NATIONAL ACADEMY OF SCIENCES

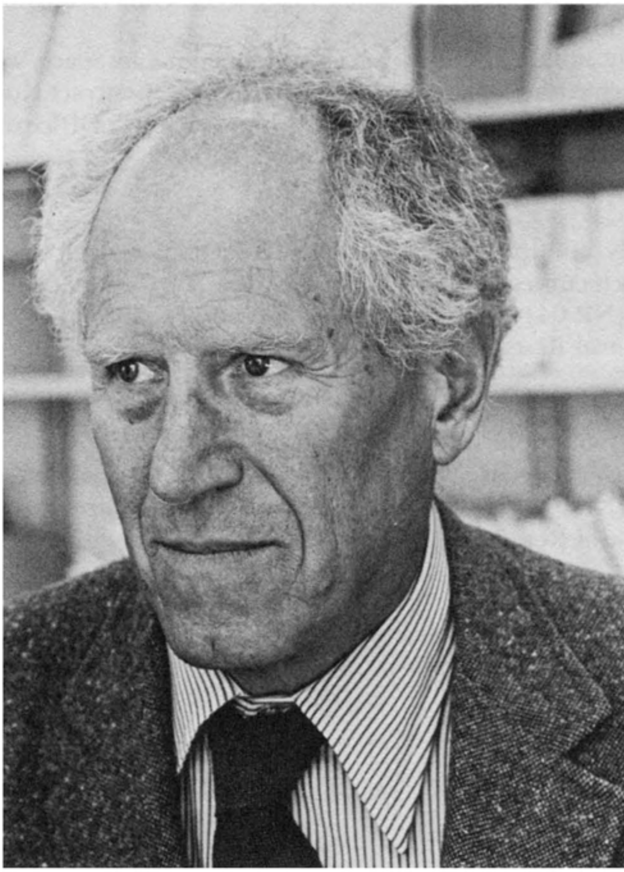
RUDOLPH KOMPFNER

1909—1977

A Biographical Memoir by

J. R. PIERCE

Biographical Memoir



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Rudi Kompfner

RUDOLF KOMPFNER

May 16, 1909–December 3, 1977

BY J. R. PIERCE

THE SUCCESSFUL PURSUIT of science and technology is something of a mystery. The way of endeavor is conspicuously marked by sterile studies and lucky flukes. Yet, I believe there are ways conducive to winning. These are illustrated in the work of Rudolf Kompfner. In writing about him, I hope that it will not be taken amiss if I refer to him consistently as Rudi. Few knew him as Kompfner or as Dr. Kompfner, and none as Rudolf.

Rudi's success in a field that he himself chose is indubitable; it is attested by numerous honors. In 1955 the Physical Society awarded him its Duddell Medal for his invention of the traveling-wave tube. This led him to give a lecture and later to write a book on *The Invention of the Traveling-Wave Tube*. He was made a fellow of the Institute of Electrical and Electronics Engineers and given its David Sarnoff Award in 1960 and its highest award, the Medal of Honor, in 1973. He received the Stuart Ballantine Medal of the Franklin Institute in 1960; the John Scott Award from the City of Philadelphia in 1974; the Sylvanus Thompson Medal of the Röntgen Society, incorporated with the British Institute of Radiology, in 1974; and the National Medal of Science in 1975. He was awarded an honorary doctor of technical science by the Technische Hochschule of Vienna in 1964 and the honorary degree of doctor of science from Oxford University in 1969. He was a fellow of the American Association for the Advancement of Science and a member of the National Academy of Engineering and the National Academy of Sciences. He served well on important committees of these organizations. He also served as a member of the Board of Trustees of Associated Universities, Inc.

Rudi succeeded—despite very real difficulties—through hard work and a constellation of qualities so various that they might be thought inconsistent. He had a driving purpose and intense application in his chosen field. Yet this did not exclude a wide range of interests and enthusiasms. He loved all good things except poetry, yet he could and did live simply. Nothing daunted him, and few things seemed beyond his range.

He was warm and open and quickly became what seemed like a lifelong friend. Felix Bloch regarded Rudi as a close friend, though they met only two years before Rudi's death, when neither was young. People were attracted to Rudi, and Rudi was attracted to those whom he felt worthy of his interest. Others, he must have ignored. I remember a lunch with Rudi and a foreign visitor. I solicited the visitor's opinions, listened intently, and commented politely. After lunch, Rudi seemed almost annoyed with me. He asked why I had bothered with such a man—he was nothing. And of course, Rudi was right.

To discuss Rudi and his career and its significance is no easy matter. He lived in many places, did many things, and interacted with many people. He was born in Vienna, Austria on May 16, 1909, the son of Bernhardt and Paula Kömpfner. His father was an accountant and a composer of Viennese songs and waltzes who played the piano in a Heurigen in the outskirts of Vienna. Rudi had a book, published in 1913, that included several of his father's compositions.

Rudi himself exhibited an early musical talent, picking out tunes on the keyboard and learning which notes went pleasingly together by trial with, apparently, little error. Piano lessons failed to teach him to read music; he memorized instantly the pieces he was told to study.

Rudi seems to have learned to cope with difficulties of life as he learned music—through exposure and talent. Toward the end of World War I, through the armistice, and for some time thereafter, Viennese children starved because of a total Allied blockade. Rudi survived because he was put on a train by the Red Cross and sent—without his parents knowing exactly where he was going—to Sweden. The months there, during which he recovered from boils and other ills of malnutrition, were spent with a deeply religious family. Their attitudes impressed him and remained fresh in his memory, though they had little long-term influence on his own beliefs.

Early reading, and particularly the works of Arago, enamored Rudi of physics. This was his lifelong love, but he was not allowed to pursue his chosen career immediately or directly. Through the influence of his uncle, Fritz Keller, an architect, he studied architecture at the Technische Hochschule in Vienna, becoming a Diplom-Ingenier in 1933.

This was a difficult time for Jews in Austria. An Englishman, Roy Franey, who had married Rudi's cousin Mowgli Jonasz, was helpful in Rudi's coming to England in 1934. Franey later succeeded in getting Rudi's parents and sister out of Austria in 1938. After Rudi had served an architectural apprenticeship with P. D. Hepworth in London from 1934 to 1936, he became managing director of Franey's firm, Almond Franey and Son, Ltd., Estate Managers and Builders, London, from 1936 to 1941.

Here we have a man who had suffered starvation during a terrible war, had been shipped off to one foreign land as a child, had been compelled to pursue a career not of his own choosing, and then had to go to another strange land and make his way as an architect. We might imagine him as disillusioned, bitter, slighting his own work or forever cut off from that which he valued most. Not Rudi.

Indeed, I believe that he learned a good deal from architecture that was valuable in his later endeavors. One thing was an appreciation of the practical aspects of any art, including that of the builder. Another was that in order to accomplish something, one must make a start.

Rudi told of staring at a blank piece of paper on his drawing board after having been instructed to design a house. A senior draftsman came, leaned over his shoulder, and saw that he was having trouble. The draftsman drew a square on the paper and told him, "The secret of getting started is to start." Rudi had his start and proceeded with the design.

Rudi became an architect of some accomplishment. According to Rudi's recollection, during a civil service examination, C. P. Snow walked in, glanced through Rudi's dossier, and said:

> "Mr. Kompfner, I see you are an Austrian and an architect."
>
> Rudi agreed.
>
> "Mr. Kompfner, Adolf Hitler was an Austrian and an architect. Tell me which is the better architect, you or Hitler?"
>
> "What I built still stands," Rudi replied.

Indeed it does. Among his works is a house in south London, described and pictured in *Small Houses, £500–£2500* (edited by H. Myles Wright, London: The Architectural Press, 1937). It is an admirable building for a narrow (30-foot wide), dark site. Rudi also designed a number of artisan's flats in the Bermondsey District.

Rudi's experience in architecture had various influences in his life. He was acutely aware of buildings, their beauties and their failings. I remember his telling me that of two buildings neighboring St. Mark's in Venice: one is marvelous; the other, trash. He insisted that the south facade of the Parliament building in Vienna is a masterpiece—far superior to the front. He speculated that this was the work of some junior architect and had escaped attention and ruination. Of lesser note, driving past a house in Summit, New Jersey, that we both admired, he said that the second-story windows were too close to the roof, which was certainly so.

Another influence of architecture was that it enhanced Rudi's natural talent for drawing. In his Viennese days, Rudi produced some striking prints in a then-current style. Later, he provided twenty-three illustrations for a book, *3 Jungen Ziehen durch Kleinasien,* in Verlag *Das Bergland-Buch,* published in 1936 and written by Rudi's closest and lifelong Viennese friend, Theo Eder.

Rudi's talent for illustration was a joy throughout his life; he recorded home, family, and a one-time pet raccoon. It served a different purpose in illustrating his technical thoughts clearly. At the blackboard, most of us fumble in trying to convey our ideas; Rudi was never unclear, never at a loss. He insisted that his students picture things accurately. One student told me that he continually demanded, "draw it to scale." That can make a real difference.

While Rudi was practicing architecture and learning through it, he began to make his way in his chosen field of physics.

How does one turn from a practicing architect to a physicist? Rudi's approach was phenomenally original. He went to the excellent Patent Office Library in Chancery Lane and read journals and books in the evening. Sometimes Peggy Mason accompanied him. He had met her at the Westminster swimming club in 1935; they were married at Caxton Hall, Westminster on April 29, 1939.

Beginning in 1935, Rudi recorded in a series of notebooks those things that interested him most. These included the television camera tubes of Zworykin and Farnsworth, and later the microwave tubes of Heil and Varian.

Soon, original ideas and inventions appeared in the notebooks. Among these is the "Relayoscope," in which a pattern of light (an image) impinging on a nonconducting photoelectric grid was to be used to control the flow of an electron beam. This led to a triple-barreled British patent, number 476,311, applied for on June 4, July 27, and August 18, 1936 and accepted on December 6, 1937. The patent covers the functions of a television pickup tube and the reproduction of infrared, ultraviolet, or X-ray images as light images. Rudi tried vainly to market this invention.

As his reading progressed, Rudi's interests definitely turned toward microwave tubes. He had original ideas for explaining the Heil tube and the klystron.

What course Rudi's activities might have taken but for the coming of World War II in September of 1939 is an unanswerable question. In June of 1940 Peggy returned from work one evening to find that he had been taken to the Brixton Police Station for internment as an enemy alien. He was interned on the Isle of Man from June to December 1940. In some way, through the intervention of Peggy, relatives, friends, and people who knew of his work, including Hugh Pocock, the editor of the *Wireless Engineer,* and by declaring himself a stateless person, Rudi was released.

During internment, Rudi never lost his balance of judgment and was always considerate and charming. He met a number of German internees, with whom he studied and discussed physics. He shared quarters with Wolfgang Fuchs, a mathematician from Cambridge who is now a professor at Cornell. They became close and affectionate friends as well as collaborators in science. Together they wrote a paper on space charge effects in velocity modulated electron beams. This was eventually published in the *Proceedings of the Physical Society.* W. E. Benham, a somewhat eccentric expert on vacuum tubes with whom Rudi began to correspond on July 9, 1941, was helpful in this connection.

Prior to his internment, Rudi had submitted a paper on magnetrons to the *Wireless Engineer.* Hugh Pocock had taken this to the Admiralty, and it was deemed unpublishable in wartime. The Admiralty wrote to Peggy, asking for details of Rudi's qualifications. She went to the Admiralty in late 1940 to see if they might have use for Rudi. Frederick Brundrett said that Rudi should see them when he was released.

Rudi was released, and, though Brundrett said that he was "neither fish nor fowl" to them, in September of 1941 he was sent to the Physics Department of Birmingham University to work under Professor M. L. Oliphant. The work he found there on high-power magnetrons, the heart of wartime radar, was a revelation.

Characteristically, however, Rudi soon turned his own endeavors in a novel direction. The fruitful outcome was the invention of the traveling-wave tube, while trying to make a better klystron amplifier for radar receivers. His fundamental idea—the continuous interaction of an electron stream and an electromagnetic wave of the same velocity traveling along a helix—was ingenious, and the realization worked!

The invention of the traveling-wave tube is characteristic of Rudi's career in several ways. The big thing of the day was the magnetron. Rudi had already written a paper on the magnetron. But at Birmingham, the heart of magnetron research, he turned his attention to something else, and, almost singlehanded, he succeeded.

He succeeded in the face of contrary advice. "Experts" told him that a coiled wire, or helix, would not transmit microwaves. Rudi didn't believe them. He wound a helix himself and made measurements. He didn't just think and argue, he did something with his own hands, and it succeeded.

Then he built a traveling-wave tube. This was important, because what he found went beyond what he had expected. Initially, he had thought only of a strong action of the electric field of the electromagnetic wave on electrons traveling at the same velocity. He found that as the current of electrons was increased, the tube broke into microwave oscillation. Not only did the electromagnetic wave act to bunch the electrons, the bunched electron beam acted to strengthen the electromagnetic wave. The helix and beam together constituted an amplifier that gave a very high gain over a very broad band of frequencies.

Rudi analyzed this phenomenon by means of a series calculation: the effect of the field on the beam, the effect of the beam on the field, and so on, back and forth. He thus explained the "Kompfner dip"—a reduction of transmission at a particular electron velocity or accelerating voltage. Joseph Hatton, a young research student who had begun to work with Rudi, pushed the analysis further.

When I read of Kompfner's work through CVD (Committee on Valve Development) reports, I was astonished. I quickly worked out a wave analysis that explained the behavior of traveling-wave tubes more to my satisfaction, and, I believe, to Rudi's. I had been considering the effect of traveling waves on electron beams. But because I didn't think of that wonderfully simple circuit, the helix, and because I only calculated and didn't build anything, I missed the most important point—the mutual interaction between the electromagnetic wave and electrons that results in a very great amplification.

In 1944 Rudi, deep in work on his traveling-wave tube, was transferred, still as an employee of the Admiralty, to the Clarendon Laboratory at Oxford. While there, he met Neville Robinson, who was working at the Services Electronic Research Laboratory at Baldock. It was characteristic that when Robinson, pursuing some ideas of his own that were only vaguely related to Rudi's interest, modified the design of the helix in order to make a narrow-band amplifier, Rudi realized that while it might not work as Robinson intended, it might possibly work as a low-noise amplifier. It did.

Beyond his work on traveling-wave tubes, Rudi became haunted with the idea of a voltage-tunable traveling-wave oscillator. His interest persisted throughout the period during which he studied for his D.Phil. in physics, which he obtained in 1951. He made some theoretical and experimental progress toward this end, partly in collaboration with Neville Robinson.

In 1950 Rudi left the Admiralty and became associated with the Atomic Energy Research Establishment, but he continued to work at the Clarendon Laboratory on microwave tubes. I had hoped that Rudi might come to work at Bell Laboratories, and we had approached him shortly after the close of World War II. At that time he applied for a visa, which was long in coming. It was granted in 1951, and he came to the Bell Laboratories at Murray Hill, New Jersey on December 27, 1951. There he found the facilities necessary to continue his work on tunable traveling-wave oscillators, and in a short time he had demonstrated electronic tuning over an unprecedented range of 10,000 megahertz—a wavelength range from 6.00 to 7.50 millimeters.

Rudi's interest in microwave tubes extended over many years, and his contributions were various, including the use of coupled helices, novel means of focusing (Slalom focusing), understanding of noise, and the effects of nonreciprocal loss. Eventually, he assumed greater responsibilities, becoming director of electronics research in 1955, director of electronics and radio research in 1957, and associate executive director, research, Communication Sciences Division in 1962.

In 1958 Rudi and I became interested in communication satellites. He was full of enthusiasm in pushing and augmenting an idea that had originally been mine. We published a paper in 1959 outlining the potentialities of such satellites. Rudi brushed up his spherical trigonometry, a subject of which I was utterly innocent, in order to calculate earth coverage areas. We traveled here and there, trying to get someone to *do* something. Finally, NASA did. The Bell Laboratories work on the Echo satellite, which was launched on August 12, 1960, was carried out in Rudi's department and under his inspiration and direction. He was also deeply involved in the Telstar experiment—the launching by AT&T in 1962 of a satellite that carried live television across the Atlantic for the first time.

But Rudi's influence at Bell Laboratories was wide and pervasive. He loved to hear and talk about novel things. He proposed new ideas without any concern for personal credit. Drafts of technical memoranda were typed on pink paper in those days. Nothing delighted Rudi more than to send out pink drafts for comment in order to stir up the reader. He said that pink was his favorite color. When what he proposed proved wrong, he was not afraid to change his mind.

The 20-foot horn-reflector antenna built to receive signals from the Echo satellite was equipped with a low-noise ruby maser amplifier built for Rudi by Derek Scovil. Charles Townes had invented the first maser in 1953, and one of Townes's students and coworkers, Jim Gordon, was already at work at Bell Laboratories. Early in 1960, when the horn reflector antenna was partially completed, Rudi invited

Townes and his students out to see it. Among the students was Arno Penzias, who was doing a thesis on radio astronomy. Penzias saw the potential of the antenna for work in this field, and Rudi was fascinated. In 1961 Penzias came to work at Holmdel, and two years later Robert Wilson, a radio astronomer from Caltech, joined him. In using the horn-reflector antenna and the ruby maser amplifier they discovered a sky background noise temperature of about 3K. This proved to be most significant; it demonstrated the existence of black body radiation left over from the big bang of creation, and in 1978 Penzias and Wilson shared the Nobel Prize for physics.

While he was interested in masers in connection with the Echo satellite, Rudi heard a talk at MIT on the superconductivity of niobium at comparatively high temperatures. This led him to think of a superconducting magnetic shield for masers. On his return to Bell Laboratories, he consulted Ted Geballe and Bernd Matthias, who were interested in these superconducting phenomena. He found that they had been unable to get the metallurgists to make the required alloys. Rudi excited the interest of Earle Schumacher and Morris Tanenbaum of the metallurgy group. This intervention led to a great deal of fruitful work, including the discovery by J. E. Kunzler of the niobium-3 tin alloy that had an unprecedented property of remaining superconducting in a magnetic field of .88 kilogauss. This work led to today's remarkable superconducting magnets.

As a part of his interest in communication satellites, Rudi wondered whether the advantages of a directive antenna on a satellite could be attained with an electronically controlled array, so that the attitude of the satellite wouldn't have to be controlled. He started with the Van Atta array, which could only send a signal back in the direction from which it had come. Working with C. C. Cutler and L. C. Tillotson, the Star array was devised. This makes it possible to guide a microwave beam down by means of a signal sent from the ground.

The laser, which can produce and amplify coherent light, is an optical maser. When T. H. Maiman first used a ruby laser to produce coherent light in 1960, Rudi became convinced that light waves would play an important part in communication. A complex program was initiated, involving many people and many ideas: sequences of lenses in large tubes buried underground, combinations of mirrors in place of lenses, and gas lenses that made use of the variation of refractive index of air with temperature.

Somewhat later, Rudi played a part in shifting the whole course of work in optical communication at Bell Laboratories. Neville Robinson remembers Rudi telling him of work at the British post office laboratories on highly transparent fibers—it was typical that Rudi went around looking for ideas. Stewart Miller, a leader in Bell Laboratories optical research, remembers that a paper written by K. C. Kao came to the attention of Rudi and himself.

Kao had made measurements that suggested that fibers made of glass or quartz much purer than any then in existence might transmit light waves over long distances with very little loss. Together, Rudi and Miller wrote a memorandum that stimulated Bell Laboratories materials people to work toward such super-transparent fibers. Such fibers have indeed come into being and into use. After Rudi left Bell Laboratories, they played an important part in his work at Oxford. Advances in the field of light-wave communication have involved many people, but Rudi played a very special role in proposing, arguing, and encouraging that all those concerned valued and appreciated.

In June of 1973 Rudi retired from Bell Laboratories and divided the rest of his years between Stanford University in the winter, where he became professor of applied physics and professor emeritus in 1974, and Oxford, where he was professor of engineering and a professorial fellow of All Souls from 1973 to 1976 and an associate member of the college from 1977 onward. At Oxford he did important work on scanning optical microscopes, on the metal coating of optical wires to make them stronger and more durable, and on holographic means for interconnecting single-mode fibers. Colin Sheppard carried things on while Rudi was away, and, as everywhere, Rudi was in close and inspirational touch with many, including Don Walsh and Hanz Motz, and also with his students, J. N. Gannaway, T. Wilson, and Peter Hale. Rudi inspired others to have good ideas and never sought credit for these—or sometimes even for his own.

The work at Oxford on scanning optical microscopes, in which the specimen is examined by means of a fine laser spot, was particularly productive. The device exhibited improvements in resolution, contrast, and depth of focus and proved particularly valuable in biological studies and in studies of integrated circuits. He hoped to gain further advantages through observing harmonics of the illumination light.

At Stanford Rudi's activities were various. Long before he went there, on April 5, 1966, he had written to Peggy of a Sunday evening meeting with Cal Quate, Marvin Chodorow, and Joe Pick, and had said that "the project of an acoustical microscope is now under way." On coming to Stanford, he was delighted by the marvelous acoustic microscope work under Quate and contributed considerably in this area, particularly concerning depth of focus.

The work of three graduate students whom Rudi supervised shows something of his interest: Celia Yeack worked on a nonlinear acoustic microscope in which the information-bearing signal is a harmonic of the frequency of illumination;

Steve Newton worked on a lenseless scanning optical microscope in which the sharp definition depends on holographic effects involving light from a pinhole aperture; and Heungsup Park worked on optical picosecond radar using dye lasers—a project intended to make it possible to examine the tissue under a person's skin.

To his students, Rudi gave endless time and sage advice and counsel. He insisted that they try the simplest way thoroughly before trying more complex solutions. He counseled them rather than dominating them. He was at once their friend and their hero. His explanations of other faculty members gave the students a deeper and wider understanding of different men and different approaches.

Beyond the work of his students, Rudi took a keen interest in the work of other Stanford faculty members, including Cal Quate, Marvin Chodorow, Tony Siegman, Gordon Kino, and Steve Harris. All welcomed his profitable discussions. He approached problems from a fresh and individual point of view. He wasn't always right, but often enough his fresh approach led somewhere. And it was an extraordinary quality of Rudi that, no matter how many projects he had in hand, he always had time to discuss and criticize a new one; no one ever found him too busy to listen.

Rudi was a member of the committee for Bill Colson's doctor's oral examination on free electron lasers. This was an idea that had originated with John Madey, who had given a complicated quantum mechanical explanation. During Colson's doctoral examination, Rudi insisted that there must be a classical explanation of the operation of the device. Rudi's last seminar at Stanford was devoted to a simple classical analysis of the original free-electron laser and related devices, some of them much earlier. And, at the end of a paper on the same subject written by W. B. Colson and S. K. Ride, the authors stated: "We are particularly grateful for the friendship and guidance offered by Peggy and Rudi Kompfner, who will remain an inspiration."[1]

Rudi invited students, faculty, and friends to his home and discussed technical matters—and other things. At a point of great success, he celebrated with the secretary and the technicians as well as the students and faculty.

For three years, Rudi conducted in his garage and home a freshman seminar on how to do research. The students and he proposed projects. One among these was chosen by vote. Analyses and experiments were then made and models were constructed. The three years' projects were: a new form of windmill, an earthquake-resistant building on rollers, and a wheelchair capable of mounting a curb.

Rudi was disappointed that in the last year a favorite proposal of his lost by one vote. That was a very small swimming pool in which one could swim long distances against a current of water, without moving at all with respect to the pool.

Rudi's versatility and originality led to a number of ingenious ideas and contraptions. When a Picturephone terminal was installed in his office, he put an excellent likeness of himself in front of the camera tube, so that those who called him found him remarkably quiet and attentive.

In his home, Rudi built a set of swinging cat doors. When he found that a raccoon got in and stole the cat's food he arranged a complicated linkage of strings, pulleys, and hooks by means of which an intruder could be excluded or trapped. Later, Rudi fed an abandoned baby raccoon, which became a pet, and built a marvelous house for it and arranged an aerial tramway to carry food to it on winter days.

For several years, Rudi devoted a great deal of time and ingenuity toward producing four-legged chairs and tables

1. W. B. Colson and S. K. Ride, "A Laser Accelerator," *Applied Physics,* 20(1979):65.

that would rest steadily on an uneven surface. Alas, a search revealed a number of patents. Nonetheless, Rudi finally did construct a table and a chair of his own design—operable, but not objects of great beauty, and perhaps of marginal utility. A different invention, a sort of mat or coaster to make the port and madeira decanters at All Souls slide more easily on the table top, has been an unqualified success.

Rudi's analysis of the noise level in the dining room of the faculty club at Stanford was sound. He argued that diners talk loudly enough to be heard across the table against the voices of other speakers. He worked out a quantitative theory. The Stanford dining room was so noisy, he showed, because diners shouted vainly across very wide tables in an effort to make themselves heard amid the din of the futile efforts of others to converse at nearby tables.

Eventually, the tables were made narrower, the diners at the same table could hear one another, and the hubbub subsided. I have not been able to trace the change directly to Rudi's insightful work.

Rudi's life was cut short in the full exercise of his powers and in full enjoyment of his family, his friends, and his world. He must have seen something of himself and of Peggy in his children, who acquired their qualities more by good example than in any other way. He lived to see his daughter married and to wheel his son's son around Palo Alto.

As he enjoyed all good things, I am sure that Rudi must have valued the many honors that came his way, but he was a modest man. His students told me that before leaving on a trip, Rudi usually told them where he was going. When he didn't, they felt that he must be going to receive some new honor, and so it proved to be.

Rudi's modesty added to the real joy that all his friends felt for him in his successes. I am grateful to have had this opportunity to write good and true things about him that he would not have said himself. But I wish to tell in words that Rudi himself wrote the true reward that his career brought him:

THE FEELING ONE EXPERIENCES when he obtains a new and important insight, when a crucial experiment works, when an idea begins to grow and bear fruit, these mental states are indescribably beautiful and exciting. No material rewards can produce effects even distantly approaching them. Yet another benefit is that an inventor can never be bored. There is no time when I cannot think of a variety of problems, all waiting to be speculated about, perhaps tackled, perhaps solved. All one has to do is to ask questions, why? how?, and not be content with the easy, the superficial answer.

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2,812,467. Electron Beam System. (Issued 11/5/57.)

1958

2,834,908. Traveling Wave Tube. (Issued 5/13/58.)
2,857,548. Electron Beam System. (Issued 10/21/58.)
2,860,278. Non-reciprocal Wave Transmission. (Issued 11/11/58.)

1959

2,867,744. Traveling Wave Tube. (Issued 1/6/59.)
2,879,442. Direct View Storage Tube. (Issued 3/24/59.)
2,891,191. Backward Wave Tube. (Issued 6/16/59.)
2,895,071. Traveling Wave Tube. (Issued 7/14/59.)
2,899,597. Apparatus Utilizing Slalom Focusing. (Issued 8/11/59.)
2,911,544. Non-reciprocal Wave Transmission Device. (Issued 11/3/59.)
2,916,657. Backward Wave Amplifier. (Issued 12/8/59.)

1960

2,922,917. Non-reciprocal Elements in Microwave Tubes. (Issued 1/26/60.)
2,925,565. Coaxial Couplers. (Issued 2/16/60.)
2,933,640. Pulse Coincidence Detecting Tube. (Issued 4/19/60.)
2,939,034. Electron Gun for Slalom Focusing Systems. (Issued 5/31/60.)
2,949,558. High Efficiency Velocity Modulation Devices. (Issued 8/16/60.)
2,955,223. Traveling Wave Tube. (Issued 10/4/60.)

1961

2,972,081. Low Noise Amplifier. (Issued 2/14/61.)
2,972,702. High Frequency Amplifier. (Issued 2/21/61.)
2,985,790. Backward Wave Tube. (Issued 5/23/61.)
3,012,204. Elastic Wave Parametric Amplifier. (Issued 12/5/61.)

1962

3,021,490. Parallel High Frequency Amplifier Circuits. (Issued 2/13/62.)
3,021,524. Scanning Horn-Reflector Antenna. (Issued 2/13/62.)
3,041,559. Microwave Filter. (Issued 6/26/62.)
3,051,911. Broadband Cyclotron Wave Parametric Amplifier. (Issued 8/28/62.)
3,067,379. High Frequency Generator. (Issued 12/4/62.)

1964

3,133,198. Traveling Wave Light Modulator. (Issued 5/12/64.)
3,151,325. Artificial Scattering Elements for Use as Reflectors in Space Communication Systems. (Issued 9/29/64.)
3,154,748. Detector for Optical Communication System. (Issued 10/27/64.)

1965

3,188,155. Beam Collector with Auxiliary Collector for Repelled or Secondarily-Emitted Electrons. (Issued 6/8/65.)
3,196,438. Antenna System. (Issued 7/20/65.)
3,224,331. Sinusoidal-Shaped Lens for Light Wave Communication. (Issued 12/21/65.)
3,224,330. Transmission of Light Waves. (Issued 12/21/65.)

1966

3,253,226. Optical Maser Amplifier. (Issued 5/24/66.)
3,273,151. Antenna System. (Issued 9/13/66.)
3,285,129. Triple Element S-Lens Focusing System. (Issued 11/15/66.)

1967

3,317,861. Spherical Reflector Elastic Wave Delay Device with Planar Transducers. (Issued 5/2/67.)

1969

3,454,768. Intracavity Image Converter. (Issued 7/8/69.)

1970

3,490,021. Receiving Antenna Apparatus Compensated for Antenna Surface Irregularities. (Issued 1/13/70.)

3,503,070. Anti-Doppler Shift Antenna for Mobile Radio. (Issued 3/24/70.)

3,503,671. Multiple-Pass Light-Deflecting Modulator. (Issued 3/31/70.)

3,503,671. Multiple-Pass Light-Deflecting Modulator. (Issued 3/31/70.)

3,506,331. Optical Waveguide. (Issued 4/14/70.)

3,506,834. Time Division Multiplex Optical Transmission System. (Issued 4/14/70.)

3,515,455. Digital Light Deflecting Systems. (Issued 6/2/70.)

3,520,584. Method and Apparatus for Obtaining 3-Dimensional Images from Recorded Standing Patterns. (Issued 7/14/70.)

3,530,298. Optical Heterodyne Receiver with Pulse Widening or Stretching. (Issued 9/22/70.)

3,532,889. Light Communication System with Improved Signal-to-Noise Ratio. (Issued 10/6/70.)

1977

4,012,950. Method of and Apparatus for Acoustic Imaging. (Issued 3/15/77.)