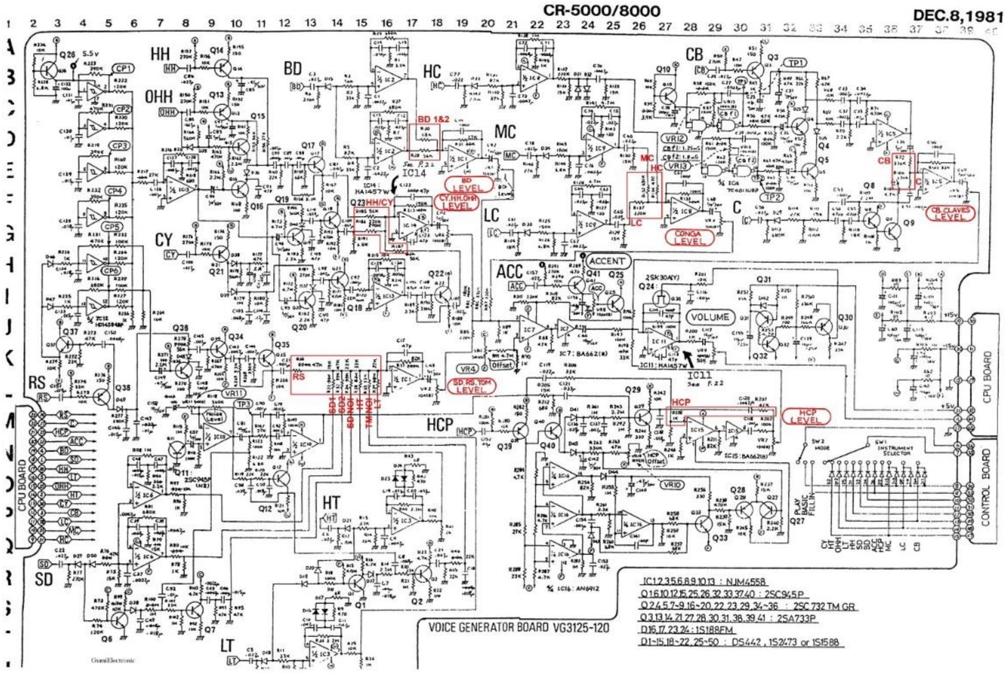


Figure 2 - Impenetrable diagrams

Which brings us to the next question: is electronics even relevant? And the answer is: absolutely. And not only for biomedical engineering. If you look at any modern product, be it consumer or specialized, it will always, and I mean **always** contain electronics. Starting from cars, which is an example of very conservative industry, and finishing things like MRI scanner, where electronics contain more than 50% of its shear weight.

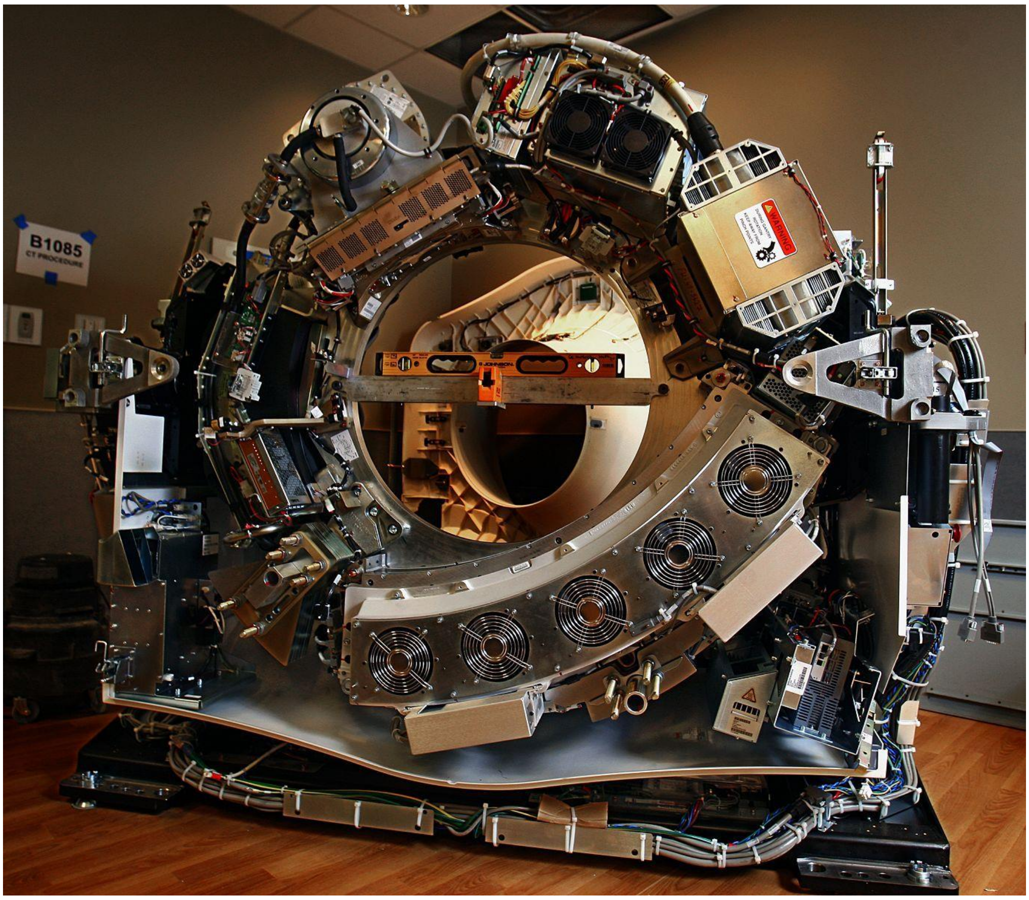


Figure 3 - MRI scanner

Well, this is all fine, but is not it depressing that you gotta be a geek to understand any contemporary product development? Well, the thing is that you do not have to be an electronics engineer nowadays to be able to design and evaluate engineering systems. It can be much more fun than for the other Steve!

Similar to almost any engineering discipline, there are layers of abstraction you can operate with and still be able to do things! The common example is a cell phone. The fact of the matter is that in modern world nobody knows how to build one from scratch. Further, you do not even have to know anything about the electronics to be able to write programs, which run on the phone and use its electronic features, thanks to modern day high-level programming environments.

Things start with a silicon chip - a physical piece of embedded electronics packed into very limited space, which can be represented as a circuit diagram, which in turn can be described as a mathematical model. You do not have to know the exact chip structure to understand what it is doing, and how to use it in your own product. Although, you still need to learn the limitations of the abstraction, as you do not want surprises to be revealed after the product is already in production. But as soon as you operate within those limits, you will be safe.

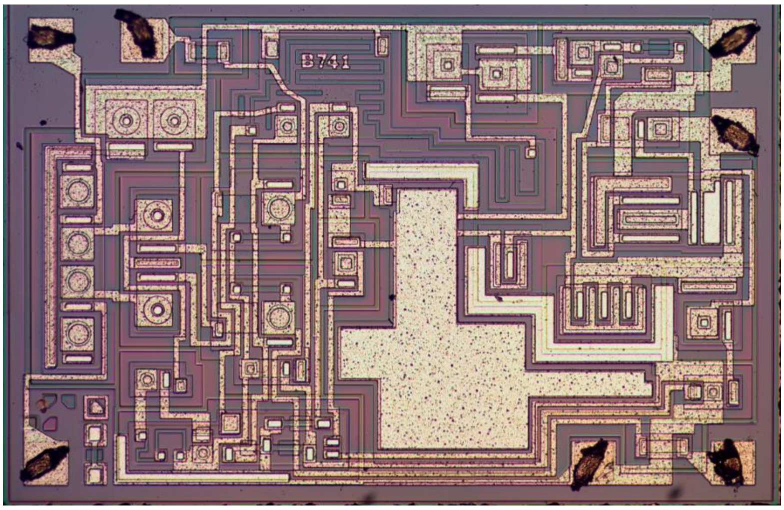


Figure 4 - Silicon Chip

No, really, the entire thing can be replaced with one diagram and a model. We call these models a Transfer Functions, and we will talk about them in detail during the second section of the course. However, the simple idea is that any system can be represented as a function in Laplace domain, which has inputs and outputs. By knowing this function, you can predict the system behavior and analyze its performance, and because someone else had already done the work of proving it, you can be sure that the actual system behaves exactly as intended when integrated into the product.

Right, when we talk about electronics, there two main areas it can be divided into. And it is a direct consequence of the types of information that the electronic bit is dealing with. They are analog, and digital. Analog electronics deals with continuous signals, meaning at any time point there is a value of a function we consider, and it can be any value. Digital electronics operate with discrete signals, meaning there is limited range of discrete values, and they are defined over discrete time intervals (also called sampling periods). The basic comparison between the two is real world VS things computer like.

Analog(ue) and Digital Signals

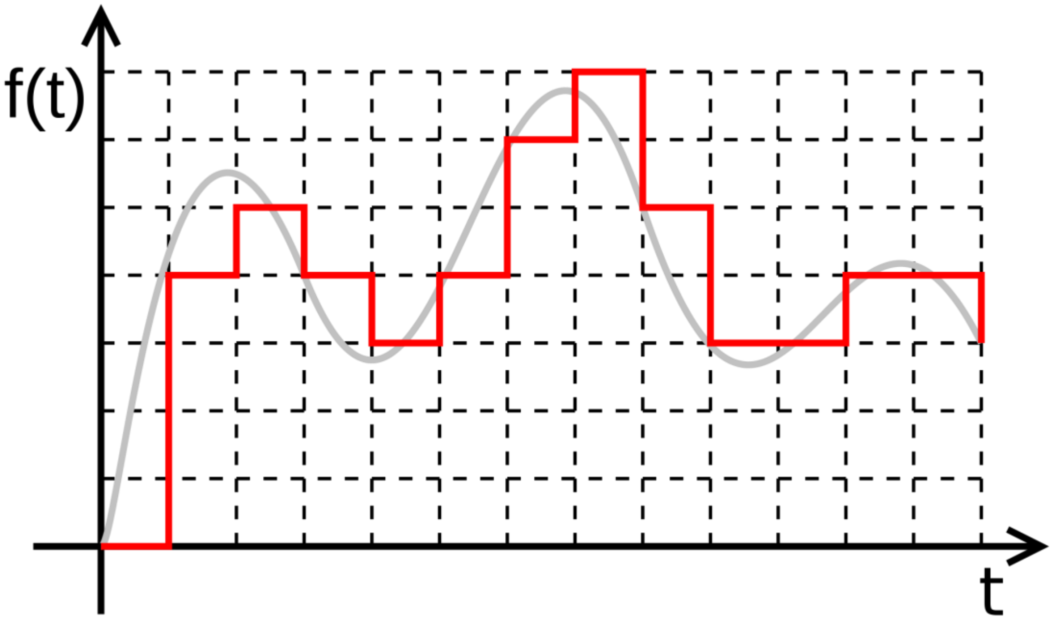


Figure 5 - Analog(ue) vs. Digital Signals

Digital electronics, a thing that computers like, operates with pulses, the most common of which is on/off pulse. That means that you only have 2 values, and the signal can only be on, or off and it can obviously code binary information. In real life you would deal with certain voltages, like 0 for off, and 1 (|or 5) for on. With the correct circuitry, this kind of signal is very robust to external noise: you can see on the Figure, that even if you distort the original signal a lot, with the selection of appropriate threshold, you can achieve near-perfect recognition of where is on, and where is of. The most common thing to do a job is a Schmidt trigger, which does exactly that, exists on every Arduino digital pin, and ensures the robust detection of pulses.

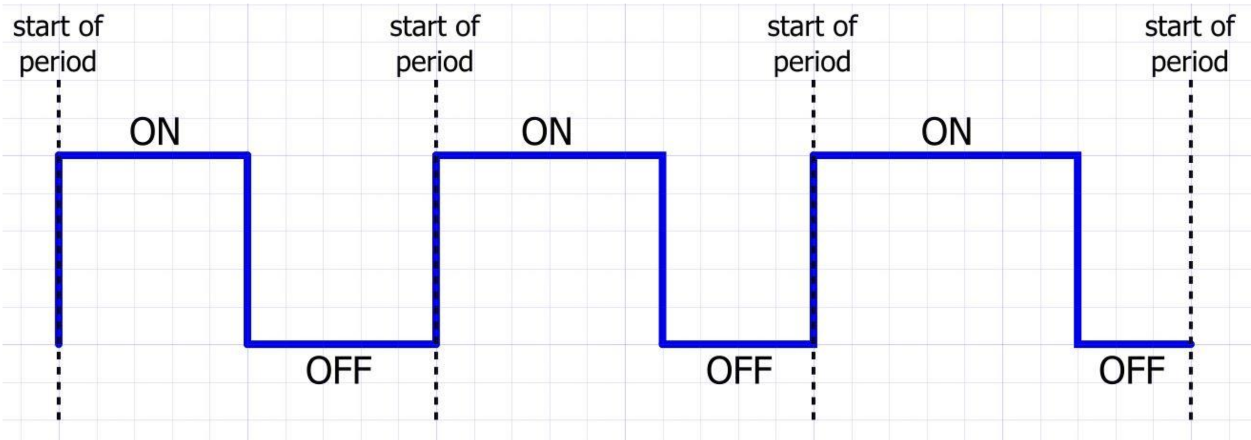


Figure 6 - Digital electronics - pulses

On and off pulses can be used to transmit something more advanced than the digital information. You can vary the time of 'on' VS 'off' pulse over the specific amount of time, and get so-called Duty Cycle, which is equal to Pulse Width (the time the signal is on) over total amount of measured time, times 100%. So if you have several consecutive pulses, you can transmit some information by encoding it in the pulse width. The beauty is: if the system you transmit this information to cannot react fast enough to each pulse (like a motor or LED). Then your actual power, or voltage, that the system "extracts" from these pulses will be equal to the duty cycle time the amplitude of the pulse: The motor due to inertia will not react fast, so its speed will be "modulated" by the duty cycle of the pulses that you send, each consecutive pulse will push the motor, and amount of additional speed it receives each time will be proportional to the amplitude of the pulse time the pulse duration, thus, if you can do it fast enough, you can control that precisely.

As was mentioned before, Duty Cycle is quite powerful tool to transmit **analog** information over digital world, and many micro-controllers, including Arduino, will have this functionality implemented by default. The standard name for technique and circuitry is Pulse Width Modulation.

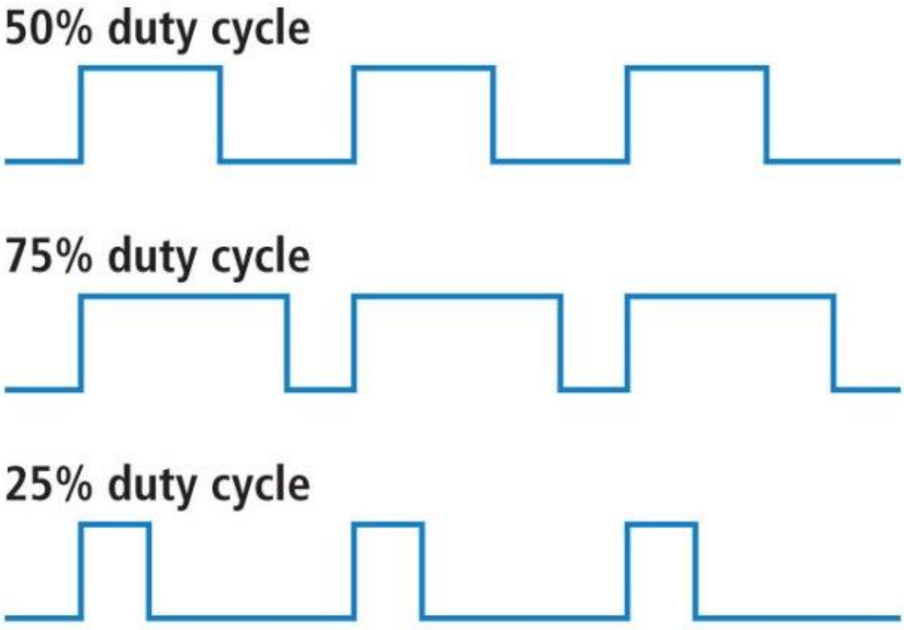


Figure 7 - Duty Cycle

One of the brilliant features of digital electronics is simplicity of implementation of formal binary logic. There are standard digital components for logical operations, such as AND, OR, XOR, and NOT. The simplest is NOT, which flips the voltage, and therefore makes zeros where there were ones, and ones where there were zeros. You can read about the rest of them and how they operate online, but the idea is that you can built very sophisticated machines using only those. Put lots of them together, add some memory, and very broadly, you made yourself a micro-controller.

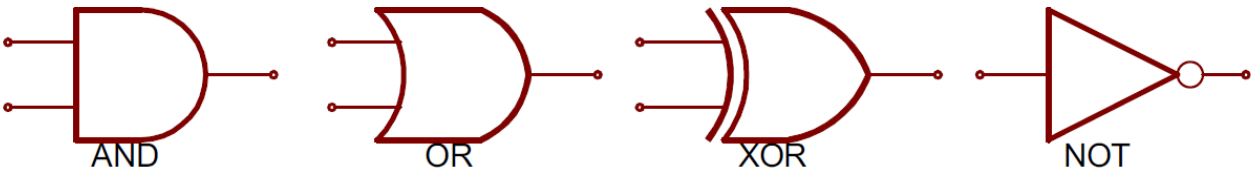


Figure 8 - Digital electronics – Logic gates

OK, the digital electronics is brilliant, but how do we convert our real-world signals into the digital world. The specific tool to perform this function is called (surprise-surprise) Analogue-to-digital converter or ADC. It takes the input signal, most commonly voltage, and produces the binary output (sequences of pulses). The most common of them would have one input and several outputs, each output would binary-code its specific register, and inside there will be some sort of threshold detector (it can also be a Schmidt trigger). The input signal goes to each detector, which turns 1 if the threshold was met, if the thresholds are logarithmically scaled with base 2, each gives you a binary digit. If your signal is small, then none of the detectors worked and the output is 000, if you start increasing it, until the lowest threshold is met, then you get 001, and so on. Obviously, there is circuitry that controls compensation voltage for every threshold activation, but it is quite easy and operates as a subtraction feedback for each register.

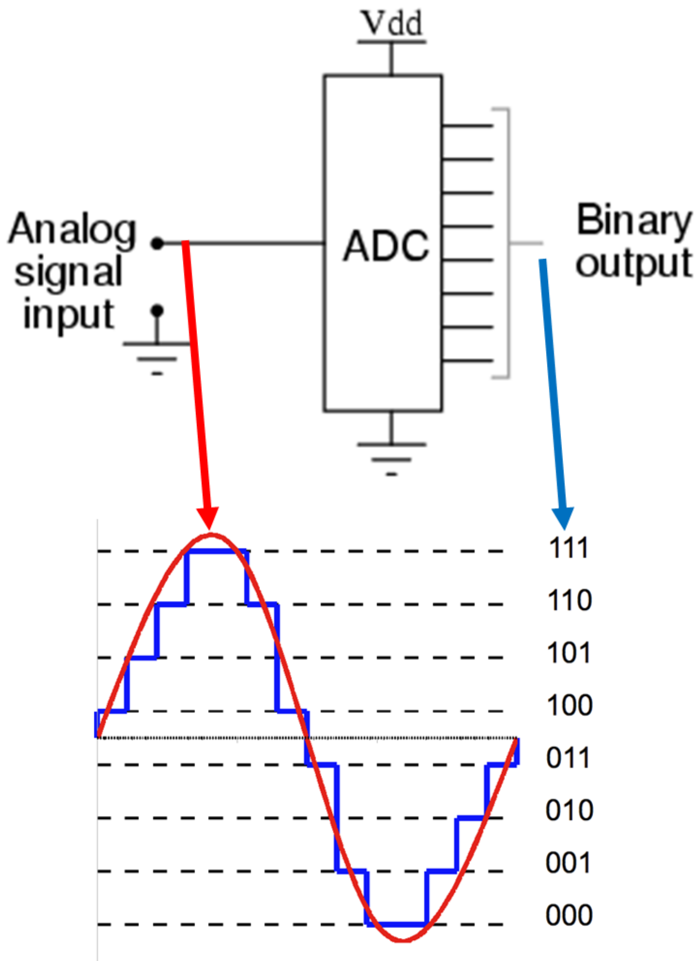


Figure 9 - Analogue to Digital converter

There are different types of ADCs which operate at different accuracy level (resolution), the sophisticated go up to 24 registers (or bits), which mean they can code a lots of numbers (precisely 2^24). They also operate at different frequencies (sampling rates), and normally sampling rate trades off resolution and vice versa.

Coming back to digital VS analogue electronics, here is a simple diagram of pure digital circuitry (also known as digital clock), it normally consist of blocks, connected to each other with wires transmitting binary signals (on-off signals). Here, for example, is the pulse generator, connected to Clock Divider (slows down the clock to 1/sec), then counter (counts pulses up to 8), then binary LED display controller, which in turn drives the LED display. Digital electronics is very easy to design, everything is standard, but it is generally expensive and requires more energy for the same job.

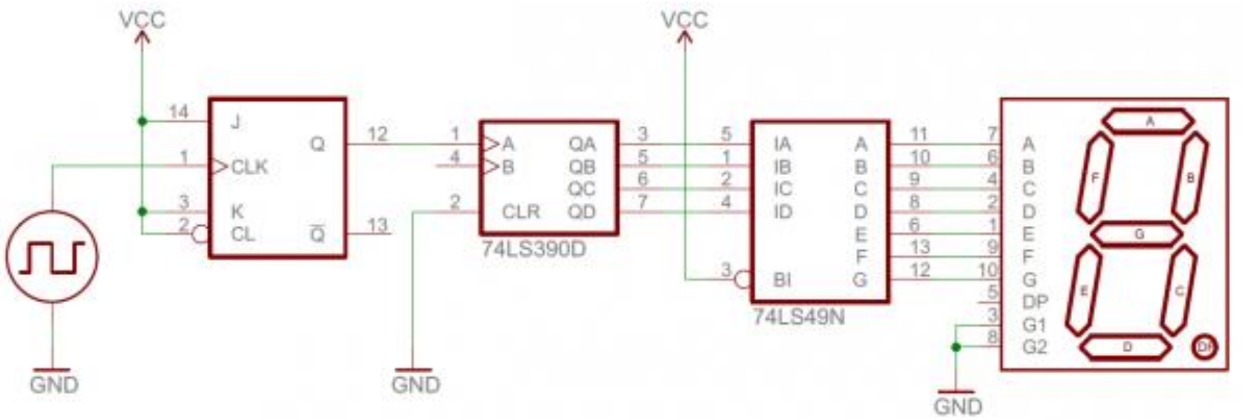


Figure 10 - Analogue vs. Digital electronics - LED display

Analogue electronics circuits are more complicated, and components are inherently analogue, this diagram shows filter, buffer, amplifier, then current converter, and speaker (all together is consumer amplifier). The analogue stuff is more complicated and noisy, so the rule of thumb is to use digital unless you cannot.

Now, to the question of schematics and basic components, you should know about resistors and capacitors (gotta be school stuff), so we will start with Bypass capacitors, a specific set of capacitors commonly connected to the digital electronic circuits. They exist to reduce the noise form the power supply to the electronic components (having much lower impedance for higher frequencies, then for lower), and act as no-connection for lower frequencies, and straight wires for higher frequencies, shorting all high-frequency noise to the ground. If we read the digital circuit, we can simply ignore them for the purpose of understanding how the diagram works.

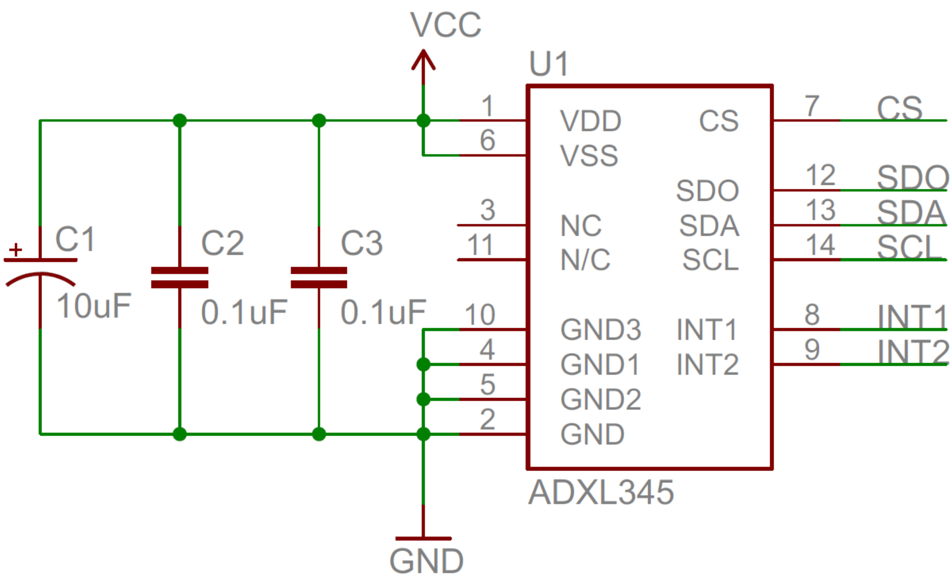


Figure 11 - Simplifying schematics – Bypass capacitors

Diodes

The next essential component on the list is a diode. It is a semiconductor device, which means that it can only transmit current in one direction. This direction is called forward, from so-called Anode (positive voltage) to cathode (negative voltage). If we apply inverse voltage (positive to cathode and negative to anode), current will not flow, and diode is 'reverse biased'.

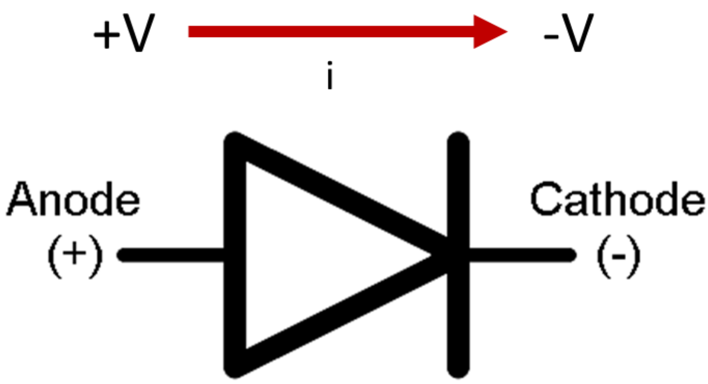


Figure 12 - Diodes – controlling current direction

So when you see a diode in the circuit, you can simplify by assuming no resistor in one direction (straight wire), and infinite resistor in another direction (gap). The most common and simple use for diode is current protection. If you remember 70s-80s toys, and importance of misconnecting the polarity of the battery, either you understand the simplicity and brilliance of protecting the expensive stuff from complete burn out by inserting a simple diode forward way on positive pin, or reverse in parallel (please take time to analyze what is happening on the screen and what is the difference).

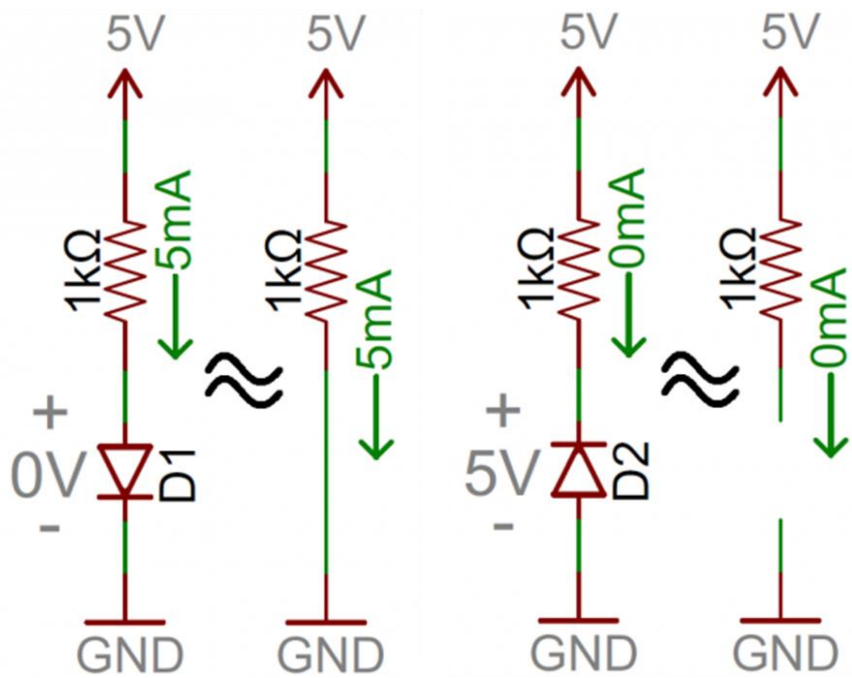


Figure 13 - Forward biased (positive voltage) and Reverse biased (negative voltage)

In reality, however, diodes are not ideal, they need certain small voltage (forward voltage) to start working, and they do not hold infinite reverse voltage (the maximum is called breakdown voltage). Also, they can only transmit limited amount of current before they start to heat a lot. Some diodes exploit these properties, and then they are specifically marked on the diagrams with funny symbols. For you, however, it is enough to say: this is a diode, I know what it is doing, move on, or google the specifics if you need to.

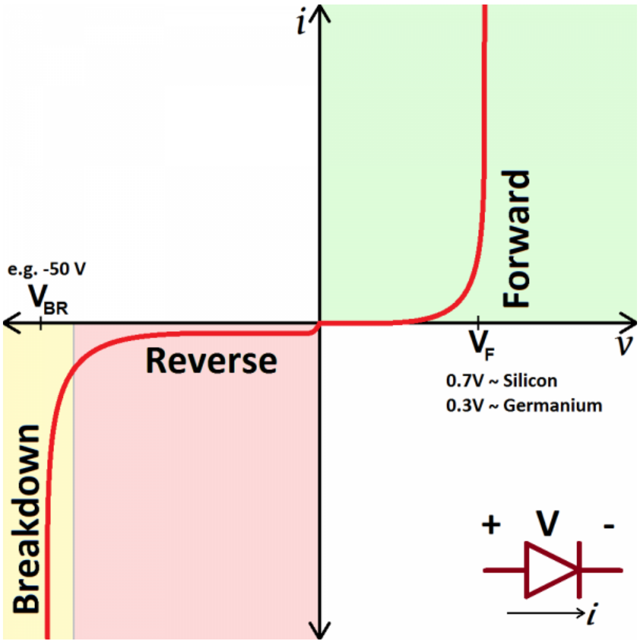


Figure 14 - Diodes in reality

The particular interesting type of the diode world are light emitting diodes, or LEDs. As name suggest, they emit light when forward biased, they are the love and joy of every engineer, and keystone of modern consumer electronics. The luminosity of LED is proportional to the current flow. Maximal current, at which diode starts to be a flaming sword, is limited at much lower values than traditional diode, so it is a good idea to add some resistor in series which is called 'limiting resistor', to avoid overheating issues and power fluctuation troubles. However, in more precise application where luminosity is a factor to control, it might be necessary to control the current directly supplied to LED.

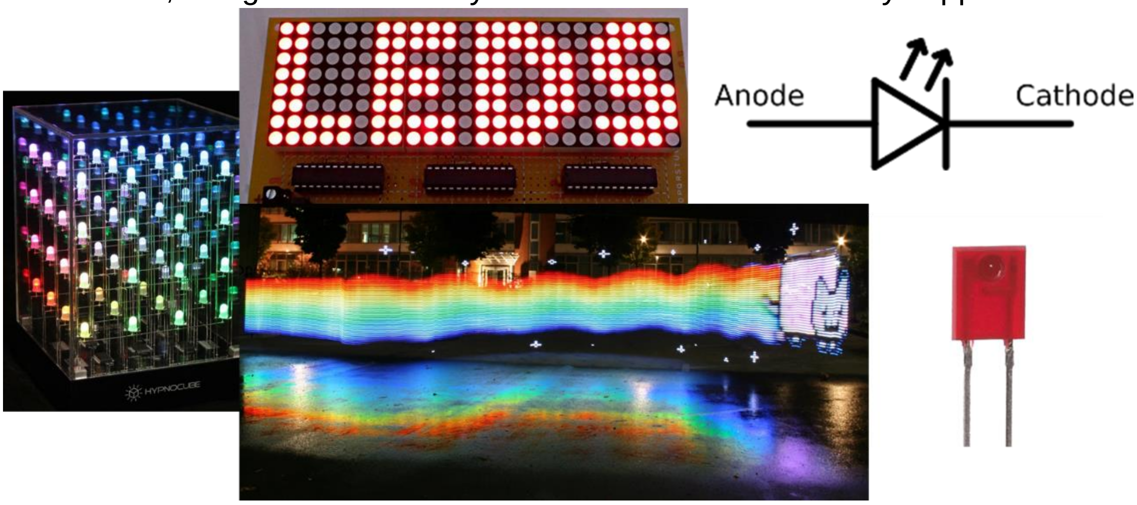


Figure 15 - Light emitting diodes - LEDs

The other type of commonly used diodes is a photo-diode. Based on the photoelectric effect, this guy acts as an inverse of LED, and generates the current which is proportional to the amount of light reaching the active photoelectric element. Depending on the composition and structure, they can generate lots of current, but then they react slowly, or can produce low current but act fast which is great solution for sensors. They are commonly used as a receiver for remote controls of the consumer TVs.

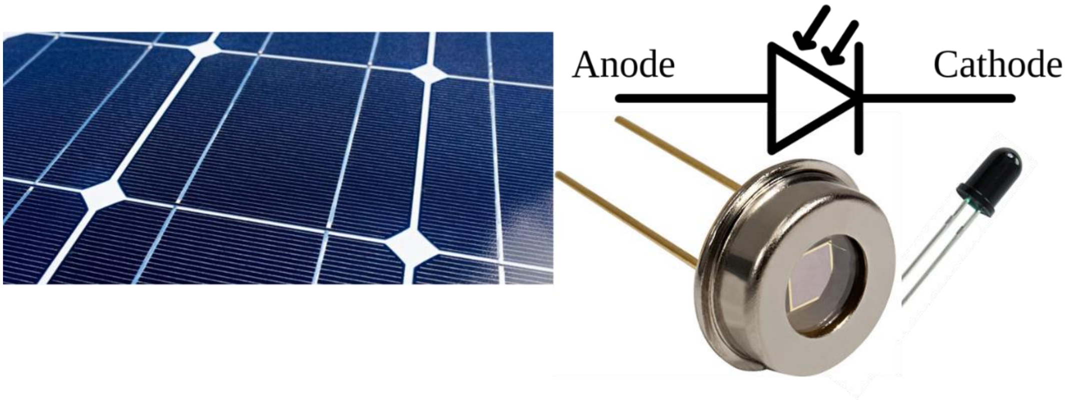


Figure 16 - Photodiode

The current generated by the diode is proportional to the incident light, so the circuit can be greatly abstracted and simplified. There are many types of them, some of which are sensitive to a specific light wavelength, and some are directionally sensitive. Again, think of them as inverse of LEDs.

Transistor

Moving on, we are now at the doorstep of the most critical component for any electronics, a Transistor. A semiconductor device, has 3 pins, and acts as either insulator or conductor between two of them (normally called Collector and Emmitor, C and E on the diagram), depending on the control signal, applied to the 3rd (called Base, or B on the diagram). To put it simply it can be described as a control valve for current passing through it, or a variable adjustable resistor. Depending on the operation mode or semiconductor physics, they can be p-n-p, where more base current mean more output current, or n-p-n, where more base current means less output current. Their main applications are: 'switching' for digital electronics, and 'amplification' for analogue.

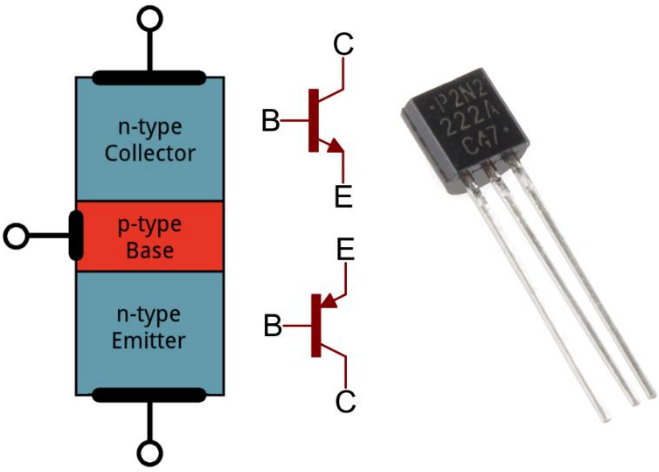


Figure 17 - Transistors

They are great for switching, where you control the flow of high current (normally high power to some heavy duty appliance) using low current (normally battery driven, or supplied by a micro-controller). Real transistors will not have infinite switching speed, and will have a have maximum current you can supply to the base (and so used with the limiting resistor), and minimum resistance at fully 'on' mode. If you see a base pin of the transistor on a diagram connected to a microcontroller digital pin, it is probably used as a switch.

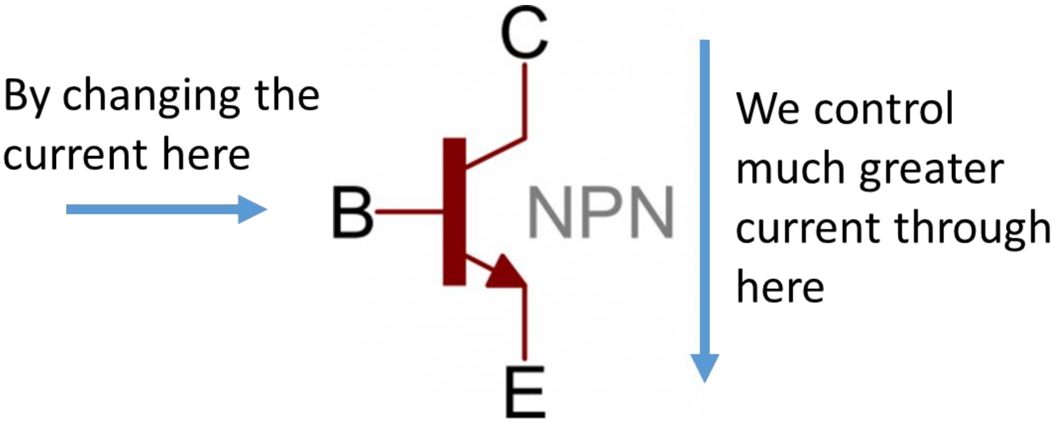


Figure 18 - Transistors(how NPN works)

Amplification properties of the transistor can be leveraged, if the base pin is connected to the low-power input signal, and emitter connected to the ground. This can produce high voltage gains and are commonly used in analogue guitar amplifiers as is.

So if you see a base of a transistor connected to the input signal on the diagram, it is probably used in amplification mode.

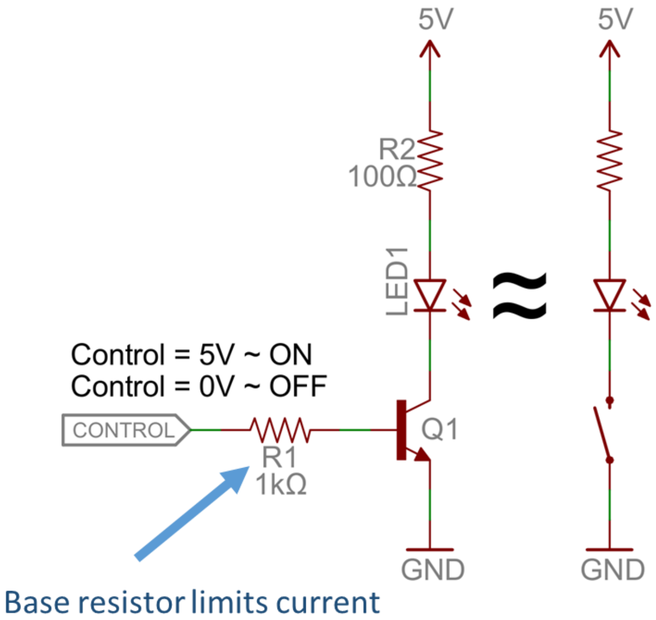


Figure 19 - Transistors – switching applications

There are many types of transistor and transistor-like components, some of them are voltage controlled, and if you want to know more, google and Wikipedia contain more than enough information about them, so the general rule: do not know something - google it, works best.

Circuits

Well, finally, now we know basic components, let's consider some circuits. Since we will look at both analogue and digital electronics, let's review 555 timer. Inside it is actually quite complicated, but as always with digital, we can consider the IC block only, which is displayed on your right. As we know already, bypass capacitors can be ignored. The rest resembles a connection of Rs and C, which we will talk about later, but the principle is that capacitor takes time to charge and discharge, and this time depends solely on the combination of capacitance and resistances around.

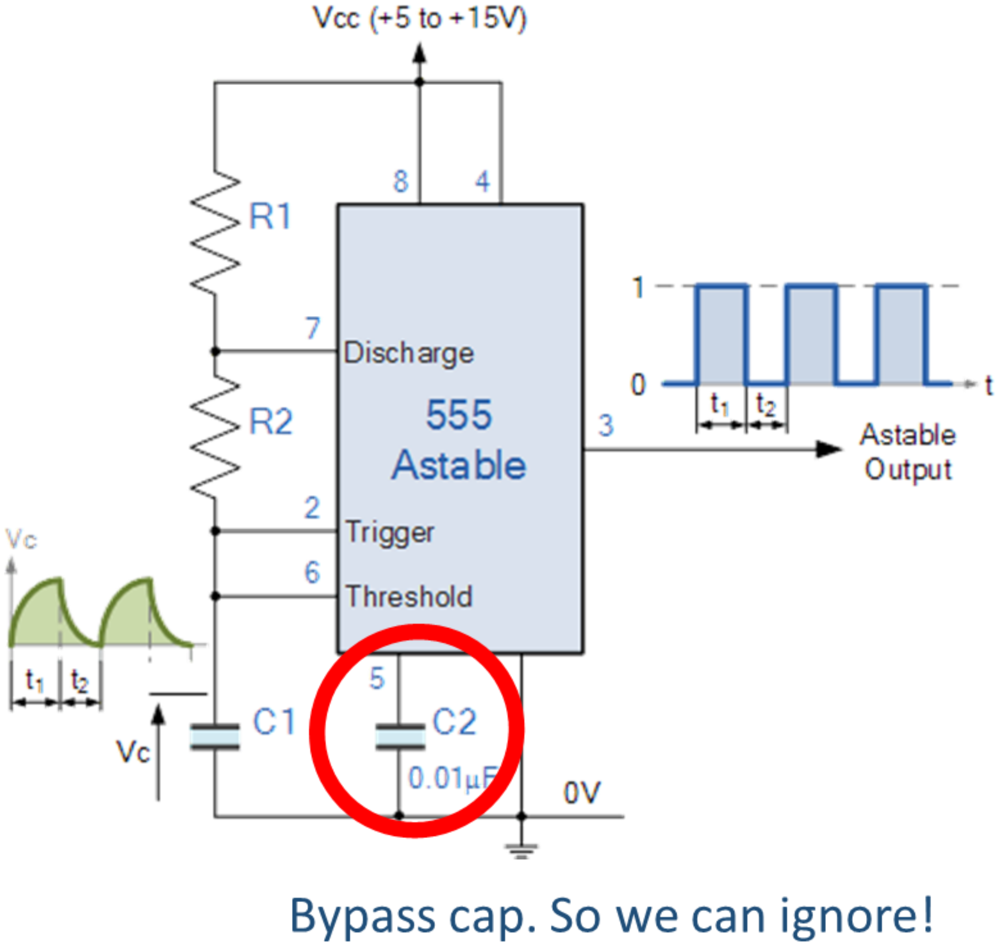
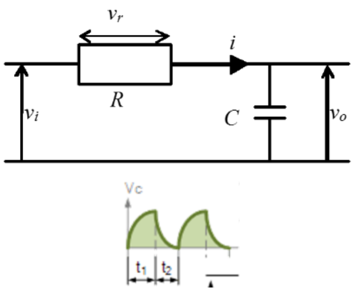


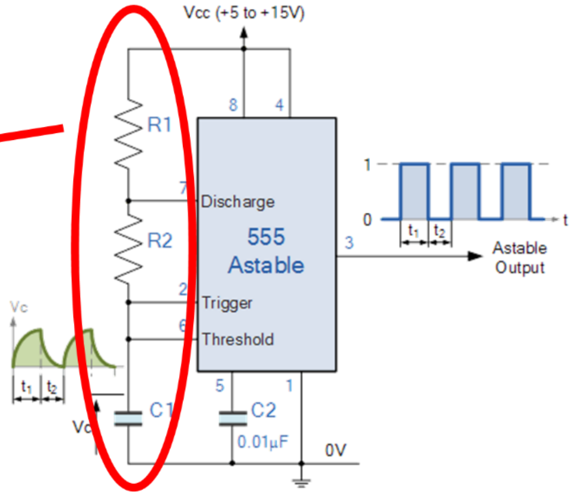
Figure 20 - Mixed Digital and Analogue – 555 Timer

We can use this to construct a circuit, which will charge, and discharge the capacitor upon reaching the certain voltage threshold, it can be easily implemented using digital logic, and this is exactly what 555 timer does. Therefore, the circuit is delivering pulses with the fixed period, which are solely dependent on three analog components and can be easily controlled.

Mixed Digital and Analogue – 555 Timer

An identical circuit formed from *R1, R2* and *C1* in the 555 timer circuit.
User programmable charge and discharge rate of capacitor.





Without the 555 timer doing anything,
all this can do is charge up to the voltage V_{CC}

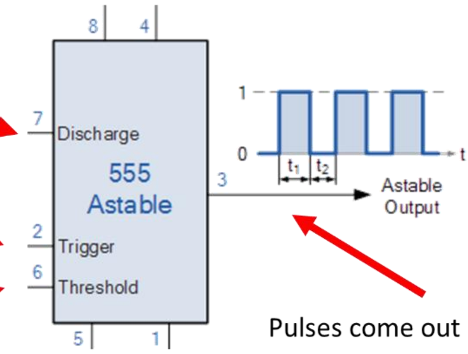
Mixed Digital and Analogue – 555 Timer

Three pins *discharge, Trigger* and *Threshold* determine what the voltage is on the *output* pin.

Either disconnected, or connected to ground when output is *low.* Used to *discharge* the capacitor C1

When voltage on this pin goes *below* 1/3 V_{CC}, the output flips from LOW to HIGH

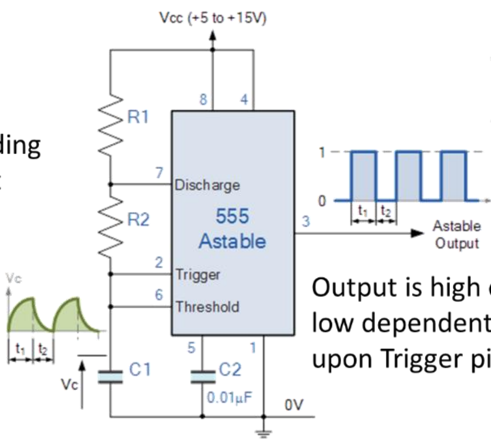
When voltage on this pin goes *above* 2/3 V_{CC}, the output flips from HIGH to LOW



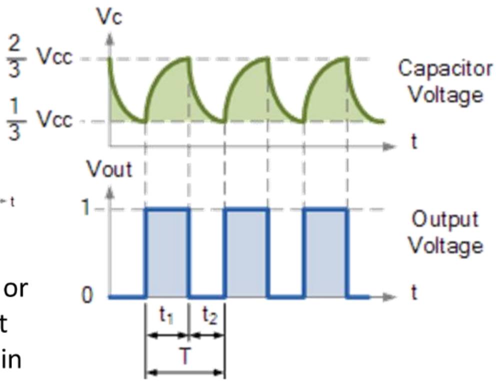
Pulses come out here

Mixed Digital and Analogue – 555 Timer

Discharge pin is connected to ground, depending upon voltage at Threshold pin



Output is high or low dependent upon Trigger pin



$$t_1 = 0.693(R_1 + R_2)C_1 \qquad t_2 = 0.693 R_2 C_1$$

The duty cycle and period can be controlled by choosing only 3 components

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