VP Bericht - Elektronik D

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***Abstract*—The here presented experiments give a brief overview on some important properties of digital circuits. For some properties, it is described how these are measure. This might serve as a good starting point for those, that want to understand how digital circuits work. Problems designing an own circuit are highlighted and solutions are presented. The importance of understanding the used digital components is emphasized.**

Contents

I. Introduction

Over the last years, more and more parts of people's life have become digital. Some people call this the digital revolution. While the devices get more packed with functionality and the complexity to build them increases, the root concept of digital technology stayed the same. There are still only two still - 0/"low" and 1/"high", which form a single bit, and input signals get converted to some output signal following well defined operations.

The main components of a digital circuits are given by resistors, capacities and transistors. From these components, logic gates (or just called gates) are constructed, that perform a single boolean operation (e.g. take two input signals, perform the AND operation on them and set a output signal based equal to the result of the AND operation). Gates are then assembled to so called integrated circuit (short: IC), that can perform more complex operations.

Logic gates are produced in different ways, which lead to different properties. Gates with the same properties are grouped into so called logic gate families. Two important logic gate families are TTL (transistor–transistor logic) and CMOS (complementary metal–oxide–semiconductor). TTLs are only made up from resistors and transistors. Typically, they require a supply voltage of 5V. A voltage lower then 1.8V is interpreted as a "low" signal. The output signal is less then 0.4V for a low and over 2.4V for a high signal. The big disadvantage compared to CMOS is the higher power usage. Where TTL uses only bipolar transistors, CMOS also uses MOSFETs. The voltage for the power supply can range from 3V to 30V. The voltage ranges detected as high/low signal depends on the power supply voltage.

The following experiments will concentrate on analysing some of the properties of CMOS ICs. This will start by determining the performed operation of some ICs and their propagation delay. Next, a pulse generator is build and examined. Finally, a simple bit shift logic is presented, which was self designed and some of the issues going with the self designing are explained.

II. Experiment: Simple Logic Gate

A. Samples and measurement setup

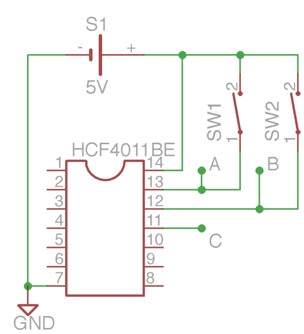


Fig. 1: Circuit diagram to measure truth table.

The circuit was setup as shown in figure 1. Based on the different input signals at A and B, different values for the output signal C were measured using a oscilloscope. As for the ICs, a HCF4001BE and HCF4011BE were used.

To measure the propagation delay, input signal A was connect to a square wave voltage generator. Input signal B was connected to ground. The IC HCF4001BE was used for this measurement. The voltage of the generator was set to 2.9V and the frequency to 1Hz. The voltage was chosen, such that a slightly lower voltage was detected as a "low" input signal. The input signal A and output signal C was visualized using a oscilloscope. The oscilloscope's trigger signal was connected to the voltage generator.

	4011			4001	
A	B	C	A	B	C
0	0	1	0	0	1
0	1	1	0	1	0
1	0	1	1	0	0
1	1	0	1	1	0

Fig. 2: Truth table measuring IC HCF40011BE and HCF4001BE.

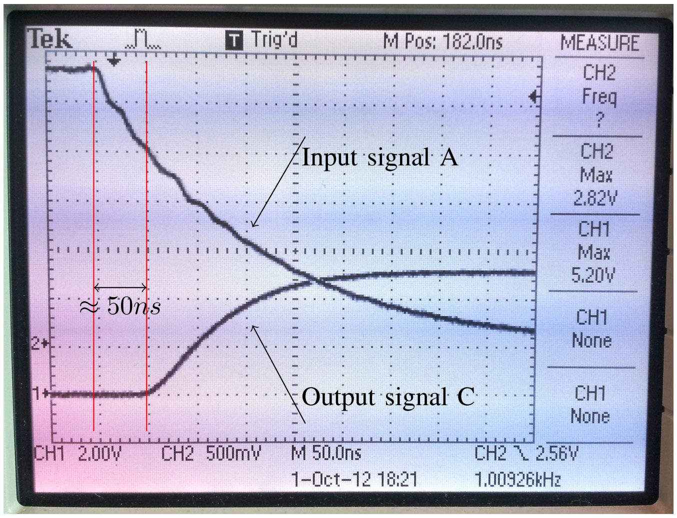


Fig. 3: Propagation delay measurement.

B. Results

For different input signals A and B the truth-table was measured as shown in table 2.

The propagation delay was measured to be around 50ns as seen in figure 3.

C. Analysis and Discussion

Based on the measurements, the IC HCF4001BE seems to be a logic NOR gate, whereas the IC HCF4011BE seems to function as a NAND gate. This fits with the specified functionality of the gates.

Looking up the propagation delay from the data sheet, it is said to be typically around 40ns and up to 75ns. This fits with the here measured delay.

III. Experiment: Pulse Generator

Pulse generators create rectangular, periodic voltage signals. In this experiment, such a generator was build and its properties examined.

A. Samples and measurement setup

The circuit was assembled as shown in figure 4. Here, the IC HCF4069UBE was used, which contains six NOT gates. The voltage difference between the output signals $O1$, $O2$ and the ground was quantified using an oscilloscope. This also allowed to visualize and measure the period of the oscillations. Different values for the resistance $R1$ and the capacity $C1$ were chosen and the resulting period of the voltage signals recorded.

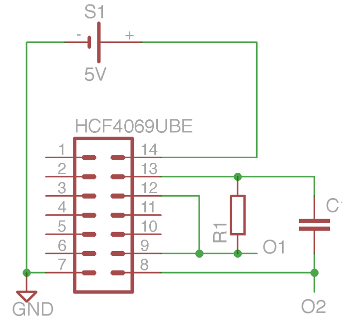


Fig. 4: Circuit diagram of astable multivibrator.

B. Functionality explanation

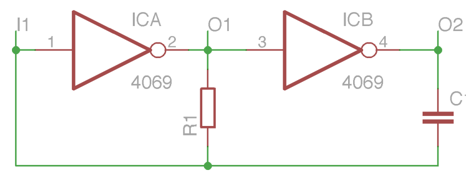


Fig. 5: Schematic drawing of the astable multivibrator circuit.

A schematic drawing of the circuit is presented in figure 5. The explanation follows the one given in [1]. Let's assume the voltage at $O1$ is set to be *high* and the capacitor is uncharged. Due to the *high* signal at $O1$, the signal at $O2$ is *low* (remember ICA and ICB are NOT gates). The capacitor is charged over the resistance $R1$. At some point, the voltage at $I1$ is high enough, such that the input signal of ICA is recognized as *high*. This causes the signal at $O1$ to become *low* and therefore the signal at $O2$ to be *high*. The charged capacitor discharges, which keeps the *high* signal at the $I1$ input for some time until the voltage on the capacitor is too low, such that the signal at $I1$ is recognized as a *low* signal. The signal at $O1$ becomes a *high* one and things start over again.

C. Results

The time diagram for the voltage at $O1$ and $O2$ is visualized in figure 6. In table 7 different period times t due to different choices of resistance R and capacity C are listed. The values for the resistances and the capacities used contain a manufacturing error of roughly up to 10%. Some of the capacities were more precise measured and are listed in the $C*$ column.

D. Analysis and Discussion

The k-value is defined as

$$k = \frac{t}{R \cdot C} \tag{1}$$

where t is the period time, R is the resistance of the resistor *R and C is the capacity of the capacitor* C. Based on the measurements, the k-values are computed in the k column of table 7. For the more precisely measured capacities $C*$, the k-value $k*$ was computed using the $C*$ value.

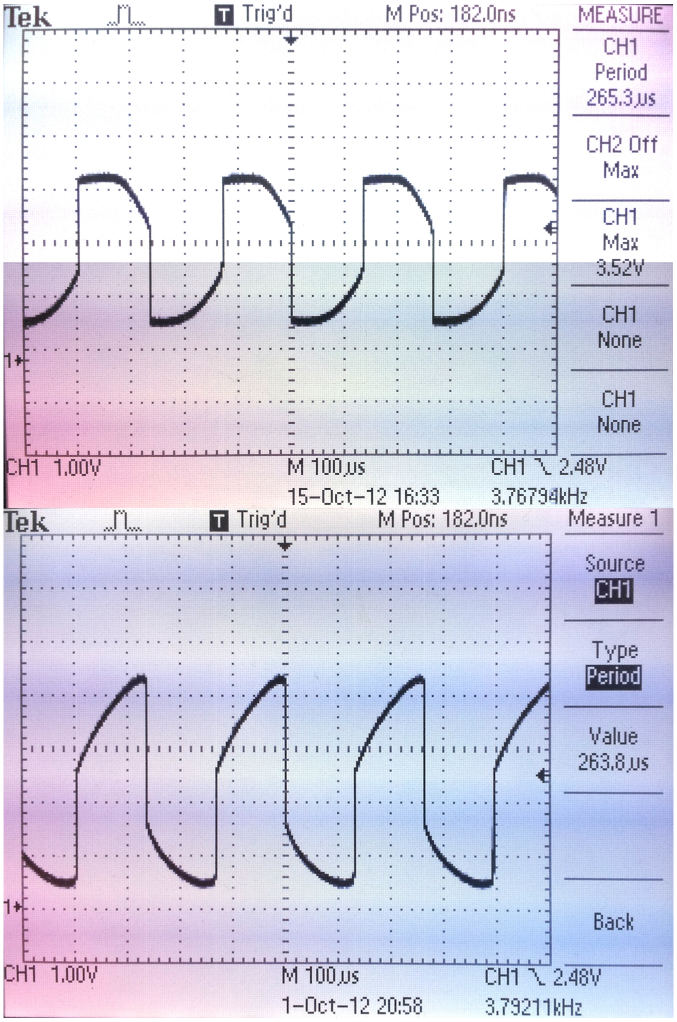


Fig. 6: Up: voltage difference at O1; bottom: voltage difference at O2. Both as function of time.

R [kOm]	C [nF]	C* [nF]	t [us]	k [s/(Om F)]	k* [s/(Om F)	Lit – <k*>
1.0	56	59.7	178	3.18	2.98	0.78
1.0	100	90	265	2.65	2.94	0.75
1.0	220	216	638	2.90	2.95	0.76
1.0	1000		2788	2.79		
1.8	56	59.7	288	2.86	2.68	0.48
1.8	100	90	430	2.39	2.65	0.46
1.8	220	216	1040	2.63	2.67	0.48
1.8	1000		4600	2.56		
3.3	56	59.7	468	2.53	2.38	0.18
3.3	100	90	700	2.12	2.36	0.16
3.3	220	216	1690	2.33	2.37	0.17
3.3	1000		7700	2.33		
39.0	1000		69760	1.79		
47.0	220	216	19600	1.90	1.93	-0.27
120.0	220	216	47520	1.80	1.83	-0.36
120.0	1000		212200	1.77		
150.0	220	216	58370	1.77	1.80	-0.40
*) = Corrected			Average:	2.37	2.46	
			Std. Deriv.:	0.45	0.43	

Fig. 7: Measurement of period time t as function of resistance R and capacity C.

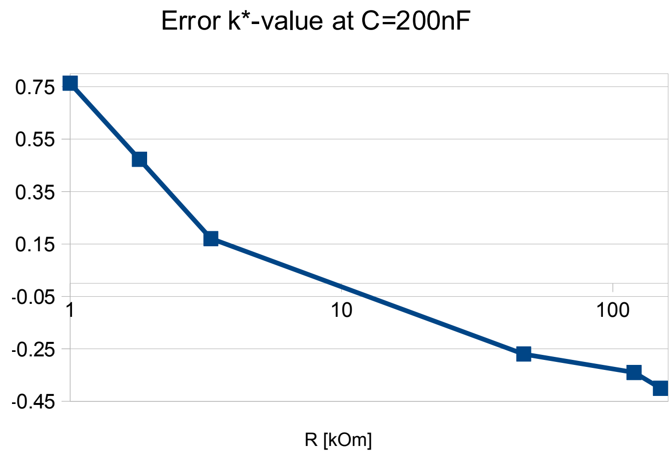


Fig. 8: Plot of error comparing literature value to computed value for k* at C = 200nF.

As mentioned in [1], the relation between t and the other quantities is given by

$$t = 2RC\ln(3) \approx 2.2RC \tag{2}$$

which yields the value of k using equation (1) as

$$k = 2\ \ln(3) \approx 2.2 \tag{3}$$

The average values of k and $k*$ given in table 7 match with the expected values for k. Using the standard derivation of the average as an indicator for the uncertainty of the here computed k and $k*$ values, the literature value is within the range of average +- standard derivation. However, the standard derivation is larger then 1/10 of the average value. This indicates a high uncertainty in the measured quantities.

The last column $Lit - k*$ holds the difference between the literature value (3) and the calculated $k*$ value and therefore is a simple error estimation. A plot of these errors for $C = 200\text{nF}$ is shown in figure 8. The x-axis is plotted logarithmically. The shape of the curve suggests a exponential relation between R and the error. As the $k*$ values are roughly the same for different choices of C, this might be an indication, that the error is mostly related to the choice of the resistance. The reason for this correspondence remained unclear to the author.

IV. Experiment: Self Build Digital Circuit

In the last experiment, a shift operation was designed and implemented. For simplicity, the shifter presented is made up of only two input signals and zero or one shift of the bits to the left. Written as a programming expression, this corresponds to:

$$\{0, 1, 2, 3\} << \{0, 1\} \tag{4}$$

where the numbers in brackets represent all possible values. The result of the calculation was visualized to the user using three LEDs.

A. *Samples and measurement setup*

To get an idea how the circuit should be setup, the required logical operations were determined as:

$$\begin{aligned} \text{LED1} &= \text{I1} \wedge \neg S \\ \text{LED2} &= (\text{I2} \wedge \neg S) \vee (I1 \wedge S) \\ \text{LED3} &= (\text{I2} \wedge S) \end{aligned} \tag{5}$$

where $I1$, $I2$ are the two input signal for the number to shift (the number to shift is represented in binary form), S indicates if a shift should happen (if high, do a shift on the input $I1$, $I2$) and LED$\{1,2,3\}$ are the LEDs showing the result of the operation.

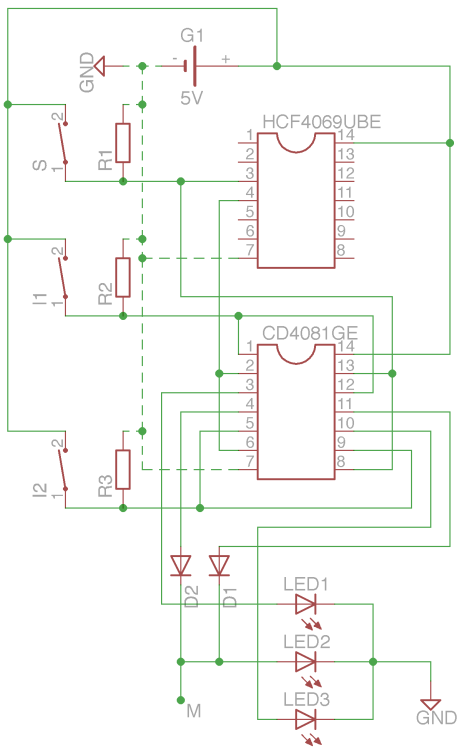


Fig. 9: Self designed bit shifter circuit.

After looking up the required components, the circuit was sketched out as shown in figure 9. The four AND operations were covered using the IC CD4081GE, the NOT operation using the IC HCF4069UBE, the OR operation was done by "just" connecting two wires at first place. In the first draft of the circuit the components R$\{1, 2, 3\}$ and D$\{1, 2\}$ were left out. The reasoning for adding them is provided in the "Analysis and Discussion" section.

To determine the propagation delay, input S was connected to a square wave generator running at 1kHz and 5V. The input I2 was opened/set to a "low" signal and the I1 input was closed/set to a "high" signal. The voltage difference at LED2 compared to GND was measured by attaching an oscilloscope at M.

B. *Results*

The output signals of the AND gates was oscillating. The LED2 was shining only very little.

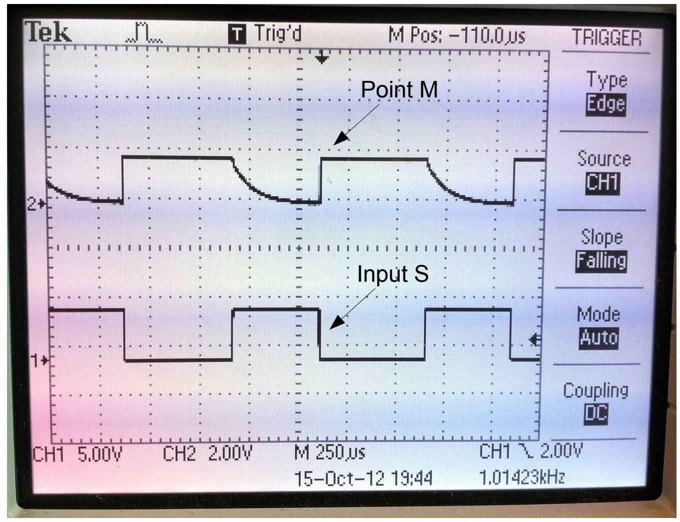


Fig. 10: Voltage difference at point M and input S compared to GND using D1=1N4148PH.

After fixing these issues (see next section), the signal at the output M was measured and is shown in figure 10.

C. *Analysis and Discussion*

The oscillation of the AND gate output signal was due to not well set "low" signal at the gates' inputs. The first draft missed out the resistors R$\{1, 2, 3\}$. It was assumed, that no input signal at a gate results in a "low" signal. For the here used AND gates, the "low" signal needed to be explicit connected to the ground. By using the resistors, the gates detected a "high" signal for closed switches. At the same time for opened switches the wire was set to a "low" signal as the resistors connected the wire to the GND. The resistors were chosen to be 100Ω. The choice of 18Ω worked as well, but the resistors got very hot and therefore got replaced by the 100Ω ones.

"Just" connecting the wires for LED2 turned also out to be a bad idea. A "high" signal at one of the wires was attenuate by the "low" signal of the other wire. Therefore, the two diodes D1 and D2 were added. This made the LED2 shine much brighter.

With these two changes, the shifter circuit was operating as planed.

The wave form measured for the point M in figure 10 was not expected. It looks like a discharge curve seen in a resistor-capacity circuit. However, the shifter circuit doesn't have any capacities at first sight. Replacing the diode D1 with a wire made the wave become rectangular. This indicated a correlation between the unexpected wave shape and the used diode.

The initially used diodes were of the type 1N4148PH. Replacing D1 with the type 1N40058912 changed the waveform's shape as seen in figure 11.

Trying to get an idea for this behavior, a simplified model was created as displayed in figure 12. The model reduces the LED to a diode. Every diode has a small inner-capacity with the order of pF. These capacities are added explicit in this model. The oscilloscope used to measure the voltage

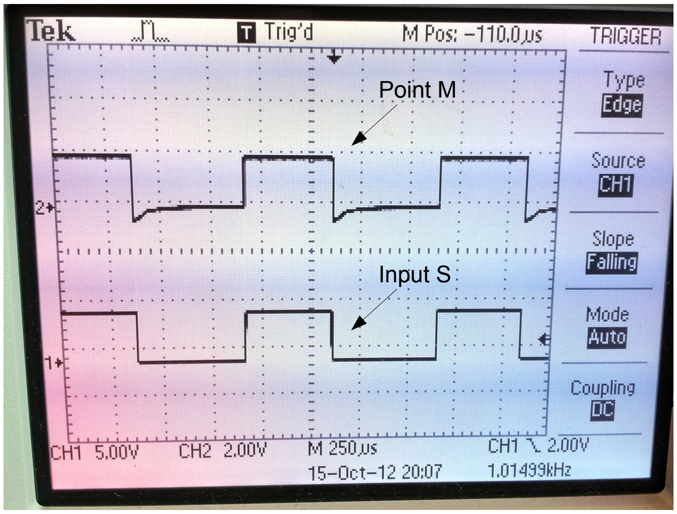


Fig. 11: Voltage difference at Point M and Input S compared to GND using D1=1N40058912

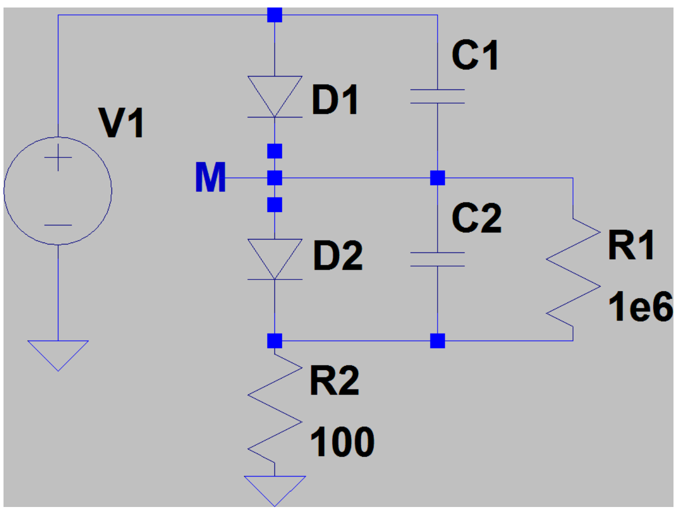
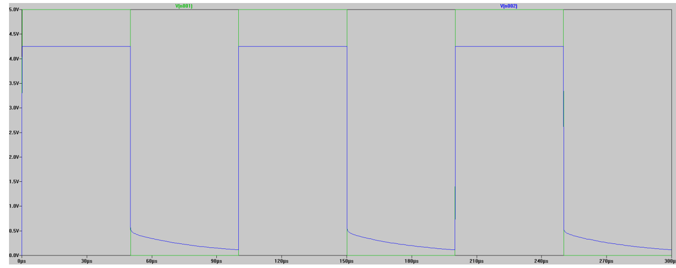
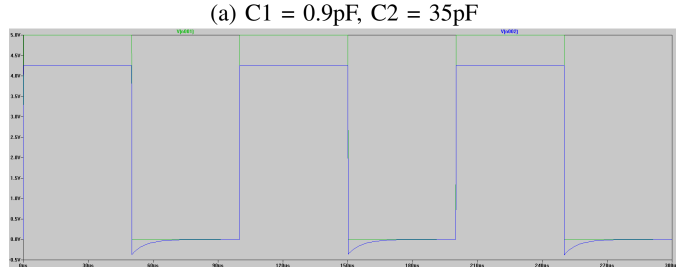


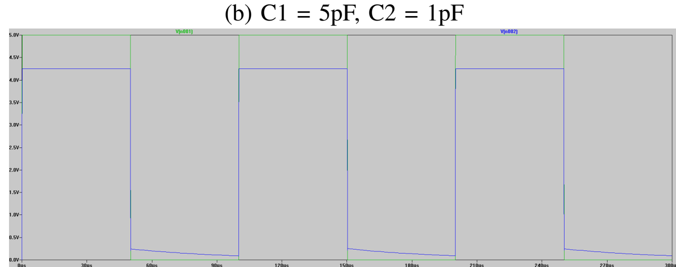
Fig. 12: Reduced circuit used for simulation.



(a) C1 = 0.9pF, C2 = 35pF



(b) C1 = 5pF, C2 = 1pF



(c) C1 = 15pF, C2 = 35pF

Fig. 13: Result running simulation for different choices of C1 and C2. Green curve: voltage of generator, blue curve: voltage at M; both compared to GND.

Component	Capacity
1N4148PH	0.9pF
1N40058912	15pF
LED (LTL-307GE)	35pF

Fig. 14: Used components and their capacities.

difference has itself a resistance of 1MΩ, which was included in the model as well. For different choices of the the capacity C1 and C2 the circuit was simulated and the results are shown in figure 13.

Looking at the used components' capacities as listed in figure 14, the capacities of the first and the last simulation match the used components. While the first simulation curve matches somewhat the shape of the measured curve in figure 10, the last simulation doesn't match the observed curve in figure 11. However, the measurement fits very well for the made-up capacities used in the middle simulation. The reason for this remains unclear to the author.

Without adjusting the diodes D1 and D2 a rectangular wave was possible to achieve by connecting M to GND using a resistor of 10kΩ. This follows the same idea as the resistors introduced at S, I1 and I2.

V. Conclusion

The experiments presented here showed some important property of digital circuits and how to measure those. Moreover, by doing a circuit from scratch, some of the issues designing a digital circuit were enlightened. Constructing a circuit requires understanding all the components. Otherwise things like the inner-capacity of diodes or the resistance of the measurement equipment might be forgotten to be taken into account. These can lead to unexpected behavior, which were relatively simple to hunt down in this setup, but are imagined to be much harder to find and control on larger circuits. Given that the here implemented circuit was simple compared to the circuits shipping with a computer/smartphone, it can only be imagined the hard work it takes to make large circuits operate precise.

The complexity even grows, as there are more and more components packed on a single chip and more functionality is covered by the same gadget. To achieve this minimization, the inner components got smaller and smaller over the last years. This cannot continue for too long anymore as physical limits are approached very soon. Future improvements might require to change from the digital circuits to circuits using light and/or quantum states.

References

[1] U. Tietze, C. Schenk *Halbleiter-Schaltungstechnik*. Springer, sechste, neue Überarbeitete und erweiterte Auflage (1983), pp 176-177