Rudolf E. Kalman and His Students

EDUARDO D. SONTAG

This article presents a series of essays written by former Ph.D. students of Rudolf Kalman, arranged chronologically by year of graduation. The influence of Rudolf Kalman's work in control theory is vast, deep, and wide. Indeed, it is fair to say that many of the most fundamental concepts in our field trace their lineage to him. An aspect of Rudolf Kalman's legacy that is perhaps less known is the influence that he had on the careers of his collaborators and students. As the essays collected here amply demonstrate, Rudolf Kalman has always been a stimulating source of novel ideas, inspiration, and challenging problems. Moreover, he inspired his students in the pursuit of excellence and originality in scientific research.

Rudolf Kalman was born on May 19, 1930 in Budapest, Hungary. He obtained the bachelor's degree in 1953, the master's degree in 1954 from MIT, and the D.Sci. degree in 1957 from Columbia University, all in electrical engineering. He worked as a research mathematician at RIAS (the Research Institute for Advanced Study in Baltimore) from 1958 until 1964. He subsequently became a professor at Stanford University (1964–1971) and later a graduate research professor in the departments of mathematics, electrical engineering, and industrial and systems engineering at the University of Florida, where he also established the Center for Mathematical System Theory (CMST), directing it until his retirement in 1992. In 1973, he was elected to an ad personam chair in mathematical system theory at the Swiss Federal Institute of Technology, Zürich, which he held until compulsory retirement in 1997.

Rudolf Kalman is a member of the U.S. National Academy of Sciences, the U.S. National Academy of Engineering, and the American Academy of Arts and Sciences. He is also a foreign member of the Hungarian, French, and Russian Academies of Science and is the holder of many honorary doctorates. He was awarded the IEEE Medal of Honor in 1974, the IEEE Centennial Medal in 1984, the Inamori Foundation's Kyoto Prize in High Technology in 1985, the Steele Prize of the American Mathematical Society in 1987, the Richard E. Bellman Control Heritage Award in 1997, and the NAE Charles Stark Draper Prize in 2008.

Rudolf Kalman had several Ph.D. students at each of the institutions where he was a faculty member. These students include the following:

Digital Object Identifier 10.1109/MCS.2010.935885

- » B.L. Ho, Stanford University, 1966
- » Pierre Faurre, Stanford University, 1967
- » Anthony Tether, Stanford University, 1969
- » Marshall Banker, Stanford University, 1971
- » Yves Rouchaleau, Stanford University, 1972
- » Eduardo Sontag, University of Florida, 1976
- » Yutaka Yamamoto, University of Florida, 1978
- » Athanasios Antoulas, ETH Zürich, 1979
- » Fumio Hamano, University of Florida, 1979
- » Pramod Khargonekar, University of Florida, 1981
- » Jaime Ribera, University of Florida, 1982
- » Bülent Özgüler, University of Florida, 1982
- » Tryphon Georgiou, University of Florida, 1983
- » Markus Spindler, ETH Zürich, 2000.



Rudolf Kalman at his office in 1974.



Yutaka Yamamoto and Eduardo Sontag at the University of Florida in 1974.

1066-033X/10/\$26.00©2010IEEE

In addition, Patrick Dewilde (Stanford University, 1970) and Ed Kamen (Stanford University, 1971), both officially students of Bob Newcomb, are considered "honorary students" of Rudolf Kalman because of their strong and close interactions with him during their Ph.D. studies. In addition, Alain Bensoussan has kindly provided an essay describing the student experiences of Rudolf Kalman's student Pierre Faurre (who passed away in 2001).

It is fitting to also mention Tsuyoshi Matsuo (who passed away in 1993), who was Rudolf Kalman's Ph.D.

A Tribute to Rudi Kalman

ALAIN BENSOUSSAN, WRITING FOR PIERRE FAURRE

y goal is to pay homage to Rudi Kalman on behalf of Pierre Faurre, his student from 1964 to 1967. Pierre Faurre, under the supervision of Rudi Kalman, wrote a remarkable dissertation on the representation of stochastic systems, thereby extending the work of his adviser on deterministic systems.

I had known Pierre since 1959 when he and I were schoolmates at the Ecole Polytechnique. He was ranked first at the entrance competitive examination and first at the end of his studies. In those days, it was not so common to go to the United States for a Ph.D., but Pierre Faurre was a visionary and saw the importance of the new approach of control and estimation that Rudi Kalman embodied. In his early connection with the French electronics company SAGEM, he also understood the potential of these methods for the guidance of systems. In fact, inertial guidance based on Kalman filtering proved a very successful domain of expertise for SAGEM.

Rudi Kalman and Pierre Faurre maintained exceptionally close relations. Upon his return to France, Pierre was expected to create a research center at the Paris School of Mines in the field of automatic control, a domain that did not exist in this famous engineering school. Because Rudi Kalman was held in such high esteem in the field of control, the director of the school, Pierre Laffitte, thought it would significantly boost the center if Rudi Kalman became its first director. Rudi accepted and was therefore able to continue close collaboration with Pierre Faurre.

Later, Rudi Kalman asked Pierre Faurre to teach at Stanford. After this, Pierre Faurre obtained a part-time top position at INRIA, where I was working under the leadership of Jacques-Louis Lions. In this way, a very active interaction took place between IRIA and the Centre d'Automatique of the School of Mines. I keep from these years the best possible memories, since I was in constant contact with Rudi Kalman, Jacques-Louis Lions, and Pierre Faurre. student at the University of Florida simultaneously with Yutaka Yamamoto and myself. I warmly recall the regular late-night conversations that the three of us had on many topics in control and systems theory. Tsuyoshi came to Gainesville while on leave from a position at Nagoya University. During his studies, he made substantial progress toward a thesis on infinite-dimensional realization theory, but since he had to return to Japan at the end of three years, his doctorate degree was officially conferred (in 1980) by Nagoya University.

After his initial leadership of the center, Rudi Kalman left it to Pierre Faurre and took a position both in Florida and at ETH Zurich. Nevertheless, Rudi was coming regularly to France to visit Pierre and conduct scientific activities. Pierre kept me in the loop, so I could follow their friendship. Early on, I had met Rudi's wife Dina, and I must say she became very popular with the French group, particularly among spouses.

I can confirm the exceptional quality of the relations between Rudi Kalman and Pierre Faurre and between their wives Dina and Pierrette. It is a great honor for me to report about it, although I remain so sad when I think about the immense loss that the absence of Pierre Faurre represents. He passed away in February 2001. Jacques-Louis Lions passed away in May 2001. I lost in the same year my best friend and my mentor. This same year, in which later on the September 11th event took place, remains a dreadful year.

But I want to conclude by expressing the admiration that Pierre Faurre had for his adviser and mentor as well as his friend. Rudi Kalman deserves it. He has been at the origin of such an essential evolution of automatic control, a kind that occurs rarely in any science.

AUTHOR INFORMATION



Alain Bensoussan is a research professor and the director of the International Center for Decision and Risk Analysis at the University of Texas at Dallas. He is professor emeritus at the University of Paris Dauphine and has an extensive research background in stochastic control, probability, and stochastic processes. He served

as president of the National Institute for Research in Computer Science and Control (INRIA) from 1984 to 1996, president of the French Space Agency (CNES) from 1996 to 2003, and chairman of the European Space Agency (ESA) Council from 1999 to 2002.

My Experiences with Prof. Rudy Kalman

ANTHONY J. TETHER

initially met Prof. Kalman when, in 1965, I took a course he was teaching at Stanford University in modern algebra theory applied to linear dynamical systems. He became my Ph.D. thesis adviser in 1966. From 1966 to late 1968, I was basically his only student and consequently did many tasks for him that resulted from his numerous consulting activities.

It is difficult for me to articulate all I learned from Prof. Kalman during this time period. We pursued many research topics that were for the most part orthogonal in their subject areas. The one specific thing I remember Prof. Kalman telling me is that I should always look at a new subject and try to formulate all the questions that were still unanswered (or at least the answers that were not known to me) and not to rest until I learned the answer. He also said that as I did this many more questions would arise and that I should track the down answers to these new questions.

He said that eventually the rate of new questions would decrease and even stop. When that happened I could be comfortable but not 100% confident that I had really searched the space. Of course I had the benefit of meeting with Prof. Kalman on a regular basis, and he had no trouble generating questions to be answered!

I have followed that philosophy throughout my life and have tried to pass it on to those who have worked for me, that they should know the answer to any question that can be asked about a subject in which they are involved, and to do so means that they have to generate questions themselves.

Digital Object Identifier 10.1109/MCS.2010.935887

Prof. Kalman is truly a unique person, and I was privileged to have had the opportunity to work so closely with him.

AUTHOR INFORMATION



Anthony J. Tether is with the Council on Competitiveness. He received the bachelor's of electrical engineering from Rensselaer Polytechnic Institute in 1964, the master's of science in 1965, and the Ph.D. in 1969 in electrical engineering from Stanford University. He was executive vice president of Systems Control, Inc.

from 1969 to 1978, and vice president for technology and advanced development at Ford Aerospace, which was acquired by Loral Corporation during that period. From 1992 to 1994, he was vice president at Science Applications International Corporation's (SAIC) Advanced Technology Sector and then was vice president and general manager for Range Systems at SAIC. From 1994 to 1996, he served as CEO for Dynamics Technology Inc. He was CEO and president of The Sequoia Group, which he founded in 1996. He was the director of the National Intelligence Office in the Office of the Secretary of Defense from 1978 to 1982, director of the Defense Advanced Research Projects Agency (DARPA) Strategic Technology Office from 1982 to 1986, and director of DARPA from 2001 to 2009. He has served on the Army Science Board, the Defense Science Board, and the Office of National Drug Control Policy Research and Development Committee. In 1986, he was honored with the National Intelligence Medal and the Department of Defense Civilian Meritorious Service medal.

My Stanford Days as a Graduate Student with R.E. Kalman

EDWARD W. KAMEN

started my graduate studies at Stanford University during the autumn quarter of 1967, after having obtained the bachelor's degree in electrical engineering from the Georgia Institute of Technology in 1967. For me, the biggest shift in going from undergraduate student to graduate study at Stanford was the level of mathematics. In particular, the system theory course sequence in electrical engineering at Stanford required that students have a strong understanding and working knowledge of linear algebra, which I did not begin to acquire until the spring quarter of 1969 when I took a linear algebra course in the Department of Mathematics. After that course, I was finally able to take System Theory 363A, the first course in Stanford's electrical engineering system theory sequence at that time. I took the course from a remarkable adjunct professor named Rod Edwards who "turned me on" to mathematical system theory as an area of study. In the next quarter, I took the first course of a two-course sequence in the Department of Operations Research titled Mathematical System Theory 347A and B, which was taught by Prof. R.E. Kalman.

In my case, Prof. Kalman's reputation definitely preceded him. Although I did not fully appreciate the significance of the Kalman filter at that time, I was in awe of him and somewhat intimidated to be taking a course from such a renowned person. I remember that on the first day of class, Prof. Kalman said that we would need to have knowledge in abstract algebra with an emphasis on rings and modules. I had just learned the fundamentals of linear algebra, so I was leery of having to move further into the realm of abstract mathematics. The students in the class with me were almost all foreign born, with the predominant component from France. This did not help to bolster my confidence, which turned out to be a correct assessment, as years later I learned that French students are routinely taught abstract algebra in their precollege education.

The first course of Prof. Kalman's two-course sequence on mathematical system theory dealt with his novel K[z]-module formulation of linear time-invariant, discrete-time systems, where K[z] is the ring of polynomials in the indeterminate z with coefficients in a field K. In the second course, taught during the winter quarter of 1970, Prof. Kalman extended his K[z]-module approach to continuous-time systems by replacing K[z] by a ring of distributions. His work was published in 1972 in the journal *Ordinary Differential Equations* in a paper coauthored with Malo Hautus. Taking the second course in Prof. Kalman's two-course sequence determined my Ph.D. thesis topic and set the stage for the research that I was to carry out during my professional career.

During 1970, I was also interacting with another Stanford professor, Robert Newcomb, who had carried out fundamental research on multiport network synthesis including the synthesis of networks containing LC and RC transmission lines. After I completed Prof. Kalman's second course on mathematical system theory, I began to wonder whether his distribution-ring formulation could be generalized to infinite-dimensional systems containing LC and RC transmission lines and other elements with irrational transfer functions. Newcomb became my thesis adviser on this topic, although much of what I had learned came from Prof. Kalman's second course and interactions with him. In fact, during 1970 I had the pleasure of being with him in a small group that was discussing research issues involving "algebraic system theory." In addition to Prof. Kalman and myself, the group included Jorma Rissanen and Malo Hautus.

After my graduation from Stanford University in June 1971, much of my subsequent research on infinite-dimensional systems and algebraic system theory can be traced back to my association with Prof. Kalman. In addition to providing expert research advice, Prof. Kalman was an outstanding classroom instructor who inspired me to carry on his tradition of teaching excellence in my own academic career. I hope that I have succeeded in some measure in that regard.

AUTHOR INFORMATION



Edward W. Kamen is Julian T. Hightower Professor Emeritus at the Georgia Institute of Technology. He obtained the bachelor's in electrical engineering from the Georgia Institute of Technology in 1967 and the Ph.D. in electrical engineering from Stanford University in 1971. From 1971 to 1981 he was on the faculty at Georgia Tech,

where he carried out research on infinite-dimensional systems and linear time-varying systems. In 1981, he moved to the University of Florida, where his research centered on two-dimensional systems and adaptive control. In 1986, he became professor and chair of the Department of Electrical Engineering at the University of Pittsburgh. While at Pitt, part of his research focused on the development of the SME filter approach to multiple target tracking. In 1991, he returned to Georgia Tech to assume the Julian T. Hightower endowed professorship. While at Tech, he was the associate director of the Manufacturing Research Center and the founding director of the Center for Board Assembly Research (CBAR), which dealt with both education and research involving printed circuit board assembly. In 2002, he retired from Georgia Tech to focus on developing techniques for trend analysis of time series data in real time, including financial data such as stock prices. He is the author or coauthor of over 200 journal and conference papers and six textbooks. He was the general chair of the 38th IEEE Conference on Decision and Control, and he is a Fellow of the IEEE.

Studying Under Prof. R.E. Kalman

YVES ROUCHALEAU

hen Prof. Kalman bustled into the classroom during my first quarter at Stanford in 1968, it seemed like a return to normalcy. He was hurrying back from a

Digital Object Identifier 10.1109/MCS.2010.935889

meeting abroad and picked up a piece of chalk to write: THE-OREM, and then PROOF. I had been through three months of generalized mayhem in Paris where I had attempted to get exams organized at the Law and Economics University. All of a sudden I was thrown several years back to my math and 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.

AUTHOR INFORMATION

Yves Rouchaleau is a faculty member at the Ecole des Mines de Paris.

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

PATRICK DEWILDE

rof. 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



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!

AUTHOR INFORMATION

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.

Rudolf Kalman as a Ph.D. Adviser

EDUARDO D. SONTAG

y path to Rudolf Kalman (from now on "REK," as he is known to his students) was based on two lucky breaks. Mathematics undergraduates at the University of Buenos Aires are required to write theses on a subject of their choosing. With no clue as to topics, I decided to browse the library bookshelves—a quaint data exploration activity, which a few readers of this publication might once have been familiar with. This is how I found *Topics in Mathematical Systems Theory* (Kalman, Falb, and Arbib, McGraw Hill, New York, 1969). It was amazing to discover that it was possible to combine the mathematical beauty of algebra with applicable mathematics, and a thesis on automata and linear dynamical systems quickly followed.

The second lucky event came in early 1972 when my PDE instructor Héctor Fattorini happened to attend the Sanibel Island Conference on Mathematical Systems Theory, during which he learned that REK was moving from Stanford to Florida and was looking for graduate students. Fattorini told me, I contacted REK, and within a few days of graduating I landed in Gainesville.

REK's role as adviser was not ordinary. For me, his only direct guidance consisted of two items, 1) upon arrival to his Center for Mathematical Systems Theory, I found waiting for me a draft of Michel Fliess' thesis on noncommutative power series and formal languages, which he rightfully recognized as highly relevant to nonlinear realization theory, and 2) he described his ideas of viewing states as elements of the Zariski spectrum, which in turn generalizes Stone's representations of Boolean rings and Gelfand's C^{*}-algebra representations. This latter dual view of states as functionals ended up being central to my thesis, which also combined elements of Fliess' approach. Other than setting these initial conditions, he expected excellence in research and did not request any specific activities, with the exception of the occasional 15-minute ride to the airport to meet a visitor, which provided a fantastic opportunity to meet them, or to help in organizing and classifying the preprint and reprint collection of the Center, which helped me appreciate the breath and depth of the control theory field.

The main influence of REK as a Ph.D. advisor was as a role model. While giving his students absolute and complete freedom to pursue their interests, he inspired the pursuit of mathematical rigor, the choice of deep and foundational problems, clarity of exposition orally and in writing, and intellectual honesty, including the critical evaluation of one's own and others' work. Unfortunately,

```
Digital Object Identifier 10.1109/MCS.2010.935891
```

this latter practice, when emulated, added questionable value to his students' professional careers.

The field of control theory was being revolutionized in the mid 1970s, and the Center was as intellectually rich an environment as one could imagine. Sabbatical and postdoc long-term visitors included Roger Brockett, "Sammy" Eilenberg, Michel Fliess, Yves Rouchaleau, Malo Hautus, and Michael Heymann, and there were many shorter-term visitors, several of them repeat visitors, such as Steve Morse, Ed Kamen, Alberto Isidori, Sanjoy Mitter, Michael Hazewinkel, Jan Willems, Héctor Sussmann, and David Elliot. Much learning came from their seminar talks, which were always animated, with REK aggressively quizzing speakers and questioning basic assumptions (for his students, another learned trait that turned out to be not always well-appreciated).

No discussion of REK is complete without the obligatory "Kalman story." One evening, or rather early morning (2 a.m. or so) in about mid-1975, I left on REK's desk at the Center a note to the extent that bilinear I/O systems realization theory could be done in a manner analogous to the Fliess/Isidori approach to internally bilinear systems. This is something that REK was seriously interested in accomplishing, and my note was, in retrospect, too short and cryptic. At some uncivilized hour, approximately 6 or 7 a.m., I got an angry call from REK summoning me to the office ASAP to report on the "absolute nonsense" that I had written. (I was deep asleep when the call came, so my recollection is imperfect, but I believe recalling an agitated REK saying how disappointed he was with me, how incredible it was that a promising student could write such stupidity, and so forth. He is not exactly known for tact and diplomacy in his dealings with people, and students were no exemption.) My response was that I was going back to sleep, but I would be



Roger Brockett, Eduardo Sontag, Mike Warren, and Alberto Isidori, closely listening to a speaker at the Center for Mathematical System Theory at the University of Florida in 1974. Roger and Eduardo are sporting the latest fashions.

glad to come to the Center around noon to discuss my note. By the time that I arrived, REK had calmed down somewhat, but he was still clearly upset with me. However, it took just five minutes at the blackboard for him to be convinced of my argument and to congratulate me on a good job. The point of the story is that just as he can be critical, REK is also even quicker to recognize when he is wrong. I was actually quite happy after this exchange!

My experience as REK's student was incredibly rewarding and useful and provided excellent preparation for my professional activities and my own role as an adviser. I owe him a deep gratitude for this.

AUTHOR INFORMATION



Eduardo D. Sontag is professor of mathematics at Rutgers University. His current research interests lie in systems molecular biology and control theory. He received his licenciado degree from the University of Buenos Aires in 1972, and the Ph.D. at the University of Florida, 1976, both in mathematics. Since

1977, he has been with the Department of Mathematics at Rutgers, The State University of New Jersey, where he is currently professor II of mathematics and a member of the Advisory Committee for the BioMap Institute for Quantitative Biology. He is also a member of the graduate faculties of the Department of Computer Science and of the Department of Electrical and Computer Engineering, the director of the Rutgers Center for Systems and Control, and a member of the Cancer Institute of New Jersey. He has authored over 400 journal and conference papers and book chapters as well as three books, including Mathematical Control Theory: Deterministic Finite Dimensional Systems (second edition, New York: Springer, 1998). His awards include the Reid Prize in Mathematics in 2001, the 2002 Hendrik W. Bode Lecture Prize from the IEEE, the 2002 Board of Trustees Award for Excellence in Research from Rutgers, and the 2005 Teacher/Scholar Award from Rutgers. He is a Fellow of the Society for Industrial and Applied Mathematics and of IEEE. He is on the editorial board of several journals. In addition, he is a cofounder and comanaging editor of the Springer journal Mathematics of Control, Signals, and Systems.

My Florida Days with Rudolf Kalman

Υυτακά γαμαμότο

received my Ph.D. in August 1978, under the supervision of Rudolf E. Kalman. It is inevitably not without some kind of emotion to realize that one is already way over the age of his mentor at the time of his own doctorate. On the occasion of this special issue, I would like to shed some light on his unique character manifested in his research.

My first encounter with Rudolf Kalman's work was his celebrated paper "On the General Theory of Control Systems," published in the proceedings of the first IFAC Congress in Moscow in 1960. I read this paper as part of a seminar course when I was a junior in Kyoto University. It was the second semester in the fall of 1971. The paper literally determined the course of my scientific life.

Until then, I was exposed only to classical control theory. Transfer functions, frequency response, Nyquist and Bode plots. Scattered results, with obvious relevance with practice, but not much of scientific excitement, and often not coherently given. This paper, instead, started with a rigorous definition of systems, introduced such notions as controllability and observability, and proved what can be deduced from them. Very transparent, yet highly suggestive in providing a fundamental view on reality.

I can still recall the surprise I felt on how control theory can be so mathematically elegant, yet simultaneously intrinsically relevant to reality. I was also deeply impressed with the truly fascinating touch with which the author related mathematical concepts to practical problems. Due to this paper, I decided to choose control theory as my major subject. Little did I know then that I was bound to become a student of the author himself.

In the early summer of 1973, my supervisor Prof. Sawaragi received a letter from Rudolf Kalman, soliciting a doctoral student. I immediately expressed my interest. Fortunately, I was admitted. I entered the mathematics department upon Rudolf Kalman's suggestion.



Yutaka Yamamoto, Efi Foufoula-Georgiou, and Tryphon Georgiou in a night out in Gainesville in 1972. (As usual, Yutaka sports a neat color-coordinated outfit.)

While I had a rather vague idea about how Ph.D. study would go when I started, Rudolf Kalman was not an ordinary adviser that the reader might imagine. He was not the usual adviser who gives you a problem and sets up a meeting once a week to check your progress. Instead, Rudolf Kalman organized many seminars at the Center for Mathematical System Theory. At that time, Eduardo Sontag and Tsuyoshi Matsuo were already at the Center as my fellow Ph.D. students, and Fumio Hamano joined the Center later. Rudolf Kalman invited many top scientists, and they gave sequences of seminars, including Samuel Eilenberg, Roger Brockett, Alberto Isidori, Stephen Morse, Edward Kamen, Jan Willems, Hector Sussmann, Sanjoy Mitter, Michael Heymann, Malo Hautus, and Aristid Lindenmayer, just to name a few; they were not even restricted to system or control scientists. It was a great opportunity to be exposed to how top scientists conduct their research and how they initiate new approaches.

These seminars were not like the ones I was familiar with. He often interrupted the speaker and started asking questions. Some questions seemed to take the speakers off track. He would pose a question on whether the theory is based on the correct assumptions or in the right framework, or even the right definitions. As a starting Ph.D. student, I was not aware how important it was to question whether we base our new theory on "right" definitions. In an ordinary seminar, we would naturally take the attitude that a definition is, after all, a definition, and we would hold our breath until we see the outcome. The seminars at the Center were very different. Rudolf Kalman always tried to see whether the theory is built on a sensible and fruitful definition.

I soon became more comfortable with examining basic hypotheses and saw how important it was to do so. Obviously, such an attitude is also very time consuming, but I was convinced that it is the right way to understand and build theoretical developments. Later his favorite citation was one from Newton, "Hypotheses non fingo." (I do not invent hypotheses.) My candid interpretation would be "I do not fiddle around with hypotheses."

He always emphasized clarity in understanding. His frequent usage of the phrase "What is crucial here is ..." reflects how he places emphasis on clarifying the role of certain key ideas. Merely proving a theorem is obviously not enough for understanding a problem. What one needs to see is the overall structure, how a certain assumption plays a crucial role in a critical step of the theory. He has an incredibly deep intuition for seeing the critical steps in the overall structure of a problem. This intuition played a great role in formulating the filtering problem in the state-space theory. That theory has flourished as Kalman filtering, and this is merely one outcome of the state-space approach that he initiated in the late 1950s.

I also had the good fortune of witnessing Rudolf Kalman's scientific taste from close by. Part of this I have already explained. He always emphasized clarity, simplicity, yet far-reaching consequences in building a scientific theory. He often criticized some immature, vague ideas by saying "that's fuzzy thinking." If we cannot elucidate the role of each component of a theory, we must be far away from the truth. This attitude is desirable but difficult to maintain. Nonetheless, I believe that it is truly imperative that every theorist should keep this attitude in his heart.

I would like to conclude this essay with a short episode from when I was leaving Florida after completing my Ph.D. I went into his office to thank him for his guidance during my Ph.D. study. He asked, "How was the education of the four years?" I do not remember how I replied precisely but somehow thanked him for his education in building a scientific discipline in me, perhaps also mentioning some hard days I had to go through in finding the right problem for my thesis and arriving at the goal. Rudolf Kalman's subsequent remark gave a deep impression on me, "Well, you may have thought in the middle of your study that you may be the only one who would not produce anything, but an experienced person like me does not think like that: If you really think about something, you usually produce something. I hope that the education was good enough for the next 40 years." This remark was a very valuable lesson on positive thinking and one that I fully agree with now.

AUTHOR INFORMATION



Yutaka Yamamoto received the Ph.D. in mathematics from the University of Florida in 1978 under the guidance of R.E. Kalman. From 1978 to 1987 he was with the Department of Applied Mathematics and Physics, Kyoto University. In 1987 he joined the Department of Applied Systems Science as an associate professor, and became a profes-

sor in 1997. He is currently a professor in the Department of Applied Analysis and Complex Dynamical Systems at the Graduate School of Informatics of Kyoto University. His research and teaching interests are in realization and robust control of distributed parameter systems, learning control systems, and sampled-data systems and its application to digital signal processing with emphasis on sound and image processing. He received the Sawaragi Memorial Paper Award in 1985, the outstanding paper award of SICE in 1987 and 1997, the best author award of SICE in 1990 and 2000, the George S. Axelby Outstanding Paper Award in 1996, and the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology Prizes for Science of Technology in 2007. He is a Fellow of the IEEE and SICE. He was an associate editor of IEEE Transactions on Automatic Control and Automatica, and is currently an associate editor of Systems and Control Letters and Mathematics of Control, Signals and Systems. He was the chair of the Steering Committee of MTNS and served as general chair of MTNS 2006. He was IEEE Control Systems Society vice president for 2005-2008 and president of ISCIE of Japan for 2008-2009.

Recollections of My Time as a Doctoral Student of R.E. Kalman

THANOS ANTOULAS

Since high school, I wanted to do a Ph.D. in physics. After graduating from the ETH Zürich with degrees in electrical engineering and mathematics, I was appointed as an assistant and doctoral student in solid-state physics at the ETH. A few months later, I heard that someone named *Kalman* was coming to the ETH from the United States. The name rang a bell, as I had encountered the *Kalman filter* in my undergraduate years. Shortly thereafter I decided to take on the challenge and do my Ph.D. under



Rudy Kalman and Thanos Antoulas on the *Flying Cloud* in December 1977.

Rudy's supervision. Rudy consulted with Eduard Stiefel, one of my former teachers and a respected professor of applied mathematics at the ETH, and he offered me a position provided that I already had a publication. That happened to be the case (my Diplomarbeit—diploma thesis—in mathematics was published in 1976). Thus started my journey in systems and control, a field about which I knew very little at the time. In the years that followed there were ups and downs; about eight months before graduating I considered abandoning the effort. Then things started falling into place. Important for this development were my encounters with Jan Willems and Paul Fuhrmann.

There are many stories of my time with Rudy Kalman that I can tell at this point. I will, however, mention only two. The first has to do with my first technical discussions with Rudy. They were concerned with the four-color problem, which was long unsolved. The conjecture asserts that every planar map can be colored with at most four colors so that no two regions with the same color share a common edge. In 1976 a proof of this conjecture appeared, but it was a *computer proof* involving exhaustive enumeration. This caught Rudy's attention. In early fall 1976 he sent me a message from Gaines-ville to get a certain book from the library and be prepared to talk about the four-color problem. Thinking that this was important for my Ph.D., I actually bought the book. After

he arrived in Zürich he told me that a *system-theoretic proof* of this conjecture was at hand. In the weeks that followed, we had many discussions. I even made a tiny contribution, which he termed the Antoulas lemma. However, the procedure seemed to hit a snag, and the proof could not be completed. For me, nevertheless, it was a powerful and elegant approach to a difficult problem. At some point, I met Stiefel in the corridor and enthusiastically announced that we had *almost* solved the four-color problem. His answer was that there are *many* people who have *almost* solved the four-color problem. Regrettably, the snag in the system-theoretic proof of the four-color problem has never been overcome.

The second story shows Rudy's taste for exclusivity. In December 1977 he organized a conference in the Caribbean. Its particularity was that the whole conference took place on a cruise ship, during the cruise. The company chosen was Windjammer Barefoot Cruises, and the ship we sailed on was the Flying Cloud. This company sailed only from ports in the British Virgin Islands, and therefore we had to fly to St. Thomas (U.S. Virgin Islands) and then take a boat to Tortola (British Virgin Islands) to catch the Flying Cloud. For five days we sailed to a number of islands, the one that remains most vividly in my mind being Virgin Gorda (British Virgin Islands). The quarters were rather tight (I shared a cabin with Yves Rouchaleau) and the atmosphere very informal. The captain had a long beard and a white cat. We got to climb the masts and jump into the sea using swinging ropes. To go ashore, we had to use small boats.

One of the most memorable parts was the lectures, which were informal and took place only while we were sailing. There was no projector, so transparencies could not be used. Instead, the speakers had to write on two big pads, which were mounted on an easel. I remember that the Gainesville students (Yutaka and Fumio) had to organize the transportation of the pads and easel to the boat. Besides Rudy and Dina Kalman, the participants included Howard Rosenbrock, Jan Willems, Steve Morse, Murray Wonham, Michiel Hazewinkel,



Rudy Kalman and Dick Bucy on the *Flying Cloud* sailing in the Caribbean in December 1977.



Yves Rouchaleau, Mike Warren, Roger Brockett, Rudolf Kalman, and Eduardo Sontag in the hallway outside the Center for Mathematical System Theory at the University of Florida in 1974.

Malo Hautus, Mike Athans, T.J. Tarn, Dick Bucy, Chris Byrnes, Alberto Isidori, Drago Siljiak, Erol Emre, as well as Rudy's students Yves Rouchaleau, Tsuyoshi Matsuo, Eduardo Sontag, Yutaka Yamamoto, Fumio Hamano, and myself.

The lectures were held either inside, in an area close to the bar, or on deck under a tent. In the latter case, because of the wind, the problem was to keep the pages of the pads from turning at random during the lectures.

At the time, Rudy had become interested in the emerging geometric control theory, which received a lot of attention after Murray Wonham published a book on the subject in 1975. Rudy did not give a talk at the conference, but assigned me to talk about what he termed the *algebraization of geometric control*, which became the topic of my Ph.D. thesis. I gave the talk inside—so I did not have to worry about the pages blowing in the wind—writing on the two pads. Wonham was listening carefully, but did not make any comments. At the time, I was relieved not to have to answer difficult questions, but later realized that this was not necessarily a sign of approval.

The five days of the conference, with all the side visits and activities, passed quickly. For the return, Rudy rented a small hydro-plane. Together with a handful of others, we flew on this plane from St. Thomas to Puerto Rico, with Rudy seated in the copilot's seat. Landing in Puerto



At the conference on the *Flying Cloud*, sailing in the Caribbean, December 1977. Top: Art Krener, Steve Morse, two nonparticipants in the conference, Steve Smale, Michiel Hazewinkel. Bottom: Scuba instructors and Eduardo Sontag.

Rico took place at sea. We then transferred to the airport, from where I flew to Miami, London, and home to Zürich. Thus, a few days before Christmas 1977, the most remarkable conference that I have attended came to an end.

AUTHOR INFORMATION



Thanos Antoulas is with the Electrical Engineering Department at Rice University. He studied at the ETH Zürich, obtaining a degree in electrical engineering in May 1975 and a degree in mathematics in November 1975. He received a Ph.D. in mathematics (Dr.Sci.) in 1979 under the supervision of Rudy Kalman. Since 1982 he has been a

professor in the Department of Electrical and Computer Engineering, Rice University, Houston. Since 2002, he has also been affiliated with Jacobs University, Bremen. In 1992 he became a Fellow of the IEEE. His research interests are in the area of linear systems and computation, including model reduction of large-scale systems. He is the author of *Approximation of Large-Scale Dynamical Systems* (SIAM, 2005). He has been an associate editor for several journals. Since 1995, he has been editor-in-chief of *Systems and Control Letters*.

My Recollections as a Student of Prof. R.E. Kalman and Life as a Student at His Center

FUMIO HAMANO

received my Ph.D. in 1979 from the University of Florida under the supervision of Prof. R.E. Kalman. While I was his student and a member of the Center for Mathematical System Theory, the Center attracted the world's best systems and control theory researchers. Visitors of high caliber were

Digital Object Identifier 10.1109/MCS.2010.935894

invited to speak at the Mathematical System Theory seminar as well as system theory-related courses. Some stayed for an extended period of time as members of the Center. The seminars were intensive and vibrant. The contents were rigorous, but intuitive ideas were also emphasized. It was understood that we needed to have clear ideas about the established body of knowledge to develop a new theory or method. Prof. Kalman was known as the founder of modern control theory. To my surprise, one day he gave me a brief personal lecture on the significance of the strong tradition in classical control theory in the United States and the importance of having a solid knowledge and appreciation of it. He then recommended that I should read an MIT Radiation Laboratory Series book written in the 1940s.

I also came to learn that an exceptional theoretician like Prof. Kalman could be a good engineer. Prof. Kalman was interested in audio systems, including the engineering details associated with them. In one of the Center seminars, he gave a talk on an optimal design for an audio record player (turntable). One day, he showed us the detailed documentation of an audio system that he was interested in buying. He seemed to have already studied the detailed circuit diagram though he told us to check the circuitry of the "compander" to which very few theoreticians would have paid attention.

Prof. Kalman was extremely well organized. He loved to pay attention to details. He had an excellent and well-maintained library in his Center. Once, when students were reshelving books, one book was placed in the wrong location. Shortly thereafter, Prof. Kalman walked into the library and, to our amazement, immediately noticed the only book that was misplaced.

His organizational skills did not stop at his professional practices. His home was also well organized. In fact, my wife was so impressed with the organization of his home and the library that she still credits her organizational skills to Prof. Kalman.

Prof. Kalman brought in many scholars to the campus. One of them was the late Prof. G. Basile. I was excited about him joining the Center because he and his colleague, Prof. G. Marro, had started the geometric theory for linear systems several years back. It was the beginning of a long friendship with Prof. Basile, first as a mentor, then as a coauthor and friend until his tragic death in an airplane accident in 2006.

I regularly teach basic modern control theory and related subjects in the Electrical Engineering Department at California State University. Every semester I feel a renewed sense of Prof. Kalman's impact on modern control theory. The lessons, training, and environment that Prof. Kalman provided for me impacted my technical and scientific thinking as well as my career.

AUTHOR INFORMATION



Fumio Hamano is with California State University, Long Beach. He received the B.E. and the M.S.E. both in control engineering from the Tokyo Institute of Technology, in 1973 and 1975, respectively, and the Ph.D. in electrical engineering from the University of Florida in 1979. Since 1989, he has been with the Electri-

cal Engineering Department at California State University where he is currently a professor. He was chair of the department from 1996 to 2005. He was an associate professor in the ECE Department at Florida Atlantic University through 1989, a visiting professor at the Department of Electrical Engineering, Computer Science, and Systems, University of Bologna, Italy, in 1994, and a lecturer for the NATO Advanced Study Institute on Expert Systems and Robotics (1990). His areas of interest are control theory and its applications, robotics, and computer vision. He was a principal investigator in projects on robot control, robot guidance with vision, robot end-effector integration, and machine vision algorithm development for industrial inspection and solar subsystem analysis and development.

Prof. R.E. Kalman—A Deeply Inspiring Mentor

PRAMOD P. KHARGONEKAR

n a letter dated March 23, 1978, Prof. R.E. Kalman wrote

Dear Mr. Khargonekar:

I am very happy to inform you that you have been admitted to the Graduate School of the University of Florida and been awarded financial aid to pursue your studies here.

I had just finished my undergraduate studies at the Indian Institute of Technology, Bombay, India. I had taken some advanced courses in control and estimation and had

Digital Object Identifier 10.1109/MCS.2010.935895

read some of his papers. Looking back, this admission letter from Prof. Kalman is perhaps the most important event that has shaped my professional career. I recall my great excitement at being able to pursue my doctorate under the world-famous master!

In a follow-up letter, I asked Prof. Kalman what I should study before arriving in Gainesville. He wrote back and said I should study commutative algebra from the book by Zariski and Samuel. I eagerly went to the book store and purchased the two volumes. As soon as I opened the first chapter, I realized how little mathematics I knew. As an electrical engineering graduate, I had some familiarity with matrices but that was about it!



Pramod Khargonekar making himself comfortable in his CMST student office, 1982. (Did Pramod imagine he'd later be a dean in the same school?)

Well, that was the beginning of a steep learning curve into all sorts of mathematics.

My most vivid impressions of my time as Prof. Kalman's student relate to the weekly seminars on mathematical system theory. Often, we would have famous control and system theorists from all over the world as visitors. These seminars were extremely lively with penetrating intellectual debate between the visitors and Prof. Kalman. Issues ranged from specific technical questions to the essence of high-quality research to far-flung fields in science and mathematics. I soaked it all in as best as I could. These experiences have formed the basis for how I have tried to mentor my own students.

When I became Prof. Kalman's student, he had just finished his paper on partial realization theory, the Euclidean algorithm, and continued fractions. I recall his seminars on this paper and being awe struck by his phenomenal skill as a speaker. His seminars were great lessons in how to communicate research results. He soon turned his attention to econometrics. And I graduated with my doctorate.

The most important lesson I learned from Prof. Kalman is the critical importance of problem selection. His taste in selecting research problems is incomparable. I recall a conversation where someone asked him what problem he should work on. Prof. Kalman's reply was, "Identify your single best idea and work on it." This response made an indelible impression on me, and it has instilled the importance of focus and not spreading oneself too thin.

When I returned to Florida in 2001 as dean of the College of Engineering, Prof. Kalman had retired. In

December 2007, I had the good fortune of being invited by the U.S. National Academy of Engineering to be at the ceremony where Prof. Kalman was awarded the Charles Stark Draper Prize. His acceptance speech was short but most memorable. He emphasized the critical importance of curiosity-driven fundamental research. I realized that even though 30 years had passed since I first met him, his intellect and wit are as sharp and impressive as they have always been and his commitment to fundamental research just as deep.

As I reflect on the 50th anniversary of the Kalman filter, I am filled with memories of the course on Kalman filtering I took at the Indian Institute of Technology, Bombay, in 1977 where I first learned about Prof. Kalman. I am overwhelmed by thoughts of gratitude to him for accepting me as his student and encouraging my professional development. And it is wonderful to think of the tens of thousands of engineers and scientists who have been influenced by the Kalman filter.

AUTHOR INFORMATION



Pramod P. Khargonekar is with the Electrical Engineering Department at the University of Florida. He received the B.Tech. in electrical engineering from the Indian Institute of Technology, Bombay, in 1977, and the M.S. in mathematics and Ph.D. in electrical engineering from the University of Florida in 1980 and 1981, re-

spectively. He has held faculty positions at the University of Florida, the University of Minnesota, and the University of Michigan. At the University of Michigan, he was chair of the Department of Electrical Engineering and Computer Science from 1997 to 2001 and also held the position of Claude E. Shannon Professor of Engineering Science. From 2001 to 2009, he was dean of the College of Engineering and is currently Eckis Professor of Electrical and Computer Engineering at the University of Florida. His research and teaching interests include systems and control theory and applications. He is a recipient of the NSF Presidential Young Investigator Award, the American Automatic Control Council's Donald Eckman Award, the IEEE W.R.G. Baker Prize Award, the IEEE Control Systems Society George Axelby Best Paper Award, the Hugo Schuck ACC Best Paper Award, and Distinguished Alumnus Award from the Indian Institute of Technology, Bombay. He is a Fellow of the IEEE and an ISI Highly Cited Researcher.

Recollections of My Life as a Student with Prof. Kalman

JAIME RIBERA

first met Prof. Rudolf E. Kalman in Barcelona during the 1977–1978 academic year. He was visiting one of his former students from Stanford, who happened to be my advisor, and Prof. Kalman interviewed me as a prospective candidate to work on my Ph.D. under his supervision at the University of Florida. In the summer of 1978, my family and I traveled to Gainesville, where I started the Ph.D. program with a Fulbright fellowship in the Industrial and Systems Engineering Department (ISE).

I spent four years at the Center for Mathematical System Theory (CMST), which had roots in three departments, electrical engineering, industrial and systems engineering, and mathematics. I was the only student from the ISE area. My fellow colleagues, both Ph.D. students like myself (Pramod Khargonekar, Fumio Hamano, Tryphon Georgiou, and others) or visiting faculty (like Giuseppe Basile) came from electrical engineering or mathematics. Prof. Kalman had the ability to continuously challenge assumed models in different disciplines with his rigorous scientific approach. This approach had two effects on people in the areas that he worked on, specifically, some decided not to pay attention, because if they did they had to challenge most of what they knew and were not ready to do it; others were more interested in the scientific truth and decided to do research on the discrepancies between the generally accepted knowledge and the irrefutable conclusions of Prof. Kalman's reasoning. Some of the visiting faculty were invited to spend time at CMST, where students benefited from their presence. I always considered this diversity of perspectives to be one of the assets of working at CMST. When Prof. Kalman focused his attention on the identification of systems in economics, I probably felt closer to the issue than the rest of my colleagues. I decided to focus my thesis research on exploring the identification of linear systems from noisy data, incorporating some operations research mathematical programming knowledge to the research field recently opened by Prof. Kalman. One of the visiting scholars at CMST was a fellow Spaniard, Juan del Hoyo, an econometrics professor with whom I enjoyed many hours of challenging discussions.

My memories of the work with Prof. Kalman during my Ph.D. years are very intense. Besides my thesis research I was assigned administrative work related to maintaining the grant contracts that financially supported CMST. It had never been so easy before, and it was never going to be so easy for me afterwards. The great respect that the officials in the Army and the Air Force showed for Prof. Kalman's work was evident in all the relations I maintained with



The famous CMST library in 1982. On the right are the "Acropress" binders of preprints, sorted by topics. REK's students spent uncountable hours classifying papers by topic.

them. We had some working sessions at CMST, exploring the areas of research that they would be interested in, and the possible fit with CMST's main research lines. I noticed the word "control" used in almost every other sentence, from some very mathematical focus on filtering of data to keep target on moving objects, to a more general C³, that is, communications, command, and control issues.

At that time Prof. Kalman had a joint appointment with the ETH in Zurich, spending winters in Gainesville and summers in Switzerland, with some extra visits to CMST during the summer. Those were intense visits, as it was the time when his Ph.D. students had an opportunity to present him with our advances and receive his comments in an interactive way (the main alternatives at the time were phone calls and snail mail). My family and I got used to receiving his calls early in the morning (early at least for a student with an embedded Spanish body clock!) with instructions for the work to be done during the day. I recall his coming into the office one afternoon with a paper that had been sent to him. He handed the paper to me with a comment indicating that there was something wrong with the proofs on the paper theorems; his intuition told him that the conclusions could not be right. It was my job that evening to find the flaw in the paper before I met him the next morning. These challenges were common at the time, and they help me appreciate the rigorousness of Prof. Kalman's approach to science development.

During one of the summers he spent in Zurich, my family and I lived in Prof. Kalman's house to take care of it. His main request was that we keep his music record collection at the appropriate room temperature to avoid damaging

the vinyl support. I remember Prof. Kalman testing different Shure phono cartridges and showing me their subtle audio differences.

The years spent at CMST with Prof. Kalman have had a lifelong influence in my career. Even though I eventually moved from pure mathematics to business applications, I have always remembered and tried to be true to the rigor of his research. I was also influenced by his lifestyle of dual appointment in two continents when I decided to accept my two current academic appointments in Barcelona's IESE and Shanghai's CEIBS.

AUTHOR INFORMATION



Jaime Ribera is a professor in the Operations Management Department at IESE Business School, University of Navarra, Spain, and a professor and the Port of Barcelona Chair of Logistics at CEIBS in Shanghai, China. He was awarded a Fulbright fellowship to pursue doctoral studies in the United States. He holds an M.Sc. in operations research and a Ph.D. in ISE (mathematical systems theory) from the University of Florida and a Dr.Eng. in industrial engineering from the Polytechnic University of Catalonia, where he is an associate professor. He was the deputy dean for faculty at the IESE Business School from 1993 to 2001, president of the European Operations Management Association (2003-2006), and secretary of the U.S. Operations Management Association (1992-1997). He served on the editorial boards of the International Journal of Operations and Production Management and is currently editor of the Harvard Business Review China and the International Commerce Review. His research interests lie in the areas of operations management improvement, health systems management, and project management. He has published teaching materials, academic research, casebooks, and textbooks. He has been active in consultancy in process improvement, supply chain management, and project management and has extensive experience working with private and public companies. He is the president of the Board of Caixa Terrassa, a savings bank in Spain.

R.E. Kalman: A Great Human Being

A. BÜLENT ÖZGÜLER

came to know about Prof. Kalman through a Turkish post-doc of his during my M.Sc. studies at Middle East Technical University. When I learned that I was accepted to carry on my doctoral studies under his supervision, I was excited, happy, and very scared.

I met him for the first time in March 1979 in his office and found out that he was no werewolf, just an ordinary middle-aged man and a nice person. The Turkish post-doc's stories of him seemed exaggerated! I remember he congratulated me for the fact that I had already published three articles from my M.Sc. thesis in the field of system theory, but that I should learn more mathematics at CMST (Prof. Kalman's research center at the University of Florida). At the first seminar I attended at CMST his advice sank in; I was totally intimidated by the level of mathematics and rushed to register for a course on abstract algebra.

Things that I gradually realized about Prof. Kalman were that all secretaries hate him, and many colleagues find him rude. What we see now in person is a tamed version. He is very energetic and puffs like a steam engine locomotive in the corridors. He is very proud of his personal library. He has done research on the mechanics of turntable needles. He eats a lot of yogurt. He is a sound-system freak. He loves to shock people by answering their letters in their native languages instead of English—I once wrote a Turkish letter for him.

I had few personal interactions with him concerning my thesis study at the University of Florida. He focused on econometrics at the time, and I learned most of the technicalities concerning my thesis topic from Pramod Khargonekar rather than from him. But he did determine my thesis topic. I went into his office and told him I could write my dissertation on one of two topics, either on a fractional approach to optimal control or on algebraic regulator theory. He listened to my summary of the results that could be included in my thesis on optimal control and said "Oh, oh! But you are neither avoiding spectral factorization nor the Riccati equation. Real progress on optimal control would come if one can avoid them altogether!" That decided it.

Years later after my return to Turkey, I had a phone call from him. He was invited for a visit to Ankara, and he wanted to get together on his arrival. At the dinner given for his honor, there was some discussion on whether the following day he should visit a museum or visit me at Bilkent University and see the campus of the first private university in

Turkey. He concluded the discussion after a while "No, no, no! I would like to go to Bülent University."

AUTHOR INFORMATION



A. Bülent Özgüler is with the Electrical and Electronics Engineering Department at Bilkent University. He received the Ph.D. from the University of Florida, Gainesville, in 1982. He was a researcher at the Marmara Research Institute of TÜBITAK from 1983 to 1986. He spent one year at the Institut für Dynamische Sys-

teme, Bremen Universitt, Germany, on an Alexander von Humboldt scholarship during 1994–1995. He has been with the Electrical and Electronics Engineering Department of Bilkent University, Ankara, since 1986. He was chair of the department from 1997 to 2006. He joined Bahçeşehir University in 2008, on leave from Bilkent University. His research interests are in the areas of decentralized control, stability robustness, realization theory, linear matrix equations, and application of system theory to social sciences. He has written over 60 research papers and is the author of *Linear Multichannel Control: A System Matrix Approach* (Prentice Hall, 1994).

Memories from My Gainesville Days as a Student of R.E. Kalman

TRYPHON T. GEORGIOU

graduated from the National Technical University of Athens in June of 1979. In the spring of 1979, shortly after I had expressed interest in joining Prof. Kalman's group at Gainesville, I met and was vetted by his former student Thanos Antoulas during one of Thanos' visits to Athens. I still have notes from that meeting, where I came to realize the beauty and breadth of the research program that I was soon going to be part of. I went to Gainesville in the fall of 1979 and was welcomed by fellow students Pramod Khargonekar, Bülent Özgüler, Jaime Ribera, and Erol Emre, who was R.E. Kalman's postdoc at the time. I met Prof. Kalman a month later when he returned to Gainesville from a trip. I distinctly recall that first meeting. After inquiring briefly about my own (limited at the time) research experience, he went on to discuss the importance of mathematics in engineering and science. He touched on modeling and how to discover structure from data as well as the fundamental role of minimality, both in the complexity of models as well as in our assumptions in developing them. Yet, with that in the background, he suggested that I take advanced algebra courses first, the importance of which became clear to me much later. From that point on, and for about a year, my interaction with Prof. Kalman was minimal. Apparently, he allowed time for osmosis to take place.

The Center was a remarkable place. Frequent visitors, seminars, together with an absolutely invaluable resource, Prof. Kalman's personal library and collection of preprints/ reprints, provided a unique environment for learning. One cannot overemphasize the tremendous benefit that we drew simply from being in charge of this collection of papers, with books organized according to LC classification and papers following his own system. The breadth of ideas and topics that I was exposed to provided the basis for much of my subsequent development. I recall that among his



A student reunion. (From left) Eduardo Sontag, Yutaka Yamamoto, Rudolf Kalman, Tsuyoshi Matsuo, and Thanos Antoulas attending the conference held in honor of Rudolf Kalman in Frascati, Italy, in May 1990.



Rudy Kalman receiving from Thanos Antoulas a draft of the book *Mathematical System Theory: The Influence of R.E. Kalman*, published by Springer, during the conference held in his honor in Frascati, Italy, in May 1990.

students we were quizzing each other on all sorts of trivia about books and papers in that collection, such as complete names of authors, titles, their LC numbers, or their relative location on the stacks!

It was almost at the end my second year, after I had already completed a joint piece of work with Pramod and Bülent on algebraic systems theory and the regulator problem, that Prof. Kalman came to my office with definite excitement to explain what he wanted me to work on for my Ph.D. thesis. From that point on, I would meet with him on a more regular basis to discuss progress and directions. At the time, besides the algebraic structure of positive sequences that I worked on, he was interested and usually immersed on another problem that was related to the errors-in-variables in econometrics. While working and discussing these problems I came to appreciate and admire his engineering insights, his strength of conviction about the importance of certain topics and issues, as well as his sense of mathematical elegance and beauty.

The Center, and of course his presence, attracted a number of remarkable individuals who had an impact on me both professionally as well as personally. These include Jacob Hammer, Ed Kamen, the late Guiseppe Basile, Tom Bullock, and most importantly Allen Tannenbaum—these and my fellow students Pramod and Bülent were my friends and mentors. During my third year, Prof. Kalman prepared for me a most educating experience—on a very short notice of a few hours, at a special Saturday morning seminar, I was asked to present my work in front of the participants of a U.S.-Japan conference that he had organized and was taking place in Gainesville. During my talk and in front of this rather large (for me at the time) audience, he questioned, challenged, and tested me in all possible ways. After the seminar I realized that had I succeeded in crossing an important point in my professional development.

I graduated and left Gainesville half a year later. It is with fondness that I always carry with me the lessons I learned and the friendship of the individuals I came to know in R.E. Kalman's Center. To Prof. Kalman I owe my gratitude for providing me with this unique experience.

AUTHOR INFORMATION



Tryphon T. Georgiou holds the Vincentine Hermes-Luh chair in electrical engineering at the University of Minnesota. He received the diploma in mechanical and electrical engineering from the National Technical University of Athens, Greece, in 1979 and the Ph.D. from the University of Florida, Gainesville, in 1983. He served on

the faculty of Florida Atlantic University (1983-1986) and Iowa State University (1986-1989). Since 1989 he has been with the University of Minnesota, where he is currently a professor in the Department of Electrical and Computer Engineering. He received the George S. Axelby Outstanding Paper award of the IEEE Control Systems Society in 1992, 1999, and 2003. He has served as an associate editor for IEEE Transactions on Automatic Control (1991–1992), SIAM Journal on Control and Optimization (1988-1995), Systems and Control Letters (1995-present), IEEE Transactions on Signal Processing (2007-present), and as an elected member on the IEEE Control Systems Society Board of Governors (2002-2005). He lives with his wife Efi and their two children, Katerina and Thomas, and enjoys long-distance running, having completed ten marathons in recent years. He is a Fellow of the IEEE. (css)

>> 25 YEARS AGO (continued from page 14)

the United States, the International Federation of Automatic Control (IFAC). The American Automatic Control Council (AACC) was created so that the U.S. would have a national member organization in IFAC. Hal Chestnut and Rufus Oldenberger were the two people primarily involved in the United States; Pawel Nowacki of Poland, John Coales of England, Alex Letov of the USSR, and other people around the world were involved. The IEEE joined AACC when it formed, in 1958, and the Professional Group on Automatic Control was asked to be the lead group on behalf of the IEEE. So the member of AACC is the IEEE, but is represented now by the Control Systems Society. That wasn't always so obvious. As a matter of fact, when the Systems, Man, and Cybernetics (SMC) Society broke away, in 1965, there was a question about who now should represent IEEE in AACC. The decision was made that it should be the Professional Group on Automatic Control, and that has continued. It is a role this Society has, but which it sometimes doesn't fully appreciate.

