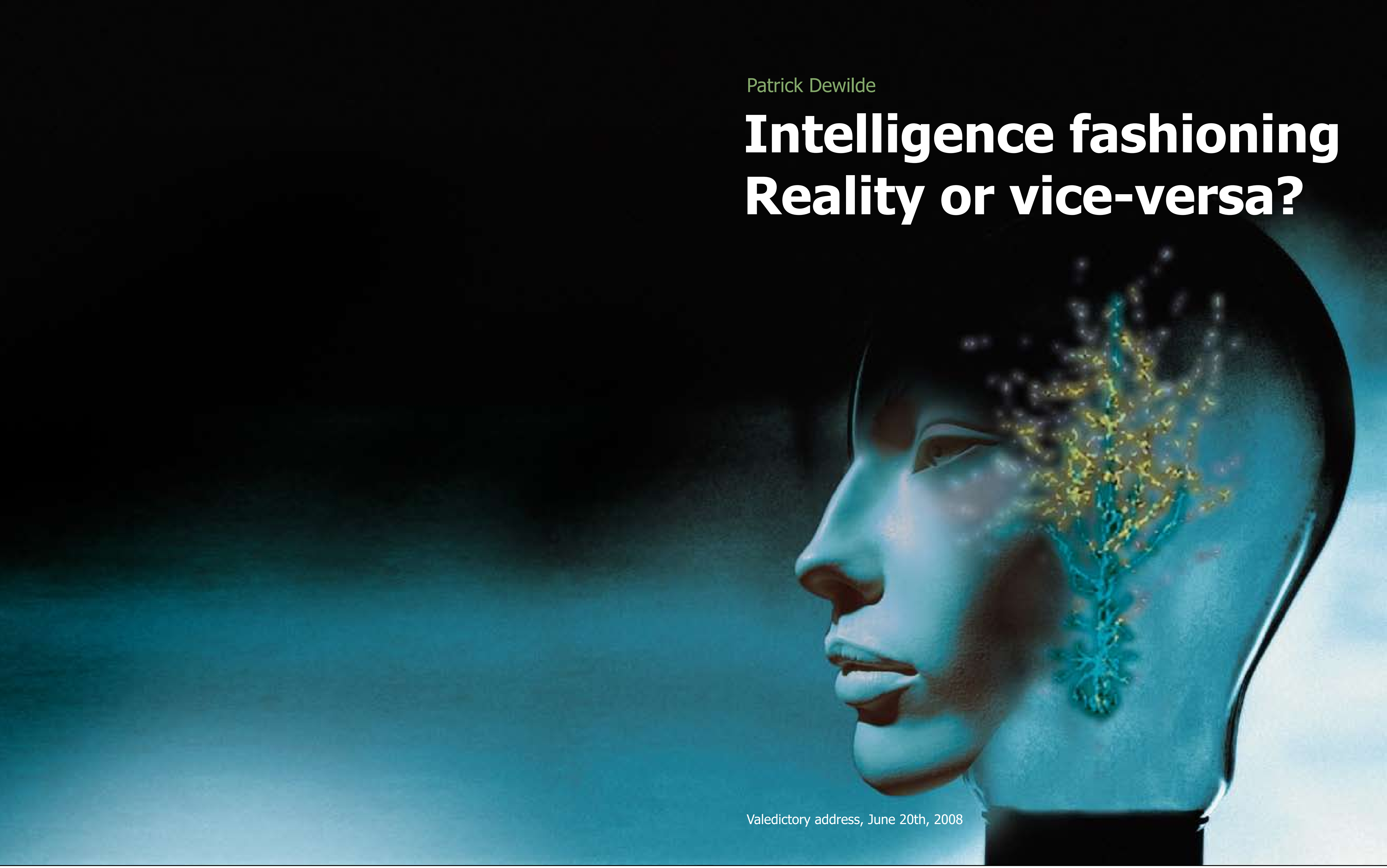
Patrick Dewilde

Intelligence fashioning Reality or vice-versa?



Valedictory address, June 20th, 2008

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Valedictory address by

Patrick Dewilde
Professor Emeritus at Delft University of Technology

June 20th, 2008

Mijnheer de Rector Magnificus, leden van het College van Bestuur,
Collegae hoogleraren en andere leden van de universitaire gemeenschap,
Zeer gewaardeerde toehoorders,

I wish to devote this valedictory address to a question that has mystified me over many years and that is also closely related, wittingly or unwittingly, to the research that I have been conducting with my students and many colleagues the world over. It is the question of the relation between intelligence and reality. Today you have heard several very distinguished speakers treating the issue of 'Designing Intelligence', and why would we like to design intelligent systems if it were not to influence the reality we live in? However, understanding the intelligent design of intelligence is not so easy as we would wish and I think worth the devotion of a considerable amount of time.

The connection between thought (concepts, ideas) and reality is one that has puzzled philosophers from the dawn of civilization. You are all familiar with Magritte's painting showing a pipe with the caption 'Ceci n'est pas une pipe' and of course we know that what we see is a painting and not a pipe, the statement is undoubtedly correct but also highly uninformative, except in a philosophical sense where it does indeed make much sense. Does our imagination touch reality? When we say that a rose is red, we imagine that something like the notion of 'red' exists, while we all know nowadays that red corresponds to a set of waves with wavelengths in the higher submicron region – and physicists will even tell you that it corresponds to a class of particles called photons. 'Ceci n'est donc pas du rouge' Magritte would say.

The first serious consideration of the relation between concepts and reality is maybe due to Plato, at least it is the best documented antique one. In the words of Bochenski[1], Plato states

> *Ideals exist independently from reality. They build a special world for and above the world of things - in which there is no time, no change and no accident*

(a 'concept' has been upgraded here to the term 'Ideal'!) For Plato, what is real is not observable and what we observe is in no way related to what truly is. The Platonic viewpoint may be thought to be very ancient, but it is espoused by modern scientists, especially mathematicians. The famous Dutch mathematician L.E.J. Brouwer was an avowed Platonist. In his view Mathematics strives at ideal concepts and happens purely within the human mind. It has no bearings on reality. The opposing view is taken by Aristotle. I paraphrase Bochenski:

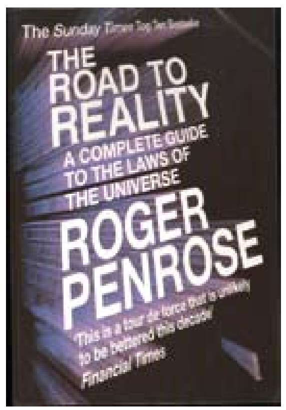
> *Ideals do exist, but only in reality. Only specific structures, repeating patterns, called 'beings' can be recognized as satisfying a law by the human mind.*

In this view, our mind is not capable of creativity, everything that we ever conceive we have seen or experienced first. We may be mistaken, but even these mistakes are misguided representations of something we have experienced. No doubt many physicists do espouse this view, for them nature is governed by laws that are deeply engraved in its functioning and can be discovered through careful observation. These laws are as real as bread and butter or one plus one is two!

What may be thought of as an in between position is the one taken by Kant, although it could be argued that Kant leans more towards the Platonic than to the Aristotelian view. According to him (again citing Bochenski),

> *Laws belong to the ideal world, but we project them on reality (which we cannot know although we do experience its effects)*

and depending on whether what is observed does or does not correspond with what the law or theory predicts we accord a greater or lesser truth value to our candidate law. So doing, there is an unbridgeable gap between thinking and reality, thinking happens in the mind, reality totally outside of it.



Besides these fundamental positions there is a host of skeptical criticism on them. I mention, not without some amusement with so much disagreement between philosophers, Descartes who said that senses always mislead us (what tends to Plato) while ancient and modern hedonistic philosophers such as Aristippus or Michel Onfray state that only what is sensed is real. Hume teaches that laws are nothing else than concepts you get used to, a statement that most of us who have grappled with college mathematics would agree to while Wittgenstein takes the most extreme position that these are all word plays that have no bearing on 'what is the case'. There is certainly plenty of reason for skepticism, witnessed by the cover of the recently appeared book 'The Road to Reality' by Roger Penrose who seems to believe that the geometric models for physics represent 'reality' (it is funny to ponder whether this is now a Platonic or an Aristotelian view, in the first case you would say that whatever one may experience, the only true reality is geometry, or conversely, geometry is what is 'really' engraved in nature!)

Given all this absurdity, what is then the case, how could we discover it and why would this have any bearing on engineering – which is the thesis I want to defend today? There is an avenue that only modern philosophers have been pursuing. It is to take a neuro-biological tack and investigate how intelligence actually works, bypassing of course, as we all do all the time, the question of whether something can actually be observed and the observation given the stamp of 'this is real' – but I want to leave philosophy at this point and move into a scientific mode which does give the predicate reality to a dispassionate and careful observation, always keeping in mind the limitations of the observer and his equipment. A total negation of reality does not lead very far, let us just agree on this much that we can agree on some mode of common reality. There are two main, hopefully congruent approaches to the understanding of intelligence. The first is the already mentioned neuro-biological tack, which studies the functioning of the main human intelligence organ, the neo-cortex, and the other is what I would call the engineering approach, it is the attempt to build intelligence in a systematic way from known mechanisms. The understanding of the first is actually checked by the second, at least if you believe in the paradigm that what you understand you should be able to construct. The approaches would be independent from each other if we would have a clear understanding of the notion of 'intelligence'. But since we do not have such a notion, the best is to carefully observe and analyze what human intelligence consists of and then check whether our attempts at artificial intelligence actually succeed in matching the original.

Neuro-biology has taken an enormous flight in recent times. For some time we have known detailed mechanisms in neurons, the role of some of the many chemicals involved, the transmission of signals along axons, the role of dendrites in picking up signals, how neurons fire when they are excited and what the role is of the refractory period, allowing for stable evaluation. These mechanisms have been emulated by artificial circuits called 'perceptrons' and 'neural nets', starting with the work of Hebb describing some of the basic mechanisms (Hebbian learning). A lot of effort at understanding basic pattern recognition mechanisms, the elaboration from single layer perceptrons to multilayer Hopfield networks, the understanding of the mathematical underpinnings of back-propagation in these networks and a number of sometimes successful but often not so successful experiments at emulating the uncanny human ability at pattern recognition have been undertaken. Many of these mechanisms are used extensively today in electronic equipment devoted to signal recognition and estimation. What they can do they do well. The problem is that they do not succeed in the most important pattern recognition tasks we humans are capable of, e.g. to recognize people and situations in a natural environment. Worse, we do not even know in principle how to program a computer or design equipment to do it. It is not a question of lack of computing power, the problem is lack of understanding.

1 J.M. Bochenski, *Wege zum philosophischen Denken, Einführung in die Grundbegriffe,* Herder-Bücherei, Band 62, Freiburg in Breisgrau, 1959

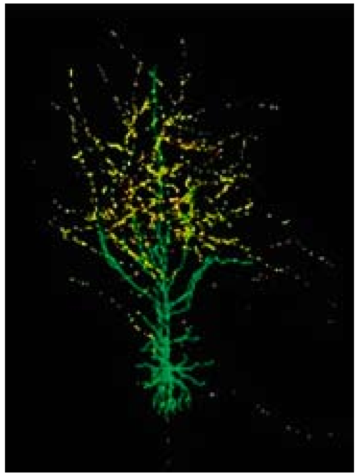


Figure 2: picture of a neuron

The only way forward is 'back to Neuro-biology'! There have been major advances in understanding the functioning of the neo-cortex as a *system*, although there are major gaps to be filled in as well. A very attractive presentation of present day insights is given in the book 'On Intelligence' by Jeff Hawkins[2], from which I borrow a few notions that connect with some of the concepts system theory and signal processing research have been grappling with. Let us follow Hawkins in discovering some of the complexities of the human intelligence systems. The first observation has to do with the visual system. You have a stable image of the small piece of world here in this auditorium when you look at me. An observer of your eyes in the meantime sees what are called 'saccades', your eye is moving all the time, from left to right, from high to low, while your neo-cortex is keeping the stable image you are perceiving. How is that possible? Try it with a camera and you will get a hyper-blurred image. After some layers of neurons, your neo-cortex creates a stable image which it continuously updates checking left and right, up and down in saccades whether it is still correct, and corrects it as soon as it finds something that has changed. How does it know that a change has occurred? It uses the existing image as a reference to predict what it should find in unchanged circumstances and only then takes action if it finds something different, telling the upper layers to adapt. The neo-cortex is sensitive to patterns, both in space and in time (thanks to some delay mechanism), which it abstracts using a language-like characterization, and which it will modify only when an unpredictable change is discovered. That is how the neo-cortex deals with reality: by prediction, pattern recognition and abstraction. A couple of pictures may illustrate the going on, for a more detailed description I have to refer to Hawkins o.c.

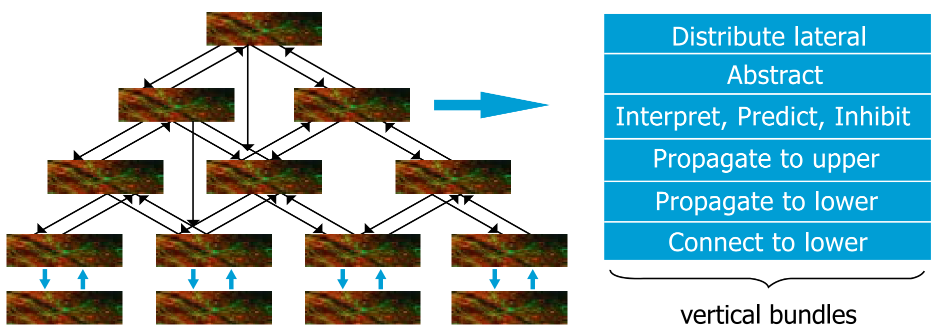


Figure 1: hierarchy of six-layered patches of neurons with lateral connections

2 Jeff Hawkins, *On Intelligence*, Times Books, Henry Holt and Co., New-York, 2004

Before continuing it is good to summarize the main properties of this system as they have been discovered by Neuro-biology. Here is a short list:

- the Mountcastle principle: the neurological system has the same structure everywhere. The basic neuron is a complex cell with thousands of connections. The neurons are arranged in six layered patches that overlap each other in lateral and vertical dimensions. These six-layered patches of neurons have a specific structure, schematically illustrated in the picture.
- Prediction-feedback: the layer above is continuously predicting what it should find, forcing layers below to check and to report.
- Innovation: only new information (innovation) is transmitted up the hierarchical system (caution: the system is not strictly hierarchical: there are many connections that cross the hierarchy, the whole system is more a matrix than a hierarchy).
- Abstraction: newly recognized patterns are given new identities, which we could call 'names', physically they correspond to connections that have been reinforced by learning.
- Dynamics: the system has intrinsic delay mechanisms in those parts where dynamics are important, obviously in the sound system, but also everywhere in the abstractive system. This happens through delays fixed in arrays.

Highly impressive as this system is, there is one basic observation that leads to caution. If erroneous abstractions are reconfirmed multiple times, then a 'reconstruction of reality' occurs that the neo-cortex believes to be right. Our brain system without further ado appears to be bad in statistics! In highly random situations bogus correlations arise which seem to be observed because they are anticipated and reconfirmed one time too many. To put it differently: the system is very apt to unwarranted beliefs selectively enhanced. There is overwhelming evidence that this phenomenon occurs frequently in daily life and practice. Medical practitioners believe in unsubstantiated treatment protocols (this has been investigated extensively leading to the conclusion that in many fields close to half the protocols have no justification). In developing countries there is a belief in 'juju' – sorcery – leading to the death of infants through hostile influences by neighbors or relatives, due to high infant mortality rates. Much economic and social policies are based on unwarranted beliefs.

There is a remedy to this ingrained defect of human intelligence, and it is mathematics, here in the guise of statistics. Let me start with voicing my unmitigated admiration for Bayesian statistics – the powerful science of counting. You do not need probability to do Bayesian statistics, the only thing you need is a honest account of your beliefs, i.e. what you happen to know about the reality you are considering, just that and no more. An example (which I got from my daughter Muriël) clarifies things – see the display! I cannot resist to give the basic Bayes formula:

*(a posteriori odds) = (likelihood ratio) * (a priori odds)*

or, more precisely, given an hypothesis H, an effect e, and a measure p counting occurrences (as in $p(H|e)$ = the relative occurrence of H when e is true)

Given beliefs: 1% sportsmen use dope
1% of the doping tests are erroneous

A sportsman tests positive. What is the chance that he is guilty?

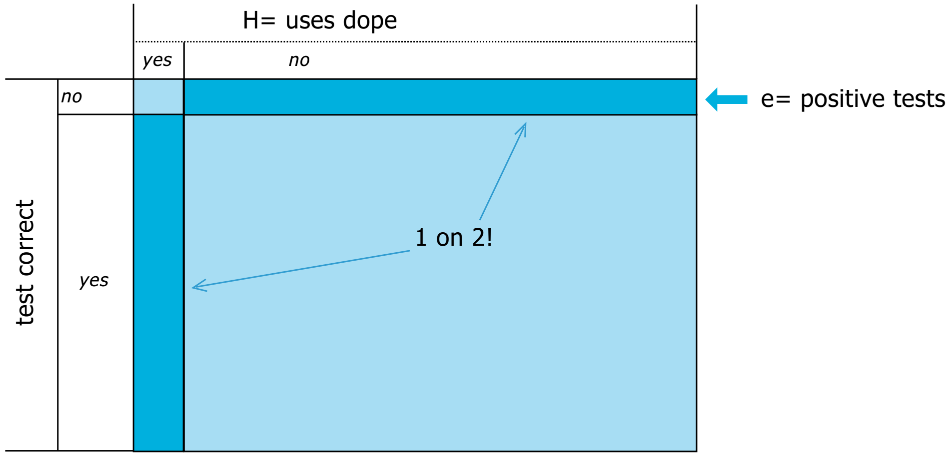


Figure 3: the number of falses is much larger in the non-dope set than trues in the dope set!

$$\frac{p(H|e)}{p(\text{not } H|e)} = \frac{p(e|H)}{p(e|\text{not } H)} \bullet \frac{p(H)}{p(\text{not } H)}$$

which tests whether a Hypothesis is valid given an effect – the conclusion – in terms of presumably known or estimated a priori data: when an effect occurs given the hypothesis and the a priori odds for the occurrence of the hypothesis in the whole population. It is especially this last factor that gives trouble to the brains (and the politicians) because they are focusing on the effects (the likelihood) and forget about the a priori odds. I dare to state (and am able to document!) that many educational and research policies are based on statistically wrong conclusions. Most dramatic is the erroneous gauging of cause-effect relations, for an account on how to reason well see the authoritative book of Judea Pearl.

The higher levels of the neo-cortex are devoted to language, but in view of the Mountcastle principle, the 'language abstraction' is active at each level of the neural system. This works by 'naming', whereby a name is coupled to a set of connections, which themselves lead to lower 'names' i.e. patterns of connections. The brain continuously verifies whether the 'abstraction' remains valid, but as we saw, it does that in a way that is statistically error prone. Mathematics on the other hand is a language with build in precision control and it is an amazing fact that our brains are capable of it. Still, going back to Socrates let me voice his caution that reaches

into the depth of our human abilities of understanding[3]:

> *all modes of knowledge express the properties and the existence of each thing using the imperfect instrument of language. Therefore no wise man will take the risk of confiding his ideas to language, and certainly not in the form of stone characters.*

But can we do otherwise?

Also Mathematics has its fundamental limitations, which have been discovered (yes, discovered within the realm of Mathematical objects) in the previous century. In the first half of the century, Bertrand Russell in his Principia Mathematica drew our attention to the mathematical impossibility of universals. There is an intrinsic contradiction between hard logic and the possibility of defining a set that contains everything: should the set of all sets that do not contain themselves contain itself (or to put it in human language: should a catalogue of all catalogues that mention themselves mention itself?) Set theory as set up by Zermelo and Fraenkel found an elegant way around this paradox by requiring the definition of the 'universal' (the world under consideration or the context) a priori. Deeper was the incompleteness theorem of Gödel roughly formulated as: any finite system of axioms that includes counting can always be extended consistently in contradictory directions leading to correct but contradictory worlds. Also this problem has found an elegant solution in Birkhoff's categoric model theory, but it surely leads to the insight that no mathematical system can be found that will cover all that is possibly true, there will always be a truth beyond...

And this phenomenon of 'having to move beyond' comes to us ingrained in 'reality' as chaos! Chaos is, technically, the fact that in many systems, an imperceptibly slight modification in initial conditions forces a totally different evolution. Some people have stated that as the 'butterfly effect': the flapping of the wings of a butterfly in South America causing a cyclone in China – but that is an incorrect image. Let me give another example that has made great impression on me: go back 500-700 years and all Europeans have common ancestors. A single girl (almost any girl!) misses an appointment with a boy 700 years ago, and none of us would be there – no Hitler, no Bush, no Balkenende, no Dewilde, none of you! You cannot say that the appointment that actually took place is the cause of our existence, because any subsequent act carries similar effects, but the farther back you go the stronger the influence on the course of events – it propagates like an epidemic. I checked the 'disappearance tree' that started with my parents (see the display) and you can see how exponentially this works (you should restrict the counting either to females or males but both sexes participate in the generation! If it continues as shown, the disappearance tree in 7 centuries would map to 2^{28} or approximately 10 billion people, de facto everybody).

Although the phenomenon of chaos (in the mathematical sense) has been known for a long time - the famous Dutch mathematician van der Pol worked on it a long time ago - a substantial body of knowledge was discovered and developed by Lorenz (who recently died). The famous

3 Plato, *Letters VII*, 344cd

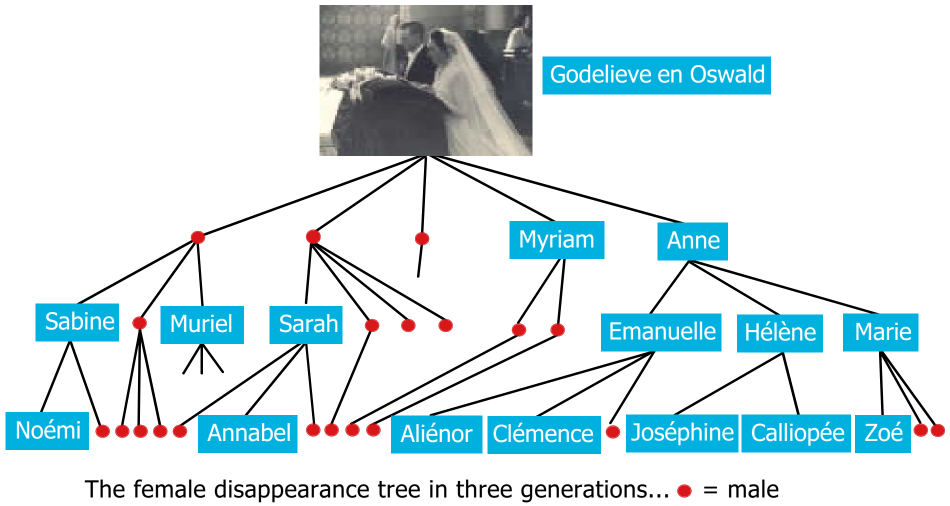


Figure 4: the picture shows all the persons who would not be there if my parents had not married. The female 'disappearance tree' in our family grows with a factor 2 per generation (typical). It works like an epidemic!

network theorist Leon Chua (to whom I am much indebted) developed very successfully the connection between chaos and network theory, and came up with electronic circuits that exhibit the many facets of chaotic behavior, both in existing and in newly conceived circuits. But it has been the merit of the Belgian Nobel laureate Prigogine to usher chaos theory into physics and to show its overwhelming importance in explaining why there is not such a thing as a single consistent theory of Physics just as there is not such thing as a single consistent Mathematics. He showed that order can and does arise in chaos as a higher level of organization[4], not covered by the underlying theory. This is called 'emergent behavior' and it is the key to understanding that indeed new sets of laws appear at higher levels of aggregation, which cannot be derived from the underlying structure. Beautiful examples are colony of ants and cyclones, but why look so far out when the working of the brain in the neo-cortex already provides a prime example.

What is emergent behavior and how does the effect arise in intelligent systems? The step to be made is to identify behavior and semantics. What moves beyond the structure and cannot be covered by it can be viewed as the 'meaning' it has – the semantics. Computer science has been very concerned with defining and understanding semantics, and rightly so, but the primacy goes again to the philosophers. The semanticist by excellence was Charles Sanders Peirce, who got as close as it can to deep insights in the notion based on a very close analysis of human consciousness. I will take a more formal path and say simply, following the 'instrumental philosophy' of the 19-eighties and the so called 'Kripke semantics' of formal Logic,

4 I. Prigogine and I. Stengers, *Order out of Chaos,* Bantam Books, USA, 1984

that the 'meaning of something is the effect that it produces in its context' (that is: the context in which its structure is defined, because as we saw with Russell we may not use universals lightly). That does not allow me to talk about 'the meaning of life' but as I do believe in the connection between meaning and effect, let me quote the very deeply touching sentence of Antoine de Saint Exupéry in maybe the most beautiful book ever written, Le Petit Prince:

C'est le temps que tu as perdu pour ta rose qui fait ta rose si importante.

The instrumental definition of semantics just given allows us to formalize the notion and use Mathematics on it. Mathematics is about structure and the truths that can formally be derived from it. It is capable of dealing in a precise way with all the notions we have encountered so far: statistics, chaos, emerging behavior and semantics. But it is and it is no more than a housemaid, it tells us what we can verifiably know and, even more importantly, what we cannot. Its great advantage is that it knows its own limitations, it is the Cinderella of science who keeps the house clean.

Maybe at this moment it is instructive to mention how I came to love Mathematics. My first teacher of Mathematics was my aunt Erica. She was a science teacher in a girls' high school in Leuven, Belgium. Early on she caught me in her nets and as a young boy I was exercising simple mathematical problems long before they were taught to me in the regular school, just for pleasure (this is the hedonistic approach to life!). The high school I subsequently attended (Sint Pieters College in Leuven) had an outstanding Mathematics (and Physics) teacher (E.H. Timmermans), who succeeded in instilling in his students not only great respect for science, but an incisive, inquisitive and highly critical approach to it. It fitted my character, in fact he found me even too aggressively inquisitive and a little heartless in talking down my opponents. But the passion these two persons (and later many others!) instilled in me stayed with me all my life.

And so, after choosing to go for Electrical Engineering but wanting to do Mathematics as well, I came to study System and Network Theory. In the course of my research career I started to realize that these fields are in fact developing 'the Mathematics for intelligence' in many ways. In this last part of my valedictory speech I want to give arguments for this statement, and to provide some illustrations to show my point. What are the main subjects of interest in System Theory? Looking at the topics my colleagues, students and myself worked on, I propose the following short list for further elaboration (although there are arguably more):

- prediction and estimation
- feedback and control
- networking and design
- computing and architectures.

In these topics I had impressive teachers to whom I want to pay tribute but I also want to give some indication of what we were able to achieve with our Network Theory unit at the TU Delft. Unfortunately, due to space and time limitations, I shall be unable to mention all the people and all the topics I should, my account will necessarily be very schematic, anecdotal and guided by the argumentation I choose for this talk rather than by the merit of the people who contributed. In particular, I shall hardly mention my many students by name although I have a very high opinion about what they have been able to achieve.

Tom Kailath

In the area of 'Prediction and Control' my foremost teacher was Tom Kailath. Our intensive collaboration in the late 70's lead to a slew of what I consider major results for which I am very grateful. Starting out from Levinson's work and the Burg algorithm, we went on to research their connection with the work of mathematicians in interpolation theory and orthogonal polynomials. During my first visit to Stanford after obtaining the Ph.D. there, remarkably enough financed by my father (I was working in Nigeria at the time), Tom asked me to look into the book of Geronimus on Orthogonal Polynomials[5]. We soon discovered the connection with Network Synthesis, in particular the connection between Isaac Schur's 1917 seminal work on scattering functions[6] with Darlington synthesis, a topic I had researched with another great teacher Vitold Belevitch during my Ph.D. period (Darlington synthesis is roughly the question whether a system can be realized by a lossless circuit). Back in Belgium, at an MBLE seminar, Vitold would at first not believe the connection was true, but soon the great impact the Schur theory could have on Network Theory became apparent. The visit of Tom in 1977 (when I was moving from Leuven to Delft) sealed our collaboration and the work eventually lead to a host of applications, including a decisive contribution to speech estimation and coding for GSM, which thanks to the R&D work of Peter Kroon, Ed Deprettere and Rob Sluyter (with strong support of Philips) produced a patent that made its way into the GSM standard and is now used by more than a billion people many times daily. One of Tom's central ideas (there are many...) was the introduction of the notion of 'innovations' in Estimation Theory. His highly insightful way of treating the Kalman filter is in particular based on it. Schur's algorithm (and hence also Darlington synthesis) can be interpreted as producing the innovations in a sequence of data. The connection between innovations, Kalman filtering, inverse scattering, numerical analysis and network synthesis is now perfectly understood, as is the connection with many more notions of functional analysis such as reproducing kernels and lifting, to which several mathematicians with whom I had the great privilege to work with Harry Dym, Rien Kaashoek, Israël Gohberg and Daniel Alpay to name but my most direct contacts. The fact that there is such a strong relation between innovations and scattering is responsible e.g. for the basic engineering fact that the reconstruction filter (sometimes called modeling filter) is a stable

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5 Ya. L. Geronimus, *Orthogonal Polynomials on a Circle and their Applications,* Amer. Math. Soc. Translations, **1954,** no. 104, 79 pp.
6 I. Schur, 'Ueber Potenzreihen, die im Innern des Einheitskreises beschränkt sind, I', *J. Reine und angewandte Math.,* **147**: 205-232, 1917

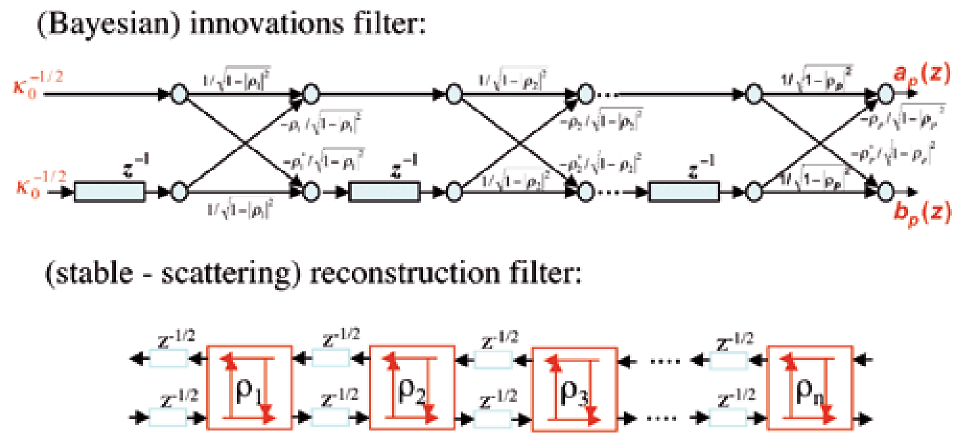
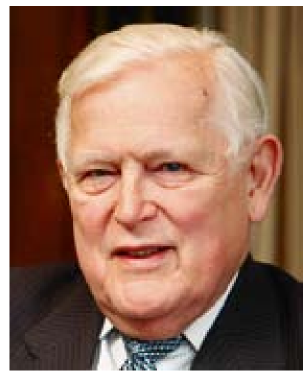


Figure 5: Innovation and reconstruction filters based on Schur interpolation

system capable of reconstructing the signal from the innovations in a faithful way. Your GSM phone calculates the innovations at the transmit side, producing a reduced set of minimal information that is being transmitted, and reconstructs the voice signal in a natural way at the receiving side. Although the idea appears simple it is not that easy to implement, because of a number of complications due to the nature of the speech signal, but in essence this explains how your GSM in fact mimics the innovations process of your brains...



Rudy Kalman

But estimation and anticipation is only one part of the story. The other side of the coin is the acting side: feedback and control. In my early research years as an assistant of Prof. De Bruijn in Leuven, I preferred signal processing and tried to avoid control. That was a mistake, and it was corrected through my contacts with Rudy Kalman, whose course on System Theory I took as a Ph.D. student in Stanford. Kalman's mathematical approach to the basic properties of systems immediately resonated with my own tastes, and I enlisted him as one of my three thesis committee members. I was studying scattering properties of electrical networks and in particular Darlington synthesis, and the connection with system theory was quickly established, although the multiplicative structure of the Darlington kind of network synthesis did not mesh well with module theory – then seen as the algebraic basis of System Theory, and still an important component of it. This situation gave rise to some hilarious moments, and the correction of some major mistakes in the literature... Mathematics does not forgive mistakes as politics does, it is humble but stubborn and absolutely faithful to truth (I do not know of any other endeavor that can make such a statement). At that time the truth appeared to be not so elegant as the inapplicable lofty theory we had thought to be true at first, but its intricacies went much deeper. Meeting reality proved to be rewarding one more time!

One extremely useful central concept in System Theory, which I first encountered in Kalman's course, proved to form the basis of much further research, it is the concept of 'Nerode equivalence' or, more extensively, that of 'Hankel map'. The Hankel map at any time *t* of the systems' evolution maps the systems' past inputs to its future outputs (assuming controlled incidence of future inputs). It is characteristic for what the system is capable of remembering of its past – or, to put it in a funny philosophical way, it describes the phenomenology of the systems' memory.

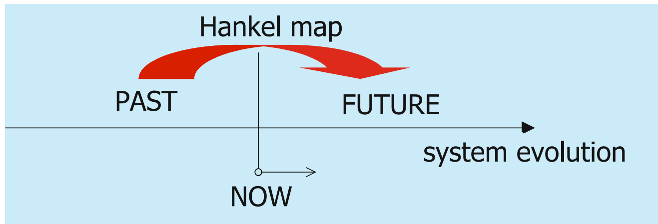


Figure 6: the Hankel map connects the past of a system to its future at each instant of time. It is the key to model reduction theory.

A central problem in systems' modeling is the problem of Model Reduction. Many systems are hopelessly complex, in their memory (called the 'state' in System Theory) there are small, unidentifiable traces of many influences of the past (remember the chaos!) which have almost no influence on the present and future behavior and which can better be forgotten when we try to model the system. The key to achieve such a model reduction is to approximate the Hankel operator. This was first done, in a very limited context, independently by Schur[7] (again!) and Takagi[8] in the early twentieth century, and then later, in the context of complex function theory, by Adamian, Arov and Krein[9]. Alle-Jan van der Veen and I discovered how to do this for linear time-varying systems, and by extension, for general matrix operators, for which there is no such thing like a complex function representation. This may be the best result we ever obtained[10], and surprisingly enough, it is the cornerstone for a new theory of generalized interpolation extensively described in the book[11] we wrote on 'Time-varying Systems and Computations' between 1993 and 1998 and which was published by Kluwer (now out of print!). In recent times, and motivated by work on multimedia signal representations in the group of Klaus Diepold in Munich, I started studying how a different class of interpolation problems could be fitted in the new framework and I was surprised to find a strong connection with control theory, namely so called 'dead beat control' as it was originally conceived by Popov and put in an elegant numerical framework by Paul Van Dooren[12]. Again the mysterious connection between estimation, control, interpolation and scattering appeared as they have become embodied in System and Network Theory.

7 I. Schur, o.c.
8 T. Takagi, 'On an algebraic problem related to an analytic theorem of Carathéodory and Fejér and on an allied theorem of Landau', *Japan J. of Math.* **1**, 83-93, 1924
9 V.M. Adamjan, D.Z. Arov and M.G. Krein, 'Analytic properties of Schmidt pairs for a Hankel operator and the generalized Schur-Takagi problem', *Math. USSR Sbornik,* **15**(1):31-73, 1971 (transl. *Iz. Acad. Nauk Armjan. SSR Ser. Math.* **6** – 1971.
10 P.M. Dewilde and A.-J. van der Veen, 'On the Hankel-norm approximation of upper-triangular operators and matrices', *Int. Eq. and Op. Th.* **17**(1): 1-45: 1993
11 P.M. Dewilde and A.-J. van der Veen, *Time-Varying Systems and Computations,* Kluwer, 1998, 454 pp.
12 P. Van Dooren, 'A unitary method for deadbeat control', *Proc. MTNS,* 1983

The thread through my exposition so far has linked the components of intelligence, as they are estimation, control and abstraction (modeling), but the impact of the evolving insights is much larger and extents to some unexpected fields. One that has kept our group's interest going is that of Computer Aided Circuit Design (or EDA = Electronic Design Automation). We focused on computational issues. Also in this area we were influenced very much by the work of Morf and Kailath in Stanford in the early eighties, and later by the work of Shiv Chandrasekaran in Santa Barbara and Ming Gu in Berkeley. The original seed was planted by Israël Koltracht (who sadly enough died recently at a relatively young age) in his thesis (the result was later published[13] with Israël Gohberg and Tom Kailath) and got code named 'Semi-separable systems of equations'. It took us a while to see and understand the fact that these systems of equations can be viewed equivalently as 'time-varying systems', and once this insight was established, the whole machinery of time-varying System Theory became relevant for large computations, with in particular the application of model reduction. This then cried for a new approach to what we would call 'Computational Network Theory', networks of computations in which data is communicated between computing units. Surprisingly enough, these networks do resemble classical electrical networks, provided conditions on the quality of the computations are enforced. Orthogonal transformations correspond e.g. to lossless circuit elements when expressed in a scattering formalism. The important point is that the underlying mathematical formalism appears to be the same.

In view of the extreme demands on computations in e.g. integrated circuit modeling, this insight may provide an answer to some of the more difficult modern issues in numerical computations for the very large systems of equations appearing in these problems. This circle of ideas, together with extensive modeling work on integrated circuits, lead to the development of the famous 'lay-out to circuit extractor' SPACE by Nick van der Meijs and his coworkers and recent results (in the STW project MICES) indicate that we may be able to solve full scale Electro-Magnetic propagation problems on IC's in a way that is substantially more accurate than possible so far (thanks to new ideas in EM-field theory proposed by my

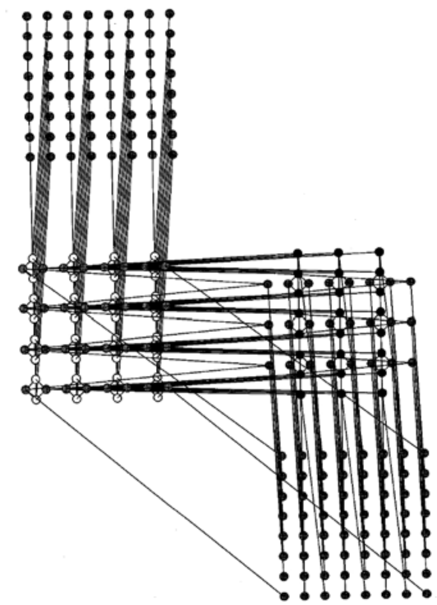


Figure 7: a computational networks (to compute the SVD!) – from the thesis of P. Held.

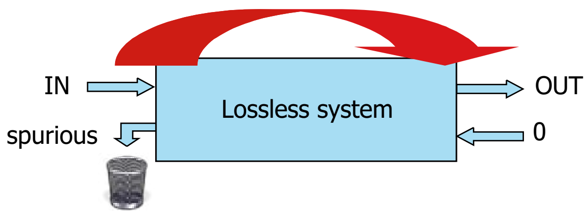
13 I. Gohberg, T. Kailath and I. Koltracht, 'Linear complexity algorithms for semiseparable matrices', *Int. Eq. and Op. Th.,* vol. **8**, Birkhäuser, 1985, pp. 780-804

much admired colleague A.T. de Hoop). We have been researching partitioning methods for multicore environments already for more than twenty years (think of 'global parallel local sequential' and 'local sequential global parallel'), long before the new trend of 'multicore processors', the challenge is to bring those results back to life – sometimes I have the feeling that our university research often comes much too early for acceptance by the industry.

Vitold Belevitch

This short account of some of my peregrinations in science would not be complete without a tribute to my teachers in Network Theory, in particular Bob Newcomb and Vitold Belevitch, but I got certainly influenced by many other researchers interested in circuits, in particular Hugo De Man, Bernard Tellegen, Alfred Fettweiss, Dante Youla, Brian Anderson, Leon Chua, Rainer Pauli, Klaus Diepold and Jan Willems. The question has been raised whether Network Theory is still a valid domain of science, and whether young students should be exposed to it in their early curriculum. My view is that Network Theory is now firmly integrated in System Theory as far as its scientific content is concerned and in Electronics for its applications, not withstanding the strong influence it has on other fields such as signal processing, control and numerical analysis. As a theoretician I feel perfectly comfortable with this integration, since also Belevitch and Youla were unwitting pioneers in Systems Theory and notably Kalman as well as B.D.O. Anderson actually made it happen (and many others later).

Figure 8: the Darlington filter realizes a transfer function using a purely and highly accurate lossless circuit. We derived necessary and sufficient conditions for its existence in the general computational setting.



System Theory (and Network Theory as part of it, as well as Electronics and Signal Processing as its application domains) has a tall order to fulfill in the future: the realization of intelligence. The topics it is concerned with are the essential building stones of the intelligent systems of the future: identification, prediction, control and abstraction. The problem is how to put these all together in a coherent whole just like our brains are able to do it. It is clear that the electronic systems we are building today lack some of the main characteristics of intelligence, in particular the close interaction between prediction and abstraction. The systems we construct are often unilaterally forward looking while our brains are permanently looking backward, adapting and intervening when things do not tally, learning by doing so. We, engineers, do not yet know how to achieve this feat, although there have been many attempts. There is a field in Computer Science called 'Knowledge Engineering' and it certainly provides very valuable insights – the internet is based on it and it is starting to have brain-like characteristics – but it does not behave like a brain yet! An integration of Computer Science, System Theory, Signal Theory and Communication is the next step towards the goal of creating truly intelligent systems. And as we know from how (Darwinian) evolution comes about, the effect of arising intelligence is such that it is a strongly self reinforcing process that conquers its environment (for the best or the worst) once it finds a productive outlet – that is also how chaos and emergent behavior works, intelligence is like an epidemic.

Be that as it may, I shall not be there to participate in the creation of the new era of intelligence, this I have to leave to our new generation of scientists. I am happy with the fact that the future of our field looks so bright. The past generations have been able to solve basic problems in System Theory (and I hope I did indeed contribute a little). New insights in other relevant fields, especially in Neuro-biology are popping up as never before, internet intelligence is encompassing the world, our understanding of the many elements of intelligence are starting to fall into place. The challenge is now to put it all together in order to engineer systems that are truly as intelligent as the human brain is. Reverse engineering from Neuro-biology will be necessary (and there is still a lot to do to understand the brain as a system), but also the building of a strong base of knowledge on what are the necessary ingredients of an intelligent system and knowhow on how to design and realize them (as we have been trying to do in our excellent facility DIMES).

Meeting reality is tough for us, humans, who are busy building abstractions that allow us to master its complexities. Often we misjudge what we see, we put together effects that do not belong together and fail to see other essential patterns because of the incorrect focus. We have a tendency to believe that a recognized pattern represents 'the truth' as if the generation of patterns our brains can recognize were also the way of reality while it is just the way of our cortex. What we believe in is but one peculiar way of seeing things, seemingly corroborated by experience, but essentially limited by our abilities to interpret correctly. Nonetheless, the mechanism of intelligence is a very powerful one. We are not just passive agents thinking and observing, but also actors whose abstractive powers are capable to engineer actions that do change the world. Based on our insights we are indeed fashioning a new world. We then observe what we have created and what we see (or often do not see) turns out to be quite different from what we intended. However impressive the human endeavor may be, I keep the uneasy feeling that we are merely a bunch of apprentice sorcerers... The old sage Lao Tzu, whose ancient poetry I much admire, cautions us in this way:

> *A wise man shall circle the square and square the circle so as not to impede and not to injure.*

Taking his advice I leave my general comments at that!

I am overly grateful for all the chances and opportunities my professional life in Delft has given me, the many opportunities for teaching, research, experimenting, coaching, interacting with people, participating in developments etc... including talking to you today. My heartfelt feelings go to all who have contributed to making my professional life so valuable (at least for me) and I am especially grateful to the people in service rendering positions who have made my daily life so pleasurable, I hope I have been able to do to them what they so gracefully did to me. My most profound feelings of appreciation go to Anne, who has been my wife and companion for forty years now, and whose support for, patience with and love of the bewildering person I have been has never failed. Without her intense efforts very little of what I was able to do would have happened.

And as far as I am concerned now, I paraphrase a small poem of my favorite poet Paul Van Ostaaijen

De sjimpansee doet niet (meer) mee
Waarom doet de sjimpansee niet (meer) mee
De sjimpansee
is
ziek van de zee
Er gaat zoveel water in de zee
Meent de sjimpansee

Ik heb gezegd,

Delft, June 20th, 2008.