Respect for Quantity

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1. Introduction

Let me start by making a comment about the title of my talk: Respect for Quantity. When I received the pre-print of the invitations I was horrified: they had turned it into "Respect for Quality". Now I have always been one to strive for quality. I have great respect for quality, who doesn't? But if I were to give a talk about quality, I would first have to define it. I'm not going to do that, because quality is subject to individuality. I am sure every one of you makes that definition every day, by the choices you are making when you buy clothes, drink wine or do research.

Now defining quantity is much more straightforward: my dictionary, for example, defines "quantity" as "a considerable amount". In my field of work, Silicon Integration Technology, this is something we can relate to. We run into very considerable amounts all the time and more often than not we find ourselves entangled in a web of activities all designed to tame this excess of quantity. This all reflects the fact that Silicon Technology is the first practical technology that manipulates and controls quantity all the way down to the atomic level and right up to the macroscopic scale where we lead our daily lives. Therefore, in my line of work: by tackling quantity we achieve quality!

2. Silicon Technology: the fragile link

Today everybody has some picture of what a chip is. In modern society chips are omnipresent and they have a profound and pervasive impact on every level of our daily lives - ranging for instance from small tagging chips, to personal computers, to communication satellites and even the whole organization of the national water supply. Modern warfare unfortunately also springs to mind. What we have been seeing in Iraq lately looks more like a highly complicated video game than old-fashioned combat.

And, of course, there is the ever-present Internet, yet another offspring of Silicon Technology. For example, to write this inaugural speech, I did not have to make one single trip to the library. In between preparing dinner, helping with homework and all the other important daily tasks that occupy your typical female professor, I could make detours to my computer and feed it with the appropriate search-words. Then I injected some key words into my semi-intelligent text-processor and there you are - this speech practically wrote itself! Well, not quite, silicon chips cannot as yet replace the human thinking machine, but to put it unambiguously: microelectronics is the principal driver of the modern Information Revolution and will surely continue to be so for quite some time.

Let's first put Silicon Technology into perspective. Technically speaking: Silicon Technology is an enabling technology, in which we build the integrated circuits or microchips that are so popularly just called .chips.. Let me sketch a diagram that illustrates more clearly where Silicon Technology belongs in the order of things (Figure 1). To do this I will attach some key numbers and quantities to the different elements in the diagram:

gigahertz speedsX-ray data stored in hosp

nanotechnology, nano-electronics,
quantum devices

data produced worldwide/year

total # transistors shipped/year

data in all US academic libraries

ital data in
short story

0. 000000001

Silicon Integration Technology

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10^{24} YOTTA

10^{-9} NANO

10^{-6} MICRO

10^{3} KILO

10^{6} MEGA

10^{9} GIGA

10^{12} TERA

10^{15} PETA

10^{18} EXA

10^{22} ZETTA

megabyte memories

atoms in living organisms

known stars in all galaxies

Figure 1: Silicon Integration Technology put into perspective.

These days the dimensions of the components in a chip are often in the order of a micron, making the total dimensions of a chip in the order of a millimetre to a centimetre. Typically a chip today will contain something like a million transistors. Over the years the components of the chips have been getting smaller and smaller, allowing higher and higher speeds of data treatment and more and more data storage. A typical computer memory chip size is megabytes. Typical speeds of data treatment and data transmission today are megahertz and gigahertz. The access to this enormous speed and capacity for data transmission and storage is what has made the whole Information Revolution possible.

A very interesting survey is now running at the University of California at Berkeley. They are trying to examine and estimate the total amount of data that is being processed on a world basis [1]. Among other things they have found that a large hospital records and stores X-ray films equivalent to terabytes of data. The contents of all the US academic research libraries amount to petabytes of information. The amount of data produced worldwide in one year is yet another magnitude . it ranges between 1 and 2 exabytes of information.

For quantities in the zetta-, yottabyte range complex co-ordinated systems have already existed for billions of years: bugs and animals contain about this number of atoms. The fascinating thing is that each and every atom has its own special function and contributes in its own special way to make the whole thing work. So biological systems are endlessly more complicated than any system ever built by man. But since, of course, they do not really lend themselves to our purpose, which is absolute control, it is nevertheless very interesting to build our own man-made systems on silicon.

And this is the point that makes Silicon Integration Technology so special: **for the achievement of successful chip integration an enormous amount of processing steps are brought together so that both on the atomic level as well as on the macroscopic level the results remain controllable, reproducible and predictable!**

This means that not only every tiny building block must be controlled but just as importantly the process of joining up the building blocks to form a chip must be minutely controlled. The price tag for this level of control is almost as impressive as the feat itself. To build and operate a modern integrated circuit fabrication cleanroom, an IC-fab, the costs run into the billion euro range. Each fab is a very finely tuned operation. The whole cleanroom environment and every single step of the chip fabrication process, and that may be as many as 400, is constantly being monitored, and often in real-time. And that includes all sequences of process steps and every end product. Potential problems must be isolated and alleviated before they become yield killers. This takes a lot of data processing. I was disappointed that the Berkeley survey did not specifically include IC-fabs. I.m sure that if .consumption of information. contours were to be drawn over the earth.s surface, very prominent peaks would appear at the locations of modern silicon chip factories.

Now to complete my diagram, I will go beyond the important place that chip-related products have taken in our daily lives. Silicon Technology has also changed the way we do research. It has provided unprecedented large computational capacity and has been a driver for the development of processing and diagnostic tools that make the manipulation of single molecules a reality. When I now place the term .nano., a lot of you will straightaway make the association to nano-technology. This has become a very popular term over the last few years to describe any type of research where the characteristic dimensions are less than about 1,000 nanometers. In Silicon Technology we have been working at those dimensions for more than 10 years. In some situations controlled 1-nanometer dimensions can now be fabricated. Such breathtaking accuracy depends on equally incredible equipment precision, and this equipment has made all sorts of manipulations on the nano-scale possible.

The father of this nano-movement is often quoted to be the Nobel laureate Richard Feynman, who in 1959 in his famous lecture .There.s plenty of room at the bottom. gave birth to the idea of building miniscule machines atom by atom [2]. He also, importantly, made the inevitable observation that controlling and manipulating atoms to make small things is fun but only becomes interesting to real life when you actually can do something with it, that is, if you can put a small device to actually do some work for you. In order to make nano-sized contraptions do work that actually makes a difference on the macro-scale, a whole lot of them have to be created and they have to be created to work together. This is what has been achieved in microelectronics, so I think that the history has proven Feynman.s foresight to be correct. Today I would like to add to his observations by taking one more glance at this diagram and underline that no matter how much room there is at the bottom, there will always be a **lot more room** at the top. And at the moment Silicon Integration Technology is the only and, therefore, very fragile link to this world of wonders.

3. Life at the intersect

It also becomes overly clear from this diagram that a laboratory producing chips occupies a special position in the world today. From my perspective, as someone working in research on Silicon Integration Technology, it means working at the meeting point between two very different research worlds: on the macro-side the chip designers and on the submicron-side the material oriented researchers, in my case mainly physicists, using the discoveries in Silicon Technology techniques to open up their own frontiers.

I began as a physics masters student in the seventies and already then I was involved in Silicon Technology. As a member of a nuclear physics group I joined in experiments where radioactive atoms were used to identify defect configurations in silicon and other semiconductors. Basically nobody in the group knew very much or even cared about the electrical properties of these materials. But already back then I got a feeling of the wonders for silicon: even at that time the quality of crystalline silicon wafers was head and shoulders above the rest. For the first it was possible to comercially buy small 2 inch wafers of silicon and the material did not break or crumble as soon as you tried to do experiments with it, as was the case for all the other possibilities, even germanium and GaAs, which are the runners up for silicon.

Here I will allow myself a couple of words about quality: you cannot work with silicon without being amazed by the properties of the material, particularly the material that.s on the market today. In wafer sizes up to 300 millimetres (in DIMES we work with a modest 100 mm size) you have near atomic flatness and purities that permit only one non-silicon atom out of every ten billion atoms of silicon. All this, combined with wonderful electrical properties, is at the heart of the matter. There is nothing else like it.

From working on purely material aspects of silicon I went on to work with silicon devices, first with Thomson CSF in St. Egrève, Grenoble, and then in the IC-Atelier in the Department of Electrical Engineering of this esteemed university. The IC-Atelier had started producing chips in 1976 and was quite typical of the cleanrooms of that time [3]. With a handful of technologists and equipment that fitted into a medium sized Dutch house you were able to run a quite reasonable silicon process. There were two driving forces for our lab: research on analogue electronics and on silicon sensors. These two directions have marked the Delft silicon integration research to this day.

In 1987 an institute for microelectronics, DIMES, was founded in Delft. A class 100 cleanroom, the DIMES IC-Processing lab, was included with the goal of running complete chip processes, which, with great success, we are still doing today. This lab is equipped with state-of-the-art production apparatus as well as some special exploratory options. To make this affordable and profitable we have maintained a 100 mm wafer size and one micron lithography is the standard, although experimentally much smaller lateral dimensions are possible. So, unlike the mainstream digital technologies we do not hunt for performance from lithographic device size reduction, but look for the opportunities found in new methods of processing and applying the silicon. We have become quite unique in what we offer, and are a very popular source of research and silicon prototyping for countless universities and industries both in- and outside The Netherlands.

Contact with these many customers is part of my daily routine. More often than not my office bears resemblance to central station rather than a haven for academic research. All sorts of people run in and out: Train personnel with questions about their timetables, overbooking, obstacles on the tracks, faulty equipment, and passengers who want to know when the train leaves, arrives, they want reservations, last minute changes, and an endless amount of information on what.s possible. There is always a sense of urgency. Nobody wants to miss the train.

Passengers can be a pretty thankless lot. On the one hand, we have the circuit designers who are used to having almost everything they design for bread-boarding work. If they design a silicon chip it invariably works in the computer. If we make it in silicon for them and it does not work, you can be quite sure who they will blame first. And if something actually did go wrong in the processing, they readily get discouraged. The physics people on the other hand are surprised if they produce something that behaves like they expected it to and even more surprised if they can reproduce it. They have no idea what goes into

Figure 3: The IC-Atelier on the 4th floor of the Electrical Engineering building, in the beginning of the 1980's.

making even the most straightforward process step reproducible and repeatable. So basically they take what we do for granted and always expect it to be ready yesterday.

Part of our work is convincing our passengers that they should think with us, take part of the risk, give us feedback that helps with the process of stabilization, and by doing so take some of the work load. Building up workable relationships can be a long and tedious process. But we have noticed: no matter what problems and delays occur, the passengers keep coming. Why is this? Well, simply because they cannot afford a car. What we offer is unique and affordable. The big billion euro fabs are too expensive (both in money and time) and cannot permit themselves the flexibility most researchers need.

But on our side, why do <u>we</u> put up with the hassle of keeping all these people happy? We would be most content to concentrate on our own ideas and research aspirations. Well, there are a number of reasons:

For the first: it is exhilarating to see something you have created become much more than you could ever manage on your own.

Also: The interaction with the other research groups forces you to make connections that can be very enlightening. Their problems become your problems. The solution becomes your new process or research project. You interact, you learn, you create, and 2 plus 2 is then very often more than 4.

And of course: The DIMES IC-Processing lab may not be a billion euro fab, but it <u>is</u> expensive, not only in money but also in effort. This brings with it the responsibility of making it work and putting it to good use. So basically: our doors are open.

Figure 4: Early photo of the DIMES IC-Processing group and colleagues from the facility support group.

Figure 5: Impressions of the DIMES IC-Processing cleanroom and measurement laboratory.

4. What we do best

More specifically, my research is focused on fully-integrated bipolar IC processes [4, 5]. My students have projects that concentrate on some aspect of a process module or device that can be used in high-speed circuits, mainly with radio-frequency (RF) or microwave circuits in mind.

But, of course, there are many more applications for the IC processes and a wide range of students and researchers make use of them.
Because the demands on the integrated circuit processes are always quite diverse, part of my efforts over the years have been devoted to developing .low-cost. bipolar IC-processes. In the IC industry .low-cost. is much more than just a money saving gimmick. While .low-cost. in many other branches means cutting corners and delivering low quality products to the masses, to us it means .low-complexity.. Now .low-complexity. is a very strange way to characterize a process that may have 200 - 300 steps or more. It is, however, a way of expressing that each step in the process is doable and repeatable and that the total can be made within a reasonable turnaround time. In DIMES we pride ourselves with short turnaround times, about one month for standardized processes, which is short enough for a masters student to complete the entire cycle of designing, fabrication and testing. In contrast, for a university design in the hands of an industrial fab, you will easily suffer turnaround times of a year or more. Moreover, for us .low-complexity. means high flexibility.
The last process that I have standardized is called DIMES-04. The basic device looks like this (Figure 6). To give you a feeling of how important flexibility is in our research, I will go through a few of the ways we change DIMES-04 to try out new device and process concepts for RF and microwave applications. We take the standardized process and add a new technology step, for example advanced epitaxial chemical-vapor-deposition, to improve the device performance (Figure 6a) [6, 7].
The total process can also be run on special wafers, which may enhance the performance of other integrated components (Figure 6b) [8]. The device performance can be improved by shrinking the vertical dimensions to the nanometer range, such as done here by using silicon-germanium epitaxy and high-power excimer laser annealing. The latter is one of the new techniques being pioneered at DIMES (Figure 6c) [9, 10, 11].
The speed of the devices is also enhanced by replacing electrically conducting materials by isolating materials (Figure 6d) [12,13]. A new method of doing this is for example by transferring the silicon wafer to glass and removing the bulk silicon. A very small island of silicon is then left in which the transistor is made.
If all these new techniques are joined together in one process, we would achieve really exceptional performance with device speeds above the 100 GHz. And I know the circuit designers would love to get their hands on that. But here I have to make a point about Silicon Integration Technology. The more advanced it gets the tougher the struggle gets

Figure 6: Some of the research that is based on the standard IC-process DIMES-04.

to advance even more. A great Dutchman, Johan Cruijff, once said .Elk nadeel heeft zijn voordeel.: .Every disadvantage has its advantage.. In Silicon Technology we learn from bitter experience that it is usually more appropriate to say .Every advantage has its disadvantage..
The silicon-on-glass processing is a fantastic example of this. For us it has opened the way to eliminating electrical parasitics BUT: as fate would have it, this perfect electrical isolation is also a perfect thermal isolation [14]. The heat generated by the device itself cannot get away and the device destroys itself. This turned out to be such a great problem that we have spent two years studying it: a very unique study I might add because nobody else can make this sort of device. The main goal is of course to solve the heat dissipation problem without putting on heat sinks that replace the electrical parasitics that you very elaborately just removed. This has led us into a world of new materials for silicon: aluminium nitride, diamond, refrigerator systems with minute cooling channels .
Here again we run into the principle .Every advantage has its disadvantage,. because most new materials are not automatically compatible with Silicon Technology. The greatest culprit is stress. The new materials just pull or tug at the silicon until it breaks. This is of course if you can get them to stick on at all. And so I can name a long list of potential showstoppers. To dissolve

these, silicon technologists have developed intimate contacts with chemists and material physicists. And Silicon Technology has long been a great driver for research in these areas.
In the examples I just showed, we define the small piece of silicon in which we make the transistor by chopping away the silicon. This process creates damage and damage creates havoc also in the electrical characteristics. When going down to smaller device sizes it is therefore interesting to find new, non-destructive ways of defining the active silicon area. In a future project we will be trying out some special deposition methods. We already use such methods to grow atomically thin monolayers and next we will be trying to grown silicon nanowires (Figure 7).

Figure 7: Today the active device area is defined by chopping away silicon (left). Future research aims at using deposition techniques to grow nanowires (right).

5. Going to the limits

These were just are few examples of the special processing ideas that are realized in silicon at DIMES. Our main research directions, devices for analog circuits and smart sensors, are also special. More globally, the technology driver already since the 1970's has been digital circuits processed in CMOS (complementary metal-oxide-semiconductor field-effect transistor technology). While our own products contain anything from a handful to some tens of thousands of devices, a CMOS chip today will easily contain a million transistors. The increase in performance of CMOS circuits has mainly been a result of steadily shrinking device size. This phenomenon was expressed by the head of Intel, Gordon Moore, in something that is commonly called Moore.s Law (Figure 8). In 1965 he observed an exponential growth in the number of transistors per integrated circuit and predicted that this trend would continue. The doubling of transistors every couple of years holds true to this day because the gate length of the CMOS transistors keeps shrinking. Today the gate length is entering the sub 100 nm range and predictions for the coming years show that 10 nm lengths should be reached by 2020. In research, devices with 30 nm gate lengths are in experimentation and 10 nm gate lengths are the object of intensive simulation.
Ten nanometer is the length of a chain of about 20 silicon atoms, so it is not expected that gate lengths will decrease much further than that. This has led to the often quoted misconception that miniaturization of electronics based on silicon will end at this point. But really, in silicon we have only just scratched the surface.

Figure 8: Moore's Law (left) and minimum feature size versus time (right).
Taken from reference [15].

Miniaturization of electronics is not only dependent on the size of the individual transistor, but also on how the transistors are connected to each other. CMOS chips are fabricated in a very thin layer on the surface of the silicon wafer: it's a two dimensional thing. But new exciting ways of treating the silicon are emerging and opening the way to <u>three dimensional</u> integration. For example with the substrate transfer processing that we are researching in DIMES, you can imagine that the circuit produced in the thin top layer is transferred and joined to a circuit on another wafer. And these two joined circuits could be transferred to yet another circuit on another wafer and the whole process can be repeated until your circuit contains not 1000x1000 transistors but 1000x1000x1000 transistors. So today.s megabyte memories could become gigabyte memories and the two dimensional gigabyte memories of tomorrow could become terabyte memories.
Now those are all very large numbers. To make it a little more tangible let.s take an illustrative example:
A telephone today has about a volume of 10x5x2 cubic centimeter and contains something like a million components. Now, of course, such a telephone is made up of more than just a silicon chip but if it were possible to integrate the whole thing on silicon and the devices were about

20x20x20 cubic nanometer and there is 1 million devices per telephone, then one telephone would be about 2x2x2 cubic micron. So in a volume of one cubic centimeter of silicon you could provide everybody on earth with a billion telephones. That.s a lot of telephones. This may not be good news for the silicon industry though because one cubic centimeter of processed silicon sells for about 500.000 euro. That does not give a very good profit margin for such a billion euro set-up. Or maybe we could open up new markets like tagging of bacteria? Keep an eye on them in case they get up to mischief. Or sell mobiles phones to plankton. The possibilities are limitless.

Figure 9: Plankton with new mobile phone. Courtesy of Spongebob:

Before we get that far, of course, there are a few bottlenecks. One is the heat dissipation problem that I discussed above. In a three dimensional brain, cooling becomes endlessly more complicated than in the planar case. But the biggest bottleneck will remain the unprecedented processing complexity.

But even if we get the basics of such high scale integration right: it.s only part of the challenge. Keeping control of the production of something like a terabyte circuit will be a whole new science in itself. As advanced CMOS processing has already shown us: every circuit is a whole and must be created as a whole. It's not like building a car: all the steps have to fit together perfectly. If by accident you make the car door too large the car still drives and you can just replace the door. If something goes wrong while making a chip you can be pretty sure that you have to start from scratch. So everybody has to get together from the start: the circuit designers, the device people, the technologists. And every step of the way must be checked and double-checked and triple-checked. This process is now a science that was christened .Semiconductor Manufacturing Science. already around 1990. It has now developed into a complex entanglement of hundreds of different manufacturing techniques, monitoring systems, self-testing procedures, that all have a windfall of acronyms:

DfM: Design for Manufacturing
BIST: Built-In Self-Test
RTL: Rapid Technology Learning
YEM: Yield Evaluation Module
DfA: Design for Analyzability
TCQ: Test Chip for Qualification
PCM: Process Control Module
OEE: Overall Equipment Effectiveness
PM: Preventive Maintenance
APC: Advanced Process Control
SPC: Statistical Process Control
TPM: Total Productive Maintenance
SEC: Statistical Equipment Control
CSF: Critical Success Factors
EM: Equipment Managers

Many of these acronyms just conceal very high-level common-sense methods of reducing the number of trial and error cycles. With all my years in Silicon Integration Technology I have become very respectful of the power of trial and error. In the early years of Silicon Technology the theory behind transistor operation was very well understood, but actually fabricating a functioning transistor was a formidable task. Endless cycles of trial and error have brought us where we are today. Of course, we are now equipped with very powerful modeling and simulation tools on all fronts. And such theoretical tools are really wonderful for helping you choose the way to go, but they cannot replace the realization in silicon. That is the only way to find out if it really works.

6. DIMES integrates researchers

So when I am asked (and this has happened at least once a year since the establishment of DIMES) to answer the question:

.Is it reasonable for a university to have a full IC-processing facility?.

my answer is YES. I think I have already stressed some of the reasons why: our unique processing capabilities, our flexibility, our short turnaround times, all make the IC processing lab a magnet for drawing students, researchers and industries alike.

One point that I have not dwelled on enough is the very special education we give our major product: young engineers and researchers. In my group the students are thrown into the depths of three very different ravines: applied physics and chemistry, semiconductor device physics and circuit integration and design. They are confronted with practical lab work, electrical measurements and high-level computer simulation programs. We use an integrated, multidisciplinary approach to make them truly multidisciplinary researchers. They suffer, and those who survive, they love it. It is a very rewarding part of my work. I get to see the gleam in their eyes when they measure one of those tiny little devices and it actually works. And together we make things that were never made before and discover effects that nobody knew anything about. Not just theories, but the real thing.

When they leave us they leave with a great respect for what it takes to make advances in microelectronics. They know that it's a question of a lot of different people working together. This is something that is recognized on many levels at the moment. At this university we are herded together by DIOCs and "speerpunten", on the European level we are in the middle of the Network of Excellence frenzy. It is with mixed feelings that I look upon and sometimes participate in these initiatives to organize future research. In microelectronics it is obviously essential. But right now, unfortunately, we are in the begin phase. Talented researchers are being bogged down by writing, reviewing, re-organizing, and re-writing all sorts of proposals. There is so little time to actually do the research. We are guinea pigs for the process of learning how to set up and control vast co-operations. Here, probably also, we could take lessons from the microelectronics industry.

7. Integrating people in a high-tech society

It is not only in research that we are struggling to absorb all the new possibilities. We live in a high-tech society and we depend on this advanced technology. I could not believe when the Dutch government early this year decided to cut down on the beta-subjects taught at high school. The political decisions that I had anticipated and thought were obvious were more like this:

The basic languages of technology: basic maths and physics, should be taught in primary school along with reading and writing. The kids can do it. Just look at what they manage on computers whether you teach it to them or not. But can we do it? We who are responsible for the future of these kids? In a system where fewer and fewer students are picking technical subjects, we seem to be caught in a downwards spiral. At the moment foreign talent is saving DIMES as a research institute. But what is going to save the Dutch high-tech engine from grinding to a halt and finally breaking down? We may in future be able to buy technology from outside Holland, but will we be able to use it? So maybe: "What the world needs now" is not another pop song, but kids with a "tech-prospect". Kids, who are not just passive users of the high-tech society, but an integral part of it.

In the meantime we enjoy all the benefits of this high-tech society. We love watching international football matches, getting the best possible medical treatment, flying to romantic destinations, but without a high-tech infrastructure there will be no TV or well-equipped hospitals or easy traveling.

But how are we coping with all the great quantities of stimulating commercial, cultural, entertaining, educating overloads in our daily lives? On one hand we have the couch potatoes and computer addicts who spend their lives in passive consumption of American soaps and endless chat-box sessions. On the other hand there are the over-energetic types who fill their lives with one activity after the other and end up with an early burnout. In between there somewhere are the sensible ones that know how to handle the many stimuli and manage to say no. But basically today our lives are **full**. To spend an evening with friends you have to compare schedules and you are lucky to find a date within the time frame of a half a year. These are the drawbacks of otherwise fantastic developments.
But of course, once more, it is all a learning process. Managing our own made-made quantity does not come naturally, it's an acquired art. And in Silicon Technology we know how difficult it can be.
So, already the impact of technology on our daily lives is great. But still we are a long way off from building anything as complex as a human body and probably our man-made yotta-complexity will take completely different forms. It is more likely to dissolve into our surroundings where it will invisibly cater to our needs. To attain such heights of complexity I am sure that concepts such as co-operation, integration, multidisciplinary, mutual respect, all will be indispensable.
Another thing I am sure of is that in the course of achieving better and better control of such complex unified systems we will also achieve a better understanding of what it is to **be** a complex but unified system. Not only because new computerized systems give the opportunity to study ourselves in ways that were never before possible but also because we will be involved in the actual process of creating and controlling complexity. How far can you keep control? When do you let the system start making autonomous decisions or chop it into smaller independent systems? Will you have to introduce elements such as reward, punishment, etc., to make the system choose what is advantageous for you. When do you start caring about what the system itself is experiencing? Will it feel sick, happy, depressed, .? If it does, will it bother you at all? And what do you do after you have put so much work into building this incredibly complicated system and you realize that it does not serve your purpose any more? Do you just pull out the plug or put it to work in the local amusement park? Which will be the whole of Mars by that time .
These are fascinating questions and the answers lie in the research of the coming centuries. Meanwhile, let.s conclude with taking one last look at what goes on in Delft.

8. And we all work together

This is the group that I started with in DIMES: the DIMES IC-Processing Group (Figure 10). A lot of these faces are still around today. They represent the knowledge and continuity that is necessary for running something as complex as a full IC-processing line. The fact that this group has stuck with it all these years even though the demands on their dedication, discipline, diversity and perseverance have always been high, shows that fighting Murphy.s Law can become addictive. I will always look upon them with the same affection that you see among old army buddies. In particular, I.d like to give recognition to my friend and colleague Bert Goudena, who always keeps me going with a cocktail of merciless criticism and invaluable support. As the Operations Manager of the DIMES class 100 cleanroom he continually, mainly unnoticed and behind the scenes, makes sure that all the different human and technical parts keep fitting together so that even the most absent-minded, arrogant or stressed researcher still gets his/her piece of silicon.
But it.s difficult to keep a good thing to yourself and so the group directly connected to the IC-Processing line has grown all but exponentially over the years. We became a part of the Laboratory of Electronic Components Technology and Materials in 1995 and the activities today

also encompass research on new materials, microwave components and circuits, and large area electronics. This group has flourished under the management talents of Prof. K. B. For me it was the start of some exciting years working together with Prof. J. S., an incredibly perceptive device physicist, and Dr.ir. L. de V., my favorite link to the world of designers. Together we work with some really fantastic PhD students. They not only give me reason to be very proud, but also keep opening new frontiers for me.
Two years ago we survived the reorganization fever and became part of the Microelectronics Sector, also expertly headed by Prof. B.. The Microelectronics Sector is the largest group of the Faculty of Electrical Engineering, Mathematics and Computer Science. We owe a lot to their input and the support of the dean Prof. J. van K..
Also we are a part of the research institute DIMES that joins the Microelectronics Sector with the Nanotechnology group of the Faculty of Technical Physics. Now keeping all this together on an almost pure motivation driven basis is a hell of a job. Today Prof. A.

Figure 10: The DIMES IC-Processing group in 1990 (top).
Members of the Laboratory of ECTM in 2002 (bottom).

B. is the present of a series of energetic DIMES directors. He has been doing an impressive job of getting us all together to make DIMES a great institute.
So, how is that for incomprehensible complexity? But that.s the organization I work in. (It is almost as complicated as the type of work I do.) But the picture wouldn.t be complete without mentioning all the other groups we have daily interactions with. Inside the university we have old silicon friends such as the IRI and new friends such as OCP. From outside the university the support of Philips Nijmegen, Eindhoven and Leuven have been invaluable. And so I could name many, many more companies, universities and equipment vendors that have worked with us in a thousand different ways: ASMI, ASML, XMR, MicroLas, Tempress Systems, Varian, Agilent, Trikon, Xensor Integration, Dynatex, MECO, Electronics Vision Group, Mierij Meteo, TNO-TPD, Seiko Epson, Heidelberg Instruments, IMEC, Flexible Optical, Catena, Universties of Twente, Eindhoven, Leuven, Ulm, Tsinghua, Fudan, KTH Kista, ETH Zürich, Naples, Barcelona, Bologna, Trento, Southampton, Surrey, .

Figure 11: The organization that I work in.

So you can see there is never a dull moment. And I must thank my children, Kevin and Zindia, for putting up with it all. It is not always obvious, but somehow they still manage to know that they are more important to me than all this. Lovingly, and in great detail, they confront me with my short-comings and educate me in the art of living as nobody else could. Lastly, a word of gratitude to my parents. Wherever I am in the world, whatever the shape and size of my family, they always have a home and a helping hand for me. I am privileged to have been sent into life with such positive baggage.

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