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1 Introduction

Digital electronics is the basis of state-of-the-art computer technology. "Digital" means that there are only clear on and off conditions in the circuit, but no interim conditions like half on or three quarters on, as known from analogue electronics. Therefore, there are fewer options on first glance. If you use many digital lines at once, there is a great many different conditions. Every single condition is referred to as a bit. An 8-bit system can represent 256 conditions at once, a 16-bit system as many as 65,636 (= 2 to the power of 16). If all conditions change quickly, huge amounts of data can be processed and complex systems like internet can be implemented.

The first attempts for the digital electronics should be performed with the simplest components possible. A typical basic component is a so-called gate, i.e. a circuit with inputs and one output. The condition at the inputs determines what happens at the output. A typical example is the NAND gate. The four-fold NAND gate 4011 used in the learning package permits many circuit versions already. Several NAND dates can be used to build circuits with other functions. Even an entire computer is, in the end, built from such basic functions.

Gates can be used, e.g., to build flipflops or memory components that maintain the last condition they have taken. A more complex flipflop is the JK-flipflop, which internally is also built from gate functions. The learning package contains a double JK flipflop 4027. The two ICs are part of the CMOS-family 4000 and may be operated at operating voltages between 3 V and 15 V. Therefore, they are great for simple experiments and battery operation at 9 V.

This is an introduction of the components. The individual experiments are performed on a pinboard. Every experiment has a circuit diagram and a setup photograph included. The respective photograph is only a suggestion; you may also place components differently. The connection wires of the individual components were partially shortened for a better overview in the photographs. However, use the connection wires unshortened so that they can still be used for further experiments.

1.1 Plug-in field

All experiments are set up on a lab experimenting board. The plug-in field with a total of 270 contacts in a 2.54 mm grid ensures safe connections of the components.

Fig. 1: The experimenting field

The pinboard field has 230 contacts in the centre area, each of which are connected conductively to five contacts with vertical strips each. Additionally, there are 40 contacts at the edge for power supply, which comprise two horizontal contact sprint strips with 20 contacts. The pinboard field has two independent supply rails. Fig. 2 shows all internal connections. You can see the short contact series in the centre field and the long supply rails at the edge.

Fig. 2: The internal contact rows

Insertion of components requires relatively high power. The connection wires therefore bend easily. It is important that the wires are inserted precisely from the top. Tweezers or small pliers will help with this. A wire is held as close to the pinboard as possible and pushed vertically down. This permits insertion of even sensitive connection wires like the tin-plated ends of the battery clip.

For the test, you need short and longer wire pieces that you need to cut to match the included circuit wire. To strip the wire ends, the insulation can be cut with a sharp knife all around.

1.2 Battery

The following overview shows the components as they actually look and as circuit symbols as they are used in circuit diagrams. Instead of a battery, you may also use, e.g., a plug-in mains adapter.

Fig. 3: The battery,
real and as circuit symbol

Do not use any alkaline batteries or rechargeable batteries, but only simple zinc carbon batteries. The alkaline battery may have a longer service life, but it has a big disadvantage: Like a rechargeable battery, it delivery very high currents of up to more than 5 A in case of error, which will strongly heat think wires or the battery itself. The short circuit current of a zinc carbon block battery, in contrast, is usually less than 1 A. This may already destroy sensitive components, but there is no danger of burns.

The included battery clip has a connection cable with flexible strand. The cable ends are stripped and tin-plated. This makes them stiff enough to plug them into the contacts of the pinboard. However, frequent plugging may cause them to lose their shape. Therefore, we recommend that the battery connections stay connected at all times and only the clip be removed from the battery.

1.3 Light-emitting diodes

The learning package contains four red LEDs. Always observe the polarity of all light emitter diodes. The minus connection is called cathode and is at the shorter connection wire. The plus connection is the anode. Inside the LED, you can recognise a cup-shaped holder for the LED crystal that is located at the cathode. The anode connection is connected to a contact at the top of the crystal with an extremely thin wire. Caution: In contrast to glow lamps, LEDs must never be directly connected to a battery. A dropping resistor is needed in all cases.

Fig. 4: The light emitter diode

1.4 Resistors

The resistors in the learning package are carbon-layer resistors with tolerances of ±5 %. The resistor material is applied to a ceramics rod and coated in a protective layer. It is labelled in the form of coloured rings. In addition to the impedance, the accuracy class is indicated as well.

Fig. 5: A resistor

Resistors with a tolerance of ±5 % are available at the values of the E24-series, with each decade containing 24 values with about equal distance to the adjacent value.

Table 1: Impedance values according to the standard series E24

1,0	1,1	1,2	1,3	1,5	1,6
1,8	2,0	2,2	2,4	2,7	3,0
3,3	3,6	3,9	4,3	4,7	5,1
5,6	6,2	6,8	7,5	8,2	9,1

The colour code is read from the ring closer to the edge of the resistor. The first two rings represent two digits, the third the multiplier of the impedance value in Ohm (Ω). A fourth ring indicates the tolerance.

Table 2: The resistor colour code

Colour	Ring 1 1st number	Ring 2 2nd number	Ring 3 Multiplier	Ring 4 Tolerance
Black		0	1	
Brown	1	1	10	1 %
Red	2	2	100	2 %
Orange	3	3	1.000	
Yellow	4	4	10.000	
Green	5	5	100.000	0,5 %
Blue	6	6	1.000.000	
Violet	7	7	10.000.000	
Grey	8	8		
White	9	9		
Gold			0,1	5 %
Silver			0,01	10 %

A resistor with the colour rings yellow, violet, brown and gold has the value 470 Ω at a tolerance of 5 %. The learning package includes resistors of the following values:

1 kΩ	Brown, black, red
10 kΩ	Brown, black, orange
100 kΩ	Brown, black, yellow
2.2 MΩ	Red, red, green

1.5 Capacitors

A capacitor comprises two metal surfaces and an insulation layer. Applying electrical voltage will lead to formation of an electrical force field between the capacitor plates, in which energy is stored. The capacity of a capacitor is measured in farad (F). The insulating material (dielectric) increases capacity as compared to air insulation. Ceramics disc capacitors use a special ceramics material with which high capacities are reached at small builds. The learning package container a ceramic disc capacitor with 100 nF (label 104, 100.000 pF).

Fig. 6: A ceramics capacitor

1.6 Scanning switch

The pushbuttons in the learning package have a normally open contact with two connections, each of which is performed double.

Fig. 7: The pushbutton

1.7 Fourfold NAND-Gate 4011

An integrated circuit (IC) contains many components in one casing. The 4011 is a CMOS-IC with four NAND-gates. The IC is protected well against electrostatic discharge and does not need to be treated with any special care. Make sure that the operating voltage is connected in the correct direction. If you install the IC in the wrong direction, it will heat up too much and be destroyed. When first inserting into the pinboard, the 14 connection legs must be aligned in parallel.

Fig. 8: The CMOS-IC 4011

1.8 Two-Fold JK-Flipflop 4027

The 4027 is a CMOS-IC with 16 connections. It contains two independent JK flipflops. As in all ICs, particularly correct connection of the operating voltage is important. The operating voltage in all ICs of the 40xx series may be between 3 V and 15 V.

Fig. 9: The CMOS-IC 4027

2 Inverter

The CMOS-IC 4011 contains four independent NAND-gates with two inputs each. An initial attempt shows use of the IC at a battery voltage of 9 V and connection of LEDs. When installing, always observe correct polarity. The plus connection is also called Vcc, the minus connection GND. For all CMOS-ICs, observe that inputs to used are connected either to Vcc or GND. Open inputs may lead to increased power intake and malfunction of the circuit. Open outputs, in contrast, are permitted.

Fig. 10: Test circuit with NAND gates

Fig. 11: Pinboard setup

The circuit uses only two of the four NAND gates (NAND 1 and NAND 4). Both inputs are connected. This turns the NAND gate into an inverter. An input condition zero is turned to an output condition one and vice versa. At the output, one LED each is connected with its dropping resistor. During this experiment, the left LED is lit while the right LED remains off.

Fig. 12: An NAND gate as inverter

The function of the circuit can be presented by a so-called truth table. In the lower gate (NAND 1), the input is applied to GND (0), the output is switched on because of this (1). In the upper gate (NAND 4), the input is applied to Vcc (1), the output is switched off because of this (0).

Input	Output
0	1
1	0

3 Contact Switch

This experiment uses a gate as inverter with open input. The input receives a protective impedance of 100 kΩ and may be touched with the finger. If they are strongly charged electrically, the protective resistance limits the discharge current.

The output condition of this circuit cannot be pre-determined, since the input has an extremely high impedance and may carry accidental charge. If the input voltage is clearly above half the operating voltage (4.5 V), the condition is deemed 1, clearly below as 0. In fact, there also is a medium input voltage where the output is also in the mid-range. The digital circuit then works similar to an analogue amplifier. This conditions should be avoided in emergency because the IC then requires much more current. Undetermined input conditions also may impair the function of a digital circuit. Open inputs must be avoided. This experiment does, however, convey an impression of how open inputs may behave.

Often, light contact with the finger is enough to change the condition. Usually, your body has a certain alternating voltage because of low capacitive coupling with the surrounding mains lines. At the output, you will see a quick 50 Hz flicker of the LED. Releasing the input causes the last condition to be retained for a while.

Fig. 13: Inverter with open input

Fig. 14: Setup with touch contact

4 NAND Basic Function

In this experiment, the actual function of the NAND gate is examined. This is an AND function with subsequent inverter. The following applies for the AND function: Only when input 1 AND input 2 are on will the output be on as well.

Accordingly, the NAND function means that: Only when input 1 AND input 2 are or will the output be off as well. This is also shown in the truth table of the NAND gate.

Input 1	Input 2	Output
0	0	1
0	1	1
1	0	1
1	1	0

Fig. 15: Connections of a NAND gate

The circuit uses two resistors with 100 kΩ to achieve the quiescent state zero. The pushbuttons can be used to switch on a one condition each. In this case, the orange LED is lit in the quiescent state. Oily when both buttons are pushed at once will it go off.

Fig. 16: Switch at the inputs

Fig. 17: Pushbutton setup

5 AND-Gate

A subsequent inverter can turn the NAND gate into an AND circuit. This time, the rule is: Only if both switches are shut will the LED be on.

Input 1	Input 2	Output
0	0	0
0	1	0
1	0	0
1	1	1

Fig. 18: AND-Gate

Fig. 19: AND test circuit

Fig. 20: Setup of the AND circuit

6 OR-Gate

Inverting the two inputs of the NAND gate first leads to an OR gate. The OR function is: When input 1 OR input 2 OR both of them are on will the output be on.

Fig. 21: OR circuit

Input 1	Input 2	Output
0	0	0

0	1	1
1	0	1
1	1	1

Fig. 22: Wiring of the OR circuit

Fig. 23: Testing the OR circuit

7 NOR-Gate

Another inverter behind the OR gate generates a not-or function (NOR). To generate a NOR gate, all four NAND gates in the 4011 are needed.

Fig. 24: Setup of a NOR gate

Input 1	Input 2	Output
0	0	1
0	1	0
1	0	0
1	1	0

Fig. 25: Wiring of the NOR experiment

Fig. 26: Testing the NOR circuit

8 RS-Flipflop

A flipflop is a circuit that independently maintains one of two conditions. A digital condition can be saved. Certain input conditions switch the output. The RS flipflop has two inputs, reset (R) and set (S). In the quiescent state, both inputs are set high (R = 1, S = 1). The output is then not determined (X) and depends on the previous history. Switching R to 0 switches the output off. Switching S to zero switches it on.

Input 1	Input 2	Output
0	0	1
0	1	1
1	0	0
1	1	x

The RS flipflop can be set up from two NAND gates, with the outputs each being fed back to an input of the other gate. The feedback leads to a condition once present being retained.

Fig. 27: Basic principle
of the RS flipflop

In the actually set up circuit, both outputs are put to LEDs. At the output of NAND 2, the inverted condition of NAND 1 appears at all times. Two resistors against Vcc ensure quiescent state 1. The pushbuttons can force a 0-condition and therefore change the output condition. When switching on the operating voltage, one of the two LEDs lights up — it is not possible to tell in advance, which one. Both buttons can be used to switch between the two conditions then.

Fig. 28: Circuit diagram of the RS flipflop

Fig. 29: Setup with R- and S-button

9 Flash Circuit

Two NAND gates, two resistors and a capacitor can be used to build an astable flipflop that independently switches back and forth. Like am RS flipflop, a feedback is used here. A condition is, however, only stable for as long as the capacitor is being charged. Then the starting condition changes. Strictly speaking, this is not a digital circuit because the input voltage of the left gate changes slowly. In the end, however, a digital signal occurs at the output and changes periodically.

Fig. 30: Astable flipflop

In the practical circuit, both NAND gates were applied with LEDs that therefore clash alternatingly. The resistors and the capacitor are selected so that a well-visible flashing at a frequency of approx. 2 Hz results. The circuit presented here is also used as a cycle source for more complex digital circuits below.

Fig. 31: Flash with two LEDs

Fig. 32: Setup of the alternating flash

10 Double Flash

Four gates can be used to set up two independent flash circuits at once. In theory, they are supposed to work at the same frequency. In practice, however, low component tolerances cause the two circuits to not work perfectly synchronously. If you touch one of the capacitors with your finger, slight heating will cause slight reduction of capacity. The corresponding flash then speeds up a little.

Fig. 33: Two identical flashes

Fig. 34: Independent flash cycle

11 Variable Frequency

The frequency of the two flashers can be varied within wide thresholds if an external resistor is switched in parallel to the 2.2-MΩ resistor in the circuit. The skin impedance is used here. Slight contact of the two wire ends leads to increase of frequency. The oscillators can be used to compare the skin impedances of two persons.

Fig. 35: Adjustable flashing frequency

Fig. 36: Setup with finger contacts

12 Frequency Divider

The CMUS-IC 4027 contains two independent JK flipflops. A JK flipflop is a relatively complex and highly diverse circuit. The first test uses the IC as toggle flipflop. The inputs R and S must be applied to GND for this, the inputs J and K to Vcc. »Toggle« means switching. The output state changes at every 0-1 condition change at the cycle input (Clock, C), i..e at every positive cycle flank. In the end, a rectangular signal is generated at the output at half the cycle frequency.

Fig. 37: The JK flipflop
as toggle flipflop

Circuits with flipflops are sensitive to interference signals. A capacitor between Vcc and GND prevents inferences that may spread across the supply lines. For high reliability of the circuits, an additional resistor of 10 kΩ is inserted in the cycle line.

Fig.. 38: use of the toggle flipflop

This experiment shows both the cycle signal and the output signal of the flipflop using LED. You can clearly see that the output state only changes at half the speed of the cycle signal.

Fig. 39: Display of basic frequency and half the frequency

13 Divider by Four

Two toggle flipflops can be switched in series. The Q output of the first flipflop controls the C-input of the second flipflop. All in all, the input frequency is divided by four.

Fig. 40: Two dividers in series

Cycle	Output 2	Output 1	Meter state
0	0	0	0
1	1	1	3
0	1	1	3
1	1	0	2
0	1	0	2
1	0	1	1
0	0	1	1
1	0	0	0

0	0	0	0

At the same time, the circuit can also be seen as a counter if the output states are considered bits of a digital figure. The state at output 1 then has to be on the right. This results in the binary figures 00, 11, 10, 01, 00. The circuit counts backwards: 0, 3, 2, 1, 0 etc. This is because the clock input reacts to the positive flank.

Fig.. 41: Divide by 2 and 4

Fig. 42: Setup of the binary counter

This circuit of toggle flipflops in sequence is also referred to as an asynchronous counter or ripple counter. The respective next stage will only switch with a delay of some nano seconds, which is not visible to the eye.

14 Stop and Go

Use two open-ended wires instead of the 10 kΩ resistor. The Rx resistor is then formed, e.g., by touch. Switch the cycle signal on and off by touching with your finger. You may let the counter run and stop it by this. Try freezing the outputs right in condition 1. Another option is in only touching the cycle input. This usually causes a 50 Hz hum to become active as cycle. This frequency is divided by 4 in total. The last output flickers well visible at 12.5 Hz. This circuit can be used as random number generator like a dice. The two LEDs show the binary number thrown.

Fig. 43: Interrupted cycle line

Fig. 44: Counter with touch contacts

15 Set and Reset

The inputs R and S can be used as for a RS flipflop. They are operated with two switches here. Additionally, the inputs are applied with impedances against GND that determine the quiescent state zero. The first counter stage can be deleted (R) or set (S) as desired now. While one of the buttons is pushed, the counter remains in the corresponding condition. The condition of the second counter stage also will no longer change.

The cycle generator was expanded by another buffer stage in the form of an inverter with the NAND 3 in this circuit. This measure improves interference resistance, which is also important for some of the following experiments.

Fig. 45: Set and reset for the first counter

Fig. 46: Button installation

16 JK-Flipflop

The JK flipflop derives its name from the inputs J and K. They are now examined in more detail. Connect the two pushbuttons with the associated resistors to the inputs J and K of the upper flipflop. Use the applied cycle to test all conditions of J and K. One function is already known from the previous tests: With J = 1 and K = 1, the output toggles at every positive cycle flank. Now also try out the other states. With J = 0 and K = 0 the output Q will retain its condition. The flipflop does not react to cycle impulses. When both inputs J and K are unequal, the flipflop assumes the J condition for Q at the next cycle impulse. Generally, the inverted output /Q shows the inverted condition of Q.

Fig. 47: Functional principle of the JK flipflop

Input J	Input K	Input C	Input Q	Input / Q
0	0	0–1	unchanged	unchanged
0	1	0–1	0	1
1	0	0–1	1	0
1	1	0–1	Toggle	Toggle

Fig. 48: Test circuit for the JK flipflop

Fig. 49: Buttons at J and K

17 Slide Register

A slide register pushes input conditions one stage forward at every cycle impulse. The 4027 can be used to set up two stages. The cycle signal is now applied in parallel to both clock inputs. The input has two buttons at J and K again. The connection to the next stage is decisive. Q leads to J and /Q to K. In case of a positive cycle flank, the first flipflop assumes the unequal conditions at J and K. At the same time, the second JK flipflop still assumes the old conditions of the first flipflop, because the new conditions only take effect with a short delay after the cycle flank.

Fig. 50: JK flipflop as slide register

In the quiescent state, both inputs J and K are zero. Push the button J now. The 1 condition is assumed at Q1 at the next cycle impulse, and by the following one at Q2 as well. You can clearly see the delay by one cycle. Release the button. Because both inputs J and K of the first stage are now 0, the output does not change. Both outputs remain on. Now push the button K. Q1 is made 0 at the next cycle impulse, and with a one-cycle delay, so is Q2. Pushing both buttons J and K toggles the first flipflop. The second one follows the conditions with a delay of one cycle. All in all, you have gotten an alternating flash.

Fig. 51: Test circuit for slide register

Fig. 52: Experiment setup slide register

18 Phase Offset 90 Degrees

Return the output signals of the two-stage slide register to the input. J and K should, however, be swapped. The result is that the first flipflop each take son the inverted condition of the second flipflop. The second one, on contrast, follows the first one as before with a delay on one cycle. All in all, both outputs switch alternatingly. This leads to two symmetrical rectangular signals with a quarter of the cycle frequency and a time delay of one cycle. The phase offset between both output signals is 90 degrees. Such signals user used, e.g., in message technology.

Fig. 53: Phase-offset output signals

Output Q1	Output Q2	Numeric value	LED 1	LED 2
0	1	1	1	0
1	1	3	0	0
1	0	2	0	1
0	0	0	0	0

Fig. 54: Phase-offset control of two LEDs

Fig. 55: Experiment setup for phase offset

Change the circuit once so that J and K are not swapped during feedback. The result is uncertain because it depends on the first condition of the flipflop after switching on. It is possible that both outputs remain permanently on or off, that they change counter-phased.

19 Bit Decoder

The above experiment had both LEDs lit for two cycles each. Now individual switching phases are decoded and displayed. this is possible by switching two more LEDs with a dropping resistor between the outputs of both flipflops. The two left LEDs are only lit when both Q outputs have an unequal condition at the time. Since they are switched antiparallel, alternating light phases occur.

Output Q2	Output Q1	Numeric value	LED 1	LED 2
1	0	2	1	0
1	1	3	0	0
0	1	1	0	1
0	0	0	0	0

Fig. 56: Display of individual bit conditions

Fig. 57: Setup with four LEDs

20 One of Four

For only one of the four LEDs to be lit at a time, the two LEDs at the right of the circuit diagram must be switched between the two flipflops accordingly. For the two remaining switching phases to be decodable, the lower flipflop's inverted output /Q is used.

Output Q2	Output Q1	Numeric value	LED 1	LED 2	LED 3	LED 4
1	0	2	1	0	0	0
1	1	3	0	0	0	1

0	1	1	0	1	0	0
0	0	0	0	0	1	0

Fig. 58: The decoder

Fig. 59: A four LED flash

21 Synchronous Counter

A multi-stage synchronous counter generally delivery the same results as a multi-stage ripple counter. The difference is that the outputs now switch precisely at the same time. For this, all stages must work with the same cycle. The cycle signal is now applied in parallel to all C-inputs of the flipflops. A flipflop cannot wait for the result of the previous stage but must know in advance whether it is to switch at the next cycle. The Q output is connected to J and K of the following stage. If Q = 1, the following cycle impulse switches both stages at once.

Fig. 60: Synchronous counter principle

In the first stage, J and K are connected to Vcc so that a toggle flipflop results. Whenever Q = 1, the following cycle impulse will switch the state. This leads to the correct counting sequence for a binary forward counter.

Fig. 61: Synchronous forward counter

Again, four LEDs are to be lit individually in sequence. All in all, a light pattern forms that looks as if a dot circled counter-clockwise.

Output Q2	Output Q1	Numeric value	LED 1	LED 2	LED 3	LED 4
0	0	0	1	0	0	0
0	1	1	0	1	0	0
1	0	2	0	0	1	0
1	1	3	0	0	0	1

Fig. 62: Circular flashing

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