the 1960s

The Transition **from Tubes to Transistors** in Dutch Higher Education

Building "E-High" on the campus of Technische Hogeschool Eindhoven, The Netherlands, ca. 1968. At least one floor of the building was allocated to the Department of Electronics of the Faculty of Electrical Engineering. Photo credit: TU/e.

By Prof. Dr Piet Bergveld, MSc (*Em.*) and Dr Karel Kuijk, MSc (The Netherlands)

The authors of this essay, Karel and Piet, both studied at TH Eindhoven (now TUE) in the early 1960s. They both grew up tinkering with radios, amplifiers, and homemade pickups as a hobby. Then it was logical to study electrical engineering, which in those years meant designing and building analog systems with electron tubes, they thought.

The first year at THE was a disappointment for both of us, as no electronics was taught whatsoever in the freshman year. However, we did receive a solid foundation in mathematics and physics, as well as theoretical subjects on electricity and magnetism. Many years later, we discovered that this is what turned us into genuine engineers.

Electronics wasn't taught until the second year of the University program (i.e., after the propaedeutic year). The teacher of Electronics was Prof. Dr K.S. Knol, who thus finally taught us electronics and it was based on the use of electron tubes, as these were still mainly used in those days. Only at the end of our studies, some knowledge in the area of transistors was imparted to us — but that was a difficult changeover for both student and teacher.

Besides a general history of the conversion from tubes to transistors, we'll tell our own (anecdotal) experience of the transition in separate text boxes. Karel gained his knowledge and experience as an employee of the Philips Research Labs (NatLab) in Eindhoven, with a short excursion as a teacher at the HTS in Eindhoven. Piet became a scientific worker at the newly founded Technical University of Twente and experienced the transition from tube to transistor there.

Construction and Use of Electron Tubes

The simplest bulb or tube was the diode, consisting of a cathode and an anode. The fact that a cathode can emit electrons is based on thermal emission. This had been (re)discovered by Thomas Edison in 1883 by the phenomenon that his incandescent lamps, with a carbon filament, turned black at the inside of the glass balloon. The first practical application was by J.A. Fleming, who patented the electron tube in 1904 — basically a diode capable of rectifying alternating current.

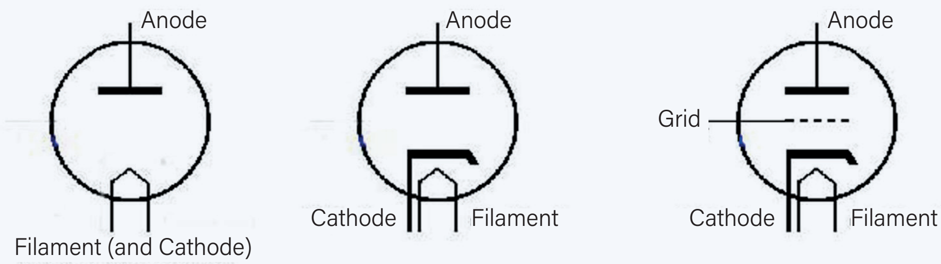
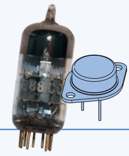


Figure 1: Symbols for a diode with only a filament, a diode with an additional cathode above the filament, and a triode.

First IC patent (Robert Noyce, Fairchild) 1961

Resistor-transistor logic chips introduced 1961

IBM Selectric typewriter 1961



A metal heated to a high temperature emits electrons. Richardson's law for current density of emission reads:

$$J = AT^2 e^{-W / kT} \qquad (1)$$

where J is the current density in A / m^2, k is Boltzmann's constant, T is the absolute temperature, W is the work function of the metal, and A is Richardson's material constant.

In 1907, Lee de Forest patented the triode he called "Audion", which allowed amplification. He mounted a grid between the cathode and anode. With a voltage on this grid, the electron flow from cathode to anode could be controlled or pinched off. That was the beginning of a lengthy development period of "amplifier lamps".

In order to reduce the excitation potential, and thus obtain greater current density, the filament was galvanically separated from the cathode and the cathode was coated with a layer with a low exit potential, such as a combination of barium oxide and strontium oxide, the so-called oxide cathode. A getter was inserted into the lamp to bind residual gases from the vacuum, visible as a mirrored layer. At Philips, this series of lamps was called "Miniwatt" because of the low incandescent current.

As the technology progressed, the lamp really became a tube, with an elongated cathode surrounded by the various cylindrically shaped grids and the anode. All constantly reducing tube size. In Figure 1 some tube symbols are drawn.

In addition, over the years a development took place with regard to the tube base. A series of at least 18 tube sockets arose, from the tube socket type 'B4' (4 pins) through, among others, the Octal socket ('IO'; 8 pins), which is still popular in amplifiers, and the Rimlock socket ('B8A'; 8 pins) to the Noval socket ('B9A'; 9 pins) which is widely used in the tube radios of the 1950s and 1960s.

In the process, the dimensions became increasingly smaller, in order to make the tubes more RF-capable and to simplify the manufacturing process.

Karel: *At the (oral) examinations, Prof. Knol was accompanied by Th. J. Weijers, MSc. He was known from the Handbooks of Radio Technology of Rens & Rens, the directors of the MTS in Hilversum. In the front section of those manuals the text: "With the cooperation of Th. J. Weijers MSc." was prominent. If as a student you drew a triode as a cathode + grid + anode during the exam, Weijers drew a balloon around it and said: "else the vacuum will escape!"*

Theoretical Explanation of Tube Operation

Improvements in the operation of an electron tube can only be obtained if one can formulate a theory for it allowing the parameters to be influenced by the construction of the tube.

The tube formulas for small signals are called the ***Barkhausensche Röhrenformel***, after the German physicist Heinrich Georg Barkhausen who formulated them. In German, an electron tube is an *Elektronenröhre*.

Barkhausen described the tube sensitivity in terms of steepness S (German: ***Steilheit***) and feedback μ of the anode voltage on the anode current, as well as the relative impact of the anode voltage D (German: ***Durchgriff***), where $D = 1 / \mu$:

$$I_a = S\,(v_{gk} + 1 / \mu\, v_{ak}), \qquad (2)$$

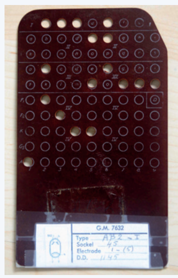
where I_a is the anode current, S is the "steepness" in mA / V, v_{gk} is the grid voltage relative to the cathode, v_{ak} is the anode voltage relative to the cathode, and μ is the feedback.

The internal resistance of the tube is:

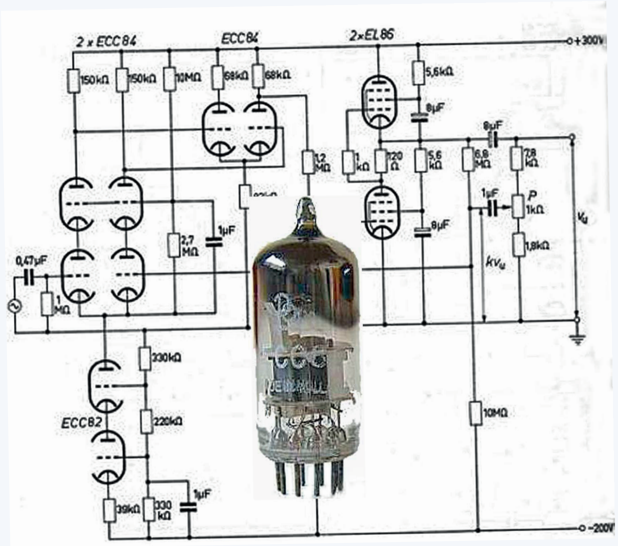
$$R_i = \mu / S \qquad (3)$$

In English, the device is called a ***valve*** or ***electron tube***, while the term "steepness" changes into ***transconductance*** or ***mutual conductance*** denoted by g_m.

The properties of a tube must be extracted from its datasheets, or measured. Many tube testers have been sold in the past, ranging from simple emission testers, which only check if the filament is not interrupted, if there are no closures between the electrodes, and if there is an anode current flowing, right up to comprehensive testers that can also measure the steepness. A simple emission tester was the Philips Cartomatic, which was usually found at electronics shops to quickly gauge a tube for clients.



In industrial, university, or college laboratories, British "AVO" tube testers, among others, were popular because they allowed complete tube characteristics to be measured, albeit by hand, which was a time-consuming task. But as a student assignment, it turned out to be very useful to gain insight into the functioning of a tube.



The circuit properties of tubes, using formula (1), is superbly explained and exhaustively treated in the textbook *Instrumentele Elektronica* (English translation: *Professional Electronics*) by G. Klein and J.J. Zaalberg van Zelst[1]. They preferred to use *dual triodes*, i.e. two triodes in one glass balloon, with as closely matching properties as possible, such as the Type ECC84. With that, they made difference amplifiers: two triodes with the cathodes interconnected, with a current source (single triode) or a resistor inserted in that cathode lead. That was the basic building block of Klein and Zaalberg van Zelst's circuits.

Zaalberg and Klein preferred triodes because their cathode current and anode currents are exactly equal. Unfortunately, the feedback μ is not that large at about 100 to 150, meaning the internal resistance R_i of a triode is not particularly high. By using a cascade circuit, which has two triodes in series, the feedback becomes really small, so the internal resistance is high. The circuit then becomes more like a real current source (i.e., having infinite internal resistance).

Another solution for obtaining a high output resistance on a tube was invented in 1926 by B.D.H. Tellegen MSc, an employee of Philips Research. During his research on triodes and tetrodes, he invented the pentode. A tetrode had an unstable region in the current/voltage characteristic of the anode. By adding an extra grid ("braking grid") at zero potential between the screen grid and the anode in a tetrode, the instability disappeared and an electron tube with a high μ was obtained — virtually the ideal current source.

However, a pentode does not have exactly the same current in the anode path as in the cathode path, because the screen grid, at a high positive potential, also captures or scavenges electrons. And it is precisely the equality of these currents that can be used in accurate analog circuits, hence the preference for triodes in high-precision electronic circuits.

Zaalberg and Klein preferred to draw a circuit with the positive voltage rail above and the negative voltage rail below, with the system ground in between. The currents then always flow from top to bottom, making the thought process much easier.

One disadvantage of using tubes was their power consumption, heat generation, and cost, among other things.

Piet: *During my vacations, I often worked at the local "radioman" Jan Timmermans in Appelscha. Jan not only sold radios but also built amplifiers which he used to rent out sound systems. In this way, he took care of the sound in the local open-air theater. And if he could not do it himself, Piet was permitted to do it, with the explicit instruction that nothing was allowed to be destroyed, because the tubes were too expensive for that. The best amplifier was equipped with an output stage with four EL34 tubes to get enough power. At a gig where the Dutch comedian André van Duin performed, then still as a band parodist, things almost went wrong. André had the habit of wandering around with the microphone, but it was fixed to a stand. He kept hitting the stone floor, causing the power tubes to rhythmically become red-hot. The current is so high that not only the cathode but also the anode becomes red-hot, with dramatic consequences. André did not react to Piet's request to stop moving the microphone, so Piet switched off the amplifier. How did it end? We are both still alive! But I never see André hauling a microphone complete with its stand anymore.*

The Transition to Transistors

From the above, it will be clear that there was a need for amplifying elements much smaller in size than the existing tubes, that did not get as hot and were cheaper to produce. If you then think of a solid-state alternative with the idea of the triode in the back of your mind, you soon come up with a piece of (semiconductor) material that acts as a resistor and on which you devise a "pinch-off" mechanism. This could possibly be done by applying an electric field perpendicular to the direction of the current. Then you obtain an electronically controlled resistance and in effect, you have devised a field-effect transistor. And so it went.

The first attempt to make a solid-state amplification element was made by J.E. Lilienfeld. In 1925, he first described the principle of a *field-effect transistor* (FET). However, because he did not possess a semiconductor material of high purity, he did not succeed in making a working transistor. On January 28, 1928, he did receive a patent though for an amplification element resembling a field-effect transistor.

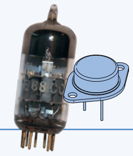
The terms cathode-grid-anode now become source-gate-drain — not illogically chosen designations for what actually happens in the new element. However, it takes many years to master technology to fabricate pure semiconductor material from e.g., germanium or silicon to make working FETs.

1 This book is still in use as a standard work by tube enthusiasts, like members of the NVHR (Dutch Association for the History of Radio) and the NFOR (Dutch Forum for Old Radios).

IEEE founded — 1963

Philips releases first cassette tape (invented by Lou Ottens) — 1963

President John F. Kennedy assassinated — 1963



On December 16, 1947, Walter Brattain and John Bardeen pricked three gold wires on a germanium crystal at the Bell Laboratories. They sent a current through it and discovered that the current could be amplified. They had invented the point-contact transistor. The word *transistor* was coined by their colleague J.R. Pierce, as a contraction of the words *transconductance* and *varistor* (variable resistor). Later, this construction of p- and n-type semiconductor was called the bipolar transistor, whose operation, however, had yet to be described. The names of the three connections were now also changed, namely emitter, base, collector.

Professors and scientific staff in our student days knew a lot about the physics and technology of tubes, but little about the physics and circuit properties of bipolar junction transistors. At that time, there were no JFETs or MOSFETs whose operation was in fact easier to understand.

It was also difficult for students to understand exactly what was happening in the transition from the p-layer to the n-layer in a semiconductor diode. And even trickier was what was going on in the thin base of an npn or pnp transistor. The first transistors were based on germanium. Because of its lower leakage current, silicon was soon used primarily for transistors. You had to learn to think in electrons and holes (never heard of them in tubes!) and then also as minority or majority charge carriers.

We did manage to make our own germanium diodes in the third or fourth year during a practical course in Materials Science. Although our devices were contained in a glass tube alright, that did not help us to comprehend how a bipolar transistor works. **Figure 2** shows the symbols for npn and pnp transistors.

And it didn't help much that the bipolar transistor (born of necessity?) was described as a kind of black box with an input current, respectively input voltage and ditto output quantities. This resulted in four parameters permitting the transistor to be described, but unfortunately without any relation to physical parameters.

In his lectures, Prof. Knol discussed *Y-parameters* and *H-parameters* for transistors, without explaining exactly when you should use what in which situation. That, in turn, depended on how the transistor was used in a circuit: grounded-emitter, grounded-base or grounded-collector.

Y parameters are *admittance* (i.e. the inverse of *impedance*) parameters, *H parameters* are hybrid parameters. Both types can be used for any linear four-pole (or two-port), so for example for a transformer, but also for a transistor or a gyrator. Hence, this approach was taken; see **Figure 3**.

The equations for *Y-parameters* are:

$$I_1 = y_{11}V_1 + y_{12}V_2 \quad (4)$$
$$I_2 = y_{21}V_1 + y_{22}V_2 \quad (5)$$

The equations for *H-parameters* are:

$$V_1 = h_{11}I_1 + h_{12}V_2 \quad (6)$$
$$I_2 = h_{21}I_1 + h_{22}V_2 \quad (7)$$

The problem for users is that this description does not have any physical background, and the professors and scientific workers did not know how to deal with that either.

Prof. Dr J.J. Zaalberg van Zelst and Prof. Dr G. Klein did come up with a physical method to describe the circuit parameters of a transistor, in the way Barkhausen had done for tubes and used in their book. They wrote the equations for small signals in a transistor as:

$$i_c = S(v_{be} + 1 / \mu \;\; v_{ce}) \quad (8)$$
$$i_b = S / \beta(v_{be} - 1 / \mu' \;\; v_{ce}) \quad (9)$$

The properties S, μ and μ' follow from the physical properties of (bipolar) transistors. Thus, the equations for the collector current and base current of a transistor work out as:

$$I_c = I_0\,(e^{qVbe\,/\,kT} - 1) \quad (10)$$
$$I_b = I_0 / \beta\;(e^{qVbe\,/\,kT} - 1) \quad (11)$$

Where *k* is Boltzmann's constant, *q* is the charge of an electron, *T* is the absolute temperature, and V_{be} is the base-emitter voltage. At room temperature, for silicon transistors, V_{be} is ~700 mV and kT / q = 25 mV at 17 °C so that I_0 is of the order of 10^{-15} A.

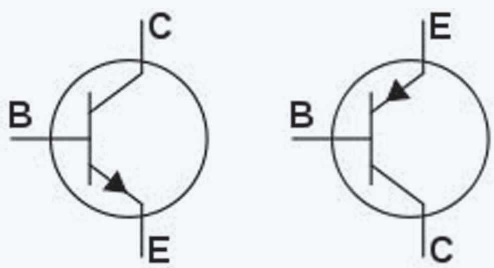


Figure 2: Symbols for npn and pnp transistors.

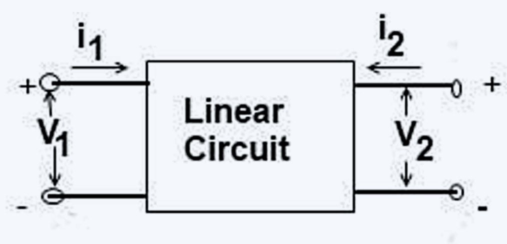


Figure 3: Linear four-pole showing currents and voltages.

Mouser Electronics founded 1964

AT&T's Picturephone demo at the 1964 New York World's Fair 1964

Moore's law 1965

Thus, in almost all practical cases, $e^{qVbe / kT}$ greatly exceeds 1, so that we can write:

$$I_c = I_0\, e^{qVbe / kT} \qquad (12)$$
$$I_b = I_0 / \beta\, e^{qVbe / kT} = I_c / \beta \qquad (13)$$

De steepness S then equals:

$$S = (dI_c / dV_{be})_{Ic=c} = q / kT\, I_0\, e^{qVbe / kT} = qI_c / kT \qquad (14)$$

It follows that for the input sensitivity at room temperature S = 40 mA/V at 1 mA collector current. The current amplification factor β from base current to collector current is about 100 to 300.

The use of these physical parameters makes working with bipolar transistors much simpler and easier to understand. As a result, this method is widely accepted.

Piet: *After graduating with Zaalberg and Klein at Philips' Natlab (in the so-called Badgang - bath corridor - at Strijp S), I started working at the THT (now TU) in Enschede. There were two chairs of Electronics established: Electronics I by Prof. C. Rodenburg MSc who focused on electronics sec and Electronics II by Prof. M.P. Breedveld who focused on the application of electronics, especially in the field of Medical Engineering. I began to work for the latter. At the Natlab I had also been working on ECG amplifiers, specifically on replacing tubes by JFETs in existing designs without degrading the properties. I noticed that students were having trouble understanding the black-box approach they were taught at the other Electronics chair, and one of the first reports I wrote, along with our engineer Gerrit Bultstra, was titled, "Transistor parameters versus transistor circuit parameters." I showed that if you "look into the emitter" of a bipolar transistor, you will see an impedance of 1/S, in the base that is β / S, and in the collector μ / S. With this simple knowledge, you can easily build any circuit you want.*
By the way, for my first assignment, building an amplifier for measuring brain activity in neurosurgeon Dr G.J. van Hoytema's Parkinson's disease project, I could not use bipolar transistors because of the high input impedance required. Good JFETs or MOSFETs were not available at that time, so I was forced to go back to the tube era. The smallest tube at the time was a so-called nuvistor, a mini-triode in a small metal case. Then a not yet mentioned disadvantage of the use of tubes appeared: the susceptibility to vibration or "microphonics". Mounted to the stereotactic device on the patient, I registered more of a tremor signal than brain action potentials through an intracranial electrode. This problem, fortunately, could be solved with a more flexible coupler. Subsequent application of suitable transistors obviously solved this problem as well.

Karel: *I graduated under Prof. Knol. During my graduation period, J.H. van den Boorn MSc supervised me. During that period, Knol became ill and he passed away before I graduated. Prof. Knol was succeeded by Prof. Zaalberg van Zelst when I had already graduated.*

After my graduation, I started working at the RadioApparaten-Lab of Philips in February 1964. I did not like that very much. My friend and fellow student Piet Bergveld graduated in Klein's group at the NatLab, from which Zaalberg van Zelst had just left as a freshly appointed professor at THE. Piet told me that the electronics practiced in "his group" was just the thing for me. With some difficulty, I managed to get into Klein's group, where I started on December 1, 1965. My first job was to correct the proofs of the book by Zaalberg and Klein. In the process, I even removed an error from a publication they had cited. The result was that Klein would occasionally stop by and say, "I've written something again. Would you like to check it over? I need another nitpicker," and he would walk away laughing loudly. After that, I corrected the English version together with a roommate (who was also a year mate).

Professor Zaalberg van Zelst introduced the physical circuit equations for (bipolar) transistors immediately after his appointment to the Chair of Electronics at THE. The scientific staff embraced this method, it went down very well!

J.H. Gits MSc and J.H. van den Boorn MSc of the Chair of Electronics then produced textbooks on electronics for higher vocational education (Dutch HBO), based on the equations with physical parameters.

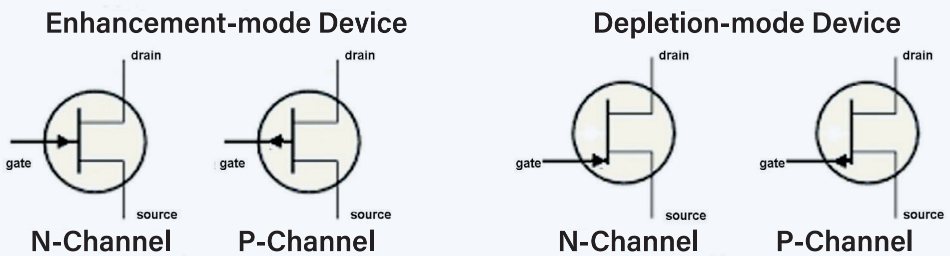


Figure 4: The circuit symbols for JFETs.

PDP-8 minicomputer invented — 1965
Amateur Computer Society PC club — 1966
IBM creates floppy disk — 1967

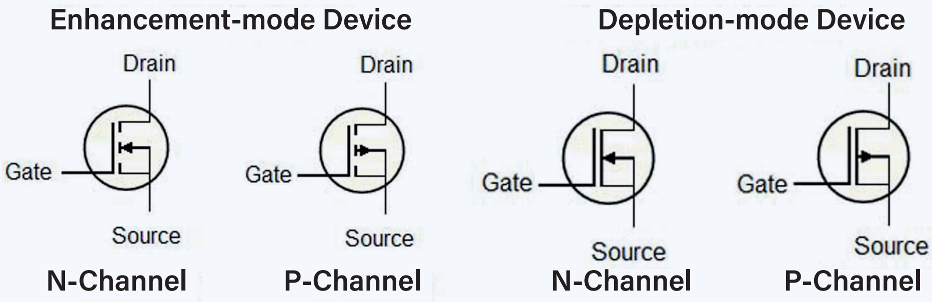


Figure 5: The circuit symbols for MOSFETs.

Karel: *When I was a teacher at the HTS in Eindhoven from 1975 to 1976, the book Electronic Circuit Design by D.J. Comer was used in the second grade. The book also started with semiconductor physics. The students made it abundantly clear that they didn't like that stuff about holes and electrons. They wanted to learn about circuits.*
I wanted to use the Gits and van den Boorn textbooks in my classes but my Electronics co-teacher was so used to the Comer book that he didn't dare make the switch. The new books weren't on the curriculum until after his retirement.

Later, the Junction Field Effect Transistor (JFET, Bell Labs, 1953) and the Metal Oxide Field Effect Transistor (MOSFET, Bell Labs, 1959) were realized. The circuit equations with physical parameters are also very suitable for this purpose.

The use of transistors changed the Electronics profession tremendously. Tubes were expensive, especially the professional dual triodes. Passive components, such as resistors and capacitors, were much cheaper. There was therefore an attempt to design a circuit with as few tubes as possible, also because tubes broke down sooner than passive components due to the high temperature of filament and anode, which limited the design possibilities considerably. The advent of transistors changed that radically: being inexpensive, they could be used in much larger numbers in a circuit. While in tubes only an electron current can flow, in bipolar transistors, JFETs and MOSFETs both electron currents and "hole" currents can flow. A great deal of design freedom emerged because, in addition, there are bipolar npn and pnp transistors, n-channel and p-channel JFETs, and n-channel and p-channel MOSFETs. In addition, there are enhancement and depletion JFETs and MOSFETs. See **Figure 4** for the symbols of junction FETs, and **Figure 5** for the symbols of MOSFETs.

The MOSFET has found tremendous application, especially in digital circuits, as we notice daily in the use of smartphones, tablets and computers. The world seems to have gone digital. But it is not; the world is analog.

In an electronic system, which is in contact with the outside world, a sensor or transducer is needed at the beginning of the system, which must accurately capture the signals from the outside world, after which accurate analog amplification first takes place. Only after that has been done can the amplified signal be converted into digital signals using an Analogue-Digital (AD) converter. Then the processing of the signal can take place, which can be done digitally much more accurately, error-free, and more complex than in analog fashion.

At the end of the chain, things in the outside world usually need to be controlled, such as an oxygen pump, an engine or a Liquid-Crystal Display. This means that the digital signals have to be converted back into analog signals.

The analog front-end and the back-end of an electronic system communicating with the outside world will therefore always remain analog.

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Karel Elbert Kuijk (1940) completed his MSc study at the Technical University Eindhoven, the Netherlands, and subsequently worked at the Philips Radio Laboratory, Philips Oscilloscopes and Philips Research. For one year, he was a teacher at the HTS (Higher Technical School) in Eindhoven. Within Philips Research he worked on tuneable lock-in amplifiers, function generators, RC oscillators, analog ICs, thin-film recording heads, magnetic bubble memories, CCDs, electroscopic fluid displays, LCDs and LED displays. The last years before his retirement he worked on active-matrix LCDs with plastic transistors. He received the bronze, silver, and gold medals from Philips Research for respectively 10, 25 and 50 US Patents. In total, he holds 65 US Patents and he has 23 publications in his name. He retired in December 2000 at which time he was Senior Research Fellow and Vice-President of Philips Research. He was appointed Officer in the Order of Oranje Nassau at his retirement.

Piet Bergveld (1940) received the MSc degree in Electrical Engineering from the University of Eindhoven, The Netherlands, in 1965 and his PhD degree from the University of Twente in 1973. In 1984 he was appointed as Full Professor in Biosensor Technology at the University of Twente. He became famous through his invention of the ISFET as well as many other types of Si sensors, developed together with 35 PhD students, resulting in 450 scientific papers. In 1995 he received the Jacob Kistemaker Award and in 2002 the Microsystems Leadership Award. In 1997 he was appointed Member of the Royal Netherlands Academy of Arts and Sciences and received the Knighthood of the Dutch Lion in 2003, the year of his retirement. Since then he is active in the field of organ-on-a-chip.

Kubrick's 2001: A Space Odyssey 1968
Sony Trinitron cathode ray tube (CRT) introduced 1968
Unibus 1969
First ARPANET message 1969