MOORE'S LAW AND BEYOND –
CONTINUITY AND INNOVATION IN MICRO AND NANO-ELECTRONICS
Perspective of two different generations

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Abstract. This paper is, in a certain sense, a dialogue between generations. More precisely, the authors are describing in parallel how do they view the evolution of electronics based on semiconductor technology along the last decades. Then, each of them is presenting how the profession of an engineer working in this field has evolved since the first integrated electronic circuits have been fabricated. They are spanning the period $1965 \div 2020$, corresponding to the rise and fall of the famous Moore's law, in fact an empirical relationship predicting (up to a certain point) the fast increase of complexity of digital integrated circuits. These tiny components have been providing the hardware support for digital information technology, fostering the third industrial revolution, based on computers, automation and communications. Today technology continues to evolve, requiring immense investments and a tremendous multidisciplinary effort, as we are speaking about digital transformation and the fourth industrial revolution (*Industry 4.0 concept*).

Keywords: microelectronics, nanoelectronics, Moore's law, microsystems, semiconductor industry, computer simulation, cyber-physical systems, interdisciplinarity.

Rezumat. Această lucrare este, într-un anumit sens, un dialog între generații. Mai precis, autorii descriu în paralel cum văd evoluția electronicii bazate pe tehnologia semiconductoarelor de-a lungul ultimelor decenii. Apoi, fiecare dintre ei prezintă modul în care a evoluat profesia de inginer care lucrează în acest domeniu de când au fost fabricate primele circuite electronice integrate. Prezentările se întind pe perioada $1965 \div 2020$, corespunzătoare creșterii și căderii faimoasei legi a lui Moore, de fapt o relație empirică care prezice (până la un anumit punct) creșterea rapidă a complexității circuitelor integrate digitale. Aceste mici componente au oferit suport hardware pentru tehnologia informației digitale, favorizând a treia revoluție industrială, bazată pe calculatoare, automatizări și comunicații. Astăzi tehnologia continuă să evolueze, necesitând investiții imense și un imens efort multidisciplinar, deoarece vorbim despre transformarea digitală și a patra revoluție industrială (conceptul de *Industrie 4.0*).

Cuvinte-cheie: microelectronică, nanoelectronică, legea lui Moore, microsisteme, industria semiconductoarelor, simulare computerizată, sisteme cibernetice, interdisciplinaritate

Contents

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A. Computing using electronics: basics of digital technology (DD)

Beyond any doubt, we are living now in a world dominated by technology. For passing from one industrial revolution to the next we do not have to wait for centuries, but decades. Digital technology has a very special role, and its evolution is explained below in very simple words.

For a long time, the humanity was looking at a machine able of computing. Mechanical versions had a limited capacity and speed. The first electronic computer (1943), based on vacuum valves, was using in fact electrical switches with two states, open and closed. The two states correspond to the two digits in Boolean algebra, 0 and 1. But representing numbers (usually written in the decimal system) in the binary system requires much more digits (and switches). Vacuum valve (the only electron device, at that time, able to be controlled as a switch) was too bulky, costly, energy consuming, unreliable) and it was replaced in the next decade by the transistor, fabricated in semiconductors. The major step, however, was using integrated circuits as building blocks of a computing system. An integrated circuit (using silicon as a semiconductor material) contained many transistors and their interconnects and was comparatively cheap, small, reliable and with low energy consumption. Thus, computing based on electron devices becomes really useful, supporting the space technology and placing the first man on the moon (1969). The today electronics uses a different type of transistor, a different silicon technology, and the performance of integrated circuits is so high that we are living in a completely different world. This is the *hardware* basis of digital technology. Honestly speaking, the *software* controlling the operation of hardware based on electronic technology is equally important, providing flexibility for various applications. Together, they are the basis of *Information Technology* (*IT*). Through computing, control (automation) and communications, IT was providing the basis of the third industrial revolution.

B. Impact of digital technology (MB)

We live in an era of tremendous progress mainly triggered by scientific and technical breakthrough. Unthinkable 50 years ago, the digital society is now a reality which expands its boundaries and meanings day after day. COVID-19 pandemic has only accelerated a process which was anyhow due to conquer the world in the decades (maybe, even, years) to come. Once a science-fiction concept, computers are now everywhere: in our cars, in our living rooms, on our desks, in our pockets, on our wrists. We surround ourselves with smart things: smart TVs, smart phones, smart watches, smart appliances, smart cars. We live in smart cities, work in smart factories. Everything is connected with everything in what became to be known as the Internet of Things (IoT).

What about people? How did they cope with all the fantastic pace of change that transformed their surroundings? More specifically, how did the people working in IT, in electronics, in computer science, in physics, chemistry or mathematics, in biology, anatomy or medicine, in all the fields directly responsible for the technological progress, deal with the breakthrough they have created? Were they 100·% responsible and can they be 100·% credited for the tremendous speed of the technical evolution they changed our lives? Did this evolution change the way R&D is performed, the way scientists interact with each other, the way they position with regards to their forerunners and to their followers? Is science history still relevant for nowadays scientific activities? Is there anything to be learnt from past experiences?

This paper aims to address these questions from the perspective of micro and nanoelectronics, based on the semiconductor technology of integrated circuits, mentioned above. Far from aiming to provide final answers, the authors wish to contribute to the debate launched by the previously listed questions. As the reality changes day by day, so do the possible answers. Sometimes, one should read work-in-progress as life-in-progress.

C. Moore's law (MB)

In April 1965, Gordon E. Moore, at the time Director of the Research and Development Laboratories in Fairchild Semiconductor division of Fairchild Camera and Instrument Corporation, published in the Electronics journal the paper "*Cramming more components onto integrated circuits*". The main thesis of the paper was that "*The complexity for minimum component costs has increased at a rate of roughly a factor of two per year […]. Certainly, over the short term this rate can be expected to continue, if not to increase. Over the longer term, the rate of increase is a bit more uncertain, although there is no reason to believe it will not remain nearly constant for at least 10 years. That means by 1975, the number of components per integrated circuit for minimum cost will be 65,000*". In 1975, Moore revisited his prediction, saying semiconductor complexity will double until 1980.

His statement became worldwide known as Moore's law. In plain English, Moore's law says that the number of transistors (most important and widely used electronic device) in an integrated circuit doubles every 2 years. Initially, this was a prediction. Throughout years, it became a target which made possible the incredible progress briefly described above (section B). We can now wear a smart watch, being as "smart" as a huge computer used to be half a century ago, because R&D people working in electronics, physics and chemistry managed to follow Moore's law and squeeze in millions and millions of transistors in smaller and smaller areas. Electronics became microelectronics and then microelectronics became nanoelectronics.

D. The rise and fall of Moore's law (DD)

The background of Moore's law (which is not a true scientific law, but an empirical prediction "law") is both physical and economical.

D.1. The physics of the integrated circuit

The devices and technologies of micro- and nano- electronics became totally different after the sixties when the Moore's law was launched (1965) and the first man was brought to the moon (1969). In 1971 we had the first microprocessor in MOS technology (developed by *Intel* company, US) and the microelectronic era begins. The key electronic device is the MOS transistor (i.e. a Metal-Oxide-Semiconductor capacitor with lateral contacts on a semiconductor surface), acting as a switch. You can shrink the dimensions of the device (reducing them in the same proportion), maintaining the same electrical performances. Another key feature: once the technological details are specified, all relevant dimensions will be found in a plane: the *lay-out* of the integrated circuit[3].

[3] It was soon apparent that you can design a complex integrated circuit focussing on the geometry of the *lay-out*, without knowing (or controlling) the technological details. Hence the *fabless companies*, companies just designing various integrated circuits with specialized software, without having direct access to fabrication. This approach was opening a wide field for innovation. It was also worthwhile to note that we need not only digital processors and

Reducing the dimensions by one order of magnitude is (roughly) reducing the area of the device by two orders of magnitude, that meaning that on the same surface you can concentrate 100 times more transistors[4]. This is the so-called *scaling*. The physical significance of the Moore's law is this process of scaling down the dimensions, while maintaining the electrical performances of individual devices, whereas increasing the complexity (and the performance) of the semiconductor chip (a piece of semiconductor packaged as an integrated circuit). The number of transistors in a microprocessor overcomes the number of inhabitants on our planet[5].

D.2. The economics related to the integrated circuit

The cost of processing is roughly proportional to the area of the semiconductor chip. Also, the area should be kept in certain limits, to control the reliability of fabrication and maintain the overall component (integrated circuit) reasonable small. That mean that you can increase the complexity (and functionality) of the integrated circuit by miniaturizing the transistor, still keeping the cost to reasonable values.

On the other hand, considerable miniaturization requires a huge increase of the cost of equipment, and therefore the cost of the fabrication facility. The increase of the cost of investments by orders of magnitude is justifiable only if you have a tremendous increase in the market for the integrated circuits. This was indeed happening. Therefore, there is an economic background of Moore's law.

Moreover, the investments cannot be done instantaneously (e.g. you have to design and construct new equipment, maybe based on new physical principles). Therefore, you need planning for years ahead. The major consequence of a credible Moore's law was the *Roadmap* for the development of the semiconductor industry. The microelectronics (conventionally starting with the first microprocessor, fabricated in MOS technology, 1971) became nanoelectronics, when the characteristic dimensions plunged below one tenths of micrometers (i.e. one hundred nanometres).

D.3. Limits of the Moore's law

There is plenty of room at the bottom: it is the well-known statement of the physicist Richard Feynman[6]. He wanted to say that in a solid material, as a regular lattice of very tiny atoms, the usual things could be fabricated at much lower dimensions. The microelectronics (electronic of MOS integrated circuits) was benefiting indeed from this perspective, but it was obvious that the miniaturization should be stopped when the atomic structure of the matter becomes relevant. The engineers anticipated that the progress predicted by Moore's law will be stopped by a so-called ***red***

memories, but also *analogue* integrated circuits, for communications and control. There is also *the other side of the medal*: we have today *silicon foundries*, companies focussed on fabrication. The best example is TSMC in Taiwan, with the most competitive technology in the world, readily accessible to leading companies launching new products. *The U.S.A. supported – including by public co-investment – the establishment and growth of GlobalFoundries to become (nota bene) the second largest foundry in the world.*

[4] These transistors should be however interconnected, by a number of metallization layers stacked on top of semiconductor surface (even 25 years ago you need 6 such layers), which means that you are building another complexity. Miniaturization also meant using new materials in MOS technology, an extremely wide front of progress.

[5] Again, things are not so simple. Complexity does not guarantee performance. The architecture of the microprocessor (i.e. rules of grouping and connecting transistors in order to process the information) is also important.

[6] Feynman, Richard P., *Plenty of room at the bottom*, talk at American Physics Society, Pasadena, C., Dec.1959, available at https://web.pa.msu.edu/people/yang/RFeynman_plentySpace.pdf.

brick wall. The end of the Moore’s law era was apparent when the Roadmap for semiconductor industry was no longer elaborated[7].

D.4. No future for a career of research in nanoelectronics?

This pessimistic approach was recently strongly counteracted by a team of world-wide specialists claiming that ***the crisis in semiconductors is false[8].*** However, to counteract the pessimism related to the future of nanoelectronics we have to plunge in a more complicated world. Let’s try!

What is really true is the fact that the extreme-ultraviolet lithography, the most advanced way to define dimensions in technology (the gate pitch – the length of the transistor, and the metal pitch) will slowly decrease to the limit in the next decade. However, we should not rely upon the initial concept of *technology node* (initially related to the gate length) since a number of things changed essentially in the nanoelectronics technology of the 21st century.

First, we are noting the fact that recent transistors have a 3D geometry, completely different from the traditional planar MOS transistor[9]. *Secondly*, there is a way to increase density of transistors by constructing them in tiers, because two layers of transistors might nearly double the density of devices (a research under development at IMEC, Belgium).

Finally, a more elaborated approach takes into account the progress in the digital technology as a whole. For computing you need processors, memories and interconnections between them. Providing connectivity between processors and memory is today a major bottleneck. Usually this was done at the package level, but in the last decade things are changing: we have now 3D chip-stacking technology with as much as 12,000 interconnects per square millimetre. We are not going to further details: the idea is that counting the number of transistors per unit area is no longer relevant for measuring the progress of semiconductor technology.

D.5. More-than-Moore electronics[10]

During the last decades, the electronics progressed also by interfacing digital circuits with the rest of the world. An electronic circuit (processing the information) interacts with the environment with *input transducers* (sensors for temperature, magnetic field, mechanical actions such as acceleration, etc.) and *output transducers* (or actuators). **A microsystem** is integrating transducers and the processing electronics. This integration can be monolithic (in a single chip) or hybrid, in a single package. We have for example micro-electro-mechanical systems (MEMS). Mechanical properties of the material are preventing excessive miniaturization. The Moore’s law has no significance in this context. The same idea is valid for MOEMS (Micro-Opto-Electro-Mechanical Systems). The above components can be also fabricated using a (modified) silicon technology, but on a separate fabrication line.

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[7] The ITRS (or International Technology **Roadmap** for **Semiconductors**) was produced annually by a team of **semiconductor industry** experts from Europe, Japan, Korea, Taiwan and the US between 1998 and 2015. There is a European version of this roadmap (see https://www.nereid-h2020.eu/roadmap) but Europe is not the leading power in semiconductors. A quite recent report on the status of this industry can be found at https://www.semiconductors.org/wp-content/uploads/2020/06/2020-SIA-State-of-the-Industry-Report.pdf.

[8] Moore, S. K., There are better ways to measure progress than the old Moore’s law, *IEEE Spectrum*, August 2020, pp. 24-30.

[9] The latest generations of transistors (constructed in a 14 nm,10 nm and 7 nm process, 1nm = 10^{-9}m) are conceived as **FinFET** structures, which do not have a planar geometry, see https://en.wikipedia.org/wiki/FinFET.

[10] **Power electronics** (involving transistors and other control devices able to dissipate electrical power) has nothing to do with Moore’s law. Other semiconductor materials are preferred such a silicon carbide.

The relevance of microsystems (or micro-nano-systems) for the present digital technology can be exemplified as follows. We are considering an electro-mechanical switch for communications[11]. In radio–frequency applications you need resonant circuits. Commuting between different frequency bands requires commuting different resonant circuits using a *mechanical switch*. An ideal switch means ultralow electrical resistance when ON (contact established), very high resistance when OFF, very low power consumed for switching. We also need a tiny device, ready manufacturable, capable to switch very fast fairly high currents and able to withstand billions of commuting cycles. The latest challenge is to operate for hundreds of gigahertz (GHz) signals (well into the millimetre wavelength region). Such an ideal devices was targeted for twenty years by big research project across the world.

The solution is provided now by MEMS technology. The idea is to replace the relay switch using an electromagnet with a cantilever actuated by an electrostatic force (simply applying a static voltage). However, the challenge was to develop an alloy for cantilever able to withstand billions of bending cycles: this is simply mechanics and material science! It seems that the solution was finally found by US companies. Applications? Commuting between frequency bands in smartphones, especially in the 5G domains (with a huge market anticipated soon). Apart from applications in all professional equipment.

Finally, we are noting that the reorientation of competences in microelectronics towards the new field of microsystems was a chance for the survival of this domain in Romania[12].

D.6 Nanotechnology

Going at lower dimensions it is more and more difficult to fabricate conventional silicon MOS transistors, but also brings new opportunities such as using carbon nanotube or graphene devices (for computing), or oxide with ferrimagnetic properties (for memories, in combination with MOS technology). Of course, a tremendous effort of research and development is necessary in order to get performances. New horizons are related to molecular electronics, nanomagnetism and spintronics, nanooptics, nanooptoelectronics and nanophotonics, microsystems (see above) are becoming micro-nanosystems, with nanosensors and nanoactuators, including nanowire / nanotube sensors, resonators, and molecular actuators (not to speak about applications in chemistry and medicine). Therefore, nanoscience and nanotechnology bring a new era in research and innovation for many applications areas, including electronics[13].

E. People's laws (MB)

As presented above, Moore's law was at the origin of the technical breakthrough we are currently witnessing. It tremendously transformed electronics, making it one of the pillars of the digital era. But what happened to people working in electronics during the 55 years that have passed since Moore's original statement?

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[11] Zorpette, G., RF MEMS deliver the ideal switch, *IEEE Spectrum*, August 2020, pp. 8-9.

[12] Dascălu, D., Learning from the past: 50 years of research in microelectronics in Romania, *NOEMA*, XVIII, 2019, 339-354; Dascălu, D. (coordonator). *Şcoala românească de micro- şi nanoelectronică*, Editura Academiei Române, 2018; Dascălu, D., O fereastră spre viitor, *Academica*, Vol. XXVIII, iulie-august 2018, pp.72- 78; Dascălu, D., IMT Bucureşti, retrospectiva ultimilor 20 de ani de evoluţie, *Market Watch*, Nr. 184, mai 2016, pp. 26-28.

[13] Details at https://www.link2nano.ro/acad/FRMNE/informations/67-ieee-transactions-on-nanotechnology-t-nano.html.

E.1. Knowledge law

First, let us talk about a contradiction and introduce a paradox. On one hand, the degree of interdisciplinarity has exponentially increased[14]. Back in the 60·s, an engineer working in electronics R&D was mainly supposed to know electronics and to have some basic knowledge of physics. Nowadays, an engineer designing a novel electronic device, or a sensor needs to master electronics, physics, theoretical chemistry, applied chemistry, material science and, often, biology. Since the device has to be part of the *Internet of Things*, the engineer should know how to handle basic concepts in computer science, also. Talking to marketing people and understanding market needs are also compulsory tasks for a modern researcher.

On the other hand, the design, simulation, experimental work and optimization on a novel electronic device got more and more complicated[15]. Typically, the work is carried in an R&D group belonging to large multinational company, to a start-up or to a university. If part of the university, the work is more likely to be funded by a company or by governmental grants. In all these situations, there is a deadline and there is a budget, there is a targeted application and there is a market. All these aspects mean that the work needs to be done at the highest technical and economic performance standards as possible. "*Best technical values in the shortest time interval, employing the lowest financial resources*" seems to be the motto of nowadays R&D. All these require highly specialized personnel, mastering a narrow knowledge area, thus being able to come up with relevant results in no time.

The two tendencies describe above create a paradox. What do nowadays R&D departments want from their employees? To know something about everything or to know everything about something?[16] This is a work-in-progress dilemma. No clear, no definite, no general answers. Just constant adaptation to each particular situation, few best practices cases, much more trial & error situations.

E.2. Data & Speed law

Since Moore's law formulation (one would say Due to Moore's law formulation), we have the Internet and we have the personal computer (desktop, laptop, tablet, mobile, etc.). Compared to a researcher in the 60·s, a person working in R&D today has access to vast amount of data. Scientific papers, patent claims, product datasheets, market report, lecture notes, tutorials are all at a click-distance. Many of them free of charge, most of them accessible via subscriptions paid by the institution the researcher works for.

Due to the computational progress, a totally new field emerged: numerical simulation[17]. Should you work as an electronics device engineer in our days, then one of your best friends is the simulator. Gone are the days when costly, risky, hard to control experiments were the only way of trying to confirm the validity of a theoretical concept. Prior to any experiment, we have now the numerical simulators. Should the data provided by the simulations show encouraging results, then, and only then, experiments will be carried out. Based on their outcomes, new simulations will be run, and then new experiments will be performed, and so on. In Moore's early days, it used to be a

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[14] Walder, A. M., *Why Should Organisations Recruit Multidisciplinary Talents*, EU Business School, December 2019.
[15] Malone, T. W., Laubacher, R., Johns, T., The big idea: the age of hyperspecialization, *Harvard Business Review*, July-August 2011.
[16] Jackson, C., *The new engineering career choice? Hyperspecialization or system generalization*, https://www.lifecycleinsights.com/system-hyperspecialized-eng/, July 2011, Accessed: 3rd of Sept 2020.
[17] S.P. Rao (editor), *Numerical simulation in engineering and science*, IntechOpen, 2018.

duo: Theory – Experiment. In Moore's law's nowadays, it is all about the scientific trinity: Theory – Numerical Simulation – Experiment.

The Internet conquering the world led to a phenomenon called globalization[18]. We can all communicate instantaneously to each other, no matter how far we physically live from each other, at basically no cost. "We" – means also researchers. Should I read an interesting published by someone from a University in UK, I can contact the person via e-mail or LinkedIn or any other social network, introduce myself and ask my questions or share my experience in the same field or suggest a future collaboration or all the above. Looking at the world Moore's law has created, one can easily come to the conclusion that quality is important, price is significant, but speed is really everything. If part of a commercially agreed schedule, a company can afford to launch an expensive electronic device, with serious technical issues, but cannot afford not to launch the electronic device. Therefore, working as a researcher or a product development engineer in electronics comes with the obligation of being always in touch with what's new. More than that, if you are involved in the first stages of the process leading to a new process, you need to be in touch with what is going to be new. Staying connected with your peers, being they are part of the company and industry you work for or from the academia, is a must.

E.3. Country for old men law

Since so many things changed, in terms of man's laws, in the last decades, is there any need for the knowledge, experience, inputs of researchers in their 60·s, 70·s, 80·s? In other words, has nowadays science (electronics, in particular), became some sort of "no country for old (wo)men"? If I am a young PhD student working on a nano-scale transistor to be employed in a device that did not exist 5 years ago, do I really need to get in contact with someone that studied for his/her PhD in the years when digital era was mentioned only in SF novels?

Sir Isaac Newton said once, in a letter: "*If I have seen further, it is by standing on the shoulders of Giants*". Every time a researcher reads a paper or a patent, applies a formula, employs a numerical simulator, runs equipment for performing an experiment, he stands on the shoulders of all his peers who contributed to those papers, patents, formulae, simulators, equipment. Individually, they might not be giants. But their tiny, sequential contributions, perfectly integrated in the system we can call history of science, contributes to what an electronics researcher invents today. After the invention is transformed into a novel concept, product or process, this new tiny contribution becomes itself part of the science knowledge to be used by the researchers from tomorrow. And so on.

However, things are that obvious. It is true that an engineer from a technology unicorn[19] might believe that he only relies on his mind and on some state-of-the-art equipment. At the same time, a retired researcher might live under the impression that his expertise is futile, his old work is good for nothing, and the new science in the new world is something he cannot comprehend. Fortunately, both are wrong. Unfortunately, they might not realize this.

In fact, the dialogue between generations[20] is possible. More than that, it is essential. Few conditions need to be fulfilled. First of all, young and experienced researchers should have common

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[18] Branstetter, L. G., Glennon, B.M., Bradford Jensen, J., *The IT revolution and the globalization of R&D*, NBER Working Paper No. 24707, June 2018.

[19] Simon, J.P., *How to catch a unicorn*, European Commission JRC Technical Reports, 2016.

[20] Schmitt, E., Hinner, J., Kruse, A., Dialogue between generations – basic ideas, implementation and evaluation of a strategy to increase generativity in post-soviet societies, Procedia – Social and Behavioral Sciences, **12** (2011), pp. 300-310; Zurba M. et al., *Intergenerational Dialogue, Collaboration, Learning, and Decision-Making in Global Environmental Governance: The Case of the IUCN Intergenerational Partnership for Sustainability, Sustainability*, 2020, 12, 498.

scientific interests. Secondly, that should speak the same (scientific) language. Beyond abbreviations and fancy new terms, there still is a bit science that can be easily communicated and understood. Thirdly, rookies should reckon that, no matter how novel they appear to be, successful technologies they work with and they contribute to still follow some old life cycle patterns. They all lose money at the very beginning and market at the very end, no matter how spectacular their ascension. Finally, mature researchers should understand that keeping constantly updated with the scientific discoveries and technological breakthroughs is one of the most pleasant endeavors. Sometimes, even synonymous with youth.

Epilogue. Good old times (DD)

The semiconductor electronics has already passed in the era of the fourth industrial revolution (*Industry 4.0*), with fully automatized processes, without human intervention. The equipment pieces are interacting autonomously. In fact, the first application of IoT (*Internet of Things*) belonged to this industry. The ultra-clean environment cannot be perturbed by a human, even if he (or she) is protected by a special costume (like in a space ship). A simple particle of dust is a terrible enemy of the semiconductor technology.

A few decades ago, the semiconductor technology was directly controlled by humans, manipulating semiconductor wafers (where the electron devices and integrated circuits have been constructed), looking at the microscope to see the tiny structures etc. The interaction with the physical reality was more obvious; as well as the interaction between people. This was important for the learning process of new specialists, in a real environment. Sometimes, research was done within the semiconductor factory[21]. Today, even in a research institute, young people are sometimes tempted to hand-over their samples to the operator going into the clean room (for processing or testing). They can just collect the computerized results … and publish?!

This year, *Politehnica* University of Bucharest, accepted (before the *pandemic*) to replace the entry examination in physics, optionally, with one in informatics. This was reflecting the interest of young people graduating the high school. On the other hand, students form IT (Information Technology) faculties are more attracted to software jobs (they seem easier to perform, are better paid).

However, the progress in technology (electronics included) it is still related to the phenomena taking place in the physical world. The digital transformation using the cyber-physical systems is invading all domains of engineering. Before simulating phenomena with sophisticated computer programs, one has to interact with physical reality, develop models a.s.o. We are concluding: computing becomes essential for research and engineering. But it is not *Alpha* and *Omega*.

[21] Banu, V., Coteț, R., Dan, P., Dunca, T., Gheorghiu, V., Popa, E., Veron, A., Wild, A., *IPRS Băneasa Silicon Technology: Industrial Research and Development*, http://www.link2nano.ro/acad/RSMNE/IPRS_Baneasa_Silicon_Technology_Research_and_Development_v5.pdf.

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