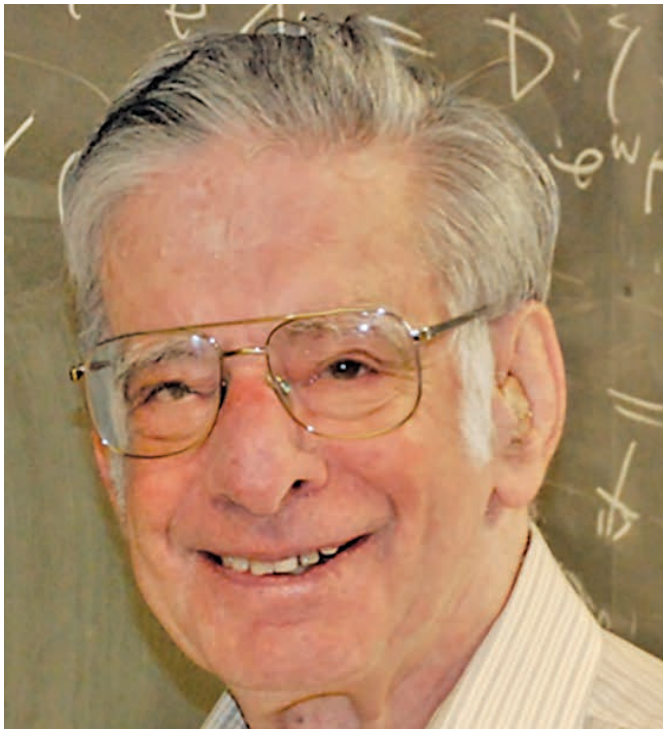
Hans F. Weinberger (1928–2017)

Don Aronson, Peter Olver, and Fadil Santosa, Coordinating Editors



Hans Felix Weinberger passed away at the age of 88 in Durham, North Carolina, on September 15, 2017. He was a member of the University of Minnesota School of Mathematics for thirty-seven years and played a vital role in bringing the School to its present eminence and in the establishment of the NSF Institute for Mathematics and its Applications (IMA) on the Minneapolis campus. He specialized in the study of various aspects of the analysis of partial differential equations, including estimation of eigenvalues, isoperimetric inequalities, and the maximum principle. More recently he turned his attention to mathematical biology.

Hans was born in Vienna, Austria. In the 1930s it became clear that, with the rise of Hitler in Germany and his influence on Austria, the situation for Jews in Austria was becoming perilous. The Weinberger family immigrated to the US in the fall of 1938. Hans was an excellent student and graduated from high school at the age of 16. He was very interested in science and became a finalist in the Westinghouse Science Talent Search in 1945. In 1950 at the age of 21 he received an ScD in mathematics at Carnegie Institute of Technology under Richard Duffin, who at the same time also supervised the work of Raoul Bott. Another classmate was the legendary John Nash, who was Hans's roommate for one semester. An account of their relationship can be found in Sylvia Nasar's book *A Beautiful Mind*.

Hans's earliest work, at the University of Maryland, was on variational methods for eigenvalue approximation, often in collaboration with Larry Payne. In addition, Hans also worked on isoperimetric problems, properties of solutions of hyperbolic and elliptic partial differential equations, and strength of materials.

In 1960 Hans joined the faculty of the University of Minnesota, where he served as department head and supervised nine PhD students, including Bert Hubbard, Roger Lui, John Osborne, and Jianzhong Zu. He wrote or coauthored more than 140 research papers, the last appearing in 2015.

Hans published three influential books: the CBMS monograph *Variational Methods for Eigenvalue Approximation* based on his lectures at Vanderbilt University; the monograph *Maximum Principles in Differential Equations* with Murray Protter; and the widely used textbook *A First Course in Partial Differential Equations*. In 1986 Hans was elected to membership in the American Academy of Arts and Sciences and was a member of the inaugural class of Fellows of the American Mathematical Society. He was Managing Editor of the *Bulletin of the AMS* from 1972 to 1977.

In 1979 Hans, George Sell, and Willard Miller submitted a proposal to establish the Institute for Mathematics and

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its Applications (IMA) at the University of Minnesota, and Hans served as its first director. Hans was very much a hands-on director, attending almost all lectures and collaborating with visitors and postdocs.

Weinberger and George Sell in 1982 at the IMA, which they founded with Willard Miller.

Avner Friedman, who succeeded Hans as IMA director, said on his passing: "In addition to being a marvelous mathematician, Hans was a kind person, always seeing the good things in people, always considerate. I was fortunate to have known him and to have had him as a very close friend. He will be missed."

Hans was modest and unassuming, but he had prodigious mathematical talent. His office door was always open, and he encouraged students, colleagues, and visitors to come in to discuss their current work. He was very quick at seeing the essence of any problem and often was able to offer extremely helpful comments and suggestions. He was, in sum, an ideal colleague.

Mark Lewis

Hans was a great teacher for me. Since first reading his work I have been in awe of him; he thought about mathematics in such a powerful way. I continually learned from him. He was always a gentleman, keeping a twinkle in his eye and a smile on his face as he dissected what I thought were some of my perfectly good proofs. He was perceptive. I remember him apparently sleeping at mathematics seminars only to come up with a very insightful question right at the end of the lecture.

Hans contributed immensely to our understanding of nonlinear reaction-diffusion systems. He coauthored a beautiful paper with Don Aronson (1975), which establishes the rate of spread of locally introduced populations, also of great interest to ecologists. Hans generalized the results of the 1975 paper to general discrete-time recursions and non-diffusive motion. This gave rise to a monumental 1982 paper that was, however, no easy read. Nonetheless it turned out to have broad-reaching scientific impacts due to the generality of the results.

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References

D. G., Aronson, and H. F. Weinberger. (1975). Nonlinear diffusion in population genetics, combustion, and nerve pulse propagation. *Lecture Notes in Math.* **446**, 5–49.

H. F. Weinberger. Long-time behavior of a class of biological models. *SIAM J. Math. Analysis*, **13**(3), 353–396.

Bingtuan Li

I first met Hans in the fall of 1998 when I was a postdoc with Mark Lewis participating in the year-long program Mathematics in Biology at the IMA. I always saw Hans at seminars, sitting in the front row and asking tough and piercing scientific questions, some of which were apparently outside the scope of mathematics. He effusively engaged in all the program activities, interacting with visitors and postdocs during discussion meetings and coffee breaks. When my postdoc mentor Mark Lewis introduced me to Hans, it marked a turning point in my academic life.

Mark had noticed that in a two-species Lotka–Volterra-type competition model, the spreading speed at which a species spreads into the equilibrium distribution of its rival may not be linearly determined and sought to address the problem analytically. The problem was related to Hans's work in the 1970s and 1980s. We had regular lively discussions, which were full of questions, ideas, answers, and, most of all, fun. As I had nearly zero background about spreading dynamics of spatial-temporal systems, understanding the meeting discussions was a constant challenge for me. Hans was patient and helpful when I asked questions, no matter how simplistic. Besides getting direct help from Hans, I also read his papers with Don Aronson published in 1970s and his remarkable 1982 paper. This paper is very abstract and not easy to read, but nonetheless written beautifully, with precision, elegance, and power. Hans and Mark initiated a research plan for studying spatial dynamics of general cooperative systems. Previous work from Roger Lui, Hans's PhD student, focused on cooperative systems with two equilibria, which extended the results from Hans's 1982 paper. Lui's results showed the uniqueness of spreading speed. Hans designed a comprehensive framework for analyzing more general systems with more than two equilibria, where multiple spreading speeds are identified, spreading speeds as lowest speeds of traveling waves are characterized, and linear determinacy is studied. It works for many spatial-temporal equations, including reaction-diffusion equations and integro-difference equations. I learned a great deal from Hans that year through his wonderful academic and personal mentorship.

Since leaving the IMA, I have continued learning from and working with Hans and Mark on wave propagation problems. Hans has given me his advice, thoughts, and comments on various problems as well as his encourage-

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ment and support. Very often I would send him an email at night, only to see his reply early morning the next day. His 1982 paper has been a source of ideas and inspiration for me to think about new problems as well as an influence on countless researchers in the field. He dedicated his life to his research and his love of mathematics and to his students, mentoring a new generation of curious and passionate mathematicians. Hans will be forever missed.

Howard Levine

During my graduate student years, my PhD advisor, Larry Payne, gave me two sets of University of Minnesota lecture notes by Hans Weinberger to read. One of them became the basis for "Variational Methods for Eigenvalue Approximation" *CBMS Notes*, #15, SIAM, 1972. These notes were extremely well written and very enlightening. I hoped that someday I would have a chance to meet their author.

When I showed up to teach at Minnesota in 1969, I saw that I was down to teach something called "mathematical fluid dynamics." My heart sank. I knew almost nothing about fluid mechanics beyond the fact that water and oil do not mix. When I told Hans, who was head, of my ignorance of the subject, he said, "Don't worry. You'll learn." That was the kind of guy he was, a Renaissance mathematician.

Once, after a particularly boring colloquium during which Hans was dozing, he asked the speaker what I considered a very deep question, which the speaker seemed pleased to answer. After the talk I asked him if he followed the talk, and he replied that he did not. So I asked him why he asked a question, and such a very good one at that. "Howard," he said, "asking a question is just being polite to our guest."

At a personal level, his office door was always open, both literally and figuratively. When I was in the department or, later, visiting IMA, I knew that if I had a scientific question, Hans would be a welcoming person to ask. Sometimes I would ask him a question by snail mail. I would invariably receive either a written reply or else a phone call. One of these exchanges led to our joint paper, "Inequalities between Dirichlet and Neumann Eigenvalues." I proposed extending a result of Payne's for such inequalities for convex domains in the plane to convex domains in several dimensions. I had a plausible argument for doing this but it wasn't plausible enough for Hans. He then proceeded to give a rigorous argument, extending the results to certain wide classes of nonconvex domains. Some people might have just published these results under their own name, perhaps acknowledging the source of the conjecture, but not Hans. "You proposed the problem; you should share in the result," he told me. He was not only a gentleman, but a real mensch!

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Catherine Bandle

The first time I encountered the name of Hans Weinberger was during my master's thesis. In those days I studied his paper on the second eigenvalue of a free membrane. By a clever trick, using Browder's fixed-point theorem, he showed that the ball has the largest second eigenvalue among all domains of the same volume. This short paper reflects the art and the originality of Weinberger's mathematics. Fascinated by this paper I then continued to read his other papers on eigenvalue estimates and isoperimetric inequalities. Many of them were written in collaboration with L. Payne. They contributed significantly to the development of the isoperimetric inequalities in mathematical physics, an area that started to become popular after the pioneering work of Pólya and Szegö. By now several of Weinberger's results belong to the classical inventory of analysis.

Unique in Weinberger's work is his deep understanding of the geometry hidden in the classical partial differential equations. This together with his physical intuition enabled him to discover many important properties of the spectrum of second and fourth order partial differential equations, and to tackle open problems in a very original and elegant way.

Needless to say how pleased I was when, during a visit at the ETH in Zürich, I had the occasion to meet him personally. I got to know him as a gentle and modest person. His open-mindedness to things other than mathematics impressed me greatly at that time. During a trip with him and [his wife] Laura to some medieval Swiss town he showed great interest in cultural matters. This impression was confirmed at a later meeting in Minneapolis where Laura and Hans brought me to a performance of Tchaikovsky's *1812 Overture*.

Nanako Shigesada

I met Hans Weinberger only twice.

My first encounter was in the early 1980s, when he was visiting Kyoto University. I still remember that I was so tense in front of him, because I majored in physics and had little professional knowledge of mathematics. In response to his friendly inquiry about my research, I somehow explained that I was working on an RD model for the spatial segregation of interacting species, a well-known phenomenon in ecology. At that time, I never supposed that we would later collaborate three times as co-authors.

Our second encounter was in April 1999 at an IMA workshop. When I stood on the stage as the second speaker on the first day, I was surprised to find Hans sitting in the first row and looking towards me. My talk was titled "Biological invasions into periodically fragmented environments: Reaction-diffusion models." It demonstrated numerically the pattern and the ray speed of the range expansion of species introduced at a point in a stripe-shaped habitat.

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During a coffee-break the next day, Hans approached and handed me a paper napkin on which he had scribbled an equation that contained enlightening suggestions for my work instantly recognizable to me. Retrospectively, this was the start of our collaboration.

One year later, Hans sent me his own draft on traveling waves in a periodically varying habitat. Although it was tough mathematically, I was able to grasp its fundamental importance after prolonged reading. For my part, I had heuristically derived a formula for the ray speed in a stripe-shaped habitat, in collaboration with my students Noriko Kinezaki, Kohkichi Kawasaki, and Fugo Takasu. When we sent our manuscript to Hans, he immediately noticed an apparent discrepancy between his ray speed formula and ours. To our great relief, however, careful cross-examination revealed that both formulas were essentially equivalent to each other. After many more rounds of such lively exchanges, our article was finalized. We offered Hans co-authorship of the article because of his indispensable contributions. However, he cordially declined our offer, saying, "If I were to become an author, I would be inclined to push for a number of changes to turn this very nice exposition into a piece of rigorous mathematics. I think this would lose your audience, and so it is not a good idea." I was impressed with Hans's strict attitude toward science. Eventually, both parties published their own separate articles (Weinberger, 2002 and Kinezaki et al., 2003).

Subsequently, my interest shifted gradually from RD models to integro-difference models that can incorporate the life history of organisms involving non-overlapping generations and various types of dispersal kernels. In 2007, I sent Hans an article on an ID version of the RD model written by Kawasaki and myself, to which he responded, "I think there are some useful ideas, and I would be happy to collaborate with you on their development." We accepted his offer with deep gratitude. From that time, he sent us an updated draft incorporating new ideas almost every week. As a consequence of these exchanges, we were able to publish this work in 2008.

In 2009, we collaborated with Hans again, primarily at his initiative, to publish an article on an RD model for a partially cooperative 2-species system.

Our third and last collaboration with Hans was in 2014–2015, this time starting with my proposal. In spatially varying habitats, organisms tend to show directed movements (taxis) toward more favorable patches. We extended our previous reaction-diffusion (RD) model to an advection reaction-diffusion (ARD) equation in which taxis is incorporated in an advection term. For this work, Hans provided mathematical proofs of the existence of the travelling wave and its speed formula as presented in the appendix of our article published in 2015.

We had fruitful interactions with Hans for 18 years, and exchanged more than 400 emails. Tracing back through these emails made me realize how sincerely and patiently Hans had been trying to convey the role and potential of mathematics to us. Hans was truly a gentleman with the warmest heart.

Roger Lui

Hans was my PhD adviser. The first problem he had me look at was generalizing the results of the famous 1937 Kolmogorov–Petrovsky–Piskunov paper from Heaviside initial data to general initial data, but before long Hans told me that the problem had been solved by Uchiyama in Japan. Hans then asked me to look at the multi-dimensional case. That turned out to be an incredibly hard problem and I believe the problem, convergence to traveling front, is still open. I was not able to solve the problem, and I even came up with a wrong proof. Hans was very forgiving and patient with me. We had weekly meetings, and I remember that during one of the meetings, Hans told me something I remember even today—don't keep repeating the same idea (if it does not work). After I was unable to make any progress on the problem for a long time, Hans told me to look at another problem. At that time, Hans had just developed a discrete-time continuous space population genetic model, which he believed was under more realistic assumptions than the Fisher's equation. He wanted me to prove for his model what KPP and Uchiyama proved for the Fisher-KPP equation. I was able to complete the first half of the problem, monotone initial data, relatively quickly, but I was stuck on the second half, initial data with compact support, for a long time, until one afternoon I tried estimating the relative difference between two functions rather than their absolute difference. That was the key idea I was missing. The rest was easy and I wrote up a 40-page note and left it in Hans's mailbox. In his office, Hans asked me to go over the proof on the board. Hans finally agreed that the proof was correct. Then I asked Hans to give me another problem to work on. He hesitated for a while and said I didn't have to do another problem. That was one of the happiest days in my life.

Weinberger with PhD student Roger Lui and John Osborn at the conference celebrating Hans's 80th birthday in October 2008.

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Hans had a profound influence on my professional life, especially the way I do mathematics. I tend not to work in one area of mathematics for a long time, and I try to adopt his style of writing, always very clear and enjoyable to read. Hans often looked at a problem and saw what the key point was; I try to do that also.

Willard Miller Jr.

Hans Weinberger was a pillar of support and leadership for the Minnesota School of Mathematics. He is my model for how one should live as a mathematician. He was a brilliant researcher, well known for his work on the maximum principle for partial differential equations, and a dedicated teacher with very high standards, but also dedicated to service and leadership for the department and to the profession. He had the unique ability to engage profitably with everyone, not just academics. Privately, he was very modest.

Hans had a great reputation among researchers in the engineering departments at Minnesota for his ability to interact with their faculty and students on their problems. For many years the course based on his textbook *A First Course in Partial Differential Equations* was required for undergraduates in the department of chemical engineering.

At the 30th anniversary celebration of the IMA in July 2012, from right to left: Weinberger (first director), Avner Friedman (second director), Willard Miller (cofounder), Douglas Arnold, and Fadil Santosa.

My first close interaction with Hans occurred in 1978. I was newly appointed as department head, and George Sell had just returned to the school after a year as rotator in the math division of the National Science Foundation, with the news that the division was about to announce a national competition for a mathematics institute. We decided to prepare a proposal for an applied mathematics-oriented institute at Minnesota, based on the strong research connections between our department, the engineering departments, and industry in the Twin Cities area. However, we needed a leader to assume the duties as director. We approached all of the leading researchers in the department but were turned down by everyone, except Hans. Most of those we contacted considered the task of preparing a proposal too time consuming with little chance of success. Hans agreed, for the good of the school. He had the vision to refine our idea of an applied mathematics institute to that of an institute on the interface between mathematics, the other sciences, engineering, and industry, where mathematicians would interact with researchers from these other disciplines to solve mutual problems. All fields of mathematics would be involved, not just traditional applied mathematics, but the emphasis would be on the outreach of mathematics to attack problems in other fields. Hans took the leadership to write these critical parts of our proposal and his vision and reputation carried the day. Ultimately, our proposal was accepted and the Institute for Mathematics and its Applications (IMA) was born with Hans as its founding director, 1982–1987, and George as associate director. It continues to this day, with many successes. The task of creating an institute from scratch was very demanding and lots of teamwork was involved, with difficulties to be overcome along the way and many stops and starts. Once I said that we were like the Three Musketeers. George said, no, that we were more like the Three Amigos.

Catherine Weinberger, Sylvia Weinberger Hewitt, and Ralph Weinberger

Our father's description of how he became a mathematician was simple: "I was a physics major, but I kept breaking things." His public biography explains that he was a finalist in the Westinghouse Science Talent Search, which led to a college scholarship, and that he completed his doctorate at a young age. But it does not clarify that he never mentioned this personal history to his own children. We only learned these details from his mother after we were grown. When queried, his explanation for his young graduation age was that most of the college-aged men were away at war, so the colleges were recruiting promising sixteen- and seventeen-year-olds and running straight through the summer to train more scientists as quickly as possible. While we were growing up, all we knew was that Dad was a mathematician, as were most of his friends.

Our childhood family life was very different from the never-ending workweek now common among scientists. Although Mom would often observe that Dad was still working in his head, he came home at 6, and he was completely a family man during the evenings and weekends. Nearly every day we would all five sit down to dinner, lovingly prepared by our mother and reliably served at 6:15 pm. Dad used this family time to teach us table manners and to show us that our experiences and opinions mattered. We would share conversation and laughter, then clear the table and do something relaxing together as a family: watch TV, do jigsaw puzzles, or play board games. Dad would often keep us company while we practiced our

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Catherine Weinberger, Sylvia Weinberger Hewitt, and Ralph Weinberger are Hans Weinberger's children.

musical instruments. On weekends we usually went on outings to a park or lake for a picnic and a swim, sometimes with other mathematician families or kids from the neighborhood. In the winter a group of mathematicians would take all the kids to the skating rink on Sunday while the moms had some time off. We also remember the adults-only parties the mathematicians shared, with waves of laughter rolling upstairs after we had been put to bed. On a day-to-day basis, we kids did not really understand what the mathematicians did at work, other than scribble on napkins and notepads in a foreign language.

Hans with his wife Laura at the IMA in 2002 and with his children on a camping trip in 1973.

As we grew, summer vacations often involved travel to conferences, camping along the way once we were old enough to pitch tents and wash dishes. When we arrived, some of our friends and their parents would be there, too. As teenagers, the other kids stopped coming and we three siblings kept ourselves amused by challenging each other to try to get the Russian mathematicians to smile and practicing our mathematician impersonations. Ralph particularly remembers a joint conference of mathematicians and biologists in Heidelberg—shortly before the inception of the IMA—where the children were encouraged by Peter and Peggy Rejto to sit in on Dad's talk. In that talk, Dad broke a problem down to its simplest essentials and made mathematical points that even we teenagers could understand. Afterward, Don Aronson teased, "So, now you know." It seemed as if everywhere we went, from Berkeley, California, to Cortona, Italy, his mathematician friends were there, too. Three times, we accompanied him for a year away from Minnesota while he visited at NYU, the University of Arizona, and Stanford. But Minnesota remained his home, and his Minnesota colleagues were his extended family.

An unwavering proponent of public schools, he was appreciative of all forms of education. He often spoke about the industrial arts training he received soon after arriving in the US. He carried those lessons with him, building cabinets in the basement, replacing flooring and masonry, and fixing anything that needed repair including plumbing and electrical work, with his son as apprentice. When a bike needed attention, Dad was there to teach us how to fix it ourselves. Later, if a headlight went out while we were borrowing the car, we were expected to drive to the store, purchase a replacement, and figure out how to install it by reading the instructions on the box. His expectations of independence and self-sufficiency began early in our lives, and served us all well.

Our dad built a lot of things in his life, but the most enduring was his family. His world revolved around our mother, his life partner and soul mate. His children, grandchildren, great-grandchild, and in-laws will always savor the memory of his welcoming embrace.

When we were in our late twenties and early thirties, our mother used to wonder what dad would do when he retired, because he had no "hobbies." She could see how much he enjoyed spending time with his young grandchildren but thought he would need something else to help fill his retirement days. In fact, mathematics would continue to fill his mind, notepads, computer, and (with technical assistance from a graduate student grandchild) his account on a Cloud-based platform, until his very last days.

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Photo of Weinberger family camping courtesy of Laura Weinberger.

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