Learn basic electronics

Daniel Bele

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Mission

Being a long-time programmer that did not understand any electronics and computer architecture, I was haunted by the *ghost in the machine* that caused many insecurities and feelings of not belonging to my operating environment. With time, it escalated to the point of no return and I was faced with a decision – all or nothing!

By the grace of finding authors devoted to different aspects of electronics, from electronics basics to building a Pong game and computer architecture, I was blessed by the courage to take a leap of faith and decide to learn electronics, and am on that path ever since.

Since I was a total electronics beginner, I had to start from the diode in order to understand the transistor. With transistors, I was able to build gates, and gates served me to build chips – adders, multiplexers, decoders…, the Pong game, the 4-bit processor, and finally complete Z80 computer with monitor, keyboard, sound, and cassette recorder.

This manuscript takes you, dear reader, to that path, throughout which I follow a very simple paradigm – in order to use a component, we must disassemble it to the greatest detail possible, prove its workings and understand it. It then becomes a building block of our comprehension.

For me, this process is fulfilling to the point that it makes me sincerely secure and happy. This manuscript is my way of giving back, and I am willing to share it freely, in order to honor the brilliance of electronics and all the authors that helped me to reach this point.

Finally, I am very thankful for being friends with Željko Stojanović, whose passion for electronics is highly motivating, and to whom I am deeply grateful for participating in this project as a technical reviewer and adviser. For that matter, please note that I take whole responsability for possible inaccuracies, if present in content. If such found, please let me know to correct them.

Daniel Bele

The building blocks

Simplicity is the ultimate sophistication.
(Leonardo da Vinci)

1. Paradigm and the basic building block

In order to present our paradigm in learning electronics, we can take an example of a full adder chip that enables binary addition. Let us use a top-down approach, and look at the datasheet of the TTL (*Transistor-Transistor Logic*) chip 7483. We will immediately notice that the chip performs the addition of two 4-bit binary words, A and B.

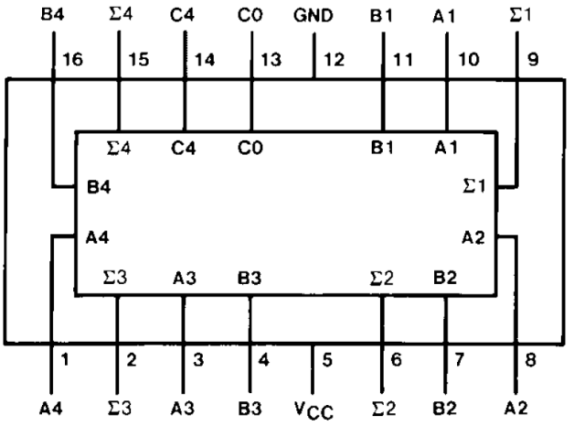

Figure 1-1 Chip 7483

If we continue our investigation to the lower level (Wikipedia, for example), we will find out that a 1-bit adder is built of XOR, AND and OR gates.

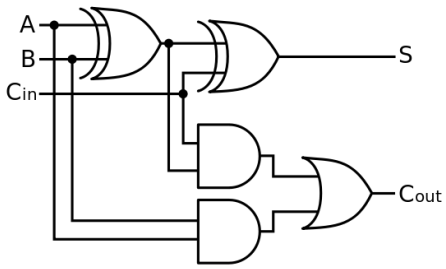

Figure 1-2 1-bit full adder
(Source: referenced)

Finally, on the very bottom level, all the gates can be built using transistors, as shown for the AND gate in the following figure.

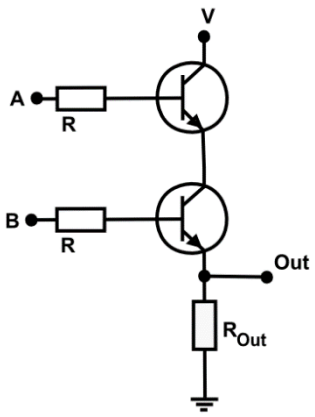

Figure 1-3 Transistor AND Gate
(Source: referenced)

If we reverse the order and approach the idea bottom-up, it becomes inevitable to understand the working principle of the transistor in order to build gates, from which we can finally build a full adder. Guided by this thought, we are essentially presenting our paradigm in learning electronics – each component that we are going to use, we must fully explain and understand to earn justification to use it as a building block.

The basic building block, therefore, is a transistor, and the first step in understanding its inner workings is inevitably the diode.

1.1. Diode

The diode is an electronic component whose conductivity depends on its polarity. To put it more simply, the diode conducts the current in only one direction. How is this possible? What is the usage of this fact? To answer these questions, we have to get acquainted with the term semiconductor.

Surprisingly, some elements of the periodic system cannot be classified as conductors that conduct the current, nor as isolators that prevent its flow. These elements are considered semiconductors because they conduct the current under certain conditions. The duality of their nature can be used very intelligently in electronic circuits, which makes them the foundation of modern electronics. Therefore, the diode has many applications, from which we can mention the conversion from alternating to direct current, which we need in order to build a simple power supply. So, let's try to understand how it works.

For example, let us consider the chemical element silicon (Si). Silicon is a semiconductor and has 4 valence electrons, which connect themselves in a pyramidal structure, inside a crystal grid. In that way, the covalent bonds are created which enable the atoms to share pairs of electrons. Since electrons are bound, they cannot travel, which makes silicon nonconducting.

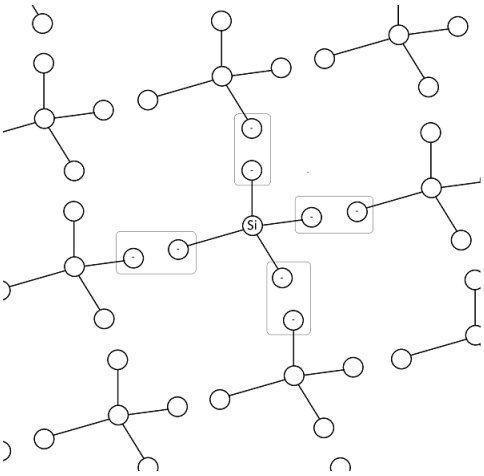

Figure 1-4 Covalent bounds of silicon atom

However, if we inject the phosphorous (P) atom with 5 valence electrons in the silicon grid, we are effectively giving it one more electron which is not bound with silicon atoms and is able to move through the grid. This process is called doping, and it creates a N-type (negative cathode) of conducting silicon with electrons as carriers. Silicon is still stable because the phosphorous atom sits nicely in the grid. It is also neutral because the ratio of protons and electrons is uniform.

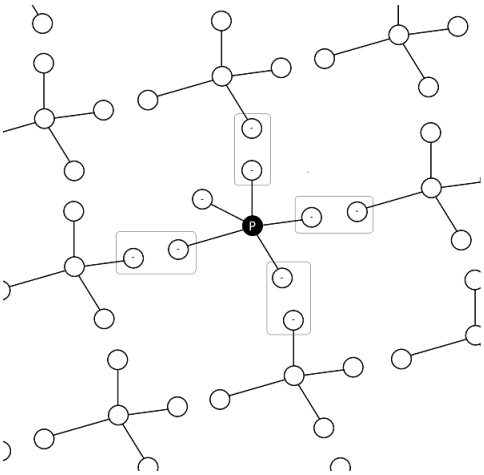

Figure 1-5 N-type of conducting silicon

On the other hand, if we inject the boron (B) atom with 3 valence electrons in the silicon grid, we will create a cavity that is missing an electron. That way, we created P-type (positive anode) of conducting silicon with cavities as carriers.

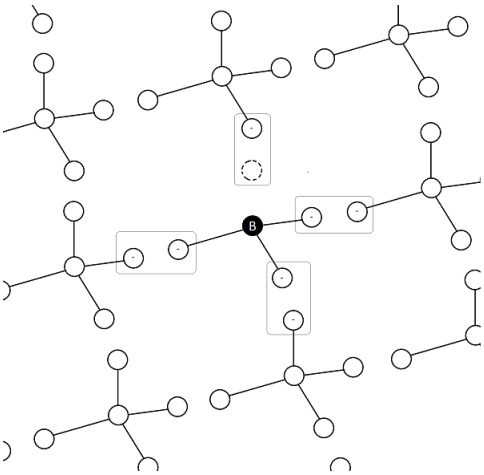

Figure 1-6 P-type of conducting silicon

N-types and P-types are not particularly interesting unless we try to connect them. Creating an NP junction, some of the additional electrons of N-type cross over to the cavities of the P-type and they form a depletion layer. It is worth mentioning that the junction is still neutral because the ratio of protons and electrons is uniform.

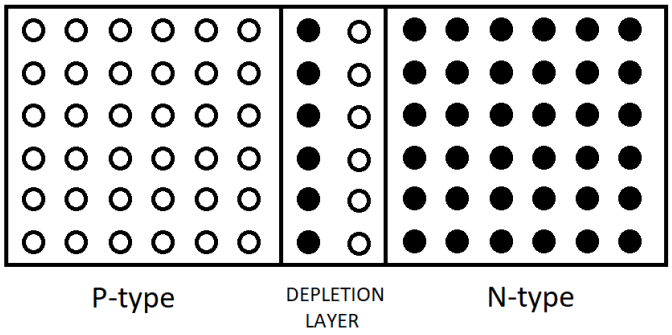

Figure 1-7 P-Connection of N-type and P-type

Now, if we connect the PN junction to the direct current of diverse polarities, we will notice interesting things. If we connect the source of direct current in a manner where the N-type is on the negative part of the source, and the P-type on the positive side of the source, the depletion layer gets smaller and the current starts flowing. This connection is called forward bias.

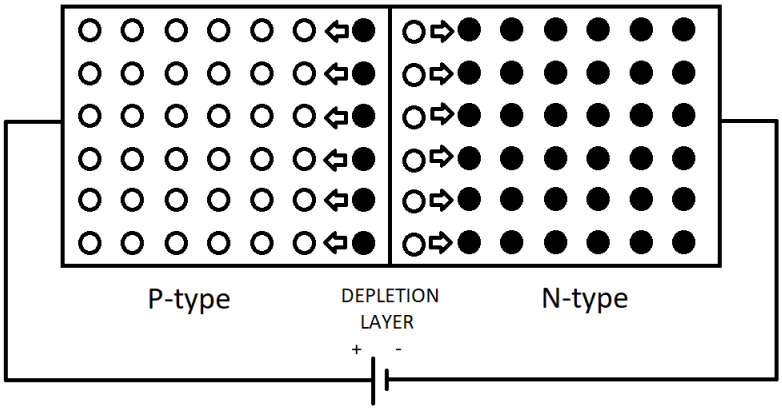

Figure 1-8 Forward bias connection

If we connect the source of direct current in opposite direction, each of the sources attracts the opposite charge and depletion becomes wider. This connection is called reverse bias and current cannot flow.

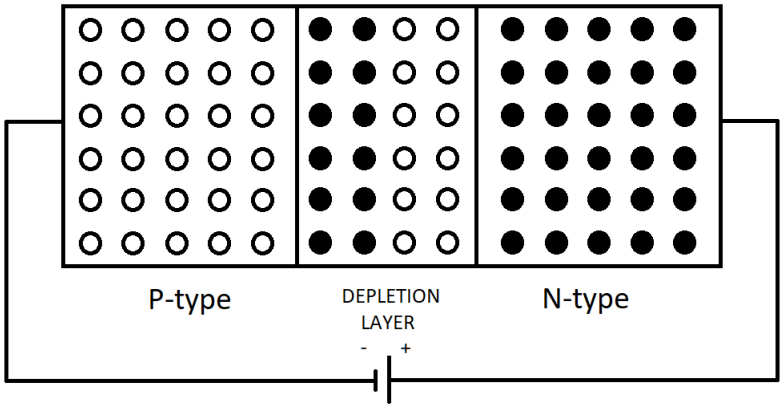

Figure 1-9 Reverse bias connection

The PN junction that we created is called a diode and we can fully understand why it conducts current in only one direction. It is important to notice that the diode needs to be exposed to a certain forward voltage in order to conduct. For silicon diode, the voltage is ~0.7 V, and for germanium diode ~0.3 V.

However, in the reverse bias connection, the diode will block the current until the reverse voltage reaches the value of its breakdown, which is very important information and needs to be consulted in the technical specification.

1.1.1. LED

One of the most common usages of the diode is LED (light-emitting diode) which demonstrates an interesting phenomenon of producing light. When the voltage on the LED reaches the required to forward bias the diode, the cavities and electrons of the depletion layer connect themselves and convert this electric energy into light. The color of the emitted light depends on the semiconductor material which

emits photons of a specific wavelength. The forward voltage drop of the diodes producing different colors differs and must be consulted in the technical specification.

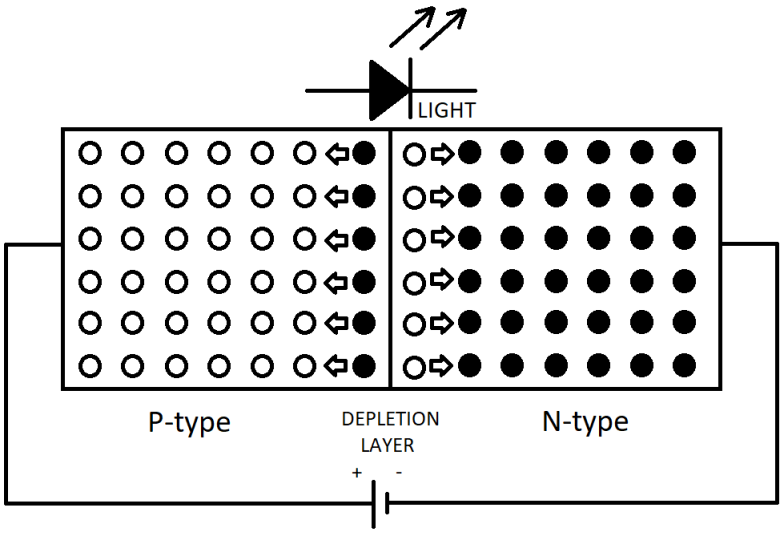

Figure 1-10 LED

1.1.2. Zener diode

Unlike LEDs, Zener diodes use a breakdown voltage property for their usage. They are specially designed for the breakdown voltage to be strictly defined, low and constant. On the left bottom side of the figure below it can be seen that after a certain current level ($I_{z(min)}$) that causes a breakdown on the diode, the voltage drop becomes constant and remains almost the same until the maximum allowable current ($I_{z(max)}$), defined by the specification. This special feature will help us to reduce or regulate the voltage when making the power supply, later in the manual.

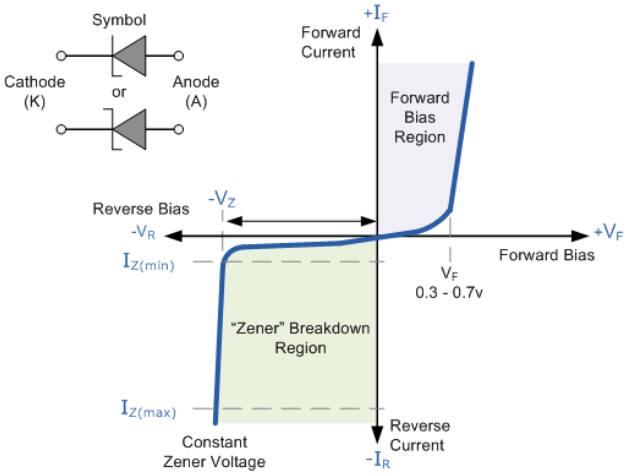

Figure 1-11 Zener diode behavior
(Source: referenced)

1.1.3. The diode experiment

In order to demonstrate the working principle of the diodes, let us experiment with them. The idea is to connect the diode and the LED in series in order to prove that the diode conducts in only one direction. But first, we must discover the proper way of orienting the diode and the LED in the circuit, which is self-explanatory from the following figure.

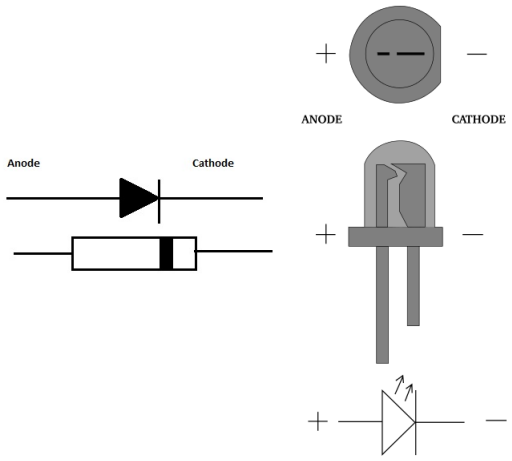

Figure 1-12 Diode and LED orientations
(Sources: referenced)

Hence, in the following experiment, we will show how the orientation of the diode can complete or break the circuit which will be manifested by the LED.

Components:

- breadboard
- 5V power supply

- 3mm red LED
- 1N4007 rectifier diode
- 150Ω resistor

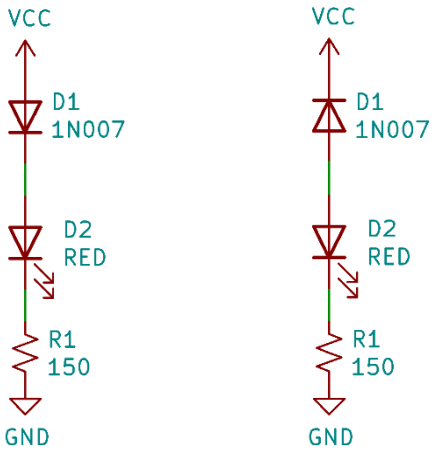

Figure 1-13 The diode experiment

During the practical realization of experiments, it is important to acquire comfort in the sense that the realized circuit does not have to fully correspond to the schematic in terms of orientation and arrangement of components. Often this is not even possible, so it is very important to get used to this fact immediately. Here, we were quite lucky, though.

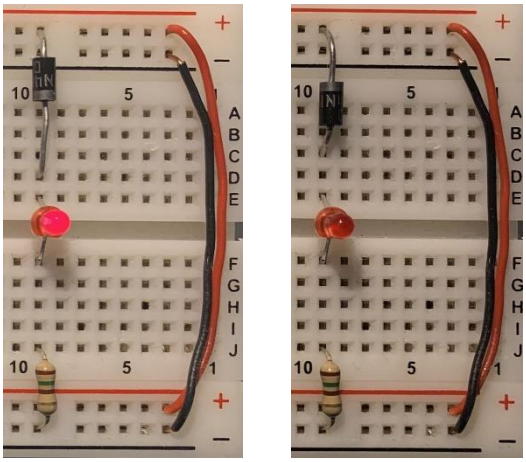

Figure 1-14 The diode experiment realization

Explanation: From the previous figure, it is obvious that the LED is lit only if we connect the diode in forward bias direction, which completes the circuit. That means that changing the orientation of the diode (or the LED) would break the circuit and the current would not flow. What is less obvious is the reasoning

behind the selection of the components, and why the diode does not glow very bright. In order to figure that out, we must dive a little deeper into the circuit and explain some basic phenomena.

First of all, let us see how much voltage we need to forward bias both the LED and 1N007 diode. If we check out the specification of the red LED diode, we can find out that the typical forward voltage drop is from 1.7 to 2V (we can use the value 1.8V for simplicity of the calculations), and the maximum rated forward current is 20mA. Further, 1N4007 diode is a silicon diode so we can expect it to have a forward voltage drop of ~0.7V. In its datasheet, it also mentioned that the maximum forward current the diode can stand is 1A. Since we need a maximum of 20mA to glow the LED, we are on the safe side here. So, at the moment we have a couple of important informations:

- we need to provide ~2.5V for both the LED (~1.8V) and the diode 1N4007 (~0.7V)
- we need a maximum of 20mA of current for the red LED
- we have a power supply of 5V, which is excessive voltage

So, we must find a way to lower the voltage from 5V to ~2.5V, not to burn the LED with excessive current. For that purpose, we use a resistor - an electrical component whose primary function is to limit the flow of electric current by producing the voltage drop across its terminals.

According to Ohm's law, the current (I) through the component, in this case, the resistor, is proportional to the voltage (V) across it, and inversely proportional to its resistance (R), as noted in the following formula:

$$I = \frac{V}{\mathrm{R}} \qquad V = I * R \qquad R = \frac{V}{\mathrm{I}}$$

From this formula, it is very easy to find the resistor value, because we have to cause a ~2.5V drop on it, and we know the current needed is 20mA:

$$R = \frac{V}{\mathrm{I}} = \frac{2.5V}{20\mathrm{mA}} = \frac{2.5V}{0.02\mathrm{A}} = 125\Omega$$

Since resistors introduce certain tolerances (the true resistance can be more or less the noted value), we used a 150Ω resistor because we wanted to be conservative enough not to burn the LED. Further, the voltage drop on the resistor dissipates electrical power which is converted into heat, so we need to take into consideration also the resistor power rating to prevent it from burning up. For that purpose we use the following formula to calculate the electrical power (P):

$$\mathrm{P} = \mathrm{I} * \mathrm{V}$$

Rearranging it according to Ohm's law, we can easily get to the following expression, that is more suitable:

$$\mathrm{P} = \mathrm{I} * \mathrm{I} * \mathrm{R} = \mathrm{I}^2 * \mathrm{R}$$

And if we supply our values, we get to the required power rating:

$$\mathrm{P} = (0.02\mathrm{A})^2 * 150\Omega = 0.06\mathrm{W}$$

Since power rating standards for resistors are 0.125W, 0.25W, 0.5W, 1W, and higher, we are perfectly safe whichever one we choose.

Finally, after the experiment, we can use a multimeter to measure the voltage drops for the different components in the circuit, and current through it, to see whether our calculations and assumptions were correct. My readings are the following:

- Voltage drops:
  - 1N007 diode: ~0.71V (correct assumption)
  - red LED: ~2.1V (wrong assumption, acceptable)
  - resistor ~2.1V (wrong calculation)
- Current: ~15mA (less than desired)

Since the current measured in the circuit is only 15mA, it is logical that the LED does not glow as bright as it would for 20mA. In other words, we were too conservative, and we could have freely used a 100Ω resistor without causing any problems.

1.2. Transistor

One way to explain the working principle of the transistor is to observe it as a means of controlling the diode conductivity. If we imagine conductivity as a value of 1 and non-conductivity as a value of 0, we have arrived at a binary, digital representation of a state, in one bit of information. It is fascinating that the most important component of digital electronics is the one that can control the state of 1 bit, and in a broader sense, the information represented by any number of bits. This role was played brilliantly by the vacuum tube until the appearance of the transistor, which provided adequate replacement with its reliability and efficiency. In digital electronics, the voltage values that define the values 0 and 1 are discrete, finite, and clearly separated, as opposed to analog in which the signal value varies continuously. Therefore, in building digital electronic devices, the transistor represents the most important building block.

The transistor we will first present is called an NPN bipolar transistor. If we understand the concept behind it, it will not be difficult for us to understand its other realizations. Like a diode, a transistor is built by connecting N-type and P-type semiconductors. Its conductivity is caused by electrons as the majority carriers and cavities as the minority carriers and is hence called bipolar.

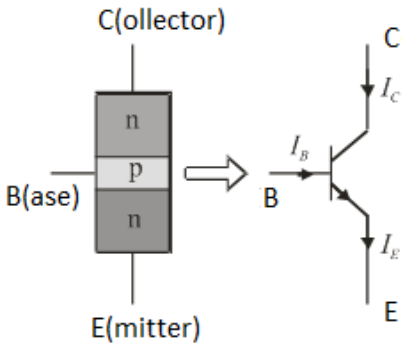

Figure 1-15 NPN bipolar transistor
(Source: refrenced)

It is clear from the figure that emitter E and collector C are composed of N-type semiconductors, while base B is composed of P-type. If we connect a voltage source of any polarity to the emitter and collector of the transistor, the current cannot flow due to the isolating NP and PN layers, so it can be considered that the circuit behaves as two diodes connected in opposite directions.

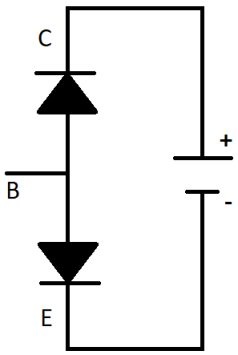

Figure 1-16 NPN bipolar transistor as 2 diodes

But if we bring enough positive bias voltage to the base, sufficient for the occurrence of permeable polarization between the P-type from the base and the N-type of the emitter, the current between the base and the emitter will flow because the emitter electrons will rush to combine with the base cavities. Finally, although the connection between the base and the collector is still impermeable polarized, part of the electrons from the emitter will still be attracted to the more positively charged collector and current will flow between the collector and the emitter. It is important to notice that the current between collector and emitter is much greater than the current between base and emitter. This happens because when electrons from the emitter arrive at the base, they do not have time to recombine with the cavities from the base but rush to recombine with the cavities from the collector which has much greater

potential. Et voilà! By bringing the pulse in a form of bias voltage from the outside, we were able to control the state, as shown in the following figure.

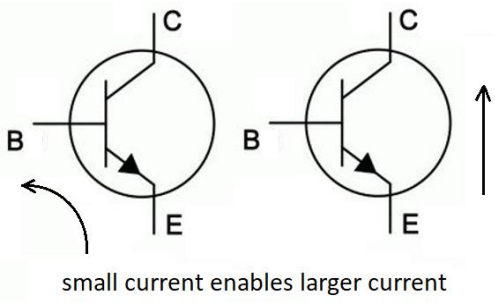

Figure 1-17 NPN transistor working principle

Please note that the figure shows the direction of the electrons, but the conventional way of showing the direction of the current is quite the opposite. This can be noted from the transistor image and the direction of the arrow. The reason for this is of historical nature and dates back to Benjamin Franklin's experiments which assumed that direction for the flow.

The following figure shows how the state of the transistor can be controlled.

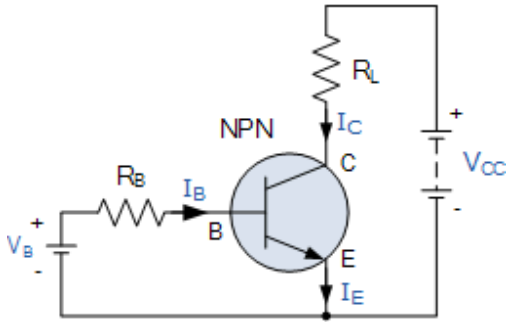

Figure 1-18 Controlling the state of the transistor
(Source: referenced)

The picture requires a little more attention so we will try to explain it. R_B is a base resistor that controls the amount of current I_B on the base, and R_L resistor controls the current I_C on the collector when the transistor conducts. The total current of the emitter IE is equal to the sum of IB and IC. It follows that the NPN transistor is a current-controlled device because the current must flow between the base and the emitter in order for the current to flow between the collector and the emitter. In other words, the base current dictates the collector current.

Increasing the current I_B (by decreasing the value of the R_B resistor) will increase the bias voltage, and thus the current I_c will rise. This implies that the transistor is a natural amplifier because small fluctuations in the base current cause larger fluctuations in the collector current. The amount of amplification is called the gain, and for current, it is expressed by the ratio of collector and base current:

$$hFE = \frac{Ic}{\mathrm{Ib}}$$

The phenomena of amplification are characteristic for every transistor which will show this behavior until it enters saturation mode in which collector current is at its maximum. On the other hand, decreasing the current I_B below the value needed for biasing the transistor, the transistor cuts off. If we take into consideration only cut-off and saturation mode, it is very easy to understand that the transistor can act also as a switch. In a cut-off mode, the transistor acts as an open switch, and in saturation mode, the transistor acts as a closed switch. This is extremely important for us because it allows us to control the state of a bit, as previously mentioned. Having this control, we can build logic gates out of transistors, which then become building blocks of logical circuits. Later experiments will demonstrate how a transistor can be used as an amplifier, and as a switch.

To understand the operation of the PNP transistor, we can think of it as a mirror image of the NPN transistor, with polarity reversed. If we bring a negative bias voltage to the base, sufficient for the occurrence of permeable polarization between the P-type of the emitter and the N-type of the base, the current between the emitter and the base will flow, causing current to flow between the emitter and collector.

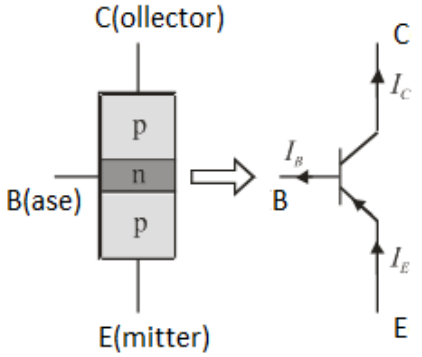

Figure 1-19 PNP bipolar transistor
(Source: referenced)

Prior to getting our hands dirty with transistor experiments, we must try to understand the working principle of the potentiometer and the switches.

1.2.1. Potentiometer

A potentiometer is a resistor with three lugs that can serve as a voltage (or current) divider or as a variable resistor. The figure shows how the middle lug, called a wiper, is movable and moves in the range from the first to the third lug. By moving the wiper, we are changing the ratio between resistances. If we connect the wiper to lug 1, there is no resistance between the wiper and lug 1, and the resistance between the

wiper and lug 3 is at the maximum. As we slide the wiper clockwise, the resistance between the wiper and lug 1 increases, while the resistance between the wiper and lug 2 decreases.

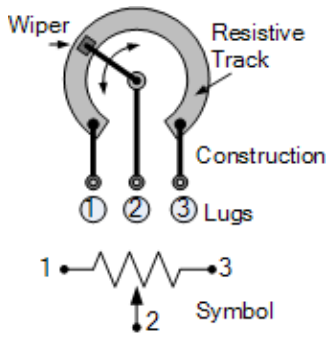

Figure 1-20 Potentiometer
(Source: referenced)

If we connect the positive voltage to lug 1 and the ground to lug 3, the output of the wiper will become a voltage divider as presented in the following figure.

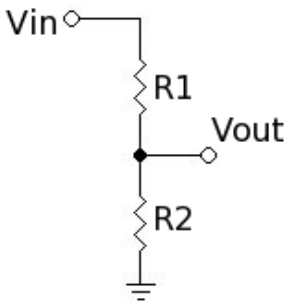

Figure 1-21 Potentiometer as a voltage divider
(Source: referenced)

The formula to calculate the output value of voltage is the following:

$$Vout = Vin \frac{R2}{R1 + R2}$$

The voltage divider is extremely important in electronics because by choosing the right ratios between R1 and R2 resistances the output voltage can be adjusted to any fraction of the input voltage.

Finally, if we short one of the lugs with the wiper, and take the output of the wiper, we get a variable resistor also called a rheostat. Now, moving the wiper effectively changes the resistance applied in the circuit.

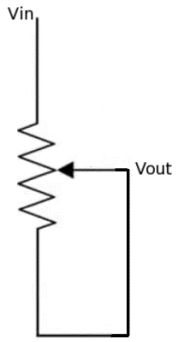

Figure 1-22 Potentiometer as a variable resistor
(Source: referenced)

1.2.2. Switches

Working with mechanical switches is extremely important, but very easy to understand. The following figure shows 4 types of switches that are self-explanatory.

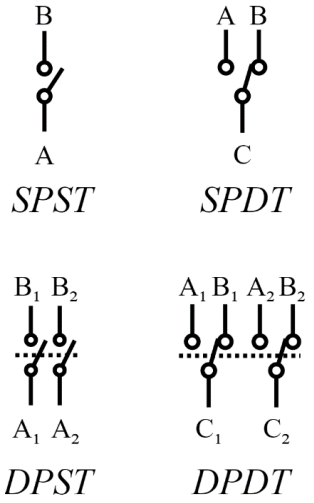

Figure 1-23 Different types of switches
(Source: referenced)

SPST - single pole single throw - a switch that turns the circuit on or off

SPDT - single pole double throw - a switch that turns on 1 of 2 circuits alternately

DPST - double pole single throw - a switch that turns 2 circuits on or off at the same time

DPDT - double pole double throw - a switch that controls 2 by 2 circuits at the same time

1.2.3. Transistor as an amplifier experiment

In order to conduct an experiment, it is necessary to determine the polarity of the transistor that will be used, which is shown in the following figure and should be consulted in the datasheet.

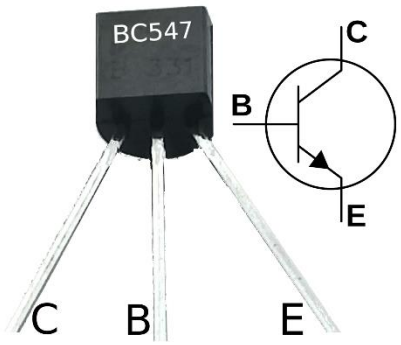

Figure 1-24 NPN BC547 transistor orientation
(Source: referenced)

Components:

- breadboard
- 5V power supply
- 3mm red LED
- BC547 NPN transistor
- 220Ω resistor
- 1KΩ potentiometer

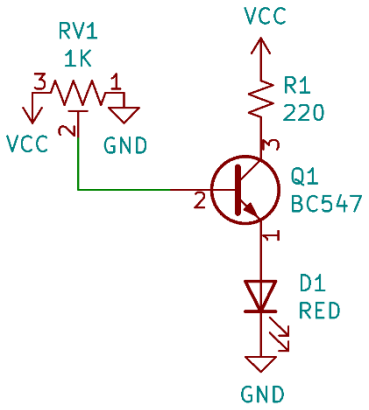

Figure 1-25 The transistor as an amplifier experiment

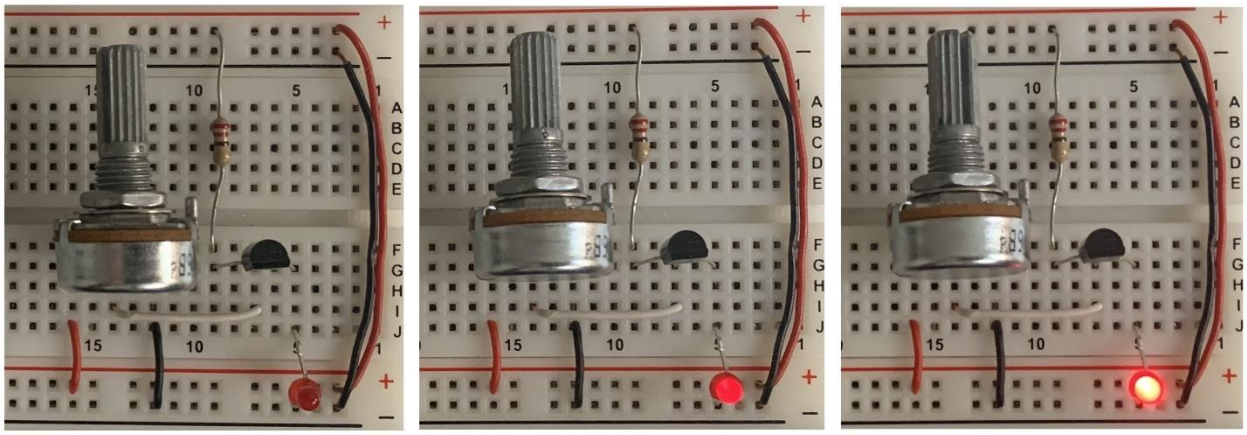

Figure 1-26 The transistor as an amplifier realization

Explanation: 220Ω resistor serves to limit the current through the LED when the transistor is in saturation and is effectively a closed switch. Transistor is connected in an emitter-follower configuration because the voltage at the emitter follows the voltage at the base – rising the base voltage will raise the emitter voltage, or in this case – across the LED. It is worth mentioning that the emitter voltage will be ~0.7V lower than the base voltage. The potentiometer acts as a voltage divider whose output voltage is biasing the base of the transistor. Let's try to find out what happens when the potentiometer is in the middle position. According to the formula, the output voltage on the base of the transistor will be:

$$Vbase = Vin\ \frac{R2}{R1+R2} = 5\text{V} * \frac{500\Omega}{500\Omega+500\Omega} = 5V * \frac{1}{2} = 2.5V$$

Then, the voltage on the emitter, or across the diode is:

$$Vled = Vbase - 0.7V = 1.8V$$

This voltage is sufficient for the LED to be biased and it starts glowing. If the position on the potentiometer is before the middle point, the emitter voltage is too low to bias the LED. And if the position on the potentiometer is after the middle point, the LED glows brighter.

A transistor amplifier circuit can easily be converted into a circuit that uses a transistor as a switch.

1.2.4. The transistor as a switch experiment

Components:

- breadboard
- 5V power supply
- 3mm red LED
- SPST pushbutton switch
- BC547 NPN transistor
- 220Ω, 2.2KΩ resistors

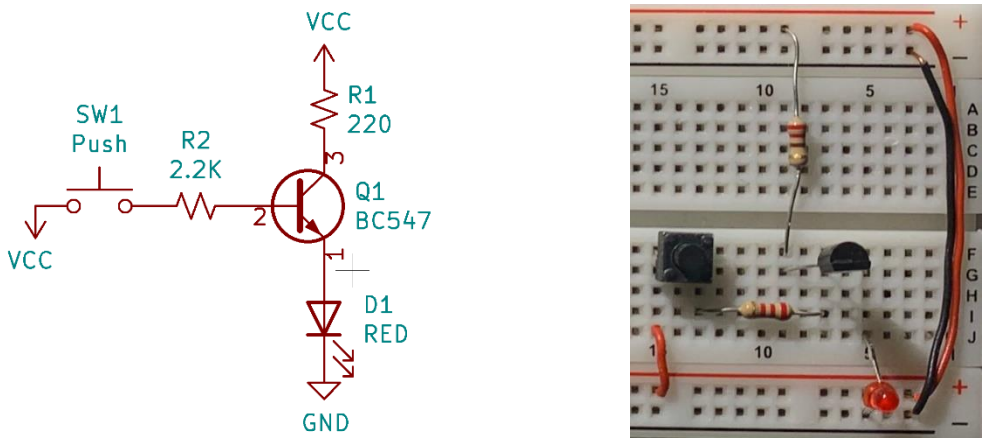

Figure 1-27 The transistor as a switch

Explanation: We added a pushbutton switch and 2.2KΩ in order to bias the transistor base. It is obvious that when we press the switch, the LED is lit and the transistor acts as a switch. The way we have chosen the resistor value is according to the formula:

$$Rbase = \frac{(V_{basesupply} - V_{baseemittter}) * hFE}{Ic} = \frac{(5V - 0.7V) * 10}{20mA} = \frac{43V}{0.02A} = 2.15\text{KΩ}$$

The value of the current gain amplification factor *hFE* can be assumed 10 for switching circuits and I_c is 20mA for the diode to glow. The idea to use a transistor as a switch in a circuit that has a switch seems like nonsense, but we can easily imagine that the bias voltage could be caused by some other digital component.

1.2.5. The transistor as a comparator experiment

A comparator is an integrated circuit used to compare voltage (or current) and whose digital result indicates which of the values is higher. It can be realized by an operational amplifier which is a linear integrated circuit, consisting of a multitude of connected transistors, diodes, resistors, and capacitors. Linear integrated circuits work with analog values, where the output signal is a linear function of the input signal value. This is exactly where they differ from digital circuits, which work with discrete values, 0 and 1, as we have already explained. But, when you think about it, when used as a comparator, the operation amplifier works with digital values, which makes it perfect for usage in digital circuits. In this experiment, we will try to realize a primitive voltage comparator with transistors.

Components:

- breadboard
- 5V power supply
- 3mm red LED
- 7 x 10KΩ resistors
- 2 x BC547 NPN transistors

- 10KΩ potentiometer

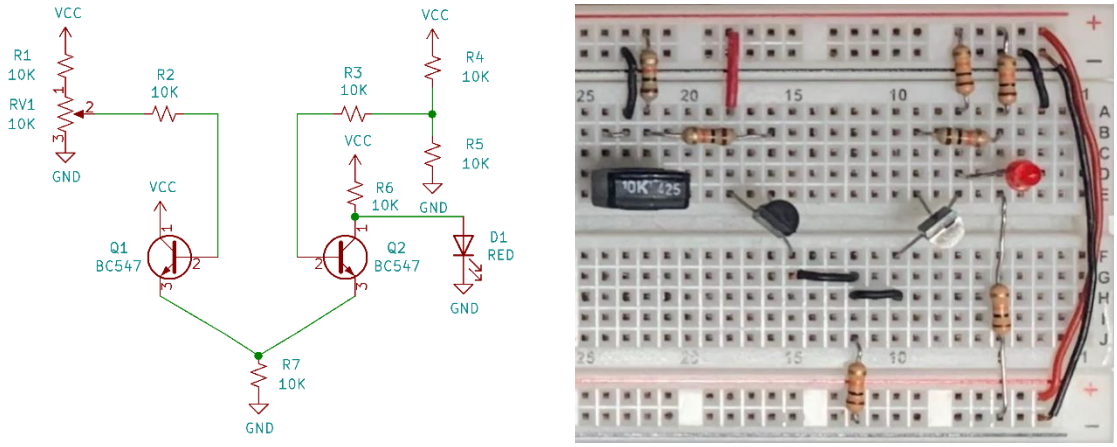

Figure 1-28 The transistor as a comparator

The base of transistor Q2 is exposed to a voltage of ~2.5V due to the voltage divider and this voltage value is our reference. The base of transistor Q1 is exposed to variable voltage because the voltage divider is defined by a variable resistor. The emitters of the transistor are connected and grounded through a 10kΩ resistor. In case the voltage based on transistor Q1 is less than the reference voltage ~2.5V, transistor Q1 is cut-off, transistor Q2 conducts and output is 0 which is demonstrated by the LED that does not light up. The variable resistor allows the voltage at the base of transistor Q1 to exceed the value of the reference voltage ~2.5V, and then the Q1 transistor conducts and the transistor Q2 cuts off. In that case, the output is 1 and the LED is lit.

References

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https://commons.wikimedia.org/wiki/File:%2B-_of_LED_2.svg

https://commons.wikimedia.org/wiki/File:TransistoriBJT.png

https://www.electronics-tutorials.ws/transistor/tran_2.html

https://www.electrical4u.com/potentiometer/

https://commons.wikimedia.org/wiki/File:Voltage_divider.png

https://commons.wikimedia.org/wiki/File:Relay_symbols.svg

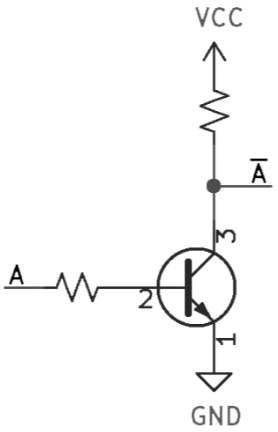
https://commons.wikimedia.org/wiki/File:BC547_transistor_pinout.png

2. Logic gates

Logic gates serve to realize different operations of Boolean algebra. To put it more simply, they implement different logical operations that are performed on one or more logical inputs and result in one logical output. The fact that Boolean algebra deals with truth, which, like our bit, can also be expressed binary, is not a coincidence. Recall that we considered conductivity as 1, which in this context can be considered true. Follows that the non-conductivity is 0 or a lie and we are back to the binary representation of one bit. In the last chapter, we were introduced to the transistor that allowed us to control that bit. In this chapter, we will use the transistors to build logic gates.

2.1. NOT

NOT logic gate inverts the input - if the input is 1, the output is 0 and vice versa. We only need one transistor for this function. Voltage VCC will only appear at the output if input A is low.



Symbol	A	Q
	0	1
	1	0
$Q = \overline{A}$		

Figure 2-1 NOT transistor connection with truth table and expression

2.1.1. NOT gate experiment

Components:

- breadboard
- 5V power supply
- 3mm red LED
- SPST pushbutton switch
- BC547 NPN transistor
- 220Ω, 2.2KΩ resistors

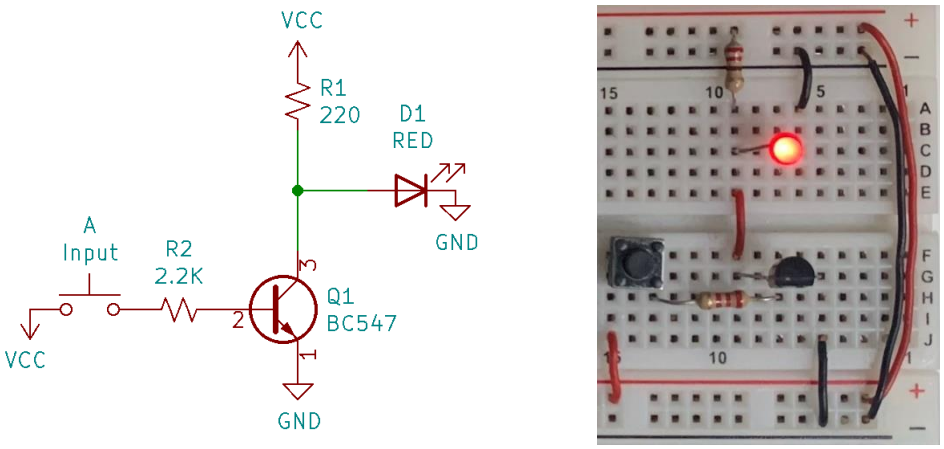


Figure 2-2 Transistor realization of NOT gate

Explanation: It is easy to notice that this experiment is very similar to the transistor as a switch experiment. The only difference is that we take collector output, instead of emitter output. That way the LED is lit, or the value of the bit is 1 if the pushbutton is not pressed. Bringing the signal from outside, by pressing the pushbutton, the bit is inverted to 0 value. Since the current tries to find the path of least resistance, it will ground itself directly through the transistor as a closed switch, instead of going through the diode. In other words, when the transistor is in saturation, it acts like a closed switch and there is no voltage differential between collector and emitter, and hence no voltage to light a LED.

We will further use chip 7404 which contains six NOT logic gates, organized according to the figure below.

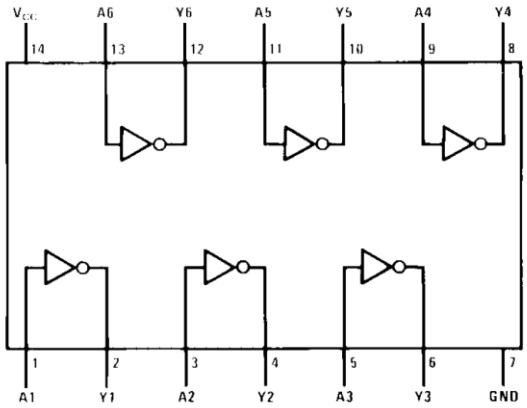
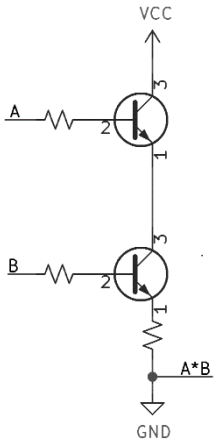


Figure 2-3 Chip 7404

2.2. AND

The AND logic gate requires that both inputs be 1 for the output to be 1, which can be clearly read from the truth table. The same is true for three or more inputs. By carefully connecting the transistors, we can easily achieve this function. The voltage VCC will appear at the output only in the case when both transistors are on, which we will enable by bringing voltage to the A and B inputs.



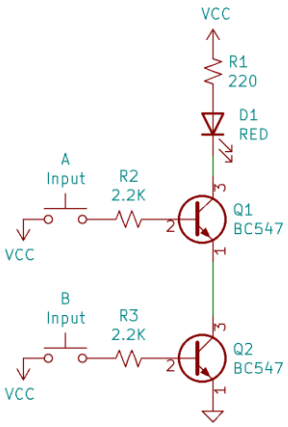
Symbol	A	B	Q
	0	0	0
	1	0	0
	0	1	0
	1	1	1
Q = A * B			

Figure 2-4 AND transistor connection with truth table and expression

2.2.1. AND gate experiment

Components:

- breadboard
- 5V power supply
- 3mm red LED
- 2 x SPST pushbutton switches
- 2 x BC547 NPN transistors
- 220Ω, 2 x 2.2KΩ resistors



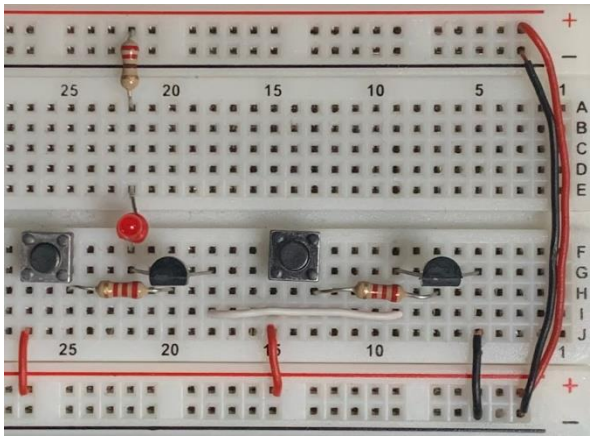


Figure 2-5 Transistor realization of AND gate

Explanation: Pressing the first and second pushbutton at the same time drives the transistors in saturation and they behave as closed switches. In that case, the current finds its path to the ground through the emitter and the LED is lit.

Now that we have built AND gate with transistors, we can use the TTL chip 7408. The chip contains four AND logic gates connected according to the figure below.

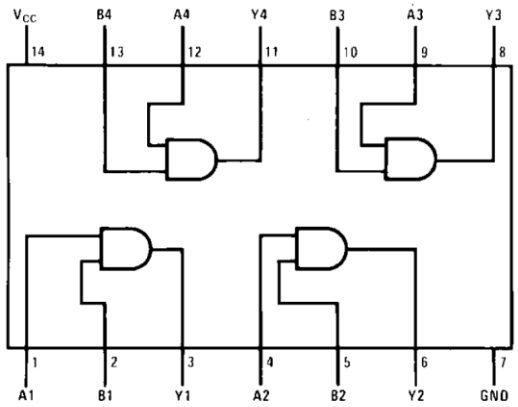
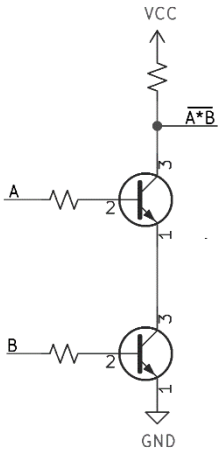


Figure 2-6 Chip 7408

2.3. NAND

The NAND logic gate requires both inputs to be 1 for the output to be 0. Analogously follows for three or more inputs.



Symbol	A	B	Q
	0	0	1
	1	0	1
	0	1	1
	1	1	0
$Q = \overline{A * B}$			

Figure 2-7 NAND transistor connection with truth table and expression

It is not difficult to understand that this is the inverted output of the AND gate. Also, it is convenient to note that the gate is almost identical to the AND gate only its output is taken from the collector, not from the emitter. Voltage VCC will not appear on the collector output only if both transistors are in saturation.

2.3.1. NAND gate experiment

Components:

- breadboard
- 5V power supply
- 3mm red LED
- 2 x SPST pushbutton switches
- 2 x BC547 NPN transistors
- 220Ω, 2 x 2.2KΩ resistors

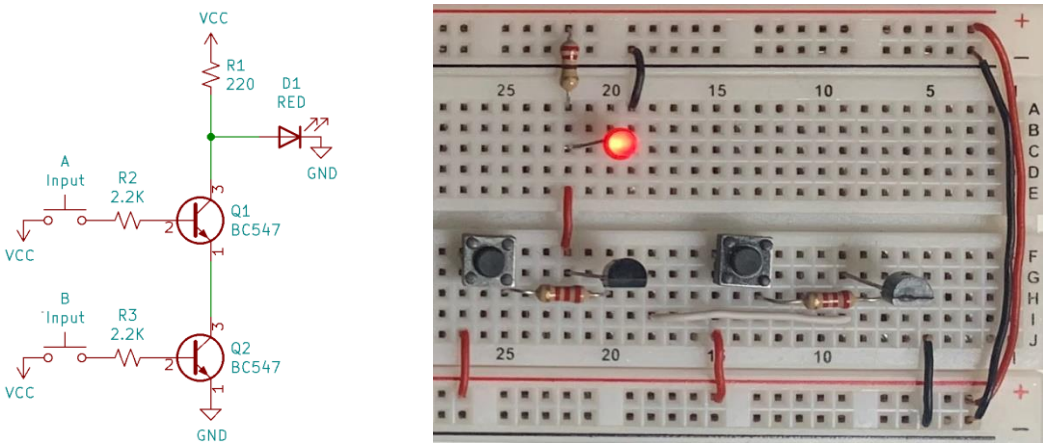


Figure 2-8 Transistor realization of NAND gate

Explanation: Pressing the first and second pushbutton at the same time drives the transistors to saturation and they behave as closed switches. In that case, the current finds its path of least resistance through transistors, and the LED turns off.

Now that we have built the NAND gate with transistors, we can use the TTL chip 7400. The chip contains four NAND logic gates, connected according to the figure below.

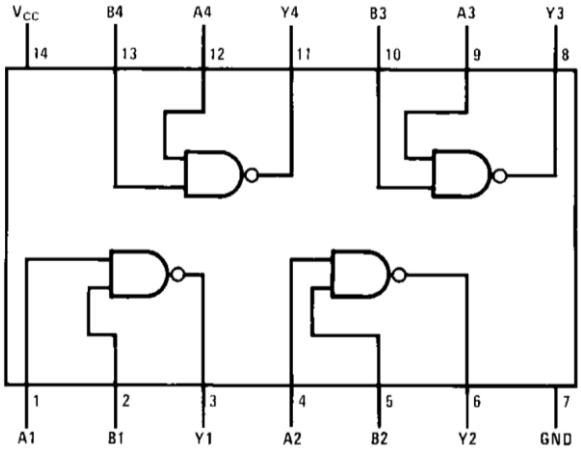
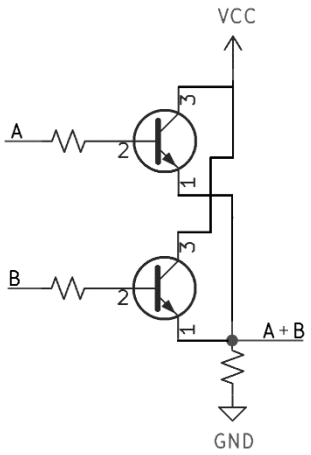


Figure 2-9 Chip 7400

2.4. OR

The OR logic gate enables the output to be 1, if any input is 1, as shown in the truth table. Analogously follows for three or more inputs. The voltage VCC will pass through to the output if the voltage is present at A or B input, or at both inputs.



Symbol	A	B	Q
	0	0	0
	1	0	1
	0	1	1
	1	1	1
Q = A + B			

Figure 2-10 OR transistor connection with truth table and expression

2.4.1. OR gate experiment

Components:

- breadboard
- 5V power supply
- 3mm red LED
- 2 x SPST pushbutton switches
- 2 x BC547 NPN transistors
- 220Ω, 2 x 2.2KΩ resistors

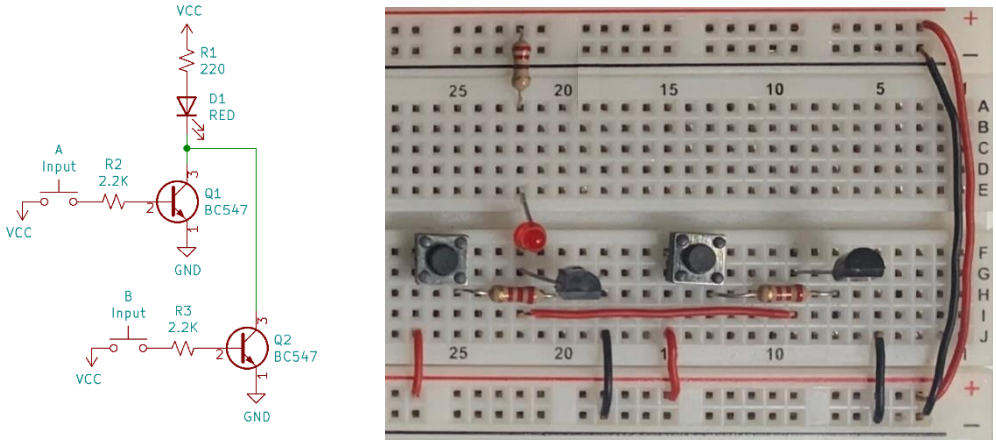


Figure 2-11 Transistor realization of OR gate

Explanation: Pressing any of the pushbuttons drives their transistor to saturation and it behaves like a closed switch. In that case, the current finds its path to the ground through the emitter and the LED is lit.

We will further use the TTL chip 7432 containing four OR logic gates, according to the figure below.

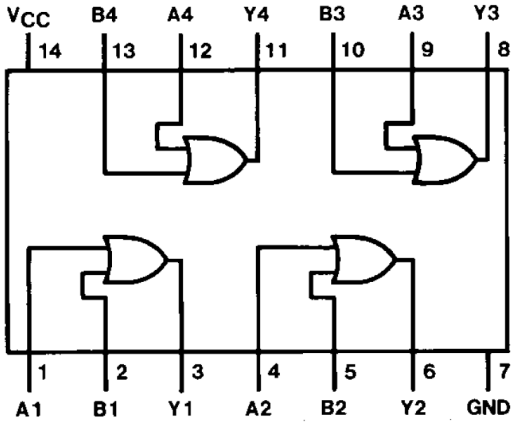
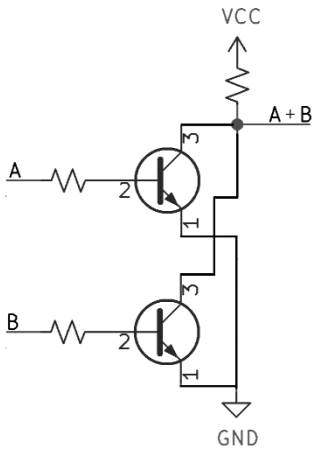


Figure 2-12 Chip 7432

2.5. NOR

The NOR logic gate requires both inputs to be 0, for the output to be 1. Analogously follows for three or more inputs.



Symbol	A	B	Q
	0	0	1
	1	0	0
	0	1	0
	1	1	0
$Q = \overline{A + B}$			

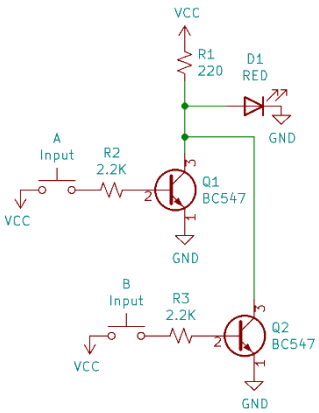
Figure 2-13 NOR transistor connection with truth table and expression

It is not difficult to understand that this is the inverted output of the OR gate. Also, it is convenient to note that the circuit is almost identical to the OR circuit, only its output taken is from the collector and not the emitter. Voltage VCC will not appear at the output only if none of the transistors is in saturation.

2.5.1. NOR gate experiment

Components:

- breadboard
- 5V power supply
- 3mm red LED
- 2 x SPST pushbutton switches
- 2 x BC547 NPN transistors
- 220Ω, 2 x 2.2KΩ resistors



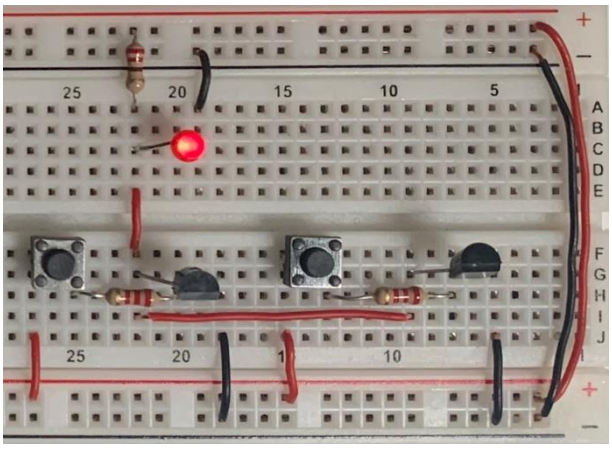


Figure 2-14 Transistor realization of NOR gate

Explanation: Pressing any of the pushbuttons drives their transistor in saturation and it behaves like a closed switch. In that case, the current finds its path to the ground through the emitter and the LED turns off.

We will further use TTL chip 7402 which contains four NOR logic gates, organized according to the figure below.

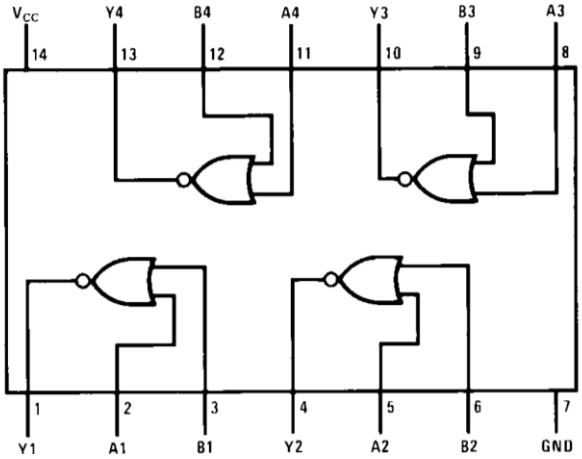


Figure 2-15 Chip 7402

2.6. XOR and XNOR

The XOR logic gate requires the inputs to be different, for the output to be 1. For multiple inputs, however, the gate needs to be viewed differently. If we have an odd number of inputs that is 1, the gate will result in output 1.

Symbol	A	B	Q
	0	0	0
	1	0	1
	0	1	1
	1	1	0
$Q = A \oplus B$			

Figure 2-16 XOR truth table and expression

According to the following figure, it can be concluded that XOR can be realized using 6 transistors. If we look in more detail, we will notice that transistors Q1 and Q2 make an OR gate, transistors Q3 and Q4 a NAND gate, and transistors Q5 and Q6 an AND gate. If A input is 1 and B input is 0, then the result of the OR circuit is 1 which leads to saturation of the Q5 transistor. At the same time, the result of the NAND circuit 1, which leads to saturation of Q6 transistor and output is 1. Analogously follows the output in a situation when A input is 0 and B input is 1. If both A and B inputs are 0, the result of the OR circuit is 0 so the output is 0 because Q5 is cut-off. If both A and B inputs are 1, the result of the NAND circuit is 0 so the output is 0 because Q6 cuts off.

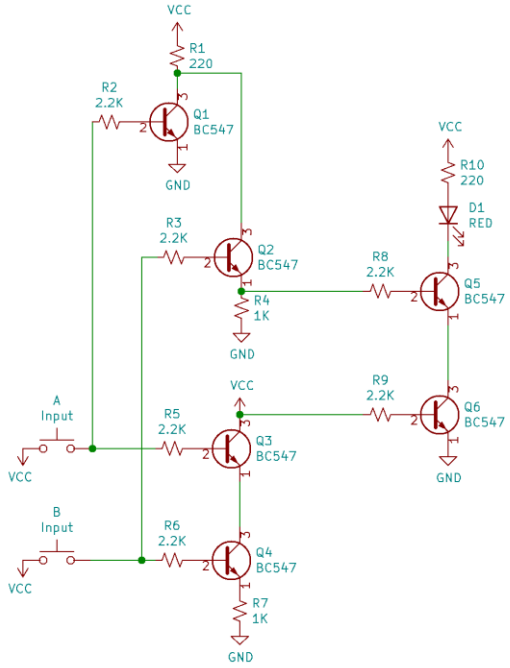


Figure 2-17 Transistor realization of XOR gate

From the explanation above, it is clear how complex it is to implement an XOR gate using transistors. We can imagine how complex it would be to build a Pong machine with only discrete components like transistors. Fortunately, we can approach the problem by applying our paradigm. We can use the TTL chips of the gates we already built and simplify the process. As already mentioned, the XOR gate can be very easily realized with NAND, OR and AND gates according to the following figure.

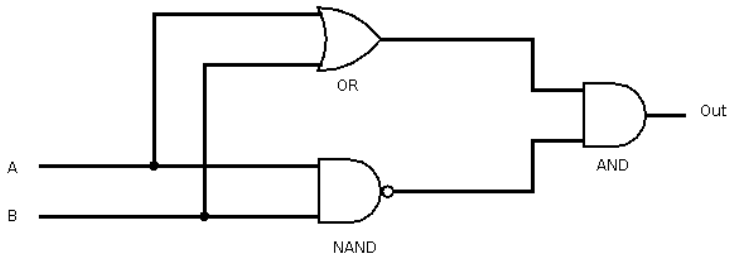


Figure 2-18 Logic gates realization of NOR gate
(Source: referenced)

But before we start with the realization, it is important to explain one more detail. Inputs A and B will be controlled by pushbuttons in such a way that pressing the pushbutton will allow a high voltage as an input value, as we have done with transistors. It is interesting to note that TTL chips have pull-up resistors at their inputs that ensure that the inputs are high, even when disconnected. What does that mean?

The concept of pull-up resistors is very simple, and consists of connecting the input to a high voltage source through a resistor, according to the figure below. By pressing the button, the input will be

grounded, so it is evident that there must be a resistor, to prevent a direct connection of voltage and ground or short circuit.

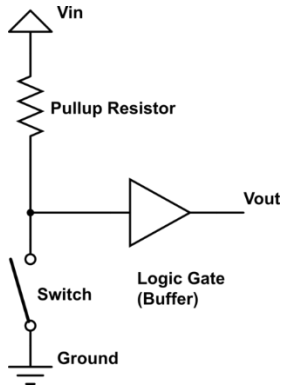


Figure 2-19 Pull-up resistor
(Source: referenced)

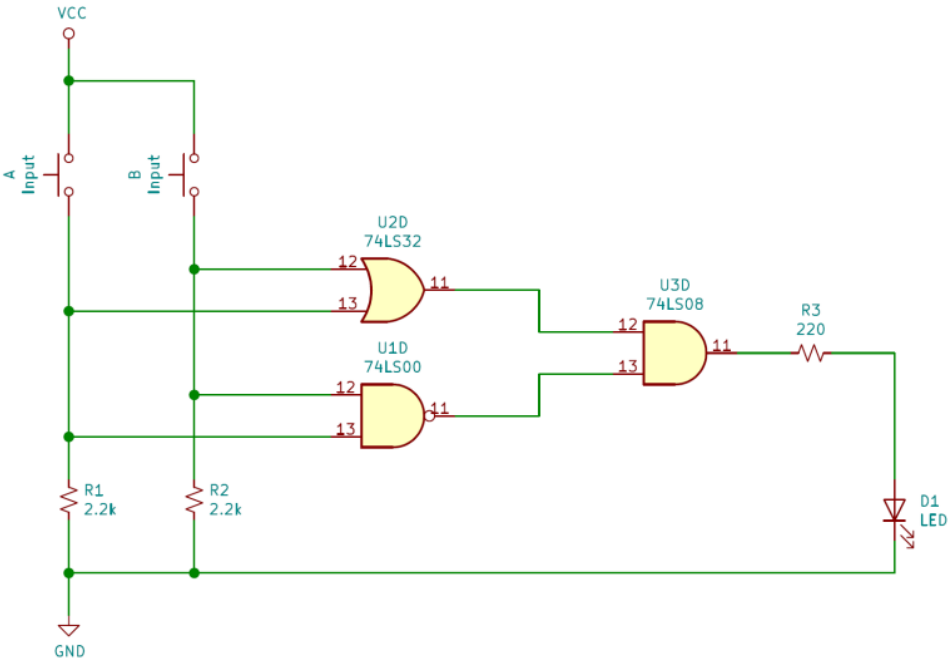
The concept of pull-down resistors is identical to pull-ups if we replace the voltage source and ground. It assures us that the input is at low voltage until we set it to a high voltage by pressing the pushbutton. When we come to think of it, a pull-down resistor is just what we need, because we have to neutralize pull-up resistors at TTL inputs.

Let us, therefore, apply these concepts to our case, in which we will use a pushbutton to connect the inputs of the circuit to high voltage. At the moment when the button is not pressed, the value sent to the input of the TTL chip is not defined, so due to the pull-up resistor at its input, the chip will interpret this value as high. We need to prevent this, so we will ground the inputs of the circuit with pull-down resistors. This ensures that when the pushbutton is not pressed, we send a low voltage value to the chip input. When we press the button, one part of the voltage will be grounded across the resistor and the other part of the voltage will represent the high input to our chip.

2.6.1. XOR gate experiment

Components:

- breadboard
- 5V power supply
- 5mm red LED
- 2 x SPST pushbutton switches
- 220Ω, 2 x 2.2KΩ resistors
- 7400 NAND, 7432 OR, 7408 AND chips with the same configuration:
    - Pin 14 as VCC, Pin 7 as ground
    - Pin 13 A input, Pin 12 as B input
    - Pin 11 as output



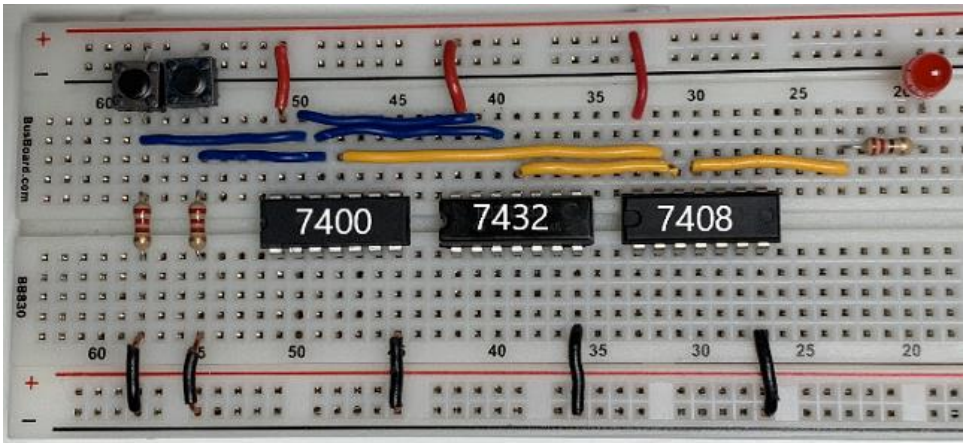


Figure 2-20 TTL chips realization of NOR gate

Explanation: The circuit is self-explanatory according to the explanations of OR, NAND and AND gates.

We can further use a 7486 chip containing four XOR gates, organized according to the figure below.

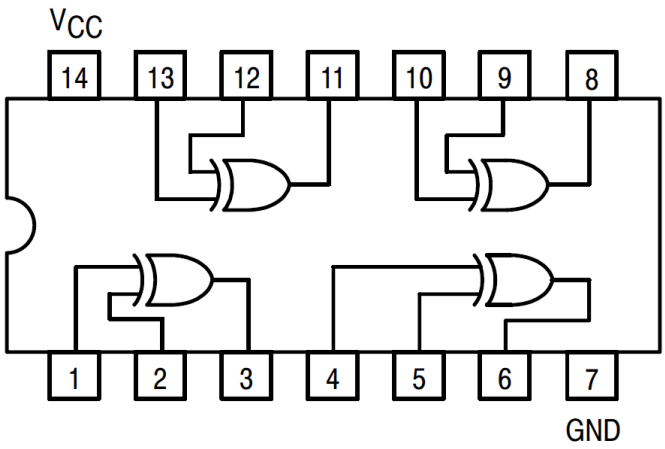


Figure 2-21 Chip 7486

Finally, we are missing only the last of the basic logic gates – the XNOR gate. With all this experience, it is very easy to understand that all this gate does is invert the output of the XOR gate. Hence, the XNOR Boolean operation for A and B operands is expressed as follows:

$$Y = \overline{\mathrm{A} \oplus \mathrm{B}}$$

Therefore, the output of the XNOR gate is 1, only if both inputs are the same. The same applies to multiple operands. The implementation of the experiment is left as an exercise to the reader.

2.7. DeMorgan's transformations

Now that we are familiar with basic logic gates, it is important to understand that our observations were guided completely according to the positive true logic. That means that we concentrated on getting high positive output as a result of the gates, mostly because we have shown output on the LED. But, in reality, it is often quite the contrary, since TTL chips are much better at sinking current than at sourcing it. In other words, TTL designers mostly use negative true logic, using low negative value as an output for true conditions, in order to drive other chips that use negative values as inputs.

In that sense, it is very important to follow DeMorgan's transformations, which enable us to understand the negative versions of our basic logic gates. For example, positive logic NAND gate can be expressed also as negative logic OR gate – if any of the inputs is low, then its inverted value becomes high input into OR gate and the result is high. As we will see, sometimes it is even easier to understand the gate by looking at it from a negative perspective.

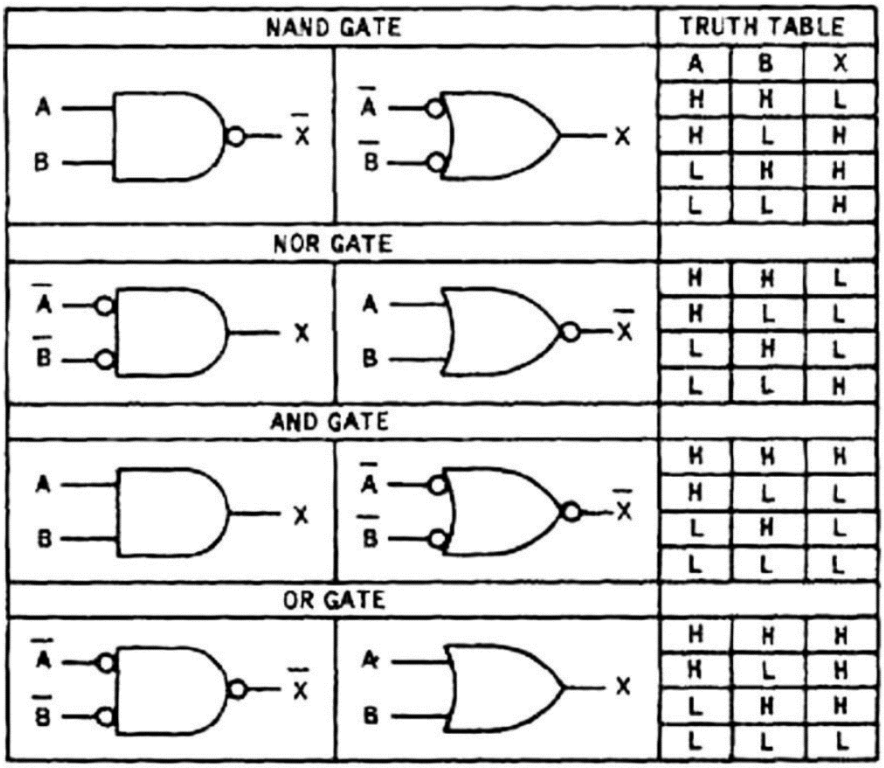


Figure 2-22 Dr. Holdens table of DeMorgan's transformations
(Source: referenced)

Note: The missing transformation of the XOR gate will be explained later in the circuits section.

References

http://sullystationtechnologies.com/npnxorgate.html

https://commons.wikimedia.org/wiki/File:Pullup_Resistor_Diagram.png

Dr. Hugo Holden – Lawn Tennis: https://www.worldphaco.com/uploads/LAWN_TENNIS.pdf

3. Combinational logic circuits

In the previous chapter, we have presented and realized logic gates out of transistors. Logic circuits, on the other hand, use a combination of gates to realize more complex functions. Logic circuits can be classified as combinational and sequential. In this chapter, we will present combinational logic circuits. A combinational logic circuit is a type of digital circuit where the output is a pure function of the input. In the following subchapters, we will build different combinational logic circuits from gates, in order to explain their behavior. At the very beginning of the chapter, we will round up our paradigm presented in the first chapter, and build a full adder.

3.1. Adder

We have finally come to a chapter in which we will realize our initial idea and establish a paradigm. In the last experiment with constructing XOR gate out of other types of gates, we have proven the power and applicability of binary, digital logic in the realization of countless functionalities. The adder represents the pinnacle of sophistication of this application.

3.1.1. Half adder

Having presented all the necessary building components, we are able to realize the half-adder according to the figure below. The truth table shows us that the binary addition is analogous to decimal, only simpler. The sum output will be 1 only when the A and B inputs are different, which we can realize with the XOR gate. The carry output will be 1 only when both inputs are 1, which we can realize with AND gate.

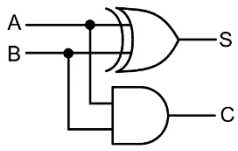
Circuit	A	B	S	C
	0	0	0	0
	1	0	1	0
	0	1	1	0
	1	1	0	1

Figure 3-1 Half adder with truth table

We can immediately see that the half adder is sufficient for binary addition of only one bit. If we want to add 2 bits in a word, we need to build a circuit that is able to do the addition of 3 bits - 2 position bits and one carry bit from the previous position.

3.1.2. Full adder

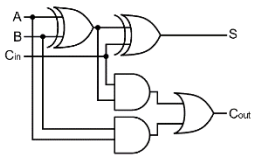
Circuit	A	B	Cin	S	Cout
	0	0	0	0	0
	0	0	1	1	0
	0	1	0	1	0
	0	1	1	0	1
	1	0	0	1	0
	1	0	1	0	1
	1	1	0	0	1
	1	1	1	1	1

Figure 3-2 Full adder with truth table

A full adder can be achieved by connecting 2 half adders, according to the previous figure. It is very easy to figure out how the circuit works, from the truth table:

- SUM is 1 when the combination of inputs A, B, and C_{in} have an odd number of 1 values
  - it can be performed with XOR gates as follows

$$\mathrm{SUM} = \mathrm{Cin} \oplus \mathrm{A} \oplus \mathrm{B}$$

- CARRY (C_{out}) is 1
  - when inputs A and B are 1 or
  - when inputs A and B are different and the C_{in} value is 1
  - it can be performed with AND, OR and XOR gates as follows

$$\mathrm{CARRY} = \mathrm{A} * \mathrm{B} + (\mathrm{A} \oplus \mathrm{B}) * \mathrm{Cin}$$

3.1.3. Full adder experiment

Components:

- breadboard
- 5V power supply
- 5mm red and green LED
- 3 x SPST pushbutton switches
- 2 x 220Ω, 3 x 2.2KΩ resistors
- 7486 XOR, 7408 AND, 7432 OR chip with configuration:
  - Pin 14 as VCC, Pin 7 as ground
  - the rest is self-explanatory from the schematic

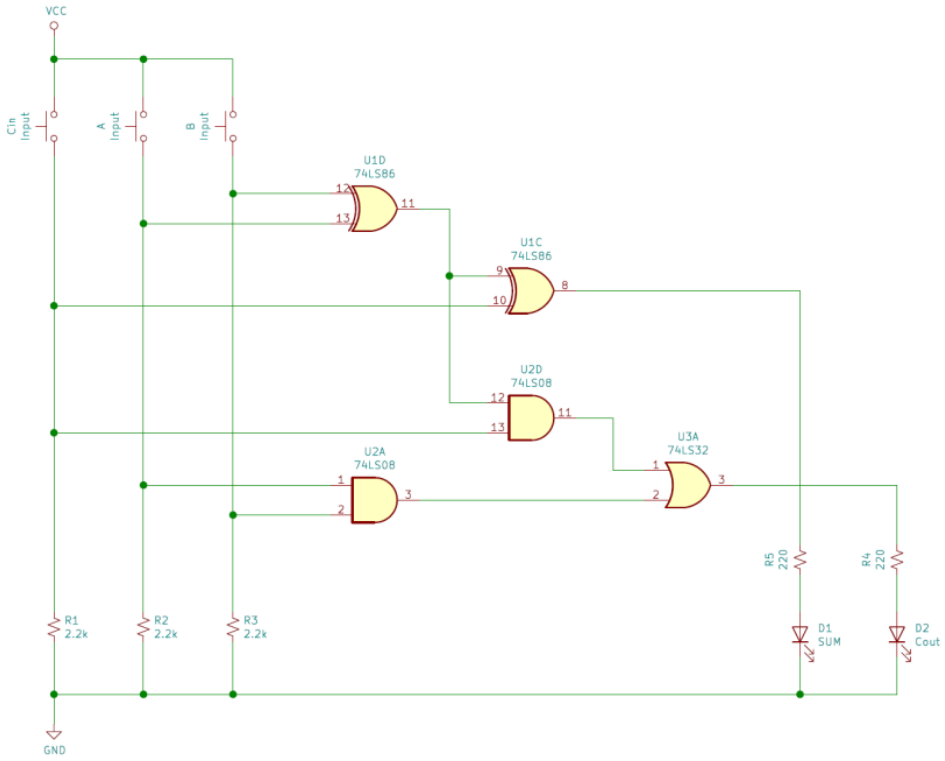


Figure 3-3 Full adder schematic

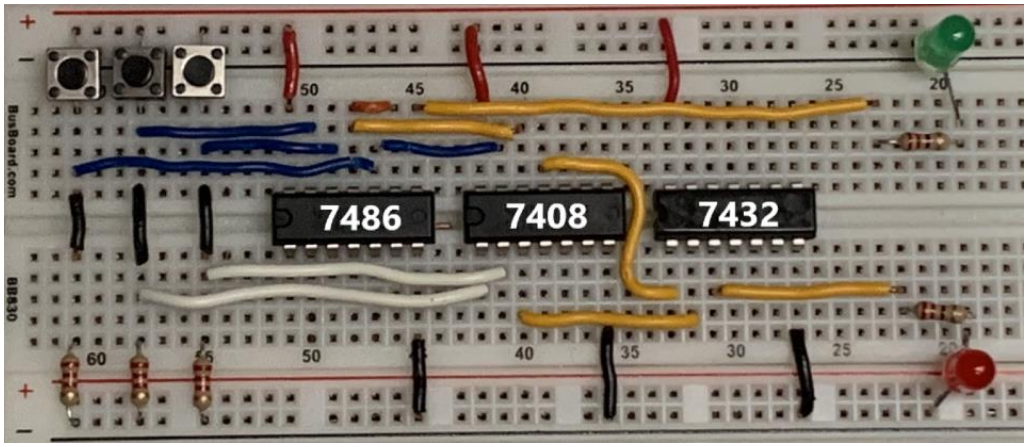


Figure 3-4 Full adder circuit

Explanation: Red D1 diode represents the sum, and it is lit only if inputs of U1C are different, in the following scenarios:

- if inputs A and B are different, the output of U1D is 1, so C_{in} must be 0
- if inputs A and B are the same, the output of U1D is 0, so C_{in} must be 1

Further, the green D2 diode represents carry, and it is lit only if any of the inputs of U3A is 1, in the following scenarios:

- if inputs A and B are both 1, the output of U2A is 1
- if inputs A and B are different, the output of U1D is 1, which makes one of the inputs of U2D value 1. C_{in} then also needs to be 1, because it makes the second input of U2D

Once we have realized the sum of the discrete components, we can use the 7483 chip which performs binary addition of two 4-bit words. This rounds up our paradigm which should be clear.

3.2. Decoder

A binary decoder serves to decode binary information by converting the input bit pattern into the output pattern of our choice. For example, the following figure shows a 2-4 binary decoder that converts 2 bits of input into a 4-bit output. The applications of decoders are limitless, but we can imagine that this decoder can be used to activate one of 4 devices by sending it a bit pulse.

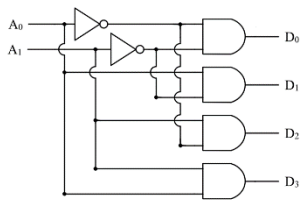
Circuit	A_0	A_1	D_0	D_1	D_2	D_3
	0	0	1	0	0	0
	1	0	0	1	0	0
	0	1	0	0	1	0
	1	1	0	0	0	1

Figure 3-5 2-4 binary decoder with truth table

3.2.1. 2-4 binary decoder experiment

Components:

- breadboard
- 5V power supply
- 5mm red, blue, yellow, and blue LED
- 2 x SPST pushbutton switches
- 4 x 2.2KΩ resistors
- 7404 NOT, 7408 AND chip with configuration:
    - Pin 14 as VCC, Pin 7 as ground
    - the rest is self-explanatory from the schematic

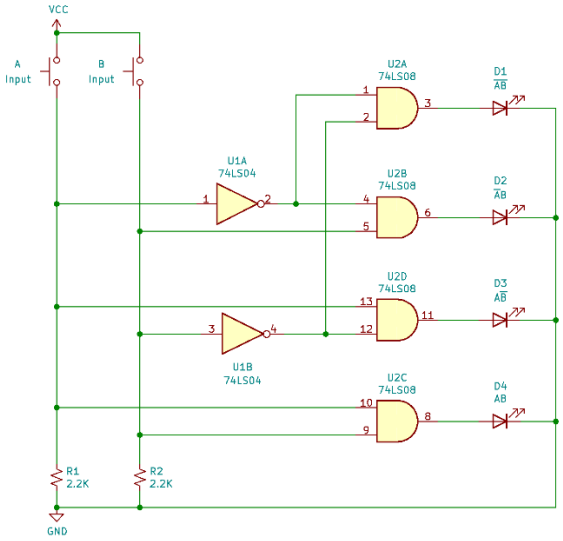


Figure 3-6 2-4 binary decoder schematic

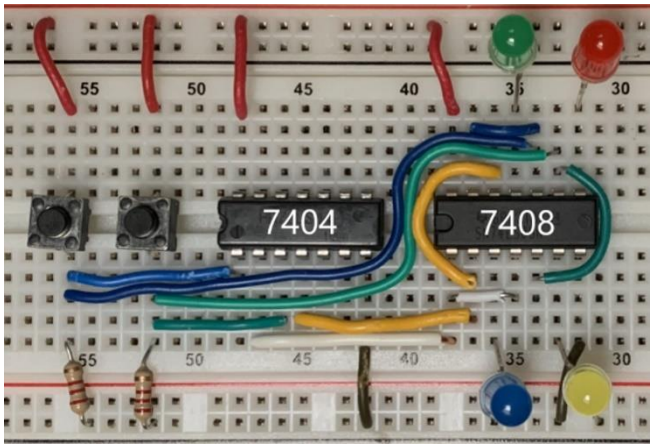


Figure 3-7 2-4 binary decoder circuit

Explanation: Diodes are lit according to the input bit pattern – D1 for 00, D2 for 01, D3 for 10, and D4 for 11.

3.2.2. BCD to 7-segement decoder

In the Pong game, for example, we will use a decoder to show scores on the screen, using a BCD (binary coded decimal) to a 7 segment decoder. Checking the datasheet of the TTL chip 7448, in the logic diagram, we can see it is built solely of logic gates which we already covered. Interestingly, the output side is built by specific AND-OR-INVERT circuits, which are very versatile and will be covered later. Also, we can see that the chip has 4 inputs (A, B, C, D) and 7 outputs (a, b, c, d, e, f, g, h).

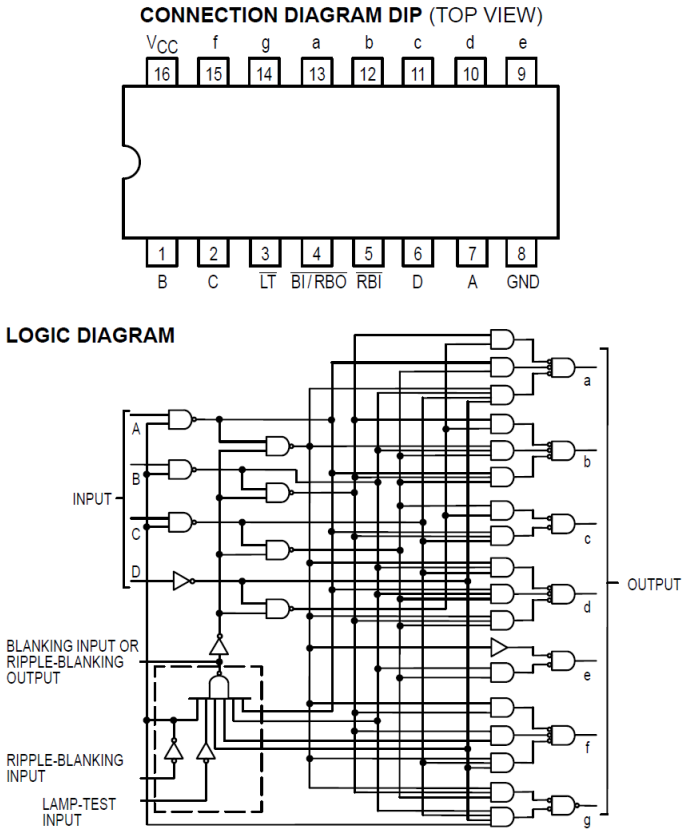


Figure 3-8 BCD to 7-segment decoder

Further, the following figure shows how binary coded decimal input pattern activates different outputs.

Digit	A	B	C	D	a	b	c	d	e	f	g
0	0	0	0	0	0	0	0	0	0	0	1
1	0	0	0	1	1	0	0	1	1	1	1
2	0	0	1	0	0	0	1	0	0	1	0
3	0	0	1	1	0	0	0	0	1	1	0
4	0	1	0	0	1	0	0	1	1	0	0
5	0	1	0	1	0	1	0	0	1	0	0
6	0	1	1	0	0	1	0	0	0	0	0
7	0	1	1	1	0	0	0	1	1	1	1
8	1	0	0	0	0	0	0	0	0	0	0
9	1	0	0	1	0	0	0	0	1	0	0

Figure 3-9 BCD to 7-segment decoder
(Source: referenced)

The outputs of the BCD to 7-segment decoder can be easily demonstrated using 7-segment displays, which use 7 LED diodes to draw a number, and many of them have an additional indicator for the decimal point. The only thing worth noticing is that it comes in two arrangements:

- common cathode – cathodes of all LED diodes are grounded together
- common anode – anodes of all LED diodes are joined together to a positive voltage source

3.2.3. BCD to 7-segement decoder experiment

Components:

- breadboard
- 5V power supply
- common cathode 7 segment display
- 4 x SPST pushbutton switches
- 4 x 2.2KΩ resistors
- 7448 BCD to 7-segment decoder chip with configuration:
    - Pin 14 as VCC, Pin 7 as ground
    - the rest is self-explanatory from the schematic

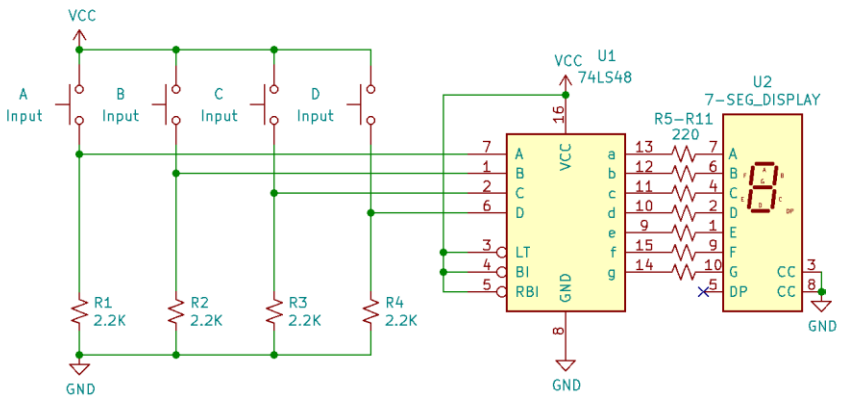


Figure 3-10 BCD to 7-segment decoder schematic

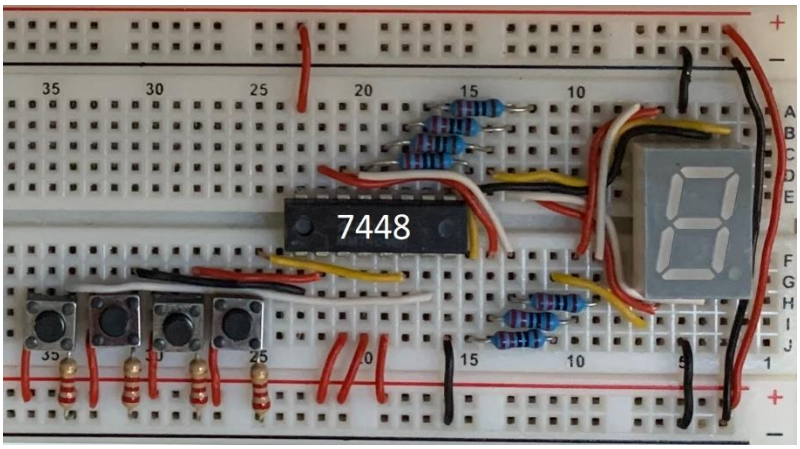


Figure 3-11 BCD to 7-segment decoder circuit

Explanation: The input pins 3, 4 and 5 of the U1 7448 chip are not used, hence are connected to a positive voltage source. Also, the decimal point input of the U2 7-segment display is not used, so it remains unconnected. The final thing to mention is that, since we are using a common cathode 7-segment display, we must ground one or both CC (common cathode) inputs.

3.3. Multiplexer

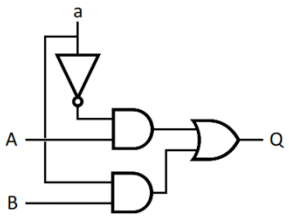
Circuit	a	A	B	Q
	0	0	x	0
	0	1	x	1
	1	x	0	0
	1	x	1	1

Figure 3-12 2 to 1 multiplexer with truth table

A multiplexer is a combinational logic circuit that allows selecting one of the input signals to be sent to the output. If we think about it, using a multiplexer within a more complex chip allows the chip to reduce the number of output pins because its combinational logic can send different signals to one and the same output. It is very similar to the decoder, which will be shown in the experiment.

3.3.1. The 4-1 multiplexer experiment

Components:

- breadboard
- 5V power supply
- 5mm blue LED
- 6 x SPST pushbutton switches
- 6x 2.2KΩ resistors
- 7404 NOT, 2 x 7408 AND, 4078 8 input OR/NOR chips with configuration:
    - Pin 14 as VCC, Pin 7 as ground

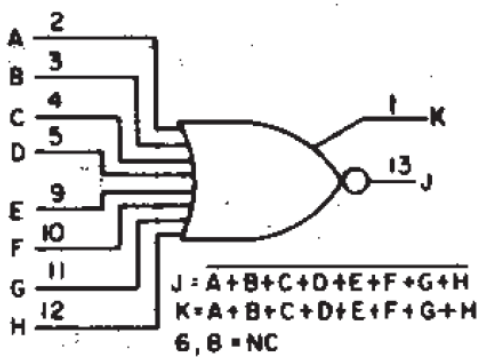


Figure 3-13 2 Chip 4078

In order to realize the circuit, and prove similarities between decoder and multiplexer, we can upgrade our binary decoder circuit from the 2-4 binary decoder experiment. If we add one more input to the AND

circuits for A, B, C, and D inputs (by adding one more AND circuit in the chain), and connect their outputs through the OR circuit, we get a simple implementation of the multiplexer. For the realization of 4 input OR, we can use TTL chip 4078 - 8 input OR/NOR shown in the figure. The chip will be used in OR configuration, which means taking the output from pin 1. Since we have 4 more inputs than needed, they are going to be neutralized by grounding.

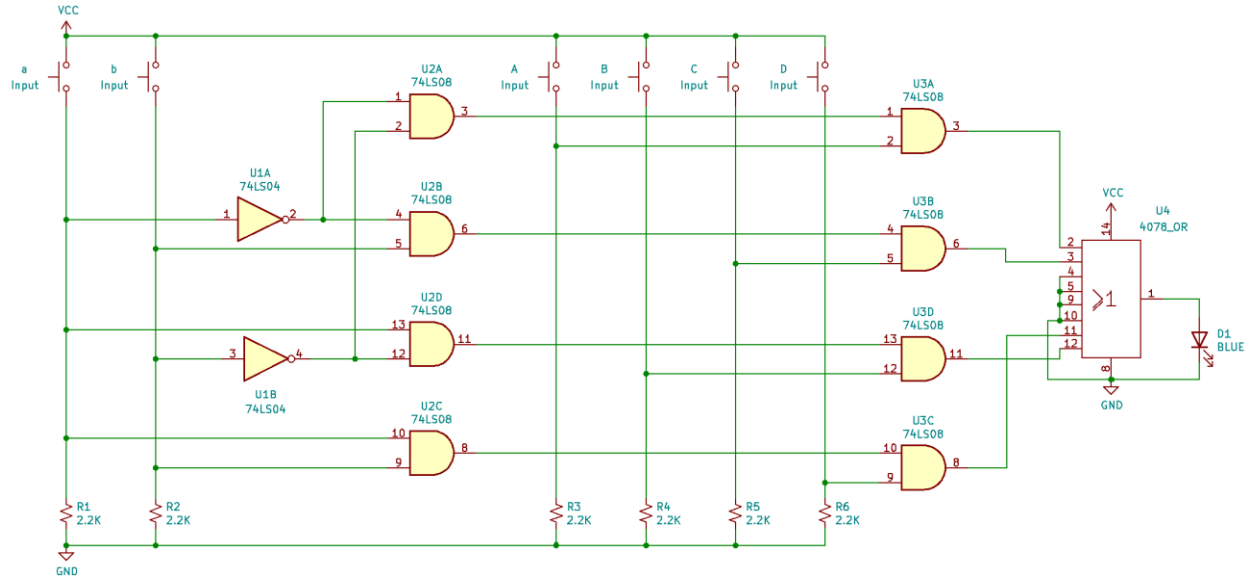


Figure 3-14 4-1 multiplexer schematic

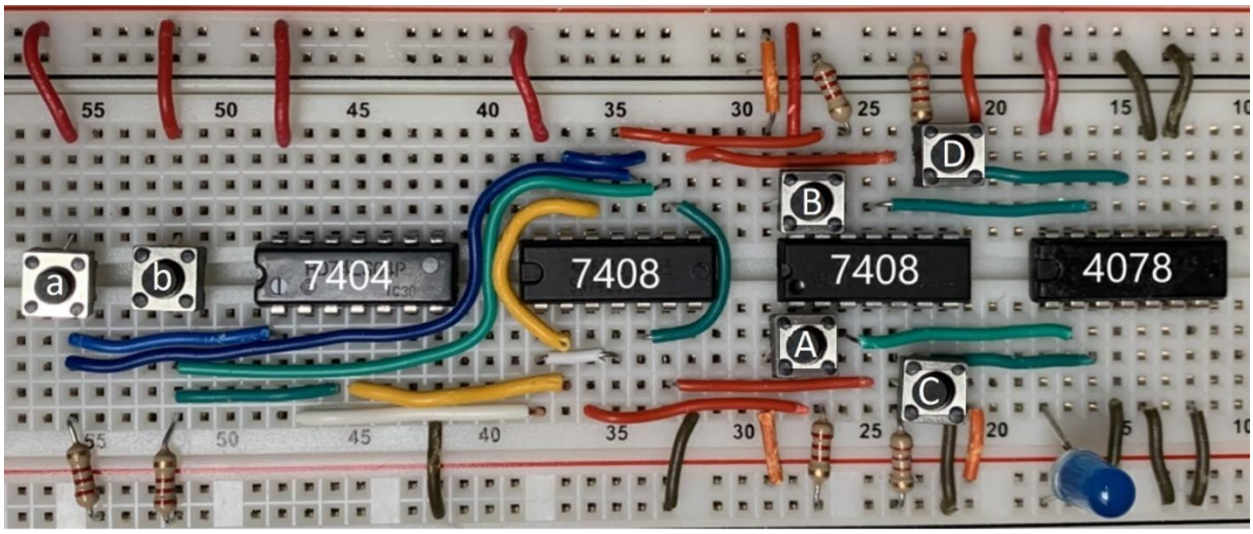


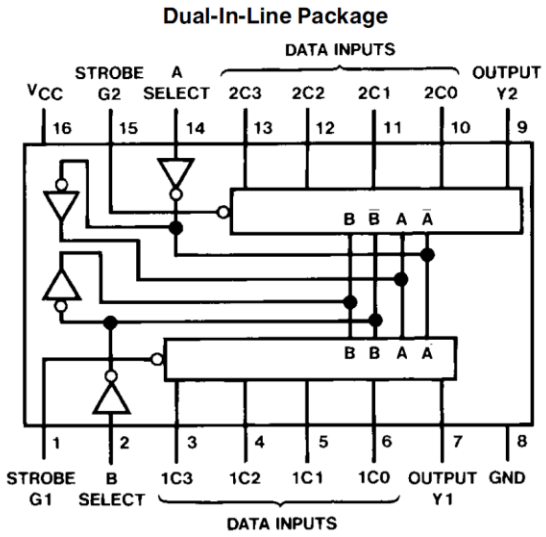
Figure 3-15 4-1 multiplexer circuit

Explanation:. a and b selector inputs are used to select between A, B, C, and D inputs whose value will appear at the output that can be demonstrated by the LED.

3.3.2. 74153 Multiplexer chip

In the context of building a Pong, we are going to need a 4-1 multiplexer, in order to distinguish the scores of two players. For that purpose, we can use a TTL chip 74153 which consists of 2 4-1 multiplexers. The connection diagram in the following figure is self-explanatory. The function table cleary shows how strobe G must be low to enable the output. Combination of A and B inputs, select one of C0, C1, C2 and C3 outputs.

Connection Diagram



Function Table

Select Inputs		Data Inputs				Strobe	Output
B	A	C0	C1	C2	C3	G	Y
X	X	X	X	X	X	H	L
L	L	L	X	X	X	L	L
L	L	H	X	X	X	L	H
L	H	X	L	X	X	L	L
L	H	X	H	X	X	L	H
H	L	X	X	L	X	L	L
H	L	X	X	H	X	L	H
H	H	X	X	X	L	L	L
H	H	X	X	X	H	L	H

Select inputs A and B are common to both sections.
H = High Level, L = Low Level, X = Don't Care

Figure 3-16 Chip 74153

3.4. AND-OR-INVERT circuit

We can build one more interesting circuit, that will give us justification to use TTL chip 7450 while building the Pong machine. The more complex function it performs on A, B, C, and D operands is the following:

$$Y = \overline{A * B + C * D}$$

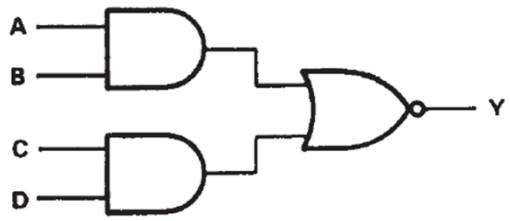
Circuit	A	B	C	D	Q
	0	0	0	0	1
	0	0	0	1	1
	0	0	1	0	1
	0	0	1	1	0
	0	1	0	0	1
	0	1	0	1	1
	0	1	1	0	1
	0	1	1	1	0
	1	0	0	0	1
	1	0	0	1	1
	1	0	1	0	1
	1	0	1	1	0
	1	1	0	0	0
	1	1	0	1	0
	1	1	1	0	0
	1	1	1	1	0

Figure 3-17 AND-OR-INVERT circuit with truth table

For the purpose of the AND-OR-INVERT circuit, we will use chip 7450 which contains two circuits.

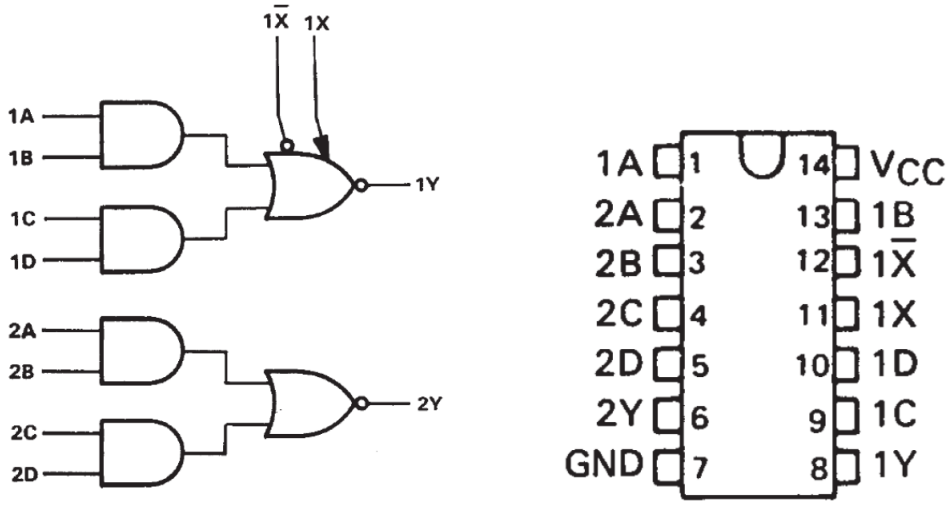


Figure 3-18 Chip 7450

The preceding figures are self-explanatory but we should mention that connections serve for the chip expansion, in order to create the circuit wider and enable it to create more complex functions with more operands, as follows.

$$Y = \overline{A * B + C * D + E * F + G * H}$$

3.4.1. And-or-invert circuit experiment

Components:

- breadboard
- 5V power supply
- 3mm red LED
- 4 x SPST pushbutton switches
- 220Ω, 4 x 2.2KΩ resistors
- 7408 AND, 7402 NOR chip with configuration:
    - Pin 14 as VCC, Pin 7 as ground
    - the rest is self-explanatory from the schematic

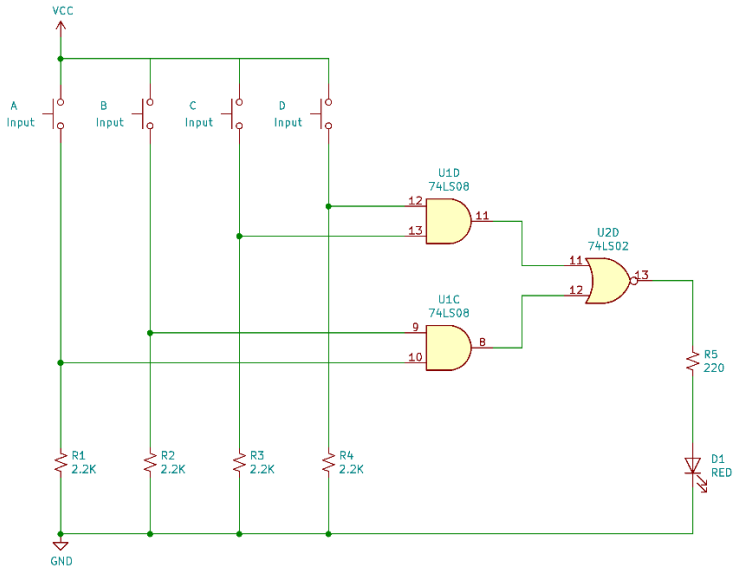


Figure 3-19 AND-OR-INVERT scheme

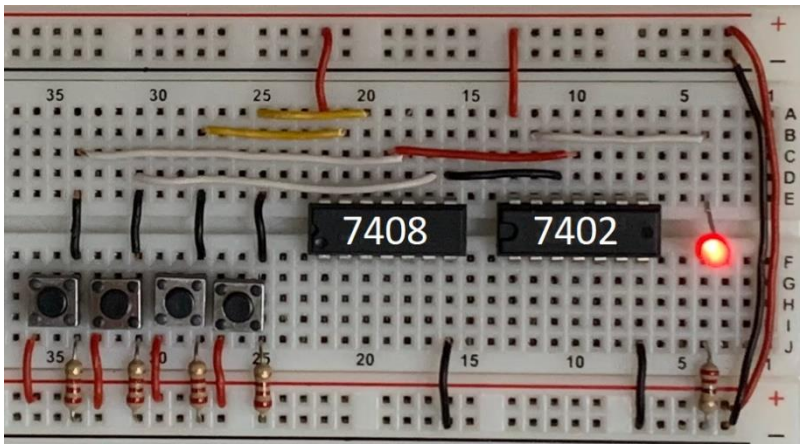


Figure 3-20 AND-OR-INVERT circuit

Note: For purpose of simplicity, we can get away without using a current limiting resistor to show results on the LED, when using the output of TTL chips.

Explanation: The circuit is self-explanatory, considering the explained AND and NOR gates. The fascinating thing about this circuit is that it can be used in many scenarios. For example, if we press A input the following happens:

- U1D results in low output
- U1C results in a value of B input and U2D inverts it
    - if B is high, U1C is high and the output of U2D is low
    - if B is low, U1C is low and the output of U2D is high

That means that this circuit can be used as a multiplexer that passes and inverts one of the inputs.

Further, the circuit can be also used as an XOR gate. Let us see what will happen if we consider the following transformations to the inputs:

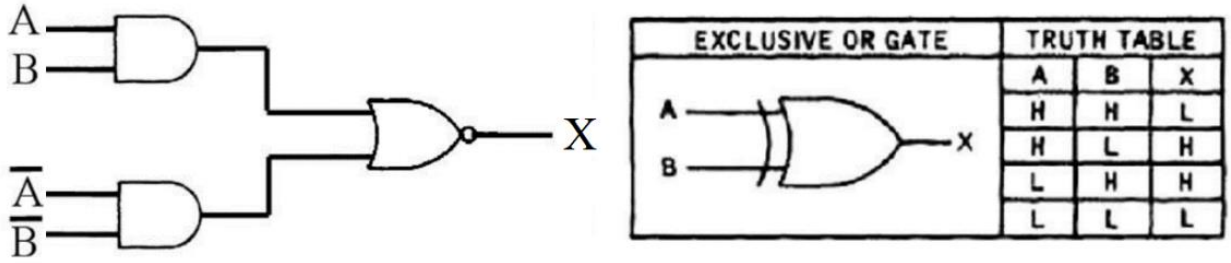


Figure 3-21 Dr. Holden's XOR gate from chip 7450

Since both inputs of the NOR gate must be low to produce a high output, it is possible only if A and B are different. An unwanted high input in the NOR gate is produced in the following scenarios:

- if A and B are both high, the output of the upper AND gate is high
- if A and B are both low, the output of the bottom AND gate is high

The versatility of this circuit and hence chip 7450 is cleverly used for calculating the vertical velocity of the ball in the Pong circuit, and it will be explained in detail later.

References:

https://www.electronicshub.org/bcd-7-segment-led-display-decoder-circuit/

Dr. Hugo Holden – Lawn Tennis: https://www.worldphaco.com/uploads/LAWN_TENNIS.pdf

4. Clocks

Before we present sequential logic circuits, we must introduce also the concept of clocks which control their outputs. For example, all the functions of the Pong game are synchronized and dependent on the master clock, so the clock presents a vasculature that will pump blood through Pong's bloodstream. The same is true for the work of the processor – everything the processor does is synchronized with the clock.

In this chapter, we will build a simple clock generator, using our basic building component, the transistor. After a discrete realization, we will introduce the 555 chip and its configurations.

Since capacitors play a significant role in clock realization, let us introduce them.

4.1. Capacitor

The capacitor is an electronic component that can store electric charges. It is incredibly simple since it can be constructed solely of 2 conducting parallel plates with insulating material, like air, between them. When we connect the power source and ground to each of the plates respectively, the capacitor charges up until it reaches the power source voltage. It is important to mention that the capacitor blocks the direct current because of the insulating material or dielectric. If we disconnect the power supply, the charge remains on the plates.

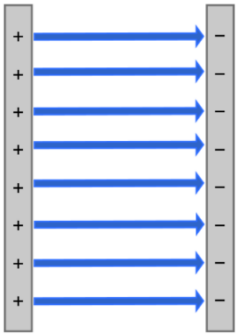


Figure 4-1 Simple capacitor
(Source: referenced)

An electrolytic capacitor, as shown in the following figure, is a polarizing capacitor in which the positive pole of the anode is made up of a metal (Aluminium) that oxidizes to create a layer of insulator (Al203). The anode is surrounded by a conductive electrolyte, connected with conducting graphite and silver that

serve as a cathode. The electrolytic capacitor is a polarizing element, so we must pay close attention to the direction of the connection.

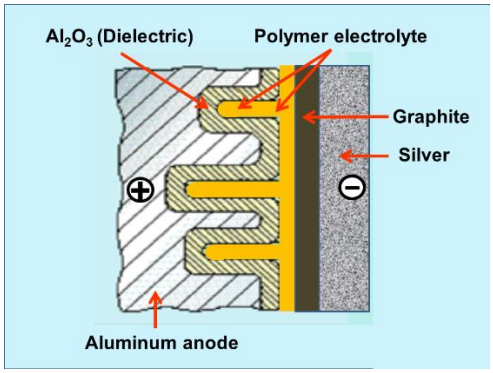


Figure 4-2 Electrolytic capacitor
(Source: referenced)

Capacitance is the property of the capacitor, measured by the amount of charge that it can store, and expressed in Farads (F).

4.1.1. RC circuit

Capacitors connected in series with resistors can introduce delay which is extremely important in electronics. It works on the very simple principle, shown in the figure below.

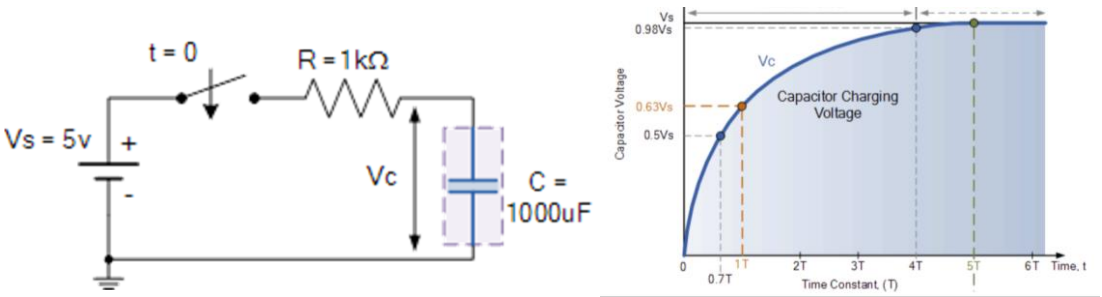


Figure 4-3 RC circuit and time constant
(Source: referenced)

When the switch is closed, the current flows and the capacitor starts to charge, trying to reach the voltage of the source to which it is exposed. The capacitor is charged through a resistor that resists the flow of current, so it will take some time until the capacitor is fully charged. This time is marked as the time constant and is calculated by multiplying the resistance of the resistor and the capacitance of the capacitor according to the formula

$$T = R * C$$

Judging by the graph, it takes 5-time constants (5T) to fully charge the capacitor. To arrive at the half voltage value, the capacitor is charged at 0.7T. For example in the figure, it is easy to calculate the time constant:

$$T = R * C = 1k\Omega * 1000\mu F = 1s$$

The voltage on the capacitor will need 5T or 5 seconds to reach a value of 5V. In order to reach the value of 2.5V, the capacitor will need 0.7T or 0.7 seconds. Let us try to prove that with an experiment.

4.1.2. The RC circuit experiment

Components:

- breadboard
- 5V power supply
- 3mm red LED
- 2 x SPST pushbutton switches
- BC547 NPN transistor
- 220Ω, 2 x 1kΩ resistor
- electrolytic capacitor 1000µF

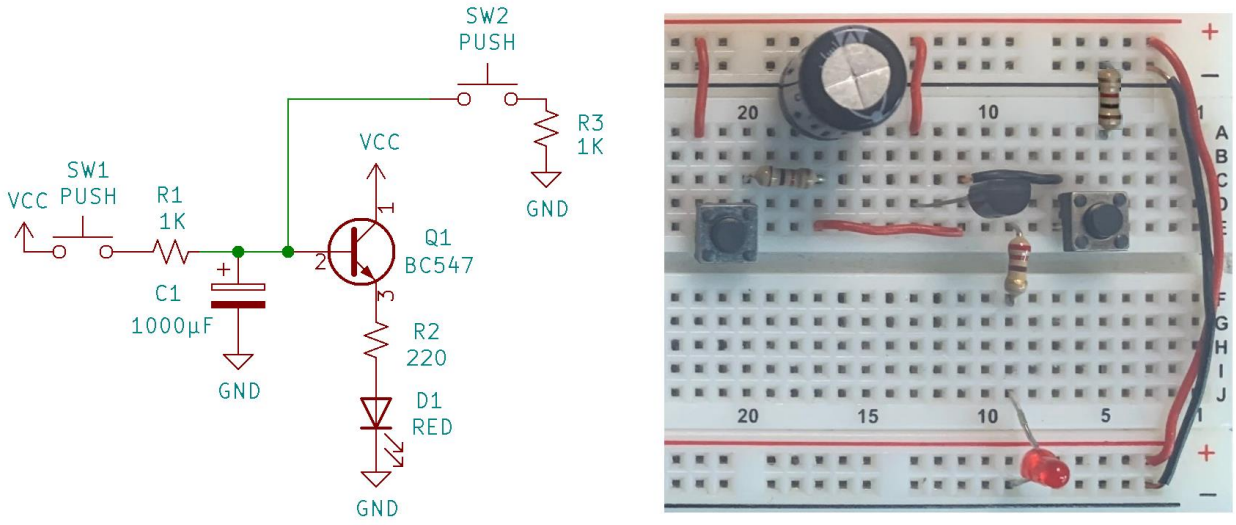


Figure 4-4 RC circuit experiment

Explanation: The left pushbutton serves to charge the 1000µF capacitor through a 1kΩ resistor. At the same time capacitor is charging, the voltage on the base of the transistor rises. Let's see how much voltage we need on the base of the transistor in order to light up the LED on the emitter. We know that the base voltage must be ~0.7 higher than the emitter voltage for the transistor to start conduction. Also, we know that the voltage on the emitter to light up the LED is ~1.8V. Therefore, the base voltage has to be ~2.5V, around half of the source voltage of 5V. As already mentioned, it will take 0.7T or 0.7s to reach that amount of voltage. The right pushbutton serves to discharge the capacitor. To conduct the experiment,

we should first use the right pushbutton to fully discharge the capacitor. Then we should use the left pushbutton to demonstrate that the LED lights up with the aforementioned delay.

The discharging of the capacitor is very similar but opposite to its charging, which is shown in the following figure.

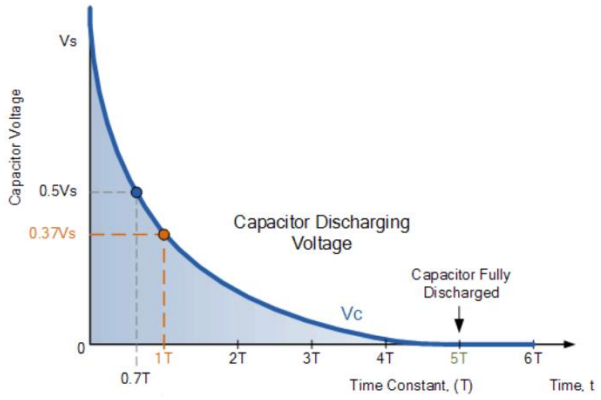


Figure 4-5 RC circuit discharging
(Source: referenced)

4.2. Transistor clock

By carefully connecting the two transistors, a simple clock can easily be achieved, as shown in the figure.

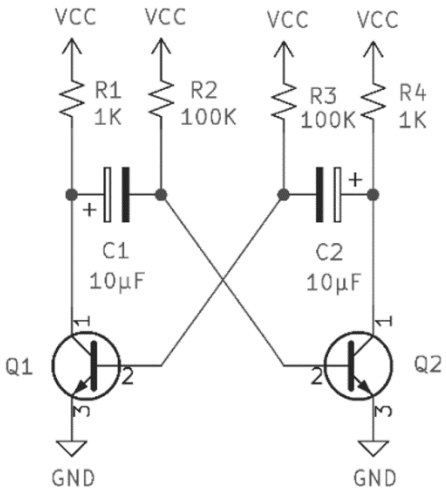


Figure 4-6 Transistor clock

What is important to notice is that the base of the Q1 transistor is connected to high voltage, as well as its collector. The difference is that the base resistor is 100 times greater. The same is true for the Q2 transistor.

The question is which of the transistors will first conduct, considering that we use the same components. The question is actually rhetorical, because the components cannot be the same, but are considered the same with certain tolerances. Therefore, one of the transistors will surely conduct first.

Let us imagine that the Q2 is cut-off and Q1 conducts. The voltage on the base of Q2 rises through the R2 resistor. When the voltage on the base of Q2 is high enough to make it conduct, the current starts flowing from the collector to the emitter of the Q2 transistor, collecting also the charges accumulated on the right side of the C2 capacitor. Since the voltage suddenly drops on the right side of the capacitor C2, the same thing happens also on its left side, causing the Q1 to cut off. Now, the Q2 conducts and Q1 is cut-off. The process now repeats for the Q1 transistor, which is perfectly explained in *Mr. Charles Platt's* book*, Make: Electronics*, which I highly recommend.

4.2.1. Transistor clock experiment

Components:

- breadboard
- 5V power supply
- 3mm red LED
- 2 x BC547 NPN transistors
- 2 x capacitor 10 µF
- 2 x 1KΩ, 2 x 100KΩ resistors

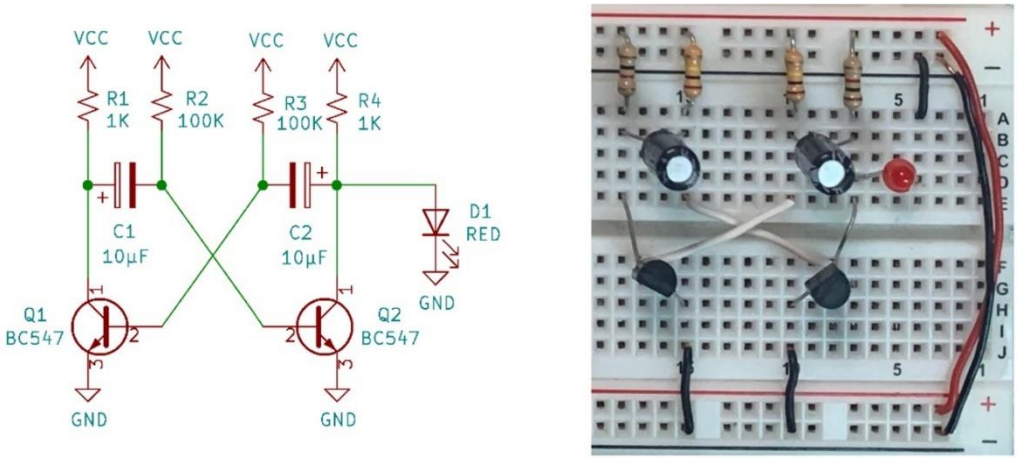


Figure 4-7 Transistor clock experiment

4.3. 555 chip

After we got acquainted with the basic concept of the delay and clock, we will use the integrated circuit 555. Specifically, we will use its flexibility when used in different configurations:

- astable
- monostable

- bistable

The figure shows the basic arrangement of pins whose meaning and usage will be introduced in different configurations.

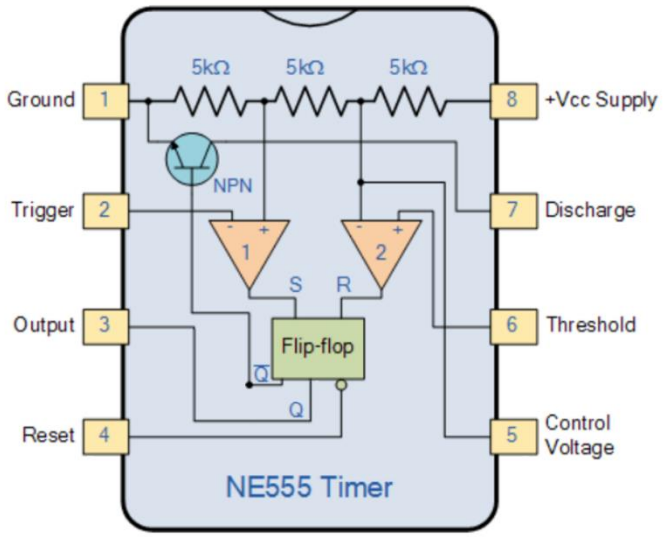


Figure 4-8 Chip 555 block diagram
(Source: referenced)

Due to its stability and configurability, the 555 chip is one of the most widely used chips. The name 555 can be attributed to its internal structure. By using three 5kΩ resistors connected in series, the circuit realizes voltage dividers that serve as reference operating voltages for this extremely advanced and popular chip.

It is important to notice that I have succeeded to understand the workings of the 555 chip through the brilliant explanation of *Mr. Charles Platt* in the book *Make: Electronics*. In the following chapters, I am only transmitting my interpretations of the aforementioned explanations, so I highly recommend the book.

4.3.1. Astable configuration

The figure below shows a simplified astable configuration of the 555 chip. In this configuration, the chip serves as an oscillator that produces accurate waveforms whose frequency can be controlled by adjusting the external RC circuit, as will be explained.

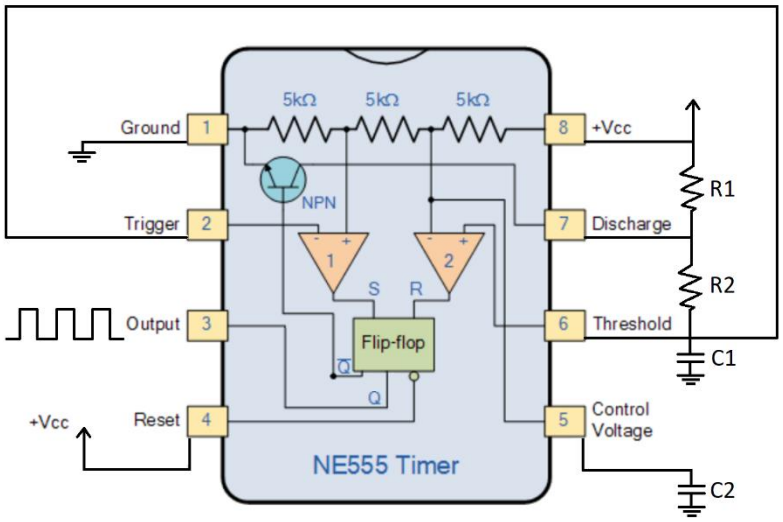


Figure 4-9 Astable configuration
(Souce: referenced)

The explanation is based on the brilliant explanation of *Mr.Charles Platt* in the book *Make: Electronics*:

- Pin 1 is connected to the ground, and the Pin 8 is connected to VCC
- Pin 5 is not used and is hence grounded via capacitor C2 to eliminate noise
- Flip-flop is a sequential logic component that is able to preserve the state of one bit and whose work we will get to know later. For now, it is important that we understand that it remembers the state
    - If the flip-flop is SET through S input, its Q output value 1 is sent to output pin 3. Also, its $\overline{Q}$ output value 0 is sent to the base of the NPN transistor
    - If the flip-flop is RESET through R input, its Q output value 0 is sent to output pin 3. Also, its $\overline{Q}$ output value 1 is sent to the base of the NPN transistor
- Comparators 1 and 2 compare voltages and are used to SET and RESET the flip-flop
    - The (+) input of comparator 1 is connected to 1/3 of a source voltage by the use of a voltage divider network and serves as a reference voltage. The (-) input of comparator 1 is connected to pin 2
    - The (-) input of comparator 2 is connected to 2/3 of a source voltage by the use of a voltage divider network and serves as a reference voltage. The (+) input of comparator 2 is connected to pin 6
- Pin 4 is used to reset the flip-flop with low input. It implicates the fact that its high input enables the flip-flop, so it is tied on VCC in order to permanently enable the flip-flop
- Pin 7 is connected to the collector of the NPN transistor and it is used to discharge the capacitor C1 when the NPN transistor conducts
- Pin 6 is connected to pin 2 in order to trigger the chip with low input

- Pins 8, 7, and 6, together with R1 and R2 resistors and C1 capacitor form an RC circuit that will control the behavior of the astable configuration

Let us try to explain the workings of the astable configuration, by following the steps:

1. If the voltage value on pin 2 is below the 1/3 of the source voltage, the output of comparator 1 is high which sets the flip-flop
2. Consequently, the Q output value 1 from the flip-flop is sent to the output on pin 3 as a high value and the positive part of the cycle begins
3. At the same, the $\overline{Q}$ output value 0 from the flip-flop is sent to the base of the NPN transistor and disconnects pin 7 from the ground
4. Since pin 7 is not grounded, the RC circuit is set in motion. Capacitor C1 starts to charge, at a rate determined by the resistance values R1 and R2, and the capacitance of capacitor C1
5. When the voltage on pin 6 is above the 2/3 of the source voltage, the output of comparator 2 is high which resets the flip-flop
6. Consequently, the Q output value 0 from the flip-flop is sent to the output as a low value and the negative part of the cycle begins
7. At the same, the $\overline{Q}$ output value 1 from the flip-flop is sent to the base of the NPN transistor and connects pin 7 to the ground
8. Capacitor C1 starts to discharge through the R2 resistor all the way to input pin 2. When the voltage at input pin 2 falls below a value less than 1/3 of the source voltage, the chip is triggered again and the cycle is repeated

It is clear that we have produced a clock oscillator and that none of the states of the chip is permanent or stable. Hence, this configuration is called astable.

It is further important to note that we have two different RC circuits – one for charging, and the other for the discharging of the C1 capacitor. In other words, the first RC circuit defines the length of the positive part of the cycle and is constructed using R1, R2 resistors, and a C1 capacitor. The second RC circuit defines the length of the negative part of the cycle and is constructed using the R2 resistor and C1 capacitor. It is obvious that this results in an inequality in the times that the output has in states 1 and 0, which is clearly shown in the figure.

Figure 4-10 Positive and negative cycles of astable configuration

To avoid this, we can reduce the influence of resistor R1 with a simple trick, by using the value of the R2 resistor much higher, so that the R1 resistor becomes insignificant.

4.3.2. Astable configuration experiment

Components:

- breadboard
- 5V power supply
- 5mm blue LED
- 220Ω, 2 x 1KΩ resistors
- 1MΩ potentiometer
- 0.01µF, 1µF capacitors
- 555 chip

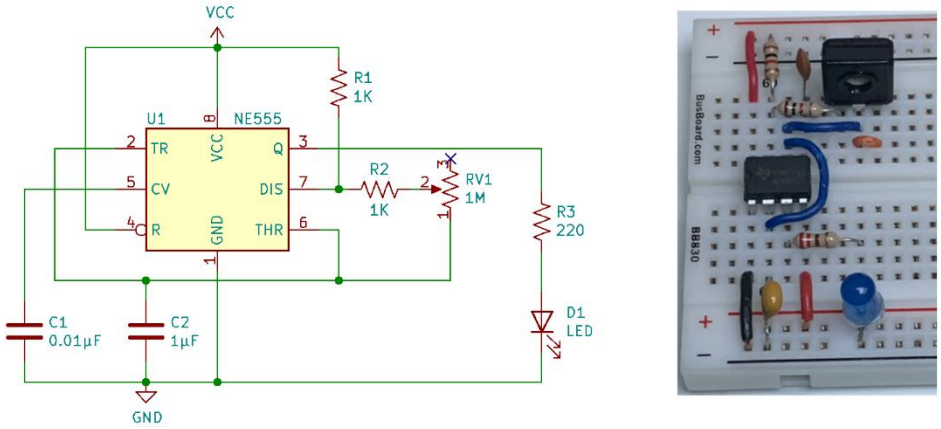


Figure 4-11 Astable configuration experiment

4.3.3. Monostable configuration

The Monostable configuration of the 555 chip allows us to create sophisticated delays within a circuit using an external RC circuit. In other words, in this configuration, the chip serves to produce a signal of fixed time duration, as will be explained. Please note that this feature can also be used for debouncing. The event of bounce can cause serious instability in a circuit and needs to be eliminated. But what is a bounce? Let us consider a circuit that needs to be controlled by a mechanical switch. When the switch is pressed, the 2 metal parts of the switch come into direct contact, but unfortunately not immediately. The parts are connected and disconnected a few times before a permanent connection is made, as shown in the input part of the following figure.

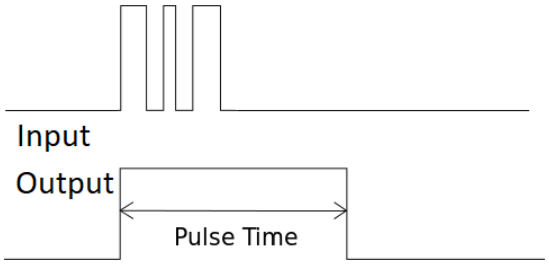


Figure 4-12 Debouncing
(Source: referenced)

For that matter, we can use the 555 chip in monostable mode as a proxy between the mechanical switch and the circuit we want to control. In that sense, we could connect the mechanical switch as an input to the 555 chip, and its output to the controlling circuit. Now, pressing the mechanical switch triggers the 555 chip which makes its output long enough to *swallow* the occurrence of bouncing, as shown in the output part of the figure. Since the 555 is actually triggered with a low input value, this figure shows only the principle, not the true workings of the monostable configuration which will be much clearer after the experiment.

The figure below shows a simplified monostable configuration of the 555 chip.

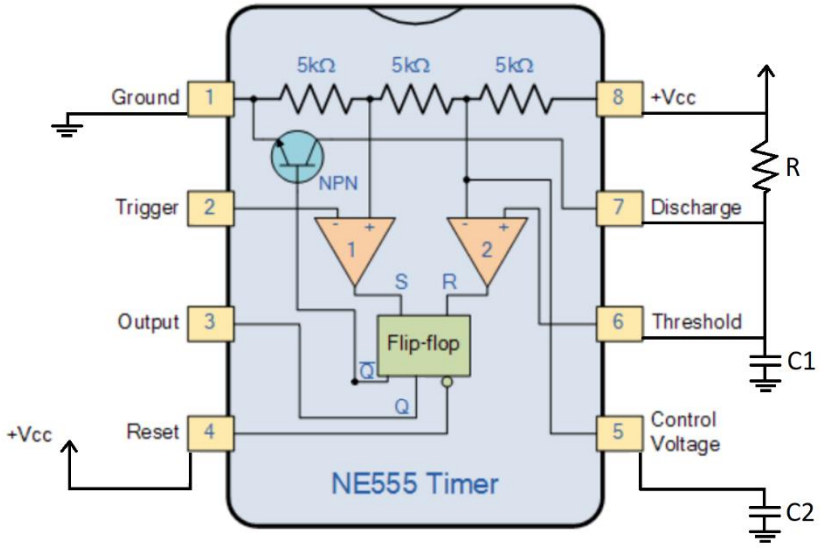


Figure 4-13 Monostable configuration
(Source: referenced)

The explanation is based on the brilliant explanation of *Mr.Charles Platt* in the book *Make: Electronics*:

- Pin 1 is connected to the ground, and the Pin 8 is connected to VCC
- Pin 5 is not used and is hence grounded via capacitor C2 to eliminate noise
- Flip-flop is a sequential logic component that is able to preserve the state of one bit and whose work we will get to know later. For now, it is important that we understand that it remembers the state
    - If the flip-flop is SET through S input, its Q output value 1 is sent to output pin 3. Also, its $\overline{Q}$ output value 0 is sent to the base of the NPN transistor
    - If the flip-flop is RESET through R input, its Q output value 0 is sent to output pin 3. Also, its $\overline{Q}$ output value 1 is sent to the base of the NPN transistor
- Comparators 1 and 2 compare voltages and are used to SET and RESET the flip-flop
    - The (+) input of comparator 1 is connected to 1/3 of a source voltage by the use of a voltage divider network and serves as a reference voltage. The (-) input of comparator 1 is connected to pin 2
    - The (-) input of comparator 2 is connected to 2/3 of a source voltage by the use of a voltage divider network and serves as a reference voltage. The (+) input of comparator 2 is connected to pin 6
- Pin 4 is used to reset the flip-flop with low input. It implicates the fact that its high input enables the flip-flop, so it is tied on VCC in order to permanently enable the flip-flop
- Pin 7 is connected to the collector of the NPN transistor and it is used to discharge the capacitor C1 when the NPN transistor conducts
- Pins 8, 7, and 6, together with R resistor and C1 capacitor form an RC circuit that will control the behavior of the monostable configuration

Let us try to explain the workings of the monostable configuration, by following the steps:

1. If the voltage value on pin 2 is below the 1/3 of the source voltage, the output of comparator 1 is high which sets the flip-flop – this can be accomplished by pressing a pushbutton or by means of some other incoming signal
2. Consequently, the Q output value 1 from the flip-flop is sent to the output on pin 3 as a high value and the positive part of the cycle begins
3. At the same, the $\overline{Q}$ output value 0 from the flip-flop is sent to the base of the NPN transistor and disconnects pin 7 from the ground
4. Since pin 7 is not grounded, the RC circuit is set in motion. Capacitor C1 starts to charge, at a rate determined by the resistance value R, and the capacitance of capacitor C1
5. When the voltage on pin 6 is above the 2/3 of the source voltage, the output of comparator 2 is high which resets the flip-flop
6. Consequently, the Q output value 0 from the flip-flop is sent to the output as a low value
7. At the same, the $\overline{Q}$ output value 1 from the flip-flop is sent to the base of the NPN transistor and connects pin 7 to the ground which discharges the capacitor
8. The cycle is over

In summary, we can express the work in the following way:

- low voltage at the input causes the high voltage at the output
- after a time defined by R and C values, the circuit returns to its stable state with low output

It is obvious that there is only one permanent stable state, hence is this configuration called monostable.

4.3.4. Monostable configuration experiment

Components:

- breadboard
- 5V power supply
- 5mm red LED
- SPST pushbutton switch
- 220Ω, 1KΩ, MΩ resistors
- 0.01µF, 1µF capacitors
- 555 chip

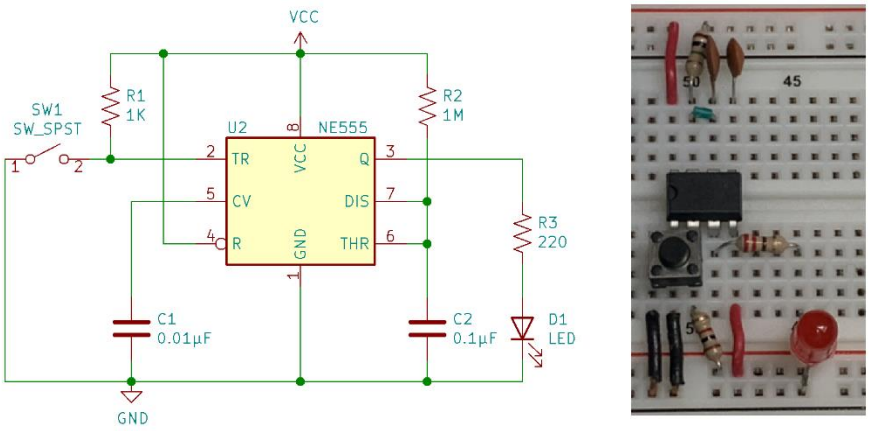


Figure 4-14 Monostable configuration experiment

Explanation: Since the input trigger signal of the 555 chip is low, we are using the pull-up resistor to ensure that the voltage is high before pressing the button. Pressing the button grounds the input pin 2 which sets the output high for the duration defined by R2 and C2 components that4 is demonstrated with LED.

4.3.5. Bistable configuration

A bistable configuration is the simplest of configurations. We will get acquainted with the concept of bistable, or flip-flop in more detail later, but for now it is enough to understand that bistable can permanently remember the state of one bit.

The figure below shows a simplified bistable configuration of the 555 chip.

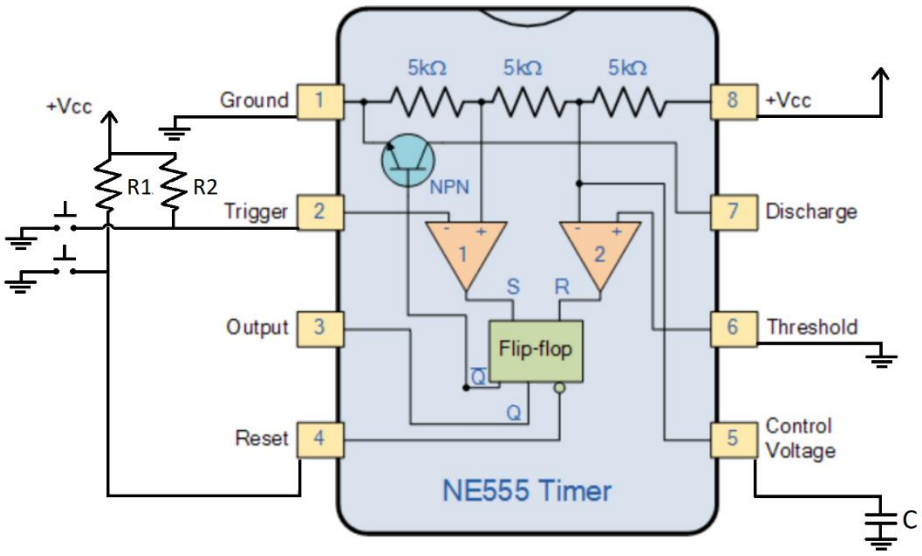


Figure 4-15 Bistable configuration
(Source: referenced)

The explanation is based on the brilliant explanation of *Mr.Charles Platt* in the book *Make: Electronics*:

- Pin 1 is connected to the ground, and the Pin 8 is connected to VCC
- Pin 5 is not used and is hence grounded via capacitor C2 to eliminate noise
- Pin 6 is not used and is hence grounded
- Pin 7 is not used in this configuration and is hence disconnected
- Flip-flop is a sequential logic component that is able to preserve the state of one bit and whose work we will get to know later. For now, it is important that we understand that it remembers the state
    - If the flip-flop is SET through S input, its Q output value 1 is sent to output pin 3. Also, its $\overline{Q}$ output value 0 is sent to the base of the NPN transistor
    - If the flip-flop is RESET through R input, its Q output value 0 is sent to output pin 3. Also, its $\overline{Q}$ output value 1 is sent to the base of the NPN transistor
- Comparators 1 and 2 compare voltages and are used to SET and RESET the flip-flop
    - The (+) input of comparator 1 is connected to 1/3 of a source voltage by the use of a voltage divider network and serves as a reference voltage. The (-) input of comparator 1 is connected to pin 2
    - The (-) input of comparator 2 is connected to 2/3 of a source voltage by the use of a voltage divider network and serves as a reference voltage. The (+) input of comparator 2 is connected to pin 6
- Pin 2 is used as the trigger pin and uses a pull-up resistor in order to be connected to VCC since triggering is done with low-value input
- Pin 4 is used as the reset pin and uses a pull-up resistor in order to be connected to VCC since resetting is done with low-value input
- The top SPST switch is used to provide a low input value from the ground to trigger the chip on the pin 2
- The bottom SPST switch is used to provide a low input value from the ground to reset the chip on the pin 4

Let us try to explain the workings of the bistable configuration, by following the steps:

1. If the voltage value on pin 2 is below 1/3 of the source voltage, the output of comparator 1 is high which sets the flip-flop. It will happen if we press the top SPST switch
2. Consequently, the Q output value 1 from the flip-flop is sent to the output on pin 3 as a high value and that value remains constant and stable after the SPST switch is released
3. If we press the bottom SPST switch, it will reset the flip-flop
4. Consequently, the Q output value 0 from the flip-flop is sent to the output on pin 3 as a low value and that value remains constant and stable after the SPST switch is released

It is important to notice that we have achieved to preserve the state of one bit, which will be explained in detail during realizing latches and flip-flops in the chapter that covers sequential circuits

4.3.6. Bistable configuration experiment

Components:

- breadboard
- 5V power supply
- 5mm red LED
- 2 x SPST switch
- 220Ω, 2 x 1KΩ resistors
- 0.01µF capacitor
- 555 chip

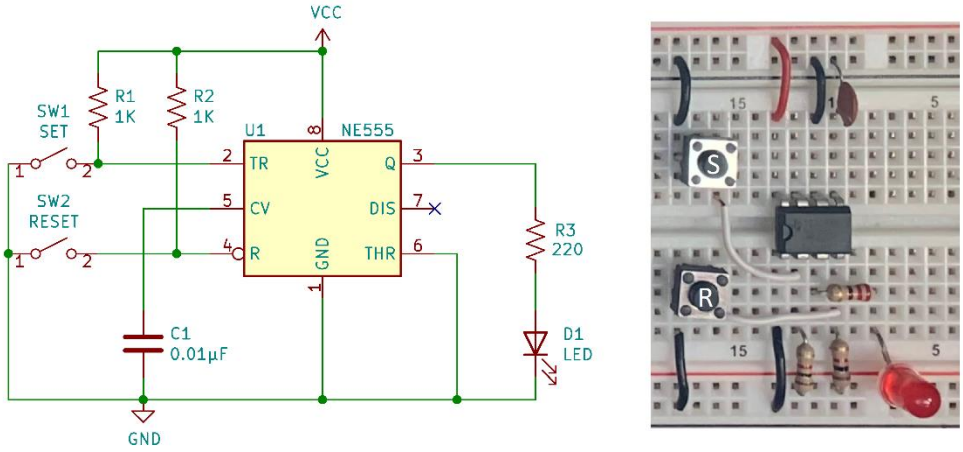


Figure 4-16 Bistable configuration experiment

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C. Platt, Make Electronics (Maker Media, 2015)

5. Sequential logic circuits

A sequential circuit is a digital circuit whose output depends not only on the current value of its input signals but also on a series of previous inputs. Its output is also often controlled by clocks, which we presented in the last chapter. The sequential circuits of our particular interest are flip-flops and counters. All those circuits have the ability to permanently store the state so we will first realize simple circuits as primitive transistor memory. Then we will use NOR and NAND logic gates to create latch and flip-flop types of memory. Finally, we will introduce counters.

5.1. Primitive transistor memory

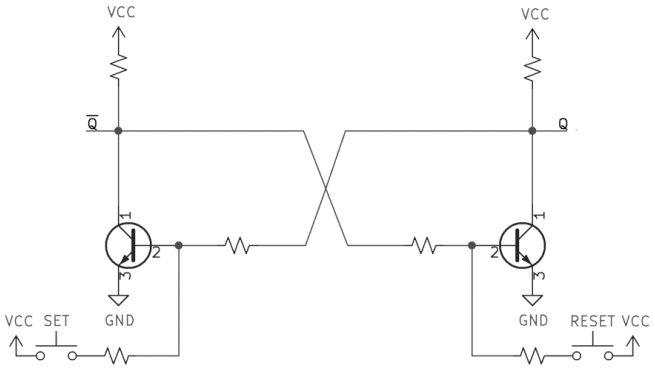


Figure 5-1 Bit of memory realized with transistors

If we connect the transistors as shown in the figures, we will create the memory of one bit. The moment we bring the voltage, it is uncertain which of the transistors will be the first to go into saturation and conduct. If the right transistor starts conducting first, the voltage on its collector is 0V which completely cuts off the left transistor and output Q is 0. If the left transistor starts conducting first, the voltage on the collector of the right transistor is 5V and the output Q is 1. However, if we introduce control signals S (set) and R (reset), we will be able to control the circuit. By applying high voltage to the S input, the left transistor will conduct and the right will be cut-off and the circuit will result in Q output 1. Conversely, by applying high voltage to the R input, the right transistor will conduct and the left will be cut-off and the circuit will result in Q output 0. What makes the circuit particularly interesting is the fact that the circuit will remember the state even after the cessation of control signals. The table below formally describes these conditions, and it is important to emphasize that the high voltage to both control inputs at the same time is prohibited. In this case, the transistors will race in order to conduct and the state is uncertain.

SET	RESET	Q
0	0	X
1	0	1
0	1	0
1	1	RACE

Figure 5-2 Truth table of transistor memory

It is convenient to note that our circuit does not differ much from the circuit with which we created the transistor oscillator. All this speaks in favor of the ubiquity and applicability of transistors, the basic building blocks.

5.1.1. Primitive transistor memory experiment

Components:

- breadboard
- 5V power supply
- 5mm blue and red LED
- 2 * SPST pushbutton switches
- 2 x BC547 NPN transistors
- 4 x 100KΩ, 2 x 4.7KΩ resistors

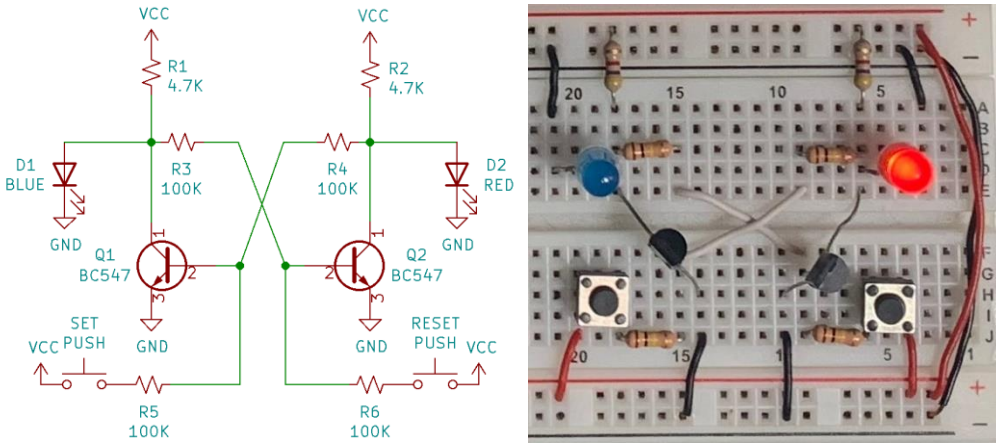


Figure 5-3 Primitive transistor memory experiment

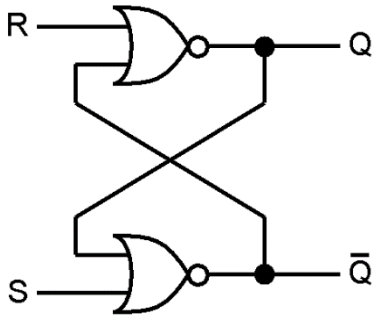
Once we have realized the memory of one bit by a transistor, we will realize it with the help of NOR and NAND circuits, which will allow us to control the state better.

5.2. Latch and flip-flop

As we have realized NOR and NAND gates in the first part of the book with transistors, now we will use them to make latches. A latch is a circuit that contains two steady states, so it is also called a bistable, and stores a value of 1 bit. We realized this extremely important component previously with the help of 555 chips when making oscillators, and now we will build it from discrete components, for a deeper understanding.

5.2.1. SR latch

By connecting the NOR gates of the 7402 chip in the interesting way shown in the picture, we will achieve 1 memory bit, called an SR latch.



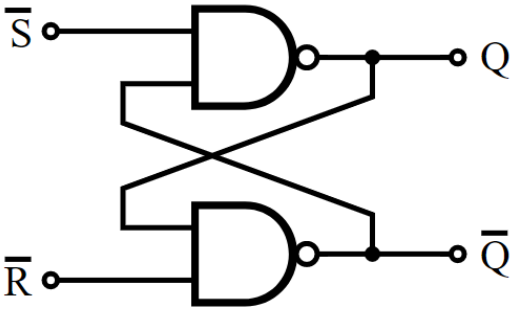
S	R	Q
0	0	X
1	0	1
0	1	0
1	1	RACE

Figure 5-4 NOR SR latch with truth table
(Source: referenced)

To understand the operation of the circuit, it is important to keep in mind that the output from the NOR gate is 1 only when both inputs are 0. Let's start by bringing the value 1 to the S input. The output of the lower NOR gate must be 0 because one of its inputs is 1. Now 0 the output of the lower gate comes to the input of the upper NOR gate, and since R is input 0, the output of the upper gate must be 1. The output of the upper gate corresponds to Q output and the value is 1. The question arises, what will happen if we return the S input to the value 0? Since output 1 from the upper NOR gate comes to the input of the lower NOR gate, the output of the lower NOR gate will certainly be 0. So now it is irrelevant what the value of S input is because at least one input of the lower NOR gate is 1, which makes its output 0..

Analogous to the above analysis, let's try to explain the opposite situation. If we bring the value 1 to the R input, the output from the upper NOR gate must be 0, because one of its inputs is 1. Now 0 the output of the upper gate comes to the input of the lower NOR gate, and since S input is 0, the output of the lower gate must be 1. The output of the lower gate corresponds to the $\overline{Q}$ output and the value is 1. What will happen if we now return the R input to 0? Since output 1 from the lower NOR gate comes to the input of the upper NOR gate, the output of the upper NOR gate will certainly be 0. So now it is irrelevant what is the value of R input because at least one input of the upper NOR gate 1 makes its output 0. This ingenious invention of connecting logic gates enables the permanent storage of state.

It is interesting that an SR latch can be easily built from NAND circuits, but it has a negative logic. In other words, the S and R inputs must be 0 to trigger the circuit. So let's build a new memory circuit, this time using a 7400 NAND chip.



$\overline{S}$	$\overline{R}$	Q
0	0	RACE
0	1	1
1	0	0
1	1	X

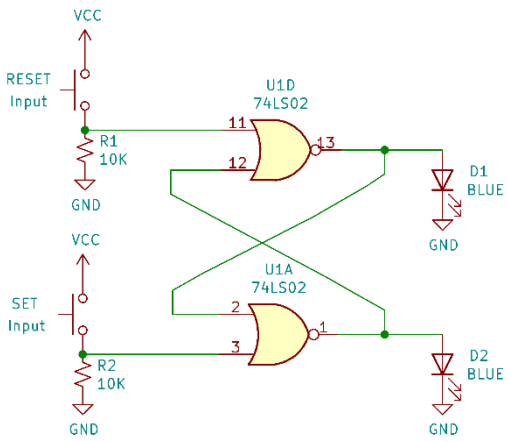
Figure 5-5 NAND SR latch with truth table
(Source: referenced)

Let us prove this with experiments.

5.2.2. NOR SR latch experiment

Components:

- breadboard
- 5V power supply
- 2 * 5mm blue LED
- 2 * SPST pushbutton switches
- 2x 10KΩ
- 7402 NOR chip



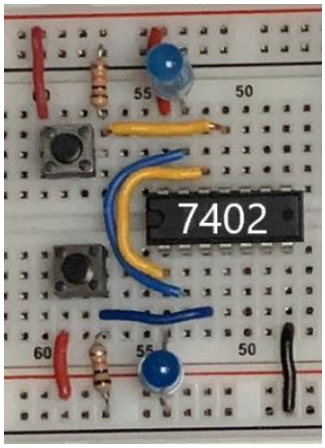


Figure 5-6 NOR SR latch experiment

5.2.3. NAND SR latch experiment

Components:

- breadboard
- 5V power supply
- 5mm red and blue LED
- 2 * SPST pushbutton switches
- 2x 10KΩ
- 7400 NAND chip

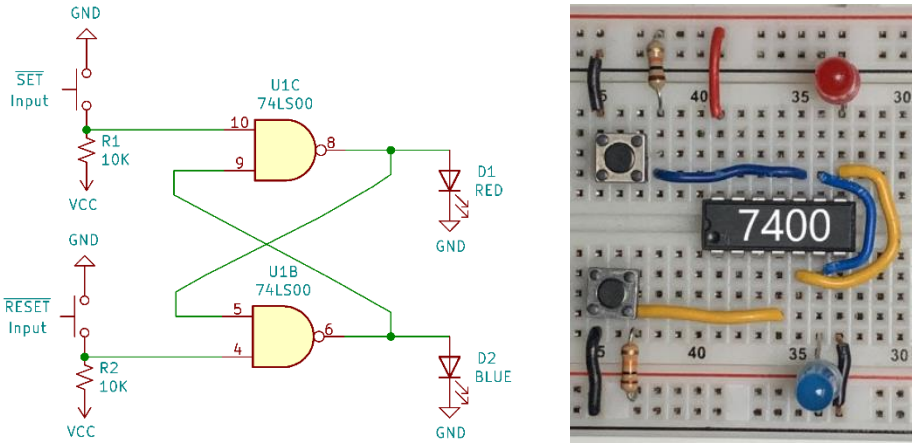
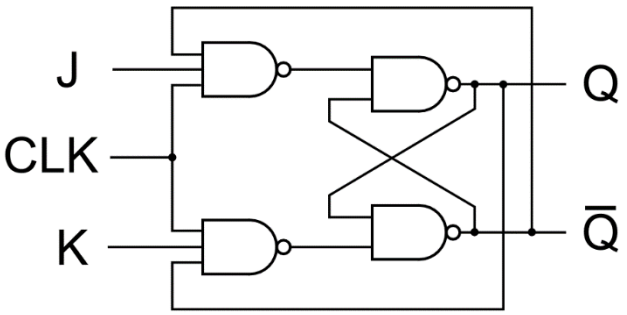


Figure 5-7 NAND SR latch experiment

5.2.4. JK flip-flop

The presented SR latches suffer from two shortcomings. The one that is evident, refers to the fact that we have a forbidden state of entry. Namely, the circuit must not be triggered by the S and R inputsl at the same time. The next problem relates to our tendency to control the circuit, that is, to be able to fire it only at the desired moment. Therefore, in the next step, by upgrading the SR latch, we will achieve a JK flip-flop that solves both of these problems. The flip-flop, unlike the latch, contains a clock that we will use to trigger the assembly.



J	K	CLK	Q
0	0	↑	X
1	0	↑	1
0	1	↑	0
1	1	↑	TOGGLE

Figure 5-8 JK flip-flop with truth table
(Source: referenced)

We can notice that the inputs changed their names - S input became J and R input became K, according to the initials of Jack Kilby, the inventor of this circuit. Furthermore, inputs J and K are now connected to the clock, but also to the opposite outputs of the circuit. Why is that so? The connection to the clock will allow us to trigger the circuit at a discrete, desired moment. Furthermore, connecting the inputs to opposite circuit outputs completely eliminates the simultaneous possibility of circuit triggering because the outputs are inverse, and we know that all NAND inputs must be of value 1 for output to be 0 and thus trigger the circuit. Finally, if the inputs J and K are values of 1 at the same time, the JK flip-flop will continuously change state from 0 to 1 and vice versa, each time the clock arrives, and this is called the toggle mode. This also solved the problem of the forbidden state of the SR latch. It is important to emphasize that the circuit is triggered by the edge of the clock, and not its entire length, which ensures proper operation. Namely, when the flip-flop is triggered along the entire length of the clock, there is a danger that the input signal could last shorter than the clock. In this case, the input signal representing the correct state would disappear before the clock, so the faulty state would be written to the circuit.

5.2.5. JK flip-flop experiment

Components:

- breadboard
- 5V power supply
- 2 * 5mm blue LED
- 2 * SPST pushbutton switches
- 3 x 10KΩ
- 7400 NAND chip, 7410 3 input NAND chip

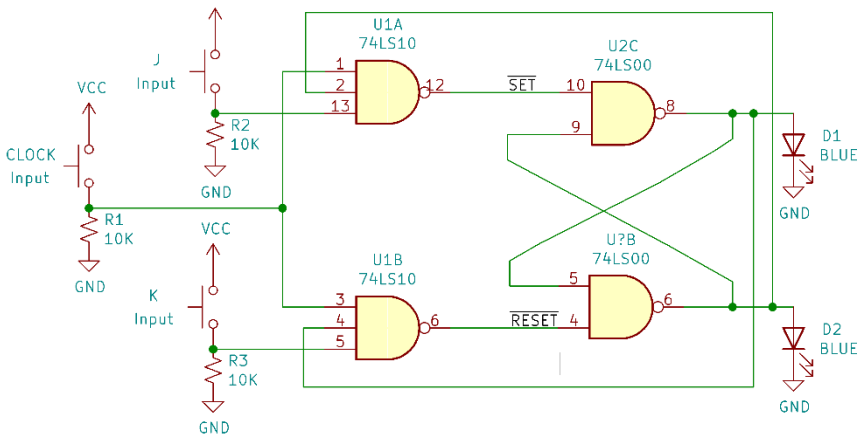


Figure 5-9 JK flip-flop schematic

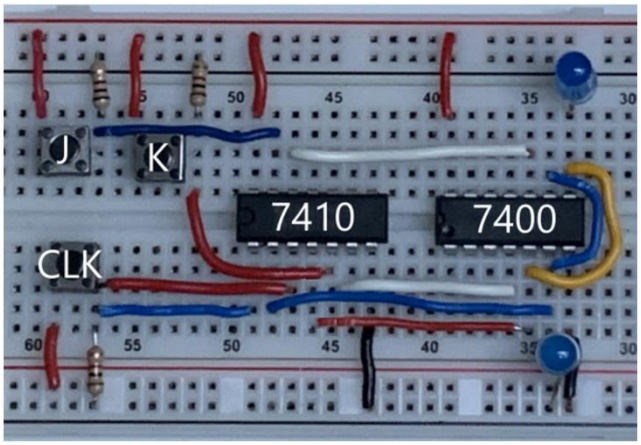


Figure 5-10 JK flip-flop experiment

From now on, we can use chip 74107 which contains 2 independent JK flip-flops.

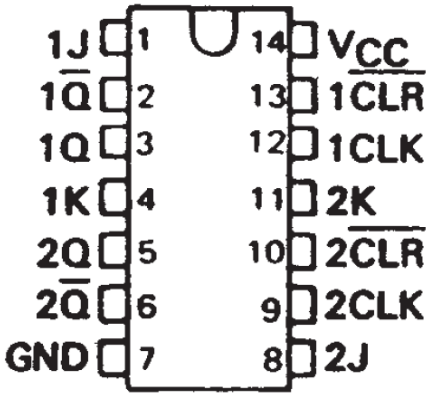
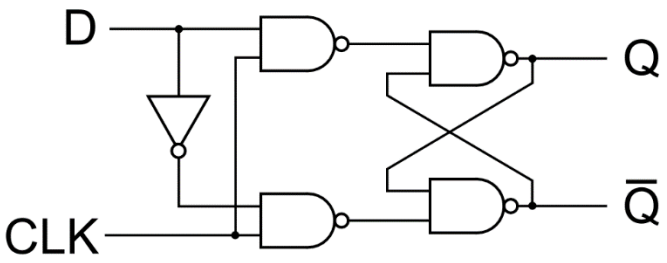


Figure 5-11 Chip 74107

5.2.6. D flip-flop

Another way to solve the problems we solved with the JK flip-flop can be solved with the D flip-flop. The problem of the simultaneous triggering of the circuit is prevented by having only a single input using an inverter. The single input is called *Data* D which is the reason for the circuit name. Since it would be totally pointless to have a circuit whose output only reflects its input, the chip is controlled by a clock. In other words, the output of the circuit will reflect the state of its input only during the edge of the clock.



D	CLK	Q
0	↑	0
1	↑	1

Figure 5-12 D flip-flop with truth table
(Source: referenced)

5.2.7. D flip-flop experiment

Components:

- breadboard
- 5V power supply
- 2 * 5mm blue LED
- 2 * SPST pushbutton SWITCHES
- 2 x 10KΩ
- 7400 NAND chip, 7404 NOT chip

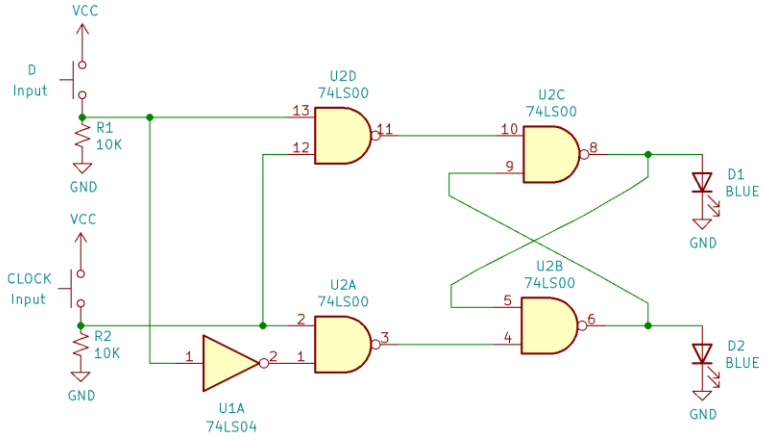


Figure 5-13 D flip-flop schematic

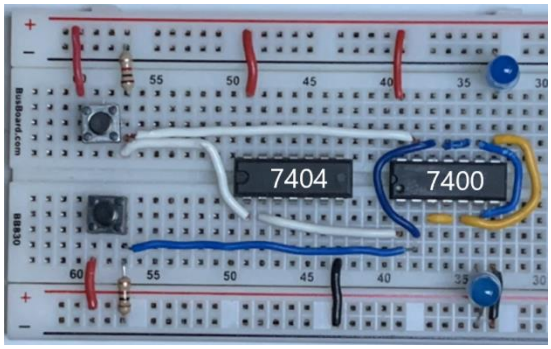


Figure 5-14 D flip-flop experiment

From now on, we can use chip 7474 which contains 2 independent D flip-flops.

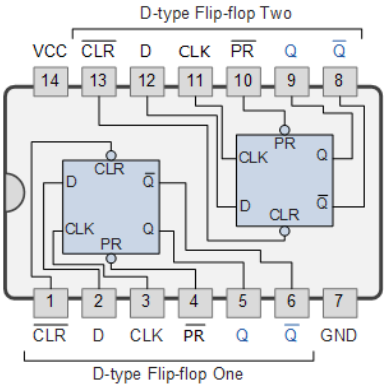


Figure 5-15 Chip 7474

5.2.8. Frequency division

Among the important applications of the flip-flop is the frequency divider. Namely, if we connect the inverted output of D flip-flop to the input and bring the clock, the clock of the halved frequency will appear on the positive output, which is shown on the top part of the following figure. It is no surprise that this circuit is called divide-by-2 counter, because frequency division will help us create counters which are extremely important digital circuits. If we want to continue to divide the frequency, we should connect the inverted output of the first flip-flop with the clock of the next flip-flop, which is shown on the bottom part of the figure.

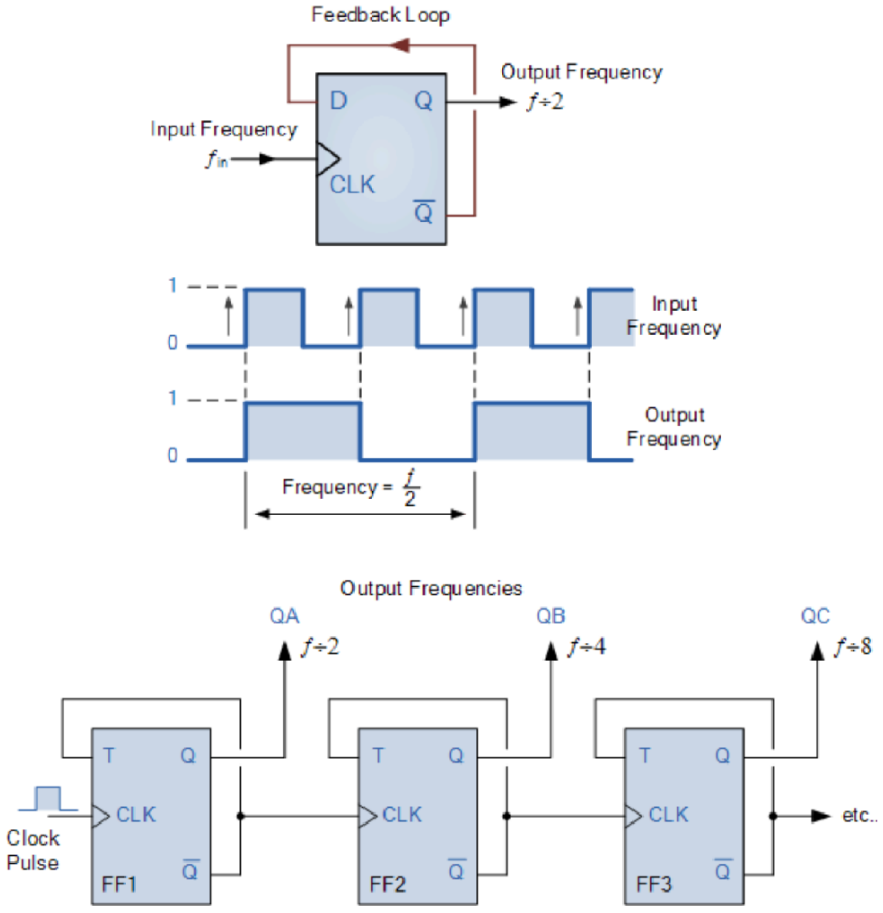


Figure 5-16 D flip-flop frequency division
(Source: referenced)

Let us create an experiment.

5.2.9. Frequency division experiment

Components:

- breadboard
- 5V power supply
- 5mm blue LED
- 7474 D flip-flop
- primitive clock circuit

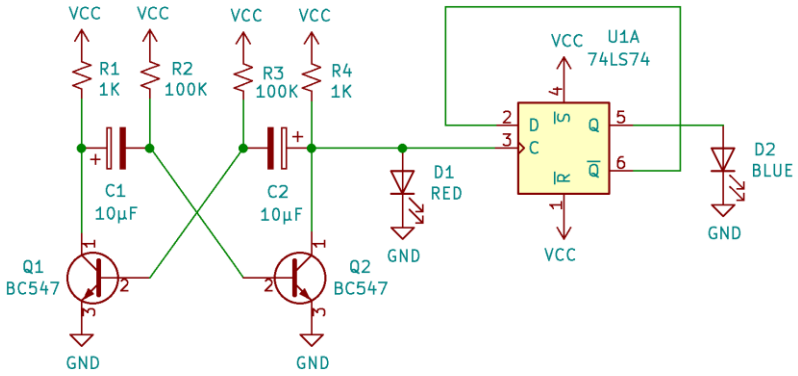


Figure 5-17 Frequency division schematics

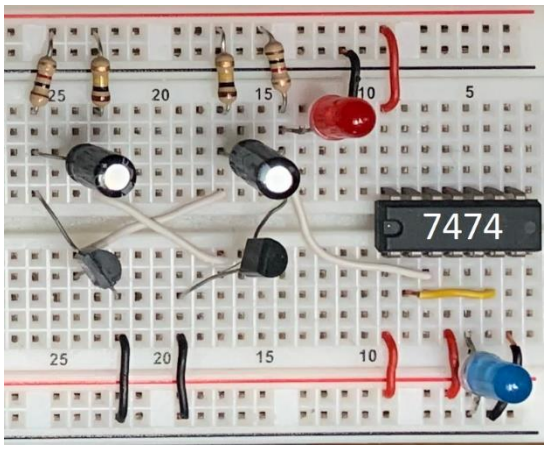


Figure 5-18 Frequency division experiment

Explanation: Inverted input pins 1 and 4 of 7414 chip represent CLEAR for resetting and PRESET for setting the value of the flip-flop. We don't use them so they are disabled by connection to VCC. Pin 6 is the inverted input that is connected to the input on pin 2. On CLOCK pin 3 we bring CLK of our primitive clock circuit. On the LED we can notice that the resultant clock is half the frequency of the input frequency.

5.3. Counters

Connecting flip-flops in series in a manner that the output of one flip-flop is fed as input to another, we get a circuit called counter, as already mentioned in frequency division circuit. Counters can be synchronous and asynchronous. If we connect the clocks of all flip-flops together, they will change their state simultaneously, and hence are called synchronous. In asynchronous counters, the outputs of previous flip-flops are used as a clock for the next flip-flops and are therefore slower than synchronous ones.

Counters are extremely important in building a processor, for example. During executing instructions, the processor keeps the address of the next instruction in the instruction address register which can be realized as a simple counter. Every time the instruction is executed, the counter increments its value in order to point to the next instruction address in the memory, so it can be fetched and executed. Let us immediately dive into an experiment

5.3.1. Stepper experiment

By carefully connecting the inputs and outputs of the D flip-flops with the clock and logic circuits, we can derive a simple stepper circuit from the figure below. The clock is fed to odd D flip-flops, and the inverted clock to even flip-flops, so this counter can be considered semi-synchronous. The explanation is based on the brilliant book *But How Do It Know?*, from *John C. Clark*, which I highly recommend.

Components:

- breadboard
- 5V power supply
- 5mm blue, yellow, and red LED
- 7404 NOT chip, 7408 AND chip, 3 x 7474 D flip-flop chip
- transistor clock circuit

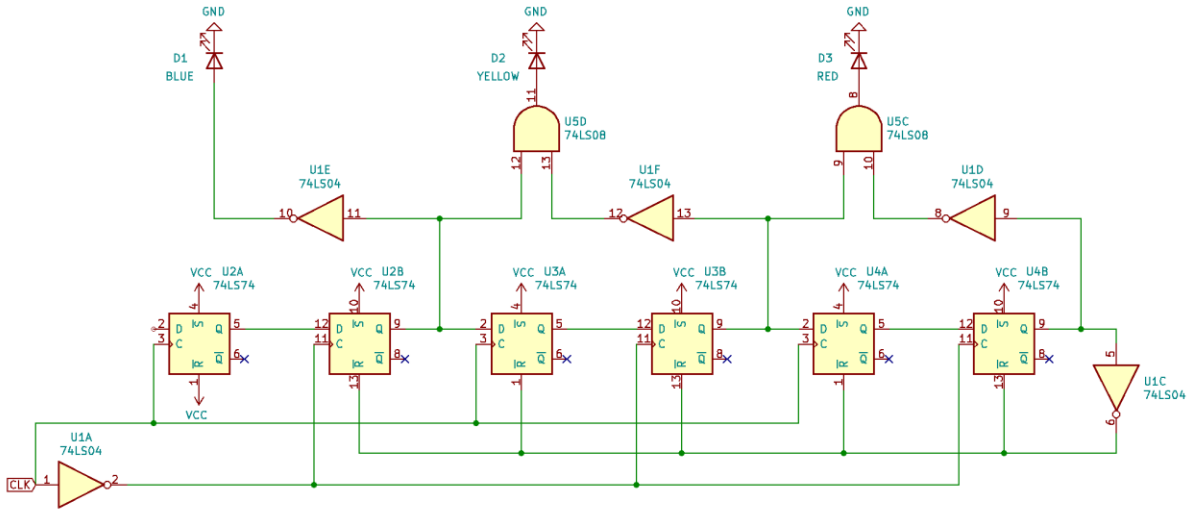


Figure 5-19 Stepper schematic
(Source: referenced)

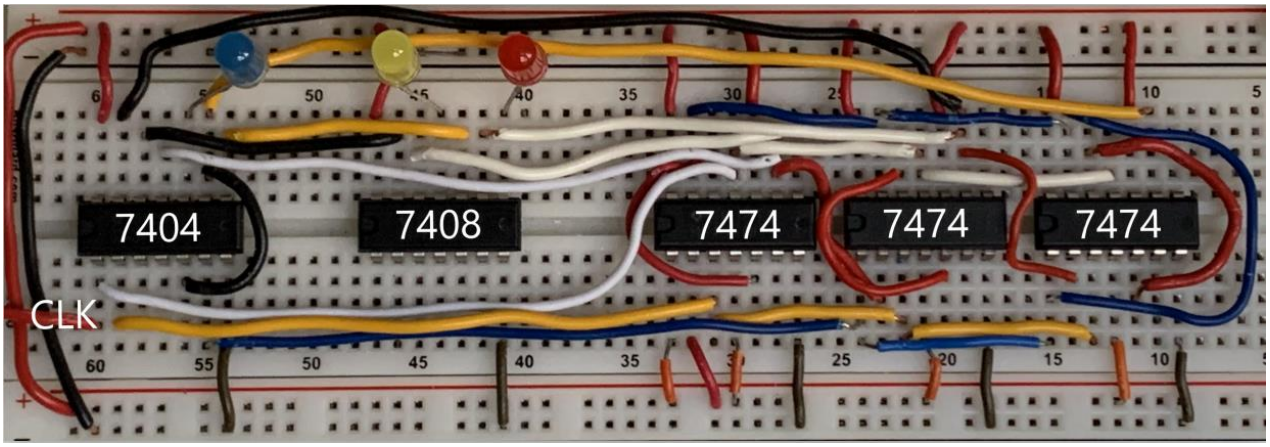


Figure 5-20 Stepper experiment

Explanation: Although D flip-flops can be in any state at startup, this state will rotate so we can freely assume that at the beginning the output of all D flip-flops, except the first one, is 0. Therefore, STEP 1 has a value of 1, and the others have a value of 0. With the arrival of the first clock, the value 1 of the first flip-flop is copied into the second flip-flop, so STEP 1 becomes 0 and STEP 2 becomes 1. When the clock is done, the inverted clock is on, so the value 1 of the second flip-flop is transferred to the third. With the arrival of the second clock, the value 1 of the third flip-flop is transferred to the fourth, so STEP 2 becomes 0, and STEP 3 becomes 1. The clock is inverted again, so the value 1 of the fourth flip-flop is transferred to the fifth. With the arrival of the third clock, the value 1 of the fifth flip-flop is transferred to the sixth, and its output leads through an inverter that resets all D flip-flops except the first one. STEP 1 has again the value of 1 and the cycle is repeated.

5.3.2. Binary counter

To create a binary counter, we will use the knowledge gained so far about the operation of JK flip-flops and frequency division. If we observe the change of bits during the binary count 0 - 15 in the following figures, we can notice that the far-right bit changes its value with each clock. The bit on its left side changes the value by half frequency and that happens when the right bit changes the value from 1 to 0. Analogously for all left bits, each left bit changes its value by half the frequency of the right when changing the right bit from 1 to 0. These observations can be applied to connecting JK flip-flops, as shown in the figure. Inputs J and K are connected to the input voltage, so the output continuously toggles the state from 0 to 1 and vice versa, with the arrival of the clock. The clock is brought only to the first flip-flop, so it changes state with each clock. Each subsequent flip-flop is triggered by an inverted output, that is, when the previous flip-flop changes state from 1 to 0, just like in the figure.

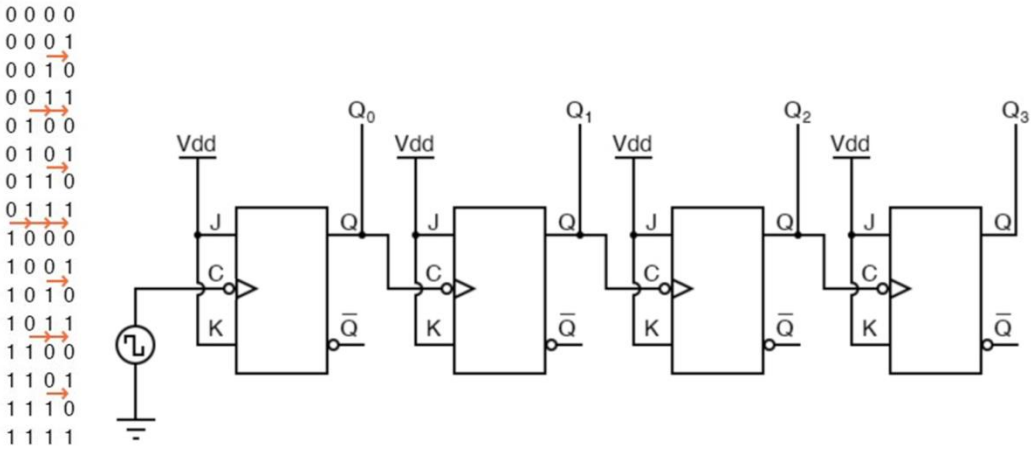


Figure 5-21 Binary counter
(Source: referenced)

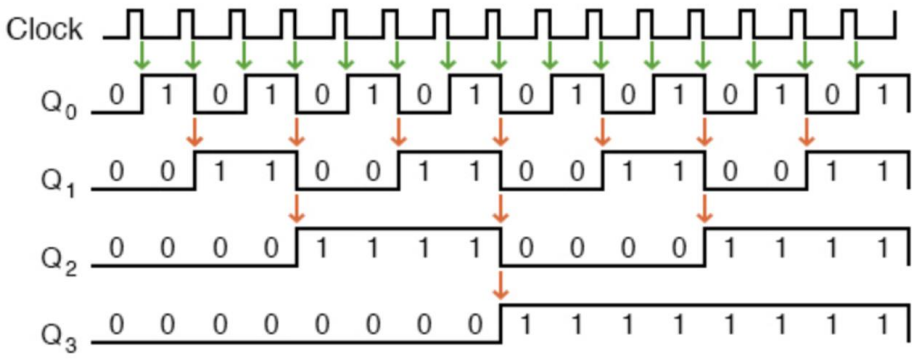


Figure 5-22 Sequences of binary counter
(Source: referenced)

This kind of architecture realizes asynchronous counters which, due to the propagation delay, have lower performance than synchronous ones. It is important to understand that every change of state requires some time. As the value of the previous flip-flop changes from 1 to 0, a clock is triggered that results in a change in the state of the next flip-flop, which also takes time. Thus, the delay is propagated from one flip-flop to another, which is called propagation delay. In synchronous counters, all flip-flops are triggered with the same clock, so they are faster because they do not suffer from propagation delay.

5.3.3. Binary counter experiment

Components:

- breadboard
- 5V power supply
- 4 x 5mm blue LED
- 2 x 74107 JK flip-flops
- transistor clock circuit

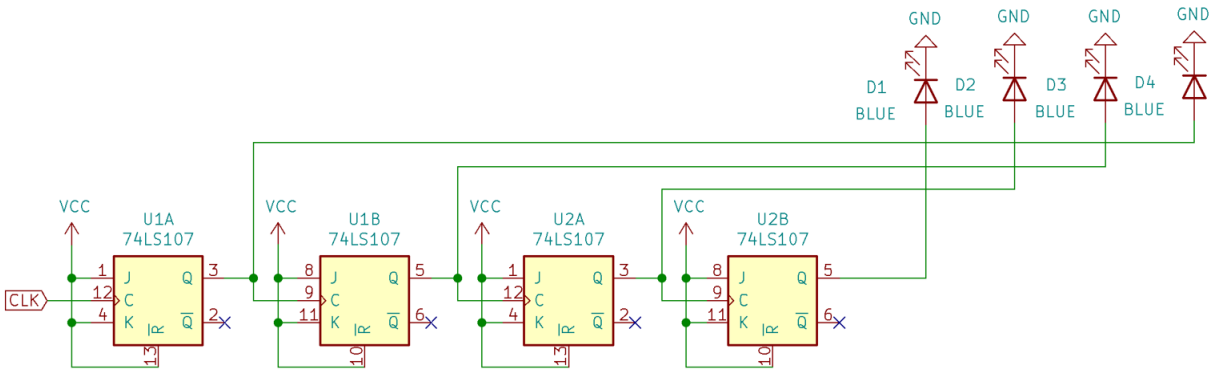


Figure 5-23 Binary counter schematic

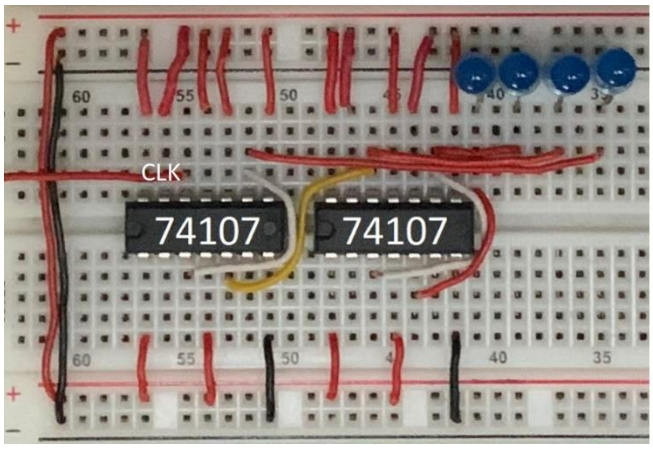
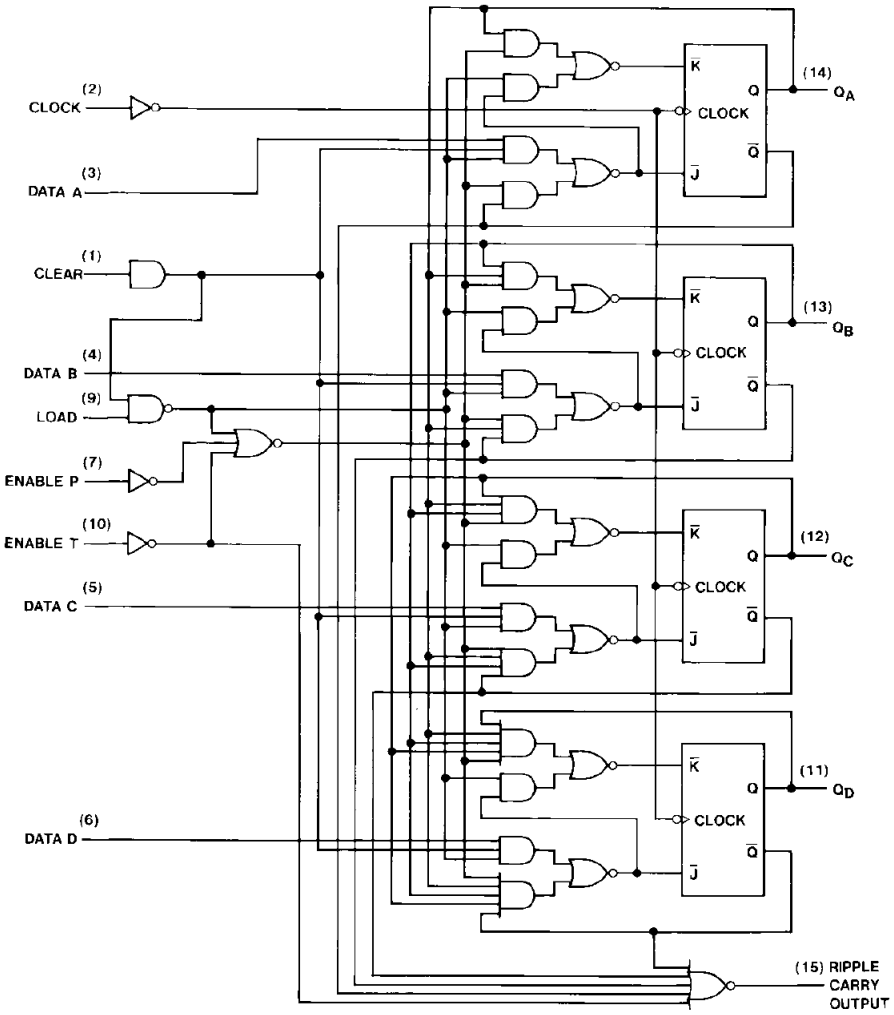


Figure 5-24 Binary counter experiment

Note: 74107 flip-flops are triggered by rising clock but it does not change the overall behavior.

5.3.4. Counter chips

During different realizations, for example, Pong game, we will use different types of counters. The first one is a 74161 synchronous counter that can be programmed to count from any preset value. The following figure shows its internal organization and pin configuration that should be consulted in the datasheet..



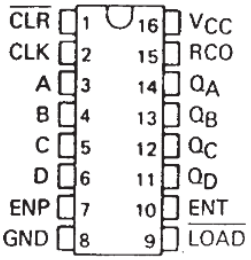
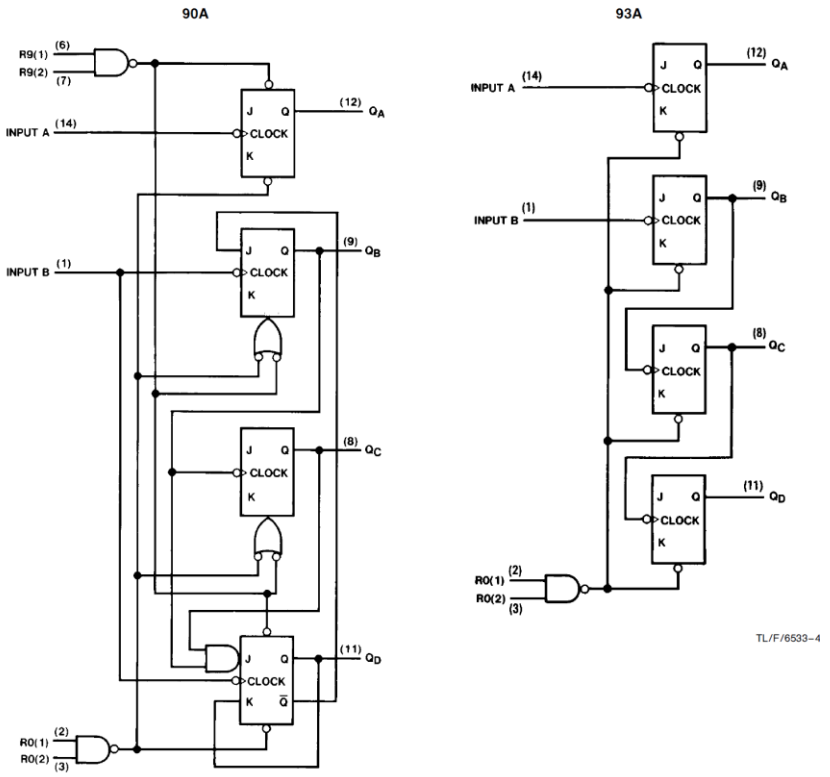
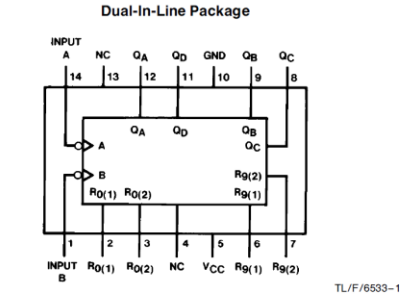


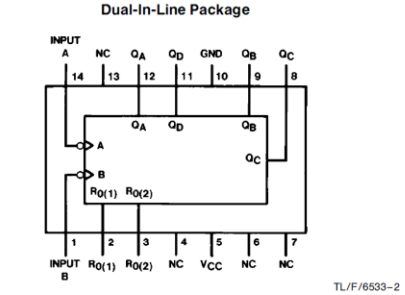
Figure 5-25 Chip 74161

Further, we will use 7490 and 7493 chips, very powerful decade and binary asynchronous counters.





Order Number DM5490J, DM5490W or DM7490AN
See NS Package Number J14A, N14A or W14B



Order Number DM7493AN
See NS Package Number N14A

Figure 5-26 Chips 7490 and 7493

References

https://commons.wikimedia.org/wiki/File:SR-NOR-latch.png

https://commons.wikimedia.org/wiki/File:SR_Flip-flop_Diagram.svg

https://commons.wikimedia.org/wiki/File:JK-FlipFlop_(4-NAND).PNG

https://commons.wikimedia.org/wiki/File:D-FlipFlop_(4-NAND,_1-NOT).PNG

https://www.electronics-tutorials.ws/counter/count_1.html

https://www.allaboutcircuits.com/textbook/digital/chpt-11/asynchronous-counters/

John C. Clark , But How Do It Know? - http://www.buthowdoitknow.com/

6. Power supply

For the last experiment of the presentation of basic building blocks, we will present a simple power supply circuit. **It is highly recommended not to implement this on your own because the voltage of the power main is deadly! Doing it wrong can cause serious injuries and death!** I will build a primitive power supply, according to the block diagram below, and then use the professional one, which is much more complex and stable. It is important to notice that I have succeeded to understand the workings of the power supply circuit through the brilliant explanation of *Mr. Stan Gibilisco,* in the book *Teach Yourself Electricity and Electronics*.

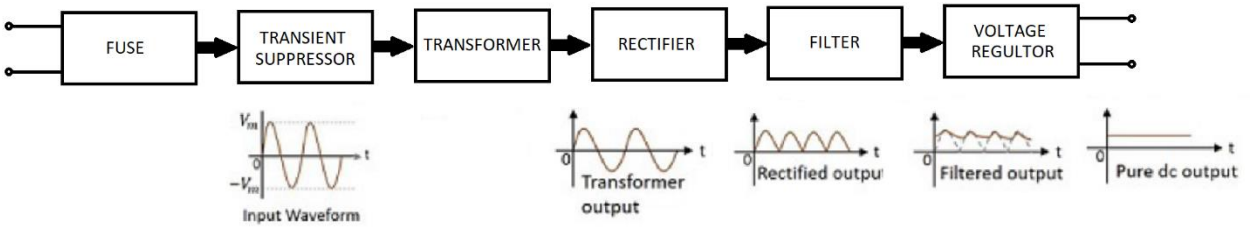


Figure 6-1 Power supply block diagram
(Source: referenced)

For the voltage source, a standard 220V AC power source is used. The fuse and transient suppressor help protect the circuit being supplied, or the load. The transformer reduces the input AC voltage and the rectifier turns it into a fluctuating DC voltage. The fluctuations are reduced with a filter, and the voltage regulator provides constant, stable direct voltage.

Fuse

In the power supply block diagram, we can notice that the fuse is the first component. A fuse is a very simple piece of wire that melts if the current exceeds a certain value. The fuse, therefore, ensures the safety of the source and the load, so that its components do not burn out in the event of a sudden and excessive increase in current.

Figure 6-2 Fuse

Transient suppressor

Although the standard voltage source is constant and stable, the possible appearance of voltage spikes of much higher values puts the load in serious danger. In addition to external causes such as thunder, magnetic fields, and static electricity, voltage spikes also occur due to sudden changes in the load connected to the source, so we must protect ourselves with a stabilizer. I will build a simplified stabilizer from capacitors that, due to their properties, can absorb these sudden changes. Capacitors with a value of 0.01 μF ground both poles of the source, according to the figure.

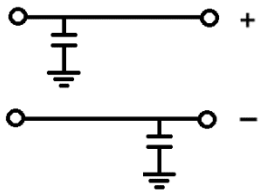


Figure 6-3 Transient suppressor

As already explained, the capacitor is a passive electronic element that serves as a reservoir of static electricity. It consists of two electrically conductive bodies separated by an insulator. Since conductive bodies do not make a connection, the capacitor blocks direct current. The charges are therefore stored at the poles of the capacitor, creating an electric field. However, for alternating current at a certain frequency, the capacitor acts as a short circuit and conducts it. According to the formula

$$Xc = \frac{1}{2\pi f C}$$

for the reactance of a capacitor, by which we express its resistance to the passage of current, it is clear that it increases with increasing frequency. The voltage spike is very short, so it is easy to compare it to high-frequency alternating current due to the formula for frequency

$$f = \frac{1}{T}$$

Therefore, in these short moments, the capacitor is conductive and easily grounds the voltage spikes and preserves the circuit. In this context, a capacitor is also called a bypass capacitor.

Transformer

In order to reduce the input voltage, the transformer is used. A transformer is a device that inductive couples two alternating current circuits. In our example in the figure, the iron core of magnetic properties is organized so that the primary and secondary windings of the wire are not in direct connection.

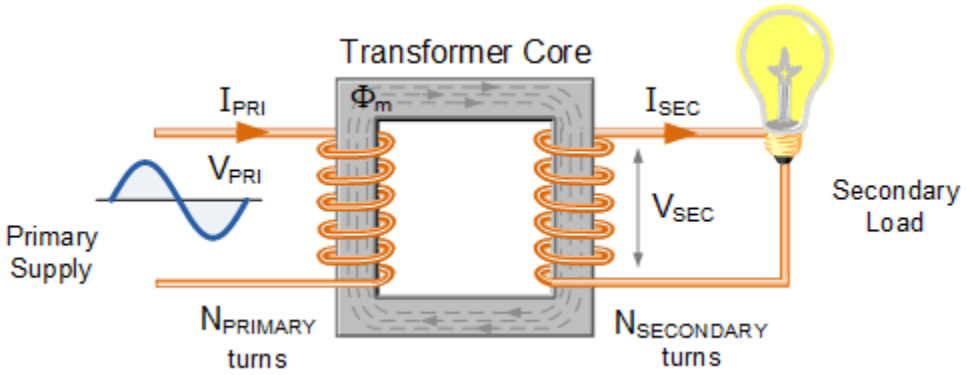


Figure 6-4 Transformer
(Source: referenced)

The alternating current with its flow through the primary winding generates a magnetic field that fluctuates around the secondary winding and induces an alternating current of the same frequency. We call this extraordinary phenomenon electromagnetic induction. The iron core has good magnetic permeability, so it facilitates the transfer of electricity from the primary to the secondary winding. Voltage amounts are referred to as winding numbers which tells us the transformation ratio formula

$$\frac{\mathrm{Up}}{\mathrm{Us}} = \frac{\mathrm{Np}}{\mathrm{Ns}}$$

If the number of secondary windings is less than the primary, as in our case, the voltage will also decrease. In this very simple way, we can, for example, reduce the input voltage from 220V to 10V. If we are interested in the transformation ratio, it is

$$\frac{\mathrm{Up}}{\mathrm{Us}} = \frac{220\mathrm{V}}{10\mathrm{V}} = 22$$

It is important to note that the transformer does not violate the principle of conservation of energy. It means that the power of the primary winding must be equal to the power of the secondary winding, considering there are no losses in the transformer. Let us express this with the formula:

$$\mathrm{Pp} = \mathrm{Ps} \rightarrow \mathrm{Up} * \mathrm{Ip} = \mathrm{Us} * \mathrm{Is}$$

It follows that the current relationship is the inverse of the voltage relationship.

$$\frac{\mathrm{Ip}}{\mathrm{Is}} = \frac{\mathrm{Us}}{\mathrm{Up}}$$

Finally, for our example, since the voltage on the primary winding is 22 times higher than the voltage on the secondary winding, the current on the primary winding is 22 times less than the current on the secondary winding.

Rectifier

Once the AC voltage is reduced, we need to figure out a way to convert it to DC. This is the purpose of the rectifier and it will convert AC to fluctuating DC voltage. The operation of the rectifier is based on the properties of the diode, which we already explained in detail. If we connect our transformer to the diode according to the schematic below, we will partially achieve our goal.

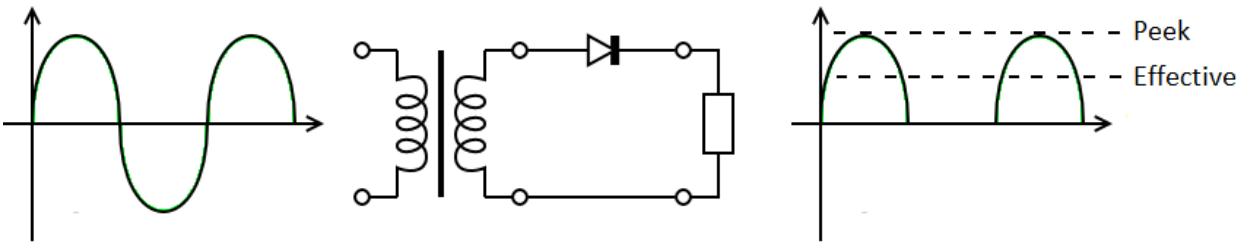


Figure 6-5 AC to DC conversion with diode
(Source: referenced)

It is not difficult to conclude from the graph that the effective voltage is significantly lower than the peak voltage because we use only one of the half-cycles of AC voltage. To take advantage of both half-cycles, e will construct a Graetz rectifier, a matrix of four diodes, as shown in the figure.

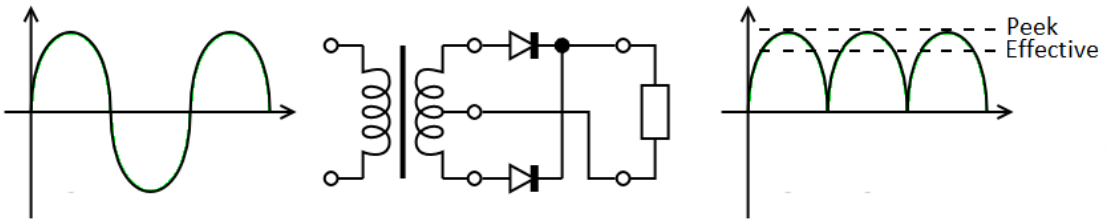


Figure 6-6 AC to DC conversion with rectifier
(Source: referenced)

The graph shows us that the effective voltage has increased. The working principle is explained in the figures below. To use the positive half-cycle, we use the first two diodes and realize a circuit.

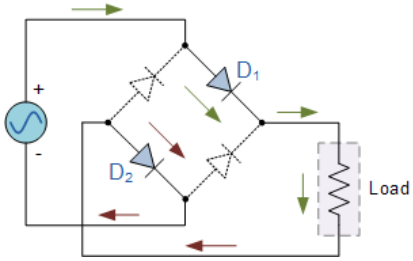


Figure 6-7 Rectifier usage of AC positive half-cycle
(Source: referenced)

To use the negative half-cycle, we use the second two diodes and realize a circuit.

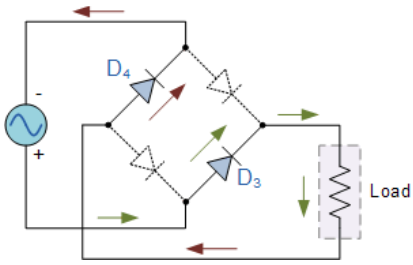


Figure 6-8 Rectifier usage of AC negative half-cycle
(Source: referenced)

Filter

To reduce fluctuations, the capacitor is used again, but this time electrolytic, of higher capacity. The principle of operation of the filter is very simple. As the voltage rises, it is stored on the capacitor. When the voltage drops, the stored voltage corrects fluctuations, acting in the same direction.

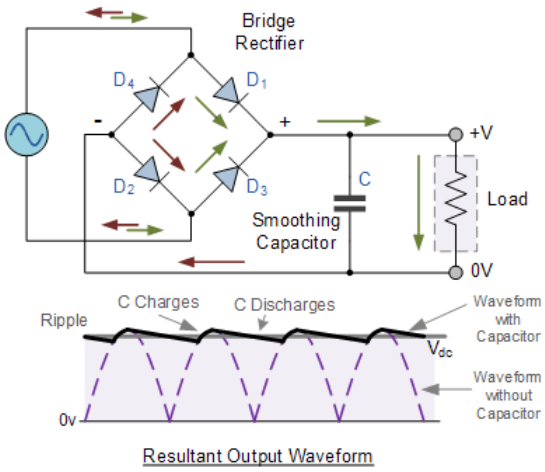


Figure 6-9 Removing the fluctuations with the capacitor
(Source: referenced)

Voltage regulator

Finally, we have a stable voltage, but much higher than the required value of 5V. In order to reduce the voltage, we will use a Zener diode. The Zener diode is specially and precisely made so that its breakdown voltage is strictly defined, low and constant. The figure shows the principle of operation of a simple voltage regulator.

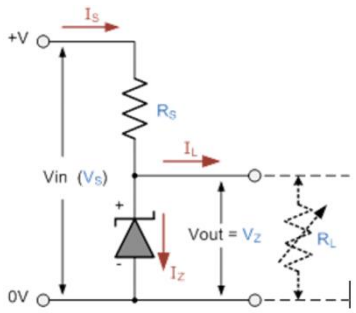


Figure 6-10 Zener diode as a voltage regulator
(Source: referenced)

It is extremely important that we do not miss that the Zener diode is turned in the opposite direction because it is driven by breakdown voltage. Also, the Zener diode must be connected in series with the resistor Rs, which serves to limit the current to which the Zener diode, and then the load, will be exposed. It is therefore necessary to check from the specification the minimum current of the Zener diode that causes conductivity, and the maximum current to which the Zener diode can be exposed. The Zener diode will easily absorb changes in current value within the prescribed current limits, keeping the voltage constant. The load is connected in parallel to the Zener diode, so it will be exposed to a voltage equal in value to the breakdown voltage of the Zener diode.

When realizing the resistor Rs, it should be ensured that the resistor can dissipate the power to which it is exposed. For example, if we want to ensure that a 30Ω resistor can withstand a current of 0.5A, the power to which the resistor will be exposed will be

$$P = I * U = I * I * R = I2 * R = (0.5A)\ 2 * 30\Omega = 7.5W$$

If we use a resistor with a rated power of 1W, it is obvious that it cannot dissipate a power of 7.5W. To solve this problem, we can create a series-parallel network of resistors of the same values, according to the figure below. If we make an n x n matrix, the rated power will increase n^2 times. In the presented case, a 2 x 2 matrix would allow 4W, so we would opt for a 3 x 3 matrix that can dissipate 9W power.

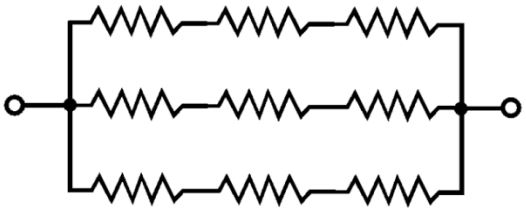


Figure 6-11 Series-parallel resistor network
(Source: referenced)

6.1. Primitive power supply realization

When designing, it is necessary to pay special attention to the selection of components that can meet the power needs. The goal is to create a 5V power supply with a maximum current of 0.5A. Hence, the selected components are as follows:

- power supply 220V
- breadboard
- fuse 63mA
- 2 x capacitor 0.015µF
- transformer with the following ratio

$$\frac{Is}{Ip} = \frac{Up}{Us} = \frac{220V}{9.6V} = \sim 23$$

- 4 x IN4007 diode – able to dissipate 3W of power
- electrolytic capacitor 1000µF
- 4 x resistor 2.2Ω, 0.25W power dissipation – 2 x 2 network will be able to handle 4 * 0.25W = 1W
- Zener diode 1N5338B - 5.1V, 5W power dissipation, ~1A maximum current, ~100mA minimum current (~10% of maximum)

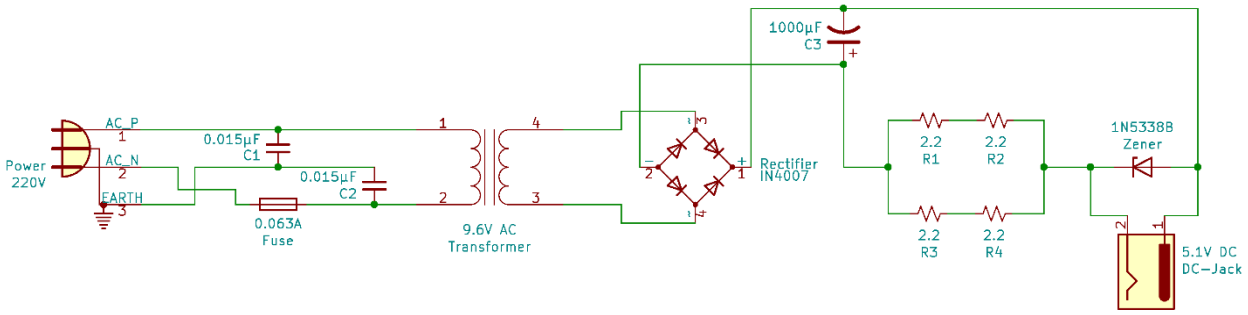


Figure 6-12 Primitive power supply schematic

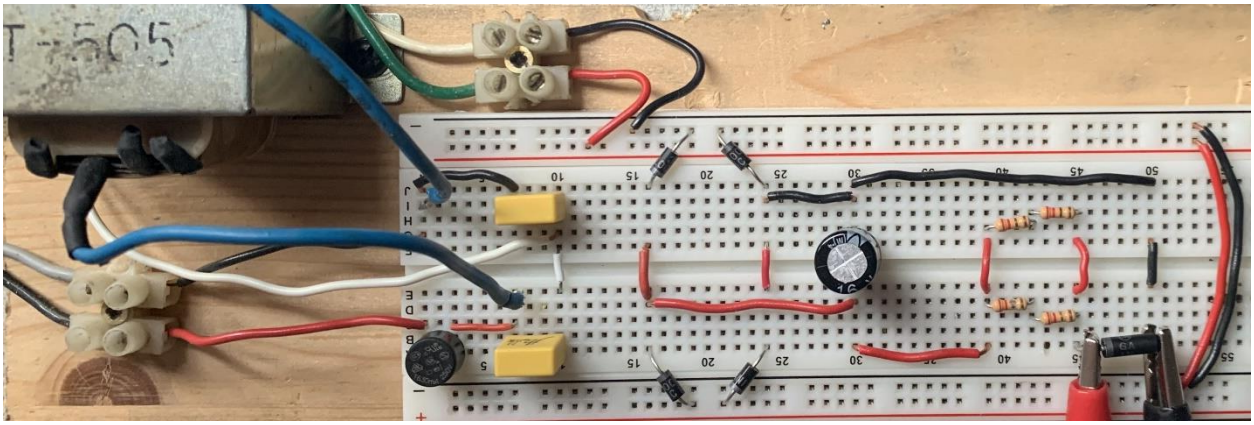


Figure 6-13 Primitive power supply

Explanation: Let's try to find a justification for the listed components. When calculating the current that will flow through the circuit, we must take into account the minimum amount of current that the Zener diode needs to conduct. If we look in the Zener diode 1N5338B datasheet, we can notice the values:

- nominal voltage 5.1V
- maximum current 930mA
- minimum current - approx 10% of maximum current = ~ 100mA = 0.1A

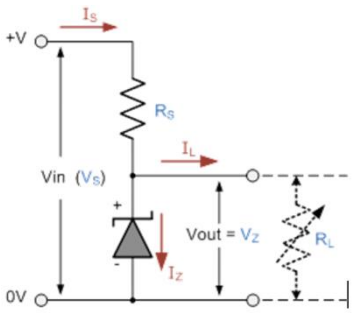


Figure 6-14 Zener diode as a voltage regulator
(Source: referenced)

Let us calculate the total amount of current needed, by looking at the previous figure:

- according to the *Kirchoffof's current law*, the sum of currents flowing into the node is equal to the sum of currents flowing out of the node

$$\mathrm{Is} = \mathrm{Iz} + \mathrm{IL}$$

- for the target current $\mathrm{IL} = 0.5\mathrm{A}$ and minimum Zener diode current $\mathrm{Iz} = 0.1\mathrm{A}$

$$\mathrm{Is} = \mathrm{Iz} + \mathrm{IL} = 0.5\mathrm{A} + 0.1\mathrm{A} = 0.6\mathrm{A} = 600\mathrm{mA}$$

Thus, the total current required is $\mathrm{Is} = 0.6\mathrm{A}$. Let us now see whether the components can withstand that amount of current.

The fuse we have chosen can withstand 63mA (0.063A) which is a lot higher than needed but acceptable. Since the primary winding voltage is 23 times *higher* than the secondary winding, the current on the primary winding is 23 times *less* than the secondary winding:

$$\frac{0.6\mathrm{A}}{23} = 0.026A$$

The IN4007 rectifier diode is capable of dissipating 3W. Since the voltage drop across the diode is ~ 0.7V, it is easy to calculate the dissipative power

$$\mathrm{P} = \mathrm{U} * \mathrm{I} = 0.7\mathrm{V} * 0.6\mathrm{A} = 0.42\mathrm{W}$$

so we are sure.

Further, let us calculate the needed resistor value Rs:

- input voltage $\mathrm{Vin} = 6.5\mathrm{V}$, output voltage $\mathrm{Vout} = \mathrm{Vz} = 5.1\mathrm{V}$
- according to the *Kirchoffof's voltage law*, the sum of the potential differences around any closed loop is zero, or

$$\mathrm{Vin} = \mathrm{VR} + \mathrm{Vz}$$

- therefore, we have a resistor voltage

$$\mathrm{VR} = \mathrm{Vin} - \mathrm{Vz} = 6.5\mathrm{V} - 5.1\mathrm{V} = 1.4\mathrm{V}$$

- now, we can calculate the value of the resistor Rs

$$\mathrm{Rs} = \frac{\mathrm{VR}}{\mathrm{I}} = \frac{1.4\mathrm{V}}{0.6\mathrm{A}} = 2.3\Omega$$

- 2.2Ω is chosen because we expect small increases in load current. Since the resistors can dissipate a power of 0.25W, we connected 4 resistors in a 2 x 2 network to withstand 4 * 0.25W = 1W, which should be enough. The calculations below should substantiate our claim, as we need ~ 0.8W:

$$\mathrm{Is} = 0.6\mathrm{A}, \mathrm{Rs} = 2.2\ \Omega$$

$$\mathrm{P} = \mathrm{I} * \mathrm{I} * \mathrm{R} = 0.6\mathrm{A} * 0.6\mathrm{A} * 2.2\Omega = \sim 0.8\mathrm{W}$$

- let's calculate whether the selected resistor corresponds to the specifications of the Zener diode. We will do this by calculating the minimum and maximum value of a resistor that can be connected in series with a Zener diode, without connecting a load. We will calculate the resistances based on the fact that the current is identical throughout the length of the series circuit. Therefore, if we take the conduction limit currents of the Zener diode, we can calculate

  $$\mathrm{Rsmin} = \frac{\mathrm{VR}}{\mathrm{I}} = \frac{1.4\mathrm{V}}{0.93\mathrm{A}} = 1.5\Omega$$

  allows maximum Zener diode current. Further

  $$\mathrm{Rsmax} = \frac{\mathrm{VR}}{\mathrm{I}} = \frac{1.4\mathrm{V}}{0.1\mathrm{A}} = 14\Omega$$

  allows minimum Zener diode current. According to calculations, resistor 2.2Ω is within the limits.

The only thing curious is how we got to the value of Vin = 6.5V. During the build, the measurements were the following:

- $\mathrm{Vpower} = 230\mathrm{V\ AC\ RMS}$
- the effective value of alternating current measured by a digital multimeter is

  $$\frac{\mathrm{Vpeek}}{\sqrt{2}}$$

  where Vpeek is the maximal amplitude value

  $$\mathrm{Vpeek} = \mathrm{Vrms} * \sqrt{2} = 230\mathrm{V} * 1.41 = \sim 324.3\mathrm{V}$$

- $\mathrm{Vtransformer} = 9.6\mathrm{V\ AC\ RMS}$

  $$\mathrm{Vpeek\_transformer} = \mathrm{Vtransformer} * \sqrt{2} = 9.6\mathrm{V} * 1.41 = \sim 13.4\mathrm{V}$$

- after putting the filter, the rectifier output with no load is

  $$\mathrm{Vrectifier} = 12.4\mathrm{V\ DC}$$

  It makes sense, because by adding a capacitor in the circuit, we get closer to maximal amplitude value $\mathrm{Vpeek\_transformer}$

- however, if we connect the load, the measured voltage on the rectifier is

  $$\mathrm{Vrectifier} = 6.5\mathrm{V\ DC}$$

  what is the value used in calculations.

It should be noted that the power supply during testing must be continuously exposed to a load not to overload the Zener diode.

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Figures