A BIT MORE
ACROSS THE
BORDER
LEON ABELMANN
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Inaugural lecture given to mark the assumption of the position as professor of 3D Magnetic Nanofabrication at the Faculty of Electrical Engineering, Mathematics and Computer Science at the University of Twente on Thursday April 10, 2014 by

LEON ABELMANN
1 Introduction

Mijnheer de rector magnificus, ladies and gentlemen.

When I was in high school, my uncle Frans gave me a “Philips Electronische Experimenteerdoo” (figure 1). The box contained a plastic board with holes, ingenious springs that you could put in the holes and under which you could mount wires, resistances and little printed circuit boards with transistors. It came with circuit diagrams so that you could assemble circuits. Oh the joy, when the circuit actually did what it was supposed to do! Burglar alarms, disco lights, radios; I loved them all. The only problem was that anything I invented myself simply led to blown-up transistors. I replaced dozens of them. Frustrated, I decided to study electronics, came to the Technische Hogeschool Twente and never really left. Until now.

I find myself in the strange position that the procedure for appointment as a professor that started three years ago concluded at the same time that I accepted a new job at the Korean Institute of Science and Technology in Saarbrücken, Germany. I now work three weeks a month across the border. So here I am, having the attention of the Twente community, and anything I say will have very few repercussions. How cool that is!

This luxury position to speak freely comes with the risk that I might say something you won’t like. It is very possible that I will be wrong somewhere. I hope you will forgive me. My favourite Feynman quote, which he probably took from Goethe, is

“Never ascribe to malice that which can be adequately explained by stupidity”

I try to remember that when I get annoyed by you, and I hope you do the same for me.
2 Education

To me, it goes without a doubt that the primary product of a university is people trained in the scientific method. These people are released into society, and honestly try to improve the lives of others. It works. Never before has there been peace for such a long time. I think this is because we have more knowledge, better communication, and really scary weapons; all products of the scientific method.

2.1 A bit more incomplete

Societies develop, and their needs change over time. This has consequences for the type of training we need to give our students. When I was trained, it was expected that the knowledge given to me would last for the bigger part of my career. The program of Electrical En-
engineering was “complete”. Of course there was more to learn, but this was a deepening of knowledge. Twente Electrical Engineers were “ready to go”. An odd misconception. Progress in science and technology is fast, and accelerating. I honestly have no clue what Twente EE students that are starting this year will be doing in 2024, five years after they graduate. Will any of them design electronic circuits until the end of their careers?

Rather than offering programmes which are “complete”, we should teach people the ability to change, to learn. This starts with a good basis in fundamentals. All of technology is rooted in classical physics (Newton, Maxwell), based on a little bit of quantum mechanics, and with relativity theory thrown in now and then. Good insight in classical physics and some basic knowledge of quantum mechanics will bring our students a long way. Proficiency in elementary calculus, geometry and algebra, experience with lumped element approaches and dealing with complex systems will do the rest. From this foundation, students should be able to rapidly absorb new fields of knowledge. This “soft skill” is far more important than completeness. I can very well imagine that we train electrical engineers without telling them how a transistor works. If, however, we train them so that they are not able to, we have failed.

2.2 A bit more active

Like all fields of knowledge, the field of education also progresses. Over the last three decades, there have been significant changes in understanding how people learn. Scientists are the first to welcome new insights. When a colleague proposes a new theory or method, we critically review it, put it to the test and if it works, we adopt it immediately. You are considered a bad scientist or engineer if you are not up to date with the newest developments in your field. Aside from being scientists and engineers, university professors are professional teachers. How weird is it that the majority ignores any progress made in the educational field, and adhere to thirty-year-old educational methods.
The insight developed over the last few decades is that people learn only when they actively process knowledge. Moreover, people learn most from making mistakes. If you're smart, you never make the same mistake twice. Why do we then still try to squeeze knowledge into the heads of students by having them sit in seminars and forcing them to read books? We know that this method does not work well. The scientific evidence is overwhelming and we know it from experience. Many successful scientists and engineers never attended classes, and never read a book starting at chapter one.

So if people only learn when they are actively dealing with the knowledge, we should design our education in that way. A standard seminar, in which the professor explains the theory and students are passive, is a waste of time. There are far better, activating learning methods, and we can probably invent many more of them, specifically designed for the topic and the group of students we are dealing with.

Inspired by, and together with, Miko Elwenspoek, I have been teaching electromagnetism for Bachelor students in Advanced Technology in the form of Problem Based Learning over the last ten years. During this time, we have been teaching the same topic for Electrical Engineers in a more classical setting. The Problem Based Learning method results in deeper insights and is far more rewarding for both students and teachers. As a result, the standard seminar has been completely abandoned by Michel de Jong and Gijs Krijnen in their new 15 EC modules, and replaced by a combination of Problem Based and Project Organised learning. Activated learning approaches are used in several of the new modules in the Twente Education Model (TOM) curricula. I sincerely hope these examples will open the eyes of our more sceptic colleagues, and that they will finally judge innovation in education the same way as innovation in science and technology.
2.3 A bit more choice

The new Twente Educational Model, in which students study a single topic full-time for ten weeks, is perfectly suited for activated learning activities. One of the major drawbacks we experienced with Problem Based Learning was that students started to neglect courses running in parallel. Now, the teaching team “owns” 40 hours per week of the students’ time for 10 weeks, which has many advantages.

Moreover, the modules are now so big that they turn into mini-programs. For example, all of electrodynamics in the EE and AT programs is now given in a period of 10 weeks. This gives students the exciting opportunity to assemble their Bachelor curriculum themselves. In such a free-choice program, the students choose what to do next from term to term. If the modules are well designed and students are properly coached, this system has many advantages. In the first place, we do not force high school students to choose a field of expertise from day one. During their Bachelor, students can discover for themselves if they are more interested in science or engineering, hardware or software, and so on. In my interviews with the coordinators of Master programs, it became very clear to me that for a specific Master’s, only a few modules are really important. The requirements to enter a Master’s degree program are more formulated with respect to level, rather than actual knowledge. A mechanical engineer doing his Master’s in a MEMS group at MESA does not need to be able to make a technically correct mechanical drawing. It is far more important for him that the student is capable in understanding what it implies that gravitation no longer plays a role and that mechanical structures show thermal vibrations. Secondly, the fact that the student chooses his modules implies ownership. With ownership comes responsibility and motivation. Finally, the student can gracefully avoid modules that are above his level. For example, we currently force students to finalize a course on electrodynamics in the AT program only to let them proceed with an industrial design master. This is frustrating, ineffective and leads to unnecessary delays.
With advantages come disadvantages. In a free-choice program, the students are not forced to participate in education as a group. Consequently, the coherence in the group of students will suffer. Secondly, and specific for the UT situation, not all modules will be taught in English. As a result, the choice for Dutch-speaking students will be larger than for foreign students. Finally, a free-choice program is not suitable for students who are indecisive. But if one actively promotes group coherence, and discourages students who cannot choose, a free-choice program would be a true asset to the University of Twente.

2.4 A bit more teamwork

For a teacher, the best thing that can happen is your students becoming better than you. Fortunately, this happened to me. Some of my PhD students are working at research labs I would never have been accepted to myself. However, they explain me that I have failed to train them in true teamwork. In the Bachelor program, we put a lot of emphasis on working in teams. There are many projects and courses in which the final grade is partly based on how well your team performed. In the Master programs, the main objective is to specialise and students are judged on individual achievements (traineeships, Master theses). This is probably alright since the necessary team-working skills have been dealt with during the Bachelor.

However, we fail to address teamwork again in the PhD programs. The university cannot be blamed. Since there are no more free funds for research, PhD students are hired in projects financed by government. There usually is one student, who has one project, with his own setup financed by that project, his own group of companies advising on the research, his own project meetings, and so forth. As a result, PhD students tend to do their work on little islands. Of course, they cooperate with other students on other islands. If I help you, you help me. But this is never teamwork in the true sense that if one of the team members fails, the team fails as a whole. In industry and in large research labs, this is however daily
practice. The last time our PhD students were truly working in a team was during the second or third years of their Bachelor’s. That is as far as they came.

At my new employer, KIST Europe, I am in the fortunate situation of having sufficient funds to hire a group of PhD students. The research director at KIST Europe, Andreas Manz, trusts me with a sizeable budget and a lot of freedom. There is no project proposal with milestones and deliverables, no user committee, no individual project meetings; just the requirement to do excellent, relevant research. This gives me the possibility to experiment with teamwork. Suppose I define only one or two projects for all students. They always publish as a team. How would I judge the individual performances of students? On what grounds do I terminate a PhD contract? On what basis do I grant PhD titles? These are questions I intend to answer in the coming years.

3 Research

3.1 Across the EE border

Magnetism has an aura of mystery. Permanent magnets attract or repel each other strongly without being in contact, yet do not hurt if you touch them. Even in academic education, the magnetic field remains mysterious. In all textbooks on electromagnetism, the electric force is first treated in great length. The magnetic force is then introduced almost as an analogy, with strong emphasis on the symmetry of electromagnetic field theory. Magnetism as the negative imprint of electricity. Feynman covers electrostatics in six chapter is his Lectures on Physics. Magnetostatics only in three. A great physicist and talented teacher of the EE department, who I will not name, even “hates” magnets.

There indeed is something wrong with magnetism. The electric

\footnote{Not because he does not understand magnetism, but because permanent magnet engineers love magnetic charges, which is a chutzpah}
force is easy to understand. Two charges attract or repel each other, along a line connecting those charges.

\[ F = qE \]

Just like people. We grasp that intuitively. However, the magnetic force is between charges that both are moving. Even worse, the forces are perpendicular to the line of movement.

\[ F = qv \times B \]

To me, this is a very non-intuitive interaction. And rightly so, because who moves? Suppose I would move along one of the charges, so that one of the charges in my coordinate system is stationary, \( v=0 \), and there is no more magnetic force (Figure 2). Indeed, the magnetic and electric forces are intimately linked with Einstein’s relativity theory. Depending on the velocity of your reference frame, the ratio between the electric and magnetic force changes. However, their combined force is independent of the velocity of the reference frame. The electric and magnetic force field should always be taken together.

\[ F = q(E + v \times B) \]

No wonder students find magnetic fields confusing. Magnetism is the only relativistic effect they experience in daily life. When you ride your bicycle in the dark, your headlight runs on relativistic forces. All other relativistic effects are too small to notice. We do not experience a contraction in space or time if we ride a bicycle. During my study, I was never informed. Fortunately, the talented teacher -who must not be named- saved me before it was too late. Since 2000 we at least mention relativity to our EE students, to comfort them if they do not understand immediately.

But we are not there yet. Even after 25 years, I still cannot explain in a simple way to a first year student why iron is magnetic, and copper is not. I have to magically induce magnetic moments on
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But we are not there yet. Even after 25 years, I still cannot explain in a simple way to a first year student why iron is magnetic, and copper is not. I have to magically induce magnetic moments on electrons, pull exchange interactions out of a hat, and hope that the students get lost before I do. And according to Feynman, if I cannot explain something to a freshman, I don’t understand it. I agree, I don’t.

Still, I have a lot of fun with magnets.

3.2 Across the EU border

Virtually all data people own is stored in magnets, on hard disk drives. Also the photographs stored on your smartphone. Even though it does not have a hard disk drive, the data on your phone will most likely be in the cloud somewhere, which means in a data-center, which means on a hard disk drive. The data is stored in a thin permanent magnetic film, in tiny little regions of alternating magnetisation, see figure 3. Since the invention of the system in 1956, the capacity of the hard disk drive has been increased by
reducing the size of the regions, the bits. This reduction has been flabbergasting. There are over $1,000,000,000$ times more bits on a square centimeter on a hard disk today, than in 1956.

The beauty of magnetic storage is that it is non-volatile. A hard disk does not need to remain connected to power or a battery to keep its data. At the same time, this is also its weakness. The only thing that prevents the data from disappearing is an energy barrier between the opposite states of magnetisation. When we reduce the size of the bits, this energy barrier reduces as well. If we are not careful, the energy barrier becomes comparable to the thermal energy in the system, and the data spontaneously gets erased. The magnetic thin film is no more a permanent magnet, but becomes super-paramagnetic. So materials scientists work hard to increase the magnetic energy density in the hard disks magnetic layer. However, we have now come to the point that there are no better materials. Today’s hard disk research is on materials with energy densities that are close to the theoretical maximum value. Over the last two decades, no new materials have been found. The only progress that can therefore be made is in clever storage architectures. The magnetic data storage community generally believes that when we pull all the tricks out of a hat, increasing the capacity by decreasing bit size can only give us a factor of 20. After that, there will be no more progress, and the hard disk as we know it today will cease to exist. Already now, the increase in data density has dramatically decreased, see figure 4. Because investments in technology become more and more expensive, the hard disk industry has been consolidating over the last decade. Today, only two major companies remain, Seagate and Western Digital, both in the USA. For university-based hard disk research in Europe, there are no more drivers.

So what next? One could imagine that we abandon magnetic material, and move to higher energy densities. Since the size of magnetic bits at the end of the magnetic data storage era will be around 4 nanometers, the natural successor would be data storage in single molecules or even atoms. This will mean the return of probe
storage technology. Following IBM, we had a lot of fun in this field at the turn of the century, but we had to stop because of a lack of market. In a sense, we were too early. We did learn a lot, and I look forward to the time when all of this knowledge can and will be reused.

Probe storage technology will buy us some time, but not much. In his visionary lecture “There is plenty of room at the bottom”, Richard Feynman estimates that you could store one bit in an area of $5 \times 5$ atoms. He might be wrong, but it cannot be much less. The students we train today will therefore witness both the end of hard disk as well as two-dimensional semiconductor storage. They will even witness the end of two-dimensional electronics. I doubt whether we are even fully aware of that. There might be a way out, but I’ll keep that for later.

3.3 Across the data storage border

Magnetic fields penetrate most materials very easily. You can also phrase this negatively: it is difficult to shield from magnetic fields. This behaviour is exactly opposite to electric fields. Why is that? All materials consist of assemblies of positive and negative electric charges. When exposed to an external electric field, positive and negative charges shift in opposite directions and shield the external field. The ratio between internal and external field is expressed by the relative dielectric constant $\epsilon_r$. In conductors, where the electrons can move freely, the shielding is perfect and the constant approaches infinity.

Materials can respond to magnetic fields in two ways. When inserted into a magnetic field, the material experiences a rate of change in of the magnetic field strength, resulting in an effective force on the electrons, similar to that of an electric field, and opposing the rate of change.
Figure 3: In your hard disk drive, data is stored in tiny regions of alternating magnetisation (image courtesy Bruce Terris of HGST - a Western Digital company.)
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Figure 4: Reduction in the size of a single bit, as a function of time, for magnetic storage (Hard disk) and electronic storage (FlashMemory). As the hard disk technology approaches the fundamental barrier, the development slows down. Fortunately, the same is true for the semiconductor technology (ITRS roadmap). At 25 atoms per bit however, also room temperature semiconductor storage will come to a halt (Feynman limit).
\[ \nabla \times E = -\frac{\partial B}{\partial t} \]  

(1)

As soon as the material is entirely in the field, the time derivative becomes zero, and so does the force. The only effect remaining is a slight shift in the trajectories of the electrons around the nucleus, which can only be described well with quantum mechanics. In general however, the effect is miniscule and can only be noticed well in a few materials like graphite or bismuth. The main exceptions are superconductors, in which the electrons experience no resistance. Once they are accelerated by the force caused by the changing magnetic field, they will not slow down anymore. This is why superconductors can levitate trains. Levitation also works with graphite and water, but on a much smaller scale (Figure 5).

The second effect is the reaction of the electrons themselves to the magnetic field, which tends to align the electron spins. This will increase, rather than decrease, the magnetic field. Quantum mechanics prohibits that all spins align in the same direction. You’ll have to excuse me, I don’t understand why. Therefore the effect is again very small. The change of magnetic field when inserting a material in a magnetic field is expressed by the relative permeability \( \mu_r \). This value is commonly very close to unity. Only in magnetic materials, where the atoms themselves have a net spin, and interact in the proper way, the effect is appreciable and \( \mu_r \) can be as high as 20,000 in special iron alloys. The interaction of water with magnetic fields is negligible. It is this feature which we have recently started to exploit, in two fields.

### 3.4 Magnetism in life sciences

Since we are composed of water and other non-magnetic materials, magnetic fields have very little effect on us. The \( \mu_r \) for human tissue is extremely low, see table 1. Moreover, magnetic field hardly interact with bio-chemical processes. This is why magnetic fields do
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Table 1: Reaction of human body tissue to electric ($\epsilon_r$) and magnetic ($\mu_r$) fields. The magnetic field has very little influence.

<table>
<thead>
<tr>
<th></th>
<th>$\epsilon_r$</th>
<th>$\mu_r-1$</th>
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<tbody>
<tr>
<td>water</td>
<td>77</td>
<td>$-10^{-5}$</td>
</tr>
<tr>
<td>blood</td>
<td>$10^3$</td>
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<td>bone</td>
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not hurt, and pass right through us. Therefore, magnetic fields are successfully applied in medical analysis, with the MRI scanner as a shining example. But magnetic fields can also be used to apply forces and torques (using either magnetic particles or non-magnetic particles in magnetic fluids), to heat magnetic particles by induction or to detect the presence of magnetic particles. My research team combines magnetic fields with microfluidic systems to study fundamental behaviour of magnetic particles in solutions, or non-magnetic particles in magnetic solutions and to apply this in lab-on-a-chip applications. Of special interest are magneto-tactic bacteria, which are self-propelling and can be controlled without having to apply large magnetic field gradients (figure 6). Together with colleagues from the Robotics and Automation group, we study manipulation of individual magneto-tactic bacteria inside micro-fluidic systems as model systems for future self-propelled medical micro-robots.

3.5 Magnetically assisted self-assembly

As mind-blowing as the achievements of lithography-based microfabrication may be, the technique remains essentially two-dimensional. In MEMS, this severely limits our design capabilities, especially for out-of-plane actuation. In micro-electronics and data storage I showed that we will hit a fundamental limit on miniaturisation when the size of bits or electric connections reaches atomic
Figure 6: A magneto-tactic bacterium has a string of nanoscale magnetic crystals that act as a compas needle. In this way, the bacteria can locate food at the bottom of ponds.
dimensions. As I promised, there might be a way out. The way forward could be in the third dimension. In my opinion, and that of my colleagues in the Transducers Science and Technology group, three-dimensional self-assembly is the only viable option in the long term. In self-assembly, the properties of the individual particles determine the final structure of the assembly. In my team, we use magnetism to tailor the interacting forces between particles (again, using either magnetic particles or non-magnetic particles in magnetic fluids). Currently, we have a lot of fun with 3D printed particles with embedded magnets, which we insert in a big aquarium and stir with air bubbles. We even managed to study self-assembly of millimeter-sized silicon cubes, using diamagnetic levitation in magnetic fluids (Figure 7). Since we can easily observe the particles, we acquire valuable fundamental knowledge that we can transfer to the micro- and nano-domain.
4 Organisation

4.1 Across the apocentre

A university educates people. No students implies no university. When the University of Twente was founded, this was crystal-clear to the generation of professors that migrated from the west to Twente. If I have interpreted it correctly, in those early days the emphasis was on education. Staff consisted of dedicated teachers who wrote their own teaching materials and created impressive lab courses.

But a university can only educate researchers if the professors do research themselves, so the PhD degrees became relevant. My generation was one of the first true PhD students, Assistenten in Opleiding (AIO’s). In the old days, a doctorate was a degree teachers obtained after spending years and years of research next to their educational tasks. New financing structures were invented, and research activities increased tremendously. In the late 1980s, new laws were introduced and doctorates could be obtained in a four-year program. This actually meant that from that point onwards, a PhD was a study. The PhD supervisor had become a teacher. Defending a PhD thesis had become an exam.

Since then, university professors have had two types of students: those in their classes following Bachelor and Master programs, and those in their laboratories doing research. The first group arrives automatically. Every year, new high school students show up. Attracting such students is a job for the external affairs office; professors are barely involved, and the education of Bachelor and Master students is a job that just has to be done. Whether the university professors do that well or not does not actually matter that much.

For the PhD students, professors have to compete for funds by writing research proposals. The research projects of PhD students are published in scientific journals, making it very easy to rank professors. Those with many externally funded projects, lots of PhD students and publications are good. Those without PhD students are bad. This development provided an ideal ground for the spread-
**spreadsheet management** virus, a type of disease that causes managers to steer based solely on numbers. Numbers are safe. Decisions become defendable. A 51% majority makes the decision. If you score less than 45 EC, you have to leave the EE program. If you score an average of 8 or higher, you will be accepted to study medicine at the UvA. You know the lot.

In science, the **spreadsheet management** virus has grown to epidemic proportions. It is childishly easy to count research proposals, papers and citations of papers. We invented metrics to measure how often a researcher is cited, such at the $h$-index (Figure 8), but nobody cares why the papers are cited. Nowadays, to judge a researcher’s quality of work, you simply need to look up his metrics in Google Scholar. I fear that my higher level managers only count my publications, but never read them. There are confirmed reports of “researchers” buying their names onto author lists of publications that will appear in a high-ranking journal. It is a good investment since in some countries a co-authorship in Science or Nature will double your salary.

It thus seems easy to measure the quality of research, far easier than measuring the quality of education. To be a successful academic, you’d better focus on research. It is alright for your career if you are a good researcher, but don’t neglect education entirely. You will become a professor. It is, however, far less acceptable if you are a good teacher, but don’t neglect research. I am very happy that my managers, Miko Elwenspoek and Ton Mouthaan, were aware of this. I like to think that I am standing here because they like the way I teach.

I hope we are on a swing. The Technische Hogeschool Twente started out with a strong emphasis on education. We moved all the way to a strong emphasis on research, to the point that we start to spin out research institutes. It seems the tide is turning. More independence for the research institutes, the “kanteling”, has not really taken place in the end. We find ourselves in the middle of educational innovation in TOM. Also in politics there seems to be a counter-reaction. National research budgets have been cut to the
point where it causes reduction in academic staff, as we recently wit-
nessed at the EWI department. And our parliament is questioning
why Delft introduced a numerus clausus on Mechanical Engineering.
As if we could ever have enough mechanical engineers...

If I’m right, and education is increasing in importance again,
we should learn from the $h$-index effect. The powers-that-be will
be tempted by the spreadsheet management virus. So we better
find a metric to measure the quality of education before they do.
This metric should not only include the opinion of students during
their study, but keep following them after they graduate. A kind of
e-index...

4.2 A bit more fun

At a university, you find many talented people that do well in our
school system. For them, there is simply no other place to go. We
should be aware of that when we design education. But that is another discussion. If you have talent, what should you do with it? There are basically three axis along which to proceed: make yourself useful to others, make money, and have fun. The make money/have fun people drew us into the credit crisis. Perhaps it would be best to find them another planet. The help others/make money type of people can be found in hospitals, for instance. It must be rewarding to save people’s lives. The help others/have fun types are found at universities (figure 9). The salaries are not bad but are insignificant compared to the average banker’s bonus. All of my colleagues at the university work because they like their job. Many of them work more hours than they are paid for, spend Sunday nights preparing educational materials, and get sleep deprived while correcting publications that PhD students hand in two hours before the deadline.

Come the spreadsheet managers. They set up research grant agencies, taking away funds for research from universities and returning it to them to compete for. Since it is big money, politics
will interfere. They add into the competition the element of utilisation. We pay you, so you better do something useful. What is your benefit for society? Simply training engineers and scientist won’t do. How will the BV Nederland benefit from your research? All this is based on the belief that universities are populated by Gyro Gearlooses, who invent gadgets with which Scrooge McDuck can make a fortune. Like the comic, this belief is naive.

The University of Twente is well known for its spin-off companies, now totalling over 700. I’ve been able to observe the start of some of the MESA spin-offs. None of them have actually made money on an invention created in a PhD project. It is their second or third product that saves them from extinction. The main contribution of the university to their succes is people, and established technology that was developed for a completely different purpose. University researchers are fully aware of this. I suspect the government financing agencies know this as well. For politicians, we however perform some sick play, in which we pretend that the research we plan to do in a project will actually lead to a product. Writing project proposals has become an art in which you try to stretch the economic impact to a point that is at the edge of reason. The companies play along. We drag them in by the hairs, counting on the loyalty of former students in those companies to help their profossors. Off the record, the companies tell us they are not truly interested in the applications we propose, which are usually too far-out anyway, but in access to talented people and new technology.

This continuing pre-occupation with utilisation kills creativity. Very often, a good idea is aborted because we cannot find a convincing application. We waste considerable time inventing workarounds to hide that we have no clue how to make money with a new, scientifically-challenging idea.

Now that I am employed by KIST, I somehow feel as if a weight has been lifted from my shoulders. I am allowed to let my PhD students do research for the sake of research only. No utilisation paragraphs, economic impact studies, user committees. Research for the fun of it. The main aim is to train researchers. We will worry
about the economic impact of their research later. My current boss, Andreas Manz, invented lab-on-a-chip technology this way. Perhaps the Scrooge McDucks in the Dutch and EU governmental offices should trust their Gyro Gearlooses, who work for fun, just a little bit more.

5 Thank you

When I was messing around with my Philips Electronische Experimenteerdoos and other projects, in the basement of my parents house, I could never have imagined I would stand, dressed up like this, before you now. I truly wonder what got me here, but know for sure that I owe a lot to many, many people.

Perhaps I owe the most to my students. One of the most rewarding benefits of a university position is that you are in the middle of a continuous stream of young, talented people. They come fresh from high school, full of expectation. They leave as different people; independent, creative, educated and all with sincere intentions to improve the world. There are too many to name them all, but I have very good memories of lunch meetings with mentor students, seminars in which students measure the length of a video tape, problem based learning sessions, discussions with teaching assistants, students in Bachelor and Master projects, etc. The most rewarding have been the PhD students I have been or am proud to supervise, simply because they stayed the longest. Arnout, Mink, Rogelio, Alexander, Johan, Wabe, Hammad, Jeroen, Laurens, Antoine, Kodai, Marc, Wenming, Tijmen, thank you very, very much.

The comings and goings of students can be tiring as well. Fortunately, the University of Twente is full of nice colleagues. Aside from all the teachers, researchers, technicians, secretaries, and managers, too many to mention, I would especially like to thank a few of the support staff who have been always there for me ever since I joined the group of Cock Lodder. Thijs, Martin, Johnny and Karen, you make the world go round!
I was a student, and I still am. There is a line of teachers, to whom I am much indebted. My physics teacher in high school, mijnheer Greydanus, taught me not to give up. Paul Lambeck taught me precision. Alfred Driessen set me on the trail of an academic career. Cock Lodder taught me how to be a good boss, and what it means to work hard. “Mag het een bitje meer zijn?” I’m afraid I will never match his qualities in these fields. Miko Elwenspoek taught me what it means to really understand something, and to look beyond the borders of electrical engineering. “... Grenzen überwinden”. Gijs Krijnen taught me the fun in mathematics. Andreas Manz shows me how to be creative in science, and I really look forward to many years of working with him.

Here, I would also like to thank the University of Twente, and especially Miko Elwenspoek and Ton Mouthaan, for offering me this position and the chance to remain connected. I will do everything I can to make the KIST Europe/UT cooperation a success.

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