physics courses, when rewriting at night the notes I had gleaned from the board during the day brought sense and order.

Even then, I realized he was not reading to us but was actually thinking in real time at the result he wanted to expound and the best way to get there. The hesitations, the shortcuts, all were enlightening when pored over later; they emphasized the delicate issues from the run-of-the-mill developments. Things a bit too tedious were left aside as a suggestion for a term paper. This was my first introduction to the development of the thought process, with a trail left behind, and to research in the making.

Even exams were somewhat surprising. Questions were often amenable to two line answers, which sometimes left you wondering whether you had not missed the point and forced you to stand up for your answer in front of yourself.

Over the course of two quarters, everything (almost) fell together. Some of my more interesting classes had concerned passive network theory, the synthesis of transfer functions, switching theory with sequential logic, the synthesis of switching networks, and digital signal processing. All of a sudden, in the middle of a discussion about rings of power series, kernels, and PIDs (not the regulator, the other one), these notions would unexpectedly turn up with a unified theory ready to be contemplated, namely, the mathematical theory of dynamical systems.

Prof. Kalman systematically built on what was already clearly understood, testing the domain of validity of the concepts at hand before moving to new ones. The notion of canonical realization was dear to him, and having directed Pierre Faurre toward Gaussian Markovian realization theory, he suggested I look at a possible extension to integer rather than real coefficients. As usual with him, this was no idle proposition; it came with leads to chapters in Jacobsen and Michael Artin that might be relevant. Right he was!

Prof. Kalman's global vision is unmatched, and he has been uniquely able to pair domains of mathematics with system theoretical applications. His intuition, vast culture, and hard work lets him see the import of heretofore untapped areas. He pioneered the use of abstract algebra in system theory through modules but also through group representations (FFT, the use of Young tableaux) or Grassmann varieties. His reappraisal of system identification came at the time Rene Thom was interested in hidden variables. It has been a privilege to see this work in the making.

Duality theory plays an important role in his work. But the latter itself presents a dual aspect. Prof. Kalman has always defended an incremental approach to the development of system theory, as opposed to brand new theories of as yet unproved usefulness, yet he always seeks high and low for new tools that can be brought to bear on his problems and to embed them in a more general unifying framework.

And, when not talking about mathematics, there is always the possibility of applying the same rigorous analysis to an equally important area: hi-fi.

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On the 50th Birthday of the Kalman Filter: Remembrances of a Great Teacher

PATRICK DEWILDE

Prof. Kalman played a determining role in my becoming a system theorist (in those times I did not address him yet as "Rudy!") In this tribute I want to concentrate on the way Rudy Kalman was able to engage, generate, and stimulate thinking in his students and how I experienced this in a meaningful way. My first contacts with him go back to 1968–1970, when he was still a professor at Stanford University, where I was a Ph.D. student, but he was in the process of moving to Gainesville, Florida. I had heard of state-space theory and its importance for circuit theory through my contacts with Vitold Belevitch and my thesis adviser Bob Newcomb, but when I came to Stanford to finish my Ph.D. I had the occasion to take a course in system theory taught by Rudy Kalman. "KFA" or the Kalman, Falb, and Arbib landmark text on system theory had just appeared and was evidently chosen as the textbook for the course. I remember how thrilled I was when I saw Rudy Kalman's commanding posture entering the classroom. Although I did not consider myself a control engineer I had heard of the Kalman filter and its tremendous impact on engineering, and I knew that it represented a decisive paradigm change, whereby control of a system would and could be done based on its algebraic properties rather than on pure input/output transfer functions. The change was not only in mathematical techniques but also and foremost in philosophy, namely, estimate the properties of a system first and then base control on its structural properties.

The distinguishing feature of Prof. Kalman's lectures was, in my view, his emphasis on concept formation. You could call it lessons in the construction of a scientific theory. The questions he addressed had to do with what the essential features are and how they could be connected with mathematical treatment. Discovering the mathematical structure of system theoretic concepts was the main theme, and if I

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must choose what was the most compelling point I learned from him, it would be the great respect he showed for the achievements of mathematics and how he gauged his own understanding of system theory by the mathematical depth of the concepts he was developing. Module theory played a major role, of course, but there was considerable more. I learned about Nerode equivalence and its connections with what has come to be called the Hankel map, the operator that links past to future in a system. Related to the Hankel map are the notions of controllability and observability, to which KFA shed substantial new light. For me it was totally exhilarating, since I could suddenly place many notions I had heard about in an appealing and highly sensible framework.

Some day in May 1970, Stanford Escondido Village, 7 a.m. I had just gotten up and had put my face under the faucet when the phone rang. Prof. Kalman at the other side of the line, "I just read Chapter 2 of your thesis and your Theorem 2.1 on minimal factorization is false. Can I see you as soon as possible?" By 8 a.m. I was in his office, and we started discussing the theory of Chapter 2 of my thesis. The topic was the multiplicative structure of transfer functions. Kalman's objection against the views I propounded was that it was contradicting some basic tenets of module theory. The setting was the multivariable system theory (better would be multiport) and the module theory referred to is the one that leads to the Smith-McMillan canonical form. We tried an example that I had cooked up in earlier discussions with Belevitch, and it soon became apparent that the state minimal multiplicative structure of transfer functions did not satisfy module-theoretic axioms—its conclusions therefore did not apply. My Theorem 2.1 and my thesis were saved, and I should say that Kalman immediately and graciously agreed, gave his approval, and signed off my thesis for which he was the second examiner. Underlying the issue were two misconceptions, both of which were quite common in the literature of those times. One was that the Smith-McMillan form would commute with polar expansions and the other that the Smith-McMillan form would commute with factorization. That the latter is untrue is pretty easy to see, but also the (more restrictive) former is untrue. The interaction just described was not the only direct influence Kalman had on my thesis. He actually did not like the redaction of an earlier version that had a more or less colloquial style, and he requested that I make the whole thesis rigorous and put it in proofs and theorems. An extremely good piece of advice, which taught me how one must perform science!

Rudy Kalman has been a prolific researcher and publisher. Besides the major discovery of the Kalman filter and the development of the underlying system theory, there were many contributions to network theory, the theory of complex functions, matrix theory, the theory of functions in several variables, and even economics. One problem, however, was that he published some basic results in languages other than English, and these results were often overlooked by researchers to their own detriment. The case occurred that supposedly new results were presented at conferences by inadvertent researchers with Rudy Kalman attending, and they had to submit to a thorough ear washing when the original author came forward and requested redress!

During my career I often had the pleasure to meet with Rudy Kalman and have in-depth conversations on a variety of topics. Most recently he has been lecturing on transformerless circuit synthesis, reconsidering an old and up-to-this date unresolved issue, whose algebraic structure is probably very deep but has not been revealed so far. It takes quite a bit of courage to take up issues on which so many well-known authorities have broken their teeth, to study the various attempts carefully, and to try to come up with a new viewpoint. To those who would doubt the practical utility of such an endeavor or who would think that the question has been superseded by modern technology (passive synthesis is not useful any more they would state), I would retort that any advance in understanding the algebraic structure underpinning electrical phenomena always has produced great benefits, sometimes solving totally unrelated questions such as in coding theory or information theory. The same may be said of the prime structure of minimal realizations of rational transfer functions, also an issue that remains unresolved.

Knowing Rudy Kalman as a professor, a mentor, and a friend has been one of the great opportunities of my career for which I am infinitely grateful!

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Patrick Dewilde is with the Institute for Advanced Study, TU München. He received the degree of electrical engineering from the University of Leuven in 1966, the license in mathematics from the Belgian Central Examination Commission in 1968, and the Ph.D. in electrical engineering from Stanford University in 1970. He has held research and teaching positions at the University of California, Berkeley, the University of Lagos in Nigeria, and the University of Leuven, Belgium. In 1977 he became a full professor of electrical engineering at the Technical University of Delft, the Netherlands. In 1981 he was named Fellow of the IEEE for his work on scattering theory. His research interests include the design of integrated circuits (VLSI) especially in the area of signal processing, large-scale computational problems, theoretical topics in system theory and signal processing, and information management. The NELSIS design system, which pioneered a unique design information management methodology, was developed under his direction. In 1993, he became the scientific director of DIMES, the Delft Institute of Microelectronics and Submicron Technology. He is the author of numerous scientific publications and the books *Large Scale Modeling of Integrated Circuits* (Kluwer, 1988) and *Time Varying Systems and Computations* (Kluwer, 1998). He was elected as a regular member of the Dutch Royal Academy of Science in 1993.