Digital Electronics

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with material from:

Manual Introduction to Digital Electronics

Manual "Physikalisches Praktikum für Vorgerückte Elektronic D" (Oct 2006)

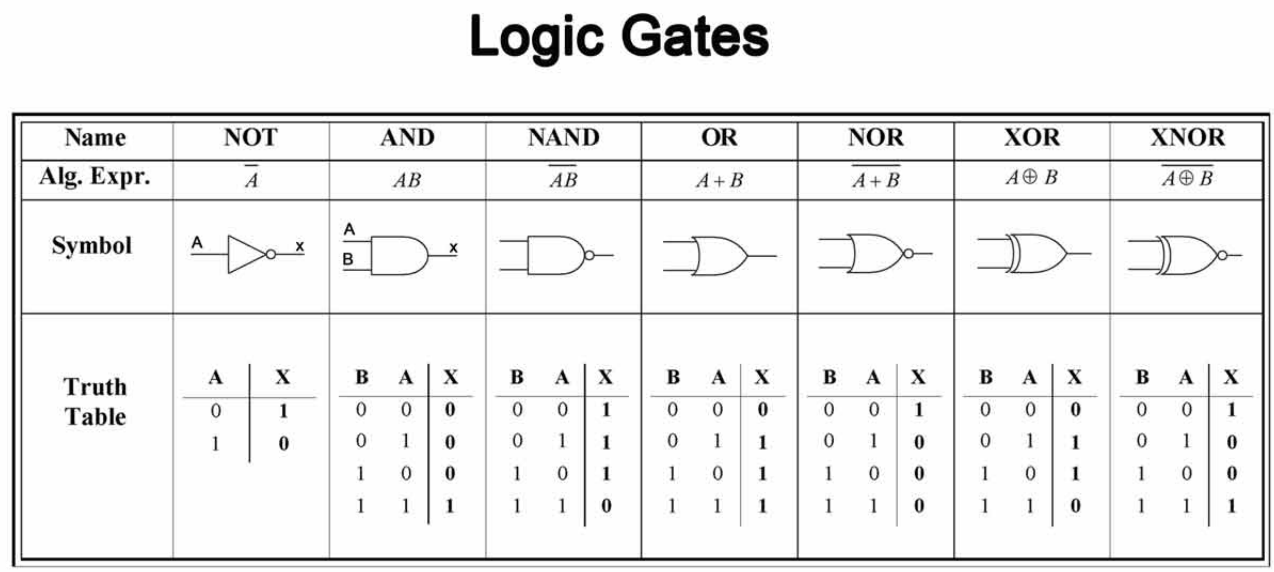
January 2022

Contents

1 Introduction

The basis of digital electronics, contrary to analog electronics, uses the binary number system representing booleans ("0" for false and "1" for true). In electronics, "1" and "0" are expressed with a voltage above and below a certain threshold, respectively. Typically, "1" corresponds to 5 V while "0" corresponds to ground (GND), but these representations can vary across electronic components.

Digital electronic circuits are usually made from large assemblies of the so-called **logic gates**, often packaged in **integrated circuits** (ICs). These logic gates perform simple logical operations (AND, OR, NOT, etc) given certain inputs ("0" or "1"). The function of a logic gate can be summarized in a truth table, which shows the expected output (X) for a given input (A and B). Examples of such truth tables are seen in Figure 1 along with their symbols. The first part of the experiment (explained in Section 3.2) consists on investigating the functionality of logic gates and characterizing their propagation time, meaning the time difference between the input and the output.



Logic Gates

Name	NOT	AND	NAND	OR	NOR	XOR	XNOR
Alg. Expr.	$\overline{A}$	AB	$\overline{AB}$	$A+B$	$\overline{A+B}$	$A\oplus B$	$\overline{A\oplus B}$
Symbol	A x	A B x					
Truth Table	A X 0 1 1 0	B A X 0 0 0 0 1 0 1 0 0 1 1 1	B A X 0 0 1 0 1 1 1 0 1 1 1 0	B A X 0 0 0 0 1 1 1 0 1 1 1 1	B A X 0 0 1 0 1 0 1 0 0 1 1 0	B A X 0 0 0 0 1 1 1 0 1 1 1 0	B A X 0 0 1 0 1 0 1 0 0 1 1 1

Figure 1: Truth tables of the most common logic gates.

Logic gates can be used in combination with other electronic components, such as resistors or capacitors, to build circuits with complex functionalities. An example of such circuit is the **astable multivibrator**, which uses two NOT gates along with a resistor (R) and a capacitor (C). Such circuit does not have a stable state and continuously switches from "0" to "1", i.e. it generates a periodic quasi-square waveform. By modifying the values of R and C it is possible to control the time the circuit takes in each of the states. Astable multivibrators are used in many applications such as amateur radio equipment, Morse code generators and TV systems. The second part of the experiment (explained in Section 3.3) consists on building an astable multivibrator and characterizing its generated square function for different combinations of resistors and capacitors.

A combination of the mentioned electronic components and additional ones (such as transistors, diodes, switches) can be used to build more complex **standalone circuits** with specific functionalities. Examples of such circuits are bit adders, bit multipliers, counters or shift registers.

The last task of the experiment is the most important one (explained in Section 3.4), where the student independently builds a circuit of choice and demonstrates its functionality.

2 Equipment

This section contains an introduction to the equipment you will use in the experiment. Please make sure to completely understand the operation of all components before usage - in doubt, contact the teaching assistant or the Help Desk. You should have informed yourself about the hazards of manipulating voltage suppliers before attending the experiment. The damage of electronic components during operation is normal - if that happens, please report it to the Help Desk so that it can be replaced.

2.1 Power supply

In the experiment you will use the DC voltage supply unit shown in Figure 2. The supply unit has three channels: channels 1 and 2 deliver a variable output voltage with a limited current that can be adjusted; channel 3 delivers a constant 5 V with 3 A and it is not required during this experiment. Hence, you should use channels 1 or 2. First, set the output voltage to 5 V (VOLTAGE knob) and the maximum current to 0.1 A (CURRENT knob); then, activate the voltage with the OUTPUT button on top of the POWER button. The "-" terminal of the corresponding channel is the ground reference potential and the "+" terminal provides the 5 V. There is no need to use the GND terminal.

Figure 2: DC voltage supply.

2.2 Waveform generator

A waveform generator creates a periodic signal as a function of time, whose shape, period and amplitude can be chosen by the user. Contrary to the voltage supply, which contains separate output terminals for "+" and "-" (used as "GND"), in the case of the waveform generator a single output terminal carries both lines. These should be split making use of the BNC connector shown in Figure 3 (where red is "+" and black is "GND"). When having multiple ground lines in your experiment (i.e. from the DC power supply and the waveform generator), make sure to connect them together to set a common reference voltage.

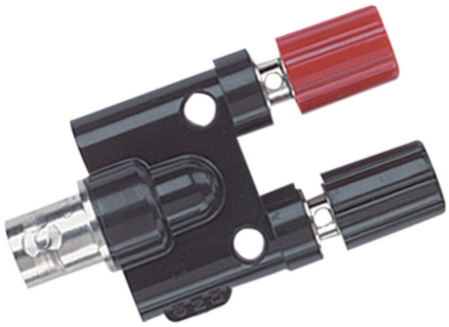


Figure 3: BNC connector for waveform generator.

2.3 Bread board and wires

The experiments should be performed on a bread board, shown in Figure 4. The "+" terminal of the voltage supply unit should be connected to the port V_a (in red), which in turn should be connected to the bus strips marked with a red line in the breadboard. Likewise, the "-" terminal of the power supply should be connected to the port V_b (in black), which in turn should be connected to the bus strips marked with a blue line in the breadboard. Afterwards, an electric circuit can be built using wires and other components. For clarity, it is recommended that all connections to the GND should be done using black or blue laboratory wires, while red wired should be used for "+" voltages.

The bread board has a set of internal connections (points at the same voltage), namely:

- all points directly beside the same red line are connected (and should be set to "+" voltage when used)
- all points directly beside the same blue line are connected (and should be set to "GND" when used)
- each five horizontal points in each segment of each row are connected among themselves

`bread board.png`

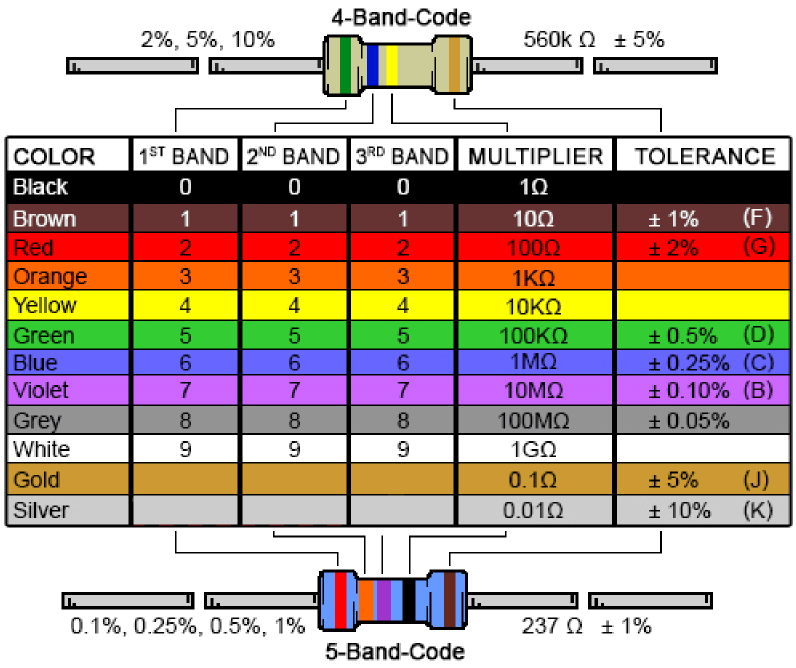
Figure 4: bread board.

2.4 Resistors and capacitors

Resistors and capacitors of different values are available to the student. The readout of the resistance follows a color code indicated in Figure 5, while for the capacitors it is written in the component. Please make sure to note down the uncertainties on these values, as you will need for error propagation in the results of your measurements.

2.5 Multimeter

A multimeter is a measurement instrument which can measure several quantities, such as the current, the voltage and the resistance. The multimeter has 4 ports at the bottom (see Figure 6):



COLOR	1ST BAND	2ND BAND	3RD BAND	MULTIPLIER	TOLERANCE
Black	0	0	0	1Ω	
Brown	1	1	1	10Ω	± 1% (F)
Red	2	2	2	100Ω	± 2% (G)
Orange	3	3	3	1KΩ	
Yellow	4	4	4	10KΩ	
Green	5	5	5	100KΩ	± 0.5% (D)
Blue	6	6	6	1MΩ	± 0.25% (C)
Violet	7	7	7	10MΩ	± 0.10% (B)
Grey	8	8	8	100MΩ	± 0.05%
White	9	9	9	1GΩ	
Gold				0.1Ω	± 5% (J)
Silver				0.01Ω	± 10% (K)

Figure 5: Color code for resistances.

depending on the measured quantity, different ports are used. For our purpose, we use the two rightmost ports to measure the voltage and/or resistance across two points in the circuit.

Figure 6: Ports of the multimeter.

2.6 Oscilloscope and test probes

Another way of measuring voltages is using an oscilloscope (see Figure 7). The oscilloscope displays the evolution of the voltage as a function of time: the horizontal axis is time, while the vertical axis is the voltage. The time and voltage units (displayed in the screen) are usually given in seconds per division and volts per division. Two channels are available for display: channel 1 in yellow and channel 2 in blue. In order to obtain static images of periodic signals, one can use the trigger function in the oscilloscope, which consists in setting a threshold on the amplitude of the signal so that the monitor displays the signal from the point where it crosses the threshold onwards. For a periodic signal, this translates in a static image in the screen.

To measure the voltages in the bread board, one can use a test probe (see Figure 8). The probe has a tip (which should be connected to the point in the circuit where we want to measure) and a reference lead (which should be connected to ground). It is important to calibrate the probe before usage. To do so, plug it to the BNC jack on the bottom right of the oscilloscope, as shown in Figure 7. By doing this, a distorted square waveform is displayed in the screen. You should

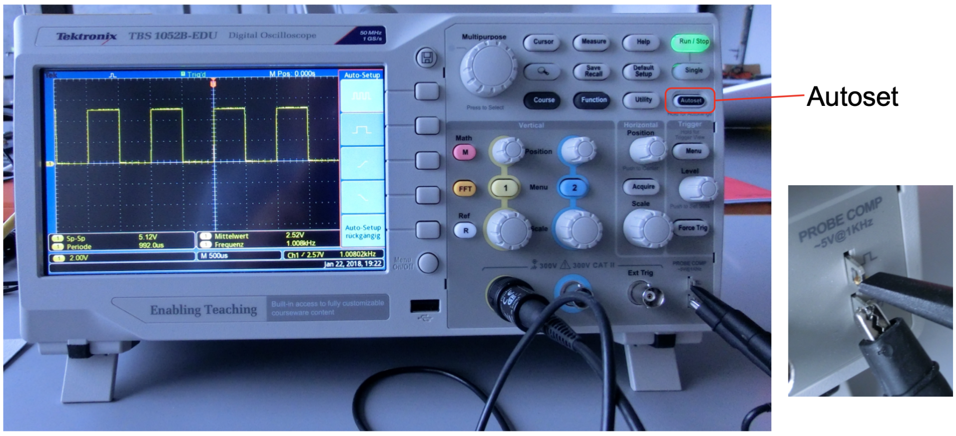


Figure 7: Oscilloscope and calibration of the test probe.

use a screw driver to fine adjust this waveform to be as close as possible to a square function. Please note that probes can have an attenuation factor, displayed in the probe itself, which will scale up or down the voltage shown in the oscilloscope. To find the real voltage one can simply use the multimeter and compare.

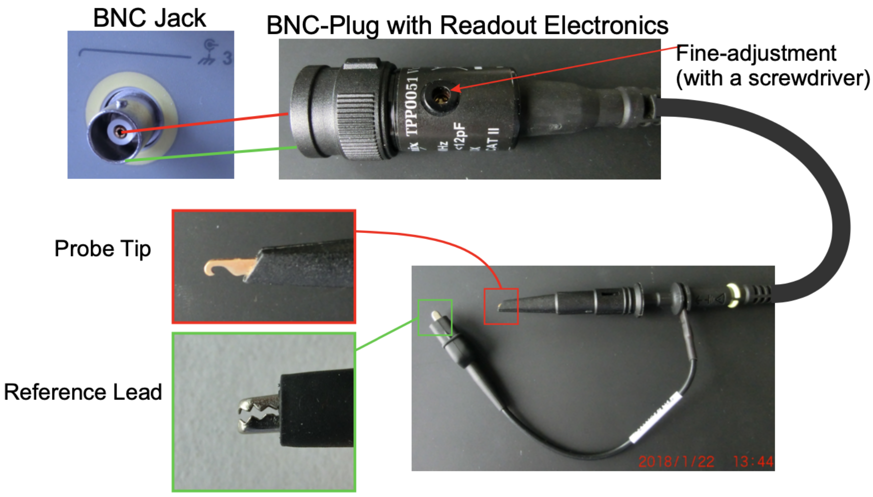


Figure 8: Test probe.

2.7 Integrated circuits

Logic gates are packaged in integrated circuits, available at the Help Desk for your usage. To know how to connect the lines of an IC, along with its technical characteristics, one can refer to the schematics in its data sheet. An example of an IC is shown in Figure 9, and its schematics is shown in Figure 10. Each leg of the IC is a pin (number) in the schematics. Note that to get the correct orientation of the IC, there is a little indentation on its upper side, also indicated in the schematics.

For an IC to work, one should apply a positive input voltage (indicated with "VDD" in pin 12 in the figure) and a reference ground voltage (indicated with "VSS" in pin 7 in the figure). A single IC can have one or more logic gates embedded; in the figure, there are 4 independent OR gates. Each logic gate takes two inputs (quoted as "A" and "B" in pins 1 and 2 in the figure).

Figure 9: Integrated circuit.

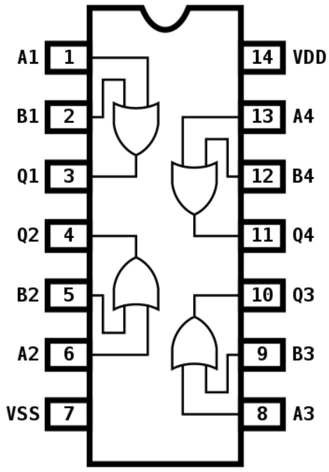


Figure 10: Schematics of the integrated circuit.

These inputs can be a positive voltage (typically 5 V) for true ("1") or a ground voltage for false ("0"), depending on the logical operation you want to test. Note than an input corresponding to "0" must always be connected to ground as **leaving a line unconnected does not mean it is at state "0"**. Each logic gate provides an output (quoted as "Q" in pin 3 in the figure). The output should be measured with a multimeter and/or the probe connected to the oscilloscope to test the functionality of the IC.

3 Tasks

This section contains a summary of the tasks you have to carry out in the experiment. After completion of each task and before moving on to the next one, you should contact the teaching assistant and provide all relevant results (photos of the circuits, photos of the oscilloscope displays, numerical results, etc).

3.1 Understanding the equipment

Start by familiarising yourself with the functioning of all the devices involved in the experiment. Set a frequency of 1 kHz with an amplitude of 10 V on the waveform generator. Connect the outputs to the bread board and check the waveform with a probe in the oscilloscope. What amplitude voltage do you measure? What is the frequency of the signal? Make sure to understand how to operate the trigger in the oscilloscope.

3.2 Investigating simple logic gates

In this part of the experiment, you will test the functionality of several ICs. Ask in the Help Desk for a NAND and a NOR gate and find the corresponding data sheet and schematics. What is the input voltage (VDD) required? How are the inputs "0" and "1" defined? Where are the different connection pins located in the IC?

Once you have understood the IC, you can set up the circuit in the bread board. For this you will need the DC voltage supply, the bread board, few wires and the IC. Start by applying different inputs ("1" or "0") combinations to the IC and check the outputs with the multimeter, the oscilloscope, or even LED diodes. Do they correspond to what is written in the truth tables? Don't forget to take a picture of the circuit.

Once you are sure both gates are expected, you can measure their propagation time, meaning the time delay between the input and the output signals. For this, you can use the same circuit from before. Keep input "A" at "0" or "1" as before, while input "B" should be connected to the waveform generated with the function generator. This waveform should be a square signal with frequency of 300 Hz and an amplitude of 5 V. In order to measure the propagation time, you should display in the oscilloscope the square input signal "B" and the output signal "Q" of the IC. Make sure to choose the input "A" such that, with the logic gate of choice, your input "B" and your output "Q" are complementary, meaning one is low when the other is high, and viceversa. The propagation time is defined as the time difference between the rising (or falling) edge of the input "B" and the falling (or rising) edge of the output "Q". The time should be measured at 50% the amplitude with the cursor of the oscilloscope. What is this value? What are the errors on the measurement? Is the propagation time consistent with the value quoted in the data sheet? Why is it important to know the propagation time of an IC?

3.3 Constructing a pulse generator

In this part of the experiment, you will construct a astable multivibrator to generate a square function. For this, you should build the circuit shown in Figure 11. Make sure to understand the working principle of such a circuit: why does it alternate between "0" and "1"? How can one change the time of the high and low states?

In order to build the circuit, you need two NOT gates (one IC can have the two gates), the DC voltage supply to provide the voltage for the IC, the breadboard, wires, three different capacitors (C from 0.1 uF to 1 uF), three different resistors (R from 1 kΩ to 100 kΩ) and the oscilloscope with the probe. Find the schematics of the NOT gates and check the pinout.

Build the circuit in Figure 11 for a given R and C. Measure the output with the probe (on the circle at the top right in the figure) and display it in the oscilloscope. What is the period (P) of the circuit? What is the duration of the high signal (width, W)? What are the errors on the measurements?

Repeat the measurements of P and W for the other combinations of R and C. Plot the measured values of P and W as a function of the product of RC. Does it behave linearly? Perform a linear

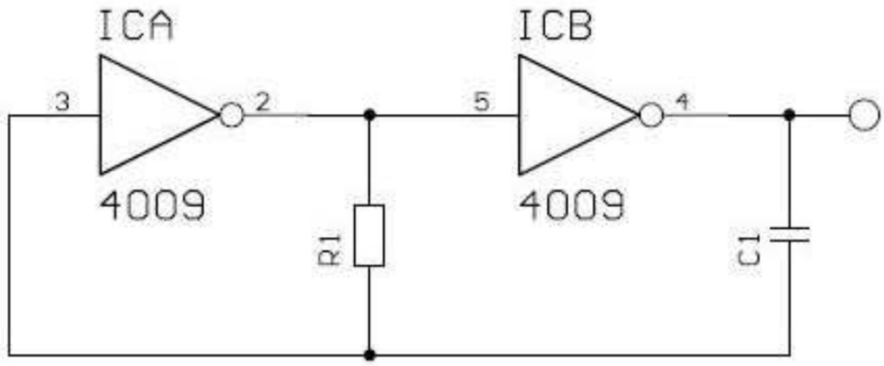


Figure 11: Circuit of a stable multivibrator, needing two NOT gates, one resistor and one capacitor.

fit of the data and extract the offset and the slope along with the corresponding errors, namely:

$$W = c_1 + k_1 \times RC \tag{1}$$

$$P = c_2 + k_2 \times RC \tag{2}$$

Now calculate the value of the duty cycle, defined as $D = W/P$, for each RC point i, namely $D_i = W_i/P_i$, and plot the results. What values of D_i do you measure? What are the errors? Does the duty cycle depend on RC and why?

Compare the values of the duty cycle measured point-by-point (as done before) to the duty cycle extracted by computing the ratio between the linear fits of P and W and evaluating it at each point, namely $D_i = \frac{c_1+k_1 \times R_i C_i}{c_2+k_2 \times R_i C_i}$. What values do you measure this time? What are the errors? Which method is more precise?

3.4 Building a standalone circuit

The final and most important part of the experiment consists on building a standalone circuit of your choice. Examples of such circuits are bit adders, bit multipliers, bit comparators, counters, etc. These are some suitable suggestions which you can find on the internet, but you are free to choose a circuit of your own. Nevertheless, before starting to build it, you should present your proposal to the teaching assistant (along with the schematics) to discuss the feasibility of your choice.

Depending on your choice, you might need to provide many different inputs to test the correct functionality of the circuit you build. In this case, it is convenient to use switches to provide the inputs, or to use LEDs or numerical displays to show the outputs. Ask for these components in the Help Desk and make sure to understand how to use them.

Being such circuits significantly more complex, it is very common to make mistakes, which are sometimes not easy to debug. Hence, to minimize debugging time, it is suggested to break the circuit down into smaller subcircuits, which you should test individually as you build them one after the other. By no means one should build the whole circuit and test it at the end - this is certainly not going to work! It is also recommended to use the wire length needed for the line path and not extremely long wires, so you can visually follow the lines along your circuit.

In order to help in the debugging, beware of some common mistakes:

- usage of the incorrect IC by mistake
- incorrect connection of the pins of the IC
- incorrect orientation of the IC
- input voltages applied are out of the tolerance range of the IC
- inputs of the IC are not connected (remember a "0" state is defined as "GND", not unconnected!)
- several grounds in the circuit are not connected among themselves
- the switch, LED or numerical displays are wrongly used

4 Report

The report should be written in such way that the reader can fully understand the different circuits built and be convinced of their correct functionality. To this end, you should explain the working principles of the circuit, the properties of the components used (along with the reference), and include pictures and the schematics of the circuit and oscilloscope displays. For the numerical results (astable multivibrator) it is important to present the plots in a readable manner and include error estimations. Do not forget the conclusions and the summary at the end. Make sure to include a section on laboratory hazards and how to prevent them at the end.

Please note that this laboratory experiment has to be conducted by a single student. You can interact with other students doing the same experiment in case you have questions, but remember the circuits must be built independently and the report must be written individually.