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Rudolf E. Kalman: Life and Works

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Abstract: Rudolf Emil Kalman passed away peacefully on 2 July 2016, at his home in Gainesville, Florida. He was 86 years old. His passing marks the end of an era. This paper is to remember and celebrate the life, the works, and the impact of a giant whose influence extends over several fields and who is considered the founder of the modern theory of systems and control.

Keywords: Rudolf E. Kalman

1. LIFE AND WORKS

Rudolf Emil Kalman was born in Budapest, Hungary on 19 May 1930. He was raised in Hungary and was the product of a remarkable secondary school system. He was taken by his father from the torments of the Second World War to the United States when he was 13.

His father was an electrical engineer and Kalman decided to follow in his father' footsteps. He studied electrical engineering at the Massachusetts Institute of Technology, where he was awarded a S.B. in 1953, and continued to undertake graduate studies there leading to a S.M. in 1954. For his doctoral work he went to Columbia University in New York City where he was advised by John Ralph Ragazzini. He was appointed as an Instructor in Control Theory at Columbia University in 1955 and promoted to Adjunct Assistant Professor in 1957. He submitted his doctoral thesis *Analysis and Synthesis of Linear Systems Operating on Randomly Sampled Data* in 1958 and was awarded a D.Sci. in that year.

Kalman's early interest in control systems was evident. His research was based upon the notion of state variable representations, and was mathematically advanced but motivated by practical problems. He also showed, even at these early years, a highly individual approach to research which has continued during the remainder of his brilliant career.

Rudolf Emil Kalman. Credit: Engineering and Technology History Wiki.

Before the award of his doctorate Kalman had begun to publish influential papers. For example in ***Physical and mathematical mechanisms of instability in nonlinear automatic control systems*** (Trans. ASME, 79, 1957, 553-563) he gives (quoting from a review by Horace Trent) ... *a lucid discussion of the stability problem for control systems containing one or more nonlinear elements. It is written in a style which appeals equally to advanced design engineers and to research workers who deal with the theory of such systems. The discussion is limited to those systems which can be treated as if they were made up of a finite number of "lumped" parts with time invariant parameters. Thus, such a system can be described by a finite number of simultaneous ordinary differential equations. The author exploits the topological approach to an analysis of non-linear systems; i.e., he examines the nature of trajectories in phase space as generated by variations of inputs, variation of initial conditions, etc., and from these results deduces quantitative information about the possible existence of nodes, foci, and saddle points. During these analyses he makes use of the method of virtual critical points. One of the main goals of the paper is to propose a classification of the types of nonlinearities which can give rise to instabilities.*

From 1957 to 1958 Kalman was employed as a staff engineer at the IBM Research Laboratory in Poughkeepsie, N. Y. With R. W. Koepcke, he made an important contribution to the design of linear sampled-data control systems using quadratic performance criteria, published as ***Optimal synthesis of linear sampling control systems using generalized performance indexes*** (Trans. ASME, Ser. D, J. Basic Engr., 80, 1958, 1820-1826), in which he applied Bellman's dynamic programming and proposed the first general solution of the noise-free regulator problem. In the presence of noise, he observed that the problem of optimal estimation of the statistical properties of the input signal can be divorced from the problem of designing a control system so as to optimize some performance index.

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After the award of his doctorate Kalman was appointed as a Research Mathematician at the Research Institute for Advanced Studies in Baltimore, Maryland.

After the Second World War, large corporations in the United States began to create research centers in order to harness scientific research that had been developed but not publically shared as part of the war effort. One of these facilities was the Research Institute for Advanced Studies of the Glenn L. Martin Company that had commercial interests in aviation. A focus of this particular corporate research center in Baltimore, Maryland was mathematics. It had attracted several outstanding mathematicians including, for example, Solomon Lefschetz, Joseph LaSalle, Jack Hale, and Harold Kushner.

Kalman found a welcoming home and worked there from 1958 to 1964. During this time he produced a series of results of outstanding importance.

He early foresaw the importance of the digital computer for the control of complex systems and developed, with J. E. Bertram of the IBM Research Center in Yorktown Hights, ***A unified approach to the theory of sampling systems*** (J. Franklin Inst., 267, 1959, 405-436). Further, he wrote jointly with J. E. Bertram two other papers: ***Control system analysis and design via the "second method" of Lyapunov.* I. *Continuous-time systems*** (Trans. ASME, Ser. D, J. Basic Engr., 82, 1960, 371-393) and ***Control system analysis and design via the "second method" of Lyapunov.* II. *Discrete-time systems*** (Trans. ASME, Ser. D, J. Basic Engr., 82, 1960, 394-400), in which he provided a comprehensive and insightful exposure of stability theory for dynamical systems and applied Lyapunov theory for the analysis and design of various different control systems.

Then, in his famous paper ***Contributions to the theory of optimal control*** (Bol. Soc. Mat. Mexicana, 5, 102-119) he gave a complete theory of linear quadratic control systems. He was instrumental in introducing the work of Carathéodory in optimal control theory, and clarifying the interrelations between Pontryagin's maximum principle and the Hamilton-Jacobi-Bellman equation, as well as the calculus of variations in general. He discovered that the matrix Riccati equation arises in the linear quadratic regulator problem as a special case of the Hamilton-Jacobi-Bellman equation provided the system to be controlled is represented in state-space form. His research not only stressed mathematical generality, but in addition it was guided by the use of the digital computer as an integral part of the design process and of the control system implementations.

In 1960 Kalman participated in the First Congress of IFAC held in Moscow. It was at this meeting that he introduced his fundamental discoveries and ideas, including the concepts of controllability and observability and their relevance in control and estimation, which were to mature during the following decade. In his paper ***On the general theory of control systems*** (Proc. First Congress of IFAC, Moscow, 1960, 481-491) he noted that … *Despite the appearance and effective resolution of many new problems, our understanding of fundamental aspects of control has remained superficial. The only basic advance so far appears to be the theory of information created by Shannon* ... and initiated the study of the theory of control, saying … *Our ultimate objective is to answer questions of the following type: What kind and how much information is needed to achieve a desired type of control? What intrinsic properties characterize a given unalterable plant as far as control is concerned?*

Kalman brought into evidence the central importance of controllability and observability in systems theory in his famous paper ***Mathematical description of linear dynamical systems*** (J. SIAM Control Ser. A, 1, 1963, 152-192). He discovered that input/output data uniquely determine only a subsystem of the given black-box linear system and that this subsystem is the intersection of the controllable and observable subsystems inside the black box. This was formalized as the famous canonical structure theorem for linear systems.

It was also during his stay at RIAS that Kalman developed what is perhaps his most well-known contribution, the so-called "Kalman filter". He obtained results on the discrete-time (sampled data) version of this problem in late 1958, and early 1959. He blended earlier fundamental work in filtering by Wiener, Kolmogorov, Bode, Shannon, Pugachev and others with the modern state-space approach and published the paper ***A new approach to linear filtering and prediction problems*** (Trans. ASME, Ser. D, J. Basic Engr., 1960, 82, 35-45) that proved to be of lasting importance. This result revolutionized the field of estimation, by providing a recursive approach to the filtering problem. His solution to the discrete-time problem naturally led him to the continuous-time version of the problem and in 1960-1961 he developed, in collaboration with R. S. Bucy, the continuous-time version of the problem ***New results in linear filtering and prediction theory*** (Trans. ASME Ser. D. J. Basic Engrg., 83, 1961, 95-108).

Kalman summarizes the contributions of this first mentioned paper as follows … *The classical filtering and prediction problem is re-examined using the Bode-Shannon representation of random processes and the state-transition method of analysis of dynamic systems. New results are:*

(1) The formulation and methods of solution of the problem apply without modification to stationary and nonstationary statistics and to growing-memory and infinite-memory filters.

(2) A nonlinear difference (or differential) equation is derived for the covariance matrix of the optimal estimation error. From the solution of this equation the coefficients of the difference (or differential) equation of the optimal filter are obtained without further calculations.

(3) The filtering problem is shown to be the dual of the noise-free regulator problem.

The impact of Kalman filtering on all areas of applied mathematics, engineering, and sciences has been tremendous. The Kalman filter proved pivotal in the success of the Apollo program that sent the first humans to the moon. The Kalman filter, and its later extensions to nonlinear problems, represents perhaps the most widely applied by-product of modern control theory. Just as examples of their diversity, one may mention the NASA Space Shuttles, US Navy submarines, aerospace weapons such as cruise missiles, autopilots, seismic data processing, nuclear power plant instrumentation, process control, weather forecasting, stock picking, econometrics, health monitoring, medical data processing, computer vision, traffic management and control, positioning, tracking, navigation, and motor control. The Kalman filter applications popularity is due to the fact that the digital computer is effectively used in both the design phase as well as the implementation phase. From a theoretical point of view it brought under a common roof related concepts of filtering and control, and the duality between these two problems.

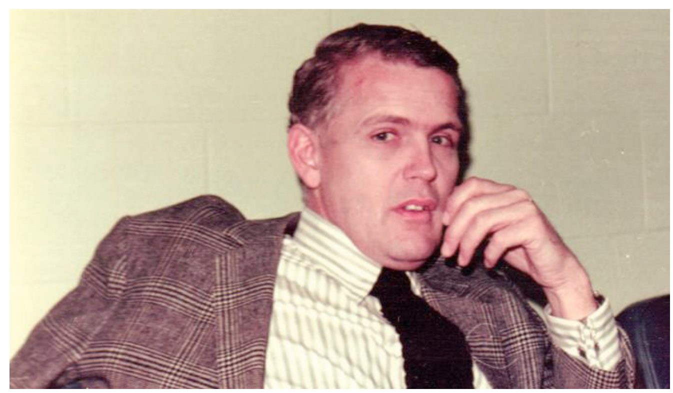
Kalman also studied the inverse problem of optimal control theory and obtained surprising results. In his paper ***When is a linear control system optimal?*** (Trans. ASME, Ser. D, J. Basic Engr., 1964, 86, 51-60) he obtained a frequency-domain characterization of optimality with respect to quadratic criteria and shown that a feedback system is optimal if and only if its sensitivity to component variations in the forward loop is diminished (not accentuated) by feedback. Thus a single criterion assures optimal as well as robust performance.

In 1964 Kalman took up the position of Professor at Stanford University where he was associated with the departments of Electrical Engineering, Mechanics, and Operations Research. During that period his research efforts shifted toward the fundamental issues associated with realization theory and algebraic systems theory. Once more he opened up new research avenues in a new and basic area, and his contributions have helped shape up a new field of research in modern system theory.

In his paper ***Irreducible realizations and the degree of a rational matrix*** (J. Soc. Indust. Appl. Math., 13**,** 1965, 520-544) Kalman showed the equivalence of two hitherto separate lines of research, one in control theory (irreducible realizations) and the other in network theory (degree of a rational matrix). He proved that the degree of a proper rational matrix Z, which is the minimal number of energy-storage elements in any realization of Z, is indeed equal to the dimension of the irreducible state space realization. He actually constructed an irreducible realization of Z from the Smith-McMillan form for the partial-fraction components of Z. In the joint publication ***Effective construction of linear state-variable models from input/output data*** (Proc. 3rd Annual Allerton Conf. Circuit and System Theory, Urbana, Illinois, 1965, 449-459), B. L. Ho and R. E. Kalman described yet another algorithm for the construction of irreducible realizations, this time based on the Taylor expansion of Z around infinity.

Inspired by the algebraic theory of automata, Kalman formulated an algebraic theory of linear systems. In his ***Algebraic theory of linear systems*** (Proc. 3rd Annual Allerton Conf. Circuit and System Theory, Urbana, Illinois, 1965, 563-577) he observed that a linear, constant, finite-dimensional system possesses an abstract description, which represents the input/output behavior of the system uniquely. The abstract description is based on modules, which supercede vector spaces. An excellent account of this idea is given in the landmark book ***Topics in Mathematical System Theory*** (McGraw-Hill, New York, 1969), which he jointly authored with P. L. Falb and M. A. Arbib. The authors write in the Preface … *This book does not pretend to be a systematic treatise. Rather, it aims to present a mathematical system theory as it is today - a lively, challenging, exciting, difficult, confused, rewarding, and largely unexplored field.*

In 1971 Kalman moved to the University of Florida, Gainesville, where he was Graduate Research Professor jointly in the Departments of Mathematics, Electrical Engineering, and Industrial and Systems Engineering. His work focused on a system-theoretic approach to the foundations of statistics, econometric modelling, and identification, as a natural complement to his earlier studies of minimality and realizability.



Rudolf Kalman in his office in 1974. Credit: Sontag, E. D., Rudolf E. Kalman and his students. IEEE Control Systems Magazine, 87, 2010.

The Caribbean, December 1977. R.E. Kalman and R.S. Bucy at a conference organized on a cruise ship. Credit: Sontag, E. D., Rudolf E. Kalman and his students. IEEE Control Systems Magazine, 87, 2010.

In Gainesville, he established the Center for Mathematical System Theory, which was unique in its scope and reputation. His superb scholarship and magnetic personality was the heart and soul of the Center for more than two decades, attracting the most brilliant colleagues and contributors in control, dynamical systems, as well as many subjects in mathematics. The Center benefited from an excellent and comprehensive library of which Kalman was justly proud and where his students spent hours classifying papers by topic.

Library of the Center for Mathematical Systems Theory Gainesville, Florida in 1982. Credit: Sontag, E. D., Rudolf E. Kalman and his students. IEEE Control Systems Magazine, 87, 2010.

During 1969-1972 Kalman acted as a scientific consultant to research centers in the Ecole des Mines de Paris, France. Starting in 1973, while continuing to hold his positions at the University of Florida, he was elected to an ad personam chair in mathematical system theory at the Eidgenössische Technische Hochschule in Zürich.

Kalman retired from the University of Florida in 1992 and held his chair in Zürich until his statutory retirement in 1997, when he became emeritus.

Kalman's ideas on statistics were thought-provoking and he had written a number of interesting articles on this topic after his retirement. For example he gave an informal lecture published as ***Probability and science*** (Nieuw Arch. Wisk., Ser. 4, 11, 1993), 51-66) in which he (quoting from a review by Zeno G. Swijtink) … *laments the explosive growth of applications of probability and questions whether probabilities exist in the real world. Randomness does, and to capture it better he proposes a new definition: random is not uniquely determined by simple classical rules. All irrational numbers are said to be random under this definition. The absence of interaction between chaos theorists and probability theorists also shows, the author concludes, how irrelevant the classical models of probability are to the real world*.

In 1995 he published ***Randomness and probability*** (Math. Japon., 41, 1995, 41-58) and in 2002 a discussion on ***What is a statistical model?: Discussion*** (Ann. Stat., 30, 2002, 1292-1294). He believes that ... *the currently accepted notion of a statistical model is not scientific; rather, it is a guess at what might constitute* (*scientific*) *reality without the vital element of feedback, that is, without checking the hypothesized, postulated, wished-for, natural-looking* (*but in fact only guessed*) *model against that reality. To be blunt, as far as is known today, there is no such thing as a concrete i.i.d.* (*independent, identically distributed*) *process, not because this is not desirable, nice, or even beautiful, but because Nature does not seem to be like that.* (*Historical aside: recall that physicists had thought at one time that aether was such a necessary, unavoidable, appealing, clear and beautiful concept that it must perforce exist; alas, all physicists now living had to learn that such argumentation cannot lead to good science.*) *As Bertrand Russell put it at the end of his long life devoted to philosophy, "Roughly speaking, what we know is science and what we don't know is philosophy." In the scientific context, but perhaps not in the applied area, I fear statistical modelling today belongs to the realm of philosophy*.

In his last decade, Kalman returned to circuit theory in a series of conference papers. In ***Algebraic invariant theory in systems research, Lecture 1*** (Proc. 21st Internat. Symp. Mathematical Theory of Networks and Systems, Groningen, 2014, 1116-1117) he announced a remarkable result summing up the algebraic network realization theory as follows … *Every generic network is uniquely characterized by its own family of invariants and covariants. A network realizes an impedance if and only if they both have the same invariants. Two different networks are globally isomorphic if and only if they have the same invariants and covariants. From the knowledge of the invariants and covariants of a network it is a straightforward task to compute all possible realizations (there may be more than one, they are all isomorphic).*

2. THE STUDENTS OF KALMAN

Quoting from Eduardo D. Sontag (2010) … *The influence of Kalman's work in control theory is vast, deep, and wide. An aspect of Kalman's legacy that is perhaps less known is the influence that he had on the careers of his collaborators and students. 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.*

The distinguishing feature of Kalman's lectures was his emphasis on concept formation. He showed great respect for the achievements of mathematics and he gauged his own understanding of system theory by the mathematical depth of the concepts he was developing.

Kalman was either the first or the second advisor of several Ph.D. students at each of the institutions where he was a faculty member. These students include the following:

B. L. Ho, Stanford University, 1966
Pierre Faurre, Stanford University, 1967
Anthony J. Tether, Stanford University, 1969
Patrick M. Dewilde, Stanford University, 1970
Marshall Banker, Stanford University, 1971
Yves Rouchaleau, Stanford University, 1972
Eduardo D. Sontag, University of Florida, 1976
Yutaka Yamamoto, University of Florida, 1978
Uwe Martens, ETH Zürich, 1978
Athanasios C. Antoulas, ETH Zürich, 1979

Fumio Hamano, University of Florida, 1979
Tsuyoshi Matsuo, Nagoya University, 1980
Pramod P. Khargonekar, University of Florida, 1981
Jaume Ribera, University of Florida, 1982
Bülent A. Özgüler, University of Florida, 1982
Tryphon T. Georgiou, University of Florida, 1983
Masaru Kamada, University of Tsukuba, 1988
Markus Spindler, ETH Zürich, 2000.

Frascati, Italy, 1990. (From left) E. Sontag, Y. Yamamoto, R. E. Kalman, T. Matsuo, and A. Antoulas. Credit: Yamamoto, Y., Rudolf Kalman – Founder of the field. Proc. 22nd International Symposium on Mathematical Theory of Networks and Systems, Minneapolis, Minnesota, 2016.

3. AWARDS AND HONORS

Kalman was elected to the U.S. National Academy of Sciences, the American National Academy of Engineering, and the American Academy of Arts and Sciences. He was a foreign member of the Hungarian, French, and Russian Academies of Science. He was awarded many honorary doctorates across the world. He became Fellow of the IEEE in 1964 and Fellow of the American Mathematical Society in 2012.

Kalman received many prizes and awards that were made to him as a consequence of his outstanding, innovative contributions. In 1962 he was named as the Outstanding Young Scientist of the Year by the Maryland Academy of Sciences. He received the IEEE Medal of Honor in 1974 … *for pioneering modern methods in system theory, including concepts of controllability, observability, filtering, and algebraic structures*. He also received the Rufus Oldenburger Medal from the American Society of Mechanical Engineers in 1976.

He was awarded with the IEEE Centennial Medal in 1984. In the year 1985, he was one of the laureates of the Kyoto Prize, inaugurated in that year by the Inamori Foundation of Japan, as … *the creator of modern control and system theory. Kalman theory, which was established in the early* 1960*s, brought a fundamental reformation to control engineering and since then laid the foundation for the rapid progress of modern control theory*. The Kyoto Prize is widely regarded as the most prestigious award available in fields which are traditionally not honored with a Nobel Prize.

Rudolf Emil Kalman, 1985. Credit: Kyoto Prize Laureates.

He received the Steele Prize of the American Mathematical Society in 1987. The citation reads … *The ideas presented in these papers are a cornerstone of the modern theory and practice of systems and control. Not only have they led to eminently useful developments, such as the Kalman-Bucy filter, but they have contributed to the rapid progress of systems theory, which today draws upon mathematics ranging from differential equations to algebraic geometry*.

Kalman was also a recipient of the Richard E. Bellman Control Heritage Award in 1997, and the National Academy of Engineering's Charles Stark Draper Prize in 2008 … *for the development and dissemination of the optimal digital technique (known as the Kalman Filter) that is pervasively used to control a vast array of consumer, health, commercial, and defense products.*

On 7 October 2009 U.S. President Barack Obama honored Kalman in an awards ceremony at the White House when he presented him with the National Medal of Science, the highest honor the United States can give for scientific achievement.

Rudolf E. Kalman receiving National Medal of Science from President Barack Obama. Credit: Remembering Rudolf E. Kalman. Herbert Wertheim College of Engineering, University of Florida.

4. REMEMBERING RUDOLF E. KALMAN

Throughout his career, Kalman led and taught by example. He was a purist in pursuing ideas to completion no matter how long or what effort that necessitated. His publications were gems, with no exception, in both elegance and scientific depth.

Kalman published over fifty technical articles, and delivered numerous lectures. His most cited article, *A new approach to linear filtering and prediction problems*, has earned 22500

Google Scholar citations. Up to now, the Kalman filter related publications exceed 489000.

Kalman not only shaped the field of modern control theory, but he was instrumental in promoting its wide usage. His superb scholarship, magnetic personality, and his lectures in universities, conferences, and industry attracted countless researchers who were greatly influenced by his ideas.

For example, his plenary lecture *The evolution of system theory: My memories and hopes* delivered at the 16th IFAC World Congress in Prague, 2005, attracted the audience of 1800 delegates from 60 countries as everyone was eager to see and hear the living legend of systems and control theory.

Kalman delivering his plenary lecture at the 16th IFAC World Congress in Prague, 2005. Credit: Michael Šebek.


Rudolf E. Kalman, former professor in mathematics at ETH Zurich. Credit: Rueegg, P., Rudolf Kalman recognized for filter. ETH News, published 03.01.2008.

Kalman was the creator of the modern theory of systems and control, and a towering figure in the related fields of Control, Signal Processing, Information, and Mathematical Sciences. He was a genuine intellectual, spoke fluently several languages, and had an amazing knowledge and interest in music. A side of Kalman which few people may have known was his attraction to sound systems and exotic sports cars.

Rudolf E. Kalman is survived by his wife, Constantina née Stavrou, their two children, Andrew and Elisabeth, and their families. His contributions to engineering remain pivotal, and he leaves behind a lasting legacy.


Credit: Georgiou, T.T., A tribute to Rudolf E. Kalman. Proc. 22nd Int. Symposium MTNS, Minneapolis, Minnesota, 2016.

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