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GENE H. GOLUB BIOGRAPHY

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The Early Years, 1932–1953

Gene Howard Golub was born on February 29th, 1932 to Bernice and Nathan Golub. His mother was from Latvia and his father from Ukraine. They both came to the United States independently of one another in 1923, and both settled in Chicago for family reasons: they each had an older sibling in the city.

Gene was born in the depth of the Great Depression. He has one brother, Alvin, who is three years older and currently lives in Chicago. Gene's father worked as a "bread man". His mother stayed home the first few years. At the age of $4\frac{1}{2}$ his mother needed to work so she took a job in a shop, sewing baseball caps, and Gene was admitted to kindergarten and spent $1\frac{1}{2}$ years there. Quite a solid kindergarten education! Gene was a student at the Haugan Elementary School for nine years. He skipped a grade, but makes a point of saying that he was not an exceptional student. At the age of 12 he started working at his cousin Sidney's pharmacy as a delivery boy, and later as a soda jerk. It was not unusual in those years for children to have to work, although he started working a little earlier than his other friends. At that point, says Gene, he was sure he was headed in the pharmacy direction. Little did he know...

Gene had a fairly well developed Jewish identity as a child. He went to Hebrew school ("Heder") from 3:15pm to 5:30pm almost every day. He learned the Hebrew alphabet and a few things about Jewish culture. His parents were very Jewish-centric. They were not religious and did not keep kosher, but Jewish holidays were observed. Gene would not go to school on Rosh Hashana and Yom Kippur, and special holiday events like the Seder, the Passover dinner, were celebrated every year. Gene's mother, whose maiden name was Gelman, had a large family in Chicago, and there were many get-togethers which kept the family close.

Gene had his Bar Mitzvah in February 1945. He did not have a sense of what was going on immediately after the war in Europe, although later on, as an adult, the holocaust greatly influenced him, his view of the world, and his personal identity. But at the age of 13, life just went on. He attended the Theodore Roosevelt High School from 1945 to 1949. The school had quite a rigid course program, without much in the way of extra-curricular activities. Three years of mathematics included algebra and geometry but no calculus. Gene remembers this period as an unremarkable one. He just "went along" as a student. He played baseball, basketball, and football but was not passionate about them.

During Gene's high school period his mother and father divorced, and after the divorce Gene saw his father only a couple of times. In December 1948 his father died, a year after the divorce. Gene continued to work in the pharmacy, and also had a job at a large department store. Following high school, he attended a community college for two years: Wright Junior College. Gene fondly remembers this period in his life. He took a variety of courses and was pretty happy. He wanted to be a chemist; and he loved political science. Then came analytic geometry and calculus, and the fun began! The teachers were good, and he made some good friends. After the two years passed he decided to go to the University of Chicago. He was admitted as a junior, and worked on a degree in mathematics. It was a big change, and an hour and a half of commuting each way did not make it easier. It was then that Gene decided to go to the University of Illinois in Urbana-Champaign for his final undergraduate year: a life-changing decision.

The University of Illinois, 1953–1959

Gene enjoyed the school, and living in a small town. He took the usual required courses such as biology and French, along with a few other courses that changed his life. Among those, one was a course on matrix theory from Franz Hohn, a very good teacher and kind man. In his first year as a graduate student, Gene took a course from the famous statistician C.R. Rao, who was at Illinois for a year. It was an advanced course in multivariate statistics, but in fact Gene learned in that course more about matrices than about statistics. Block Gaussian elimination and other matrix algorithms were introduced, and the course helped Gene gain a knowledge of matrix manipulations.

Gene had a part-time job working for a physicist at the accelerator center. In the final semester he took a programming course in the mathematics department, and learned how to program for the ILLIAC. Professor John Nash offered him a position as an assistant at the computing lab. It was 1953 and times were a little different than today: not everything revolved around computing.

Gene's first task was to program Milne's method. Given the primitive computing environment, it was hard! And given the method's weak stability properties, the program Gene had written was not used extensively later on. Gene went on to write a lot of statistical applications. This included a variety of matrix algorithms, and he became very familiar with the library and started feeling very comfortable around matrices. Many of the computer programs were in "half precision" arithmetic: 20 bits, and 1,024 words of memory.

Gene remembers very fondly his days at the University of Illinois and the many friendships formed. Several of the people he met, such as Bill Gear who was also a student at the same time and ended up having the same PhD advisor as Gene, became lifelong friends. People were sociable, cultured, and liked music and books. There were superb people around in terms of academic ability: David Wheeler from Cambridge (the inventor of the subroutine) came from the UK and developed the basic libraries. Gene in fact never took a course in numerical

analysis per se, but studied a great deal from the elegant programs of Wheeler simply by looking at the code and trying to understand it. Stanley Gill of the famed Runge–Kutta–Gill method then came. David Muller was a faculty member of the computing lab, and his method for solving nonlinear equations was very well known and a source of interest. In addition, Gene met Charles Wrigley, who was born in New Zealand and received his PhD in London. Wrigley was a psychometrician who was tremendously interested in computing and taught Gene about factor analysis. Through Wrigley Gene met Harry Harman, Louis Guttman, and many other distinguished psychometricians. It was a stimulating environment.

Gene was going to study statistics, but it was initially unclear under whose supervision. Bill Madow, whom he was considering, was on sabbatical, and Rao was around for a year but then left. Madow came back from California (where he had his sabbatical), but he eventually decided to go back to California. Abe Taub took Gene as a student. He was an applied mathematician, and had a close connection with John von Neumann. He gave Gene a paper written by von Neumann and others, about the use of Chebyshev polynomials in solving linear systems. As it turned out later, that paper had a decisive effect on Gene's research direction. So, even though he was working on a degree with a specialty in statistics, he ended up doing numerical analysis.

Gene's relationship with Taub was complex, but clearly Taub's influence on the direction Gene's career took was instrumental. Gene got financial support, attended conferences, and worked in the summers in various places. In summer 1955 he worked at the RAND corporation in California. He met George Dantzig and worked on the simplex method. Many other prominent people were around: Ken Arrow, Richard Bellman, David Blackwell, Herbert Scarf, and so on. The following summer he went to work for TRW in Los Angeles. His boss there was David Young, and George Forsythe as well as other prominent numerical analysts were around.

For his "6th" birthday in 1956 Gene had a special surprise: a few of his friends bought him a 1940 Chrysler with automatic transmission. We will reveal here that they paid the whopping amount of $50 for the car. Gene learned to drive and in summer 1956, while in California, he bought a Plymouth and drove it back to Illinois. In summer 1957 he worked at Bell Labs in New Jersey.

During his work on his thesis, Gene programmed the Chebyshev method and noticed that one of the parameters was converging, and then discovered it converged to the SOR parameter. The work of James Riley, whom he had met at TRW and who showed how the Richardson second order method was related to SOR, was helpful for Gene in simplifying the Chebyshev method for matrices with Property A.

Interestingly, while working on his thesis, Gene noticed that red/black ordering applied to a tridiagonal matrix had the property that the reduction leaves you with a tridiagonal matrix. It never appeared in his thesis. But it was an important idea which also prepared him for his singular value decomposition (SVD) work and the Fast Poisson Solver.

In 1959 Gene's advisor, Taub, invited Richard Varga to visit Illinois. Varga was a rising star, and when Gene talks about this he laughs and says that he

suspects that Taub invited Varga to check him out! Gene and Varga discovered that they were working on similar things and Varga invited him to write a paper together. Collaboration started later on that year when the two met in Paris at a meeting. This led to what later turned out to be the first influential and major paper in Gene's career.

After the PhD, 1959–1962

Towards the end of his PhD studies, Gene applied for fellowships. He was awarded an NSF fellowship, and decided to go to Cambridge, England. He was at Cambridge for 15 months, from the spring of 1959 until July 1960. He renewed his acquaintance with Velvel Kahan who was also there as a postdoc. They were in a small office together for a while. It was a very nice experience: a period of "chilling out" after an intense term at Illinois. Velvel had a car and they drove around. They would often go to the National Physical Laboratory in London, where Jim Wilkinson was. One of the lectures was given by Cornelius Lanczos. It was there when Gene took note of the singular value decomposition. He may have heard about it earlier, but Lanczos was a great lecturer, and it stuck into Gene's head that you could use this decomposition. A few years later, the memory of this lecture would play a pivotal role in Gene's seminal work on computing the SVD.

While at Cambridge, Jim Snyder (a physicist who later became the head of the Computer Science Department at Illinois) mentioned that he was consulting at Berkeley and asked if Gene wanted to apply to the Berkeley National Laboratory. Gene did. He returned to the USA, bought a new car and drove off to Berkeley, to start his job in July 1960. It was a data analysis type of job, and Gene did not like it. But he did meet Paul Concus, and that began a long friendship and a collaboration. In December 1960, Gene decided to quit his job. In January 1961 he went down to Los Angeles to work again for TRW, which had become STL: Space Technology Laboratories. There were approximately a dozen mathematicians around, and consultants from Berkeley, UCLA, and other places were coming and going. But despite enjoying his job, Gene felt that he wanted eventually to be in a university.

The Stanford Years, 1962–

In the spring of 1962, STL sent Gene to a few places for recruiting. He went to Michigan, Wisconsin, Case, and in each of these places he himself was offered a job! In the meantime, he wrote to Forsythe and inquired about a position at Stanford. Forsythe wrote back, offering either a visiting assistant professorship, or a research associate position. Gene never received the letter. At some point Forsythe called him, to ask if Gene had the habit of answering his mail. Gene took on the visiting assistant professor position and started in the math department at Stanford in August 1962. Later on, Forsythe converted his position into a permanent one.

Gene fondly remembers the early years at Stanford: Forsythe was a magnet to other people, and there was an influx of visitors. Forsythe had wonderful students: Cleve Moler, James Ortega, Beresford Parlett, Jim Varah, and others. As Forsythe took on more administrative responsibilities, Gene took a lot of his responsibilities in the numerical analysis area. Gene acknowledges how much he learned from Forsythe about how to run things at a place like Stanford and how to aspire to be a good colleague and member in the community. Unfortunately, Forsythe died in 1972, after 15 years at Stanford. Gene describes Forsythe as an early founder of the numerical analysis community and praises his vision, wisdom and integrity.

The first years at Stanford marked Gene's rise to prominence. Ideas and papers were generated, collaborations and friendships formed. Gene graciously gives much of the credit for his success to his collaborators, their abilities, their collegiality, and their friendship. He describes the great work of Forsythe in forming the Computer Science Department of Stanford in 1966 (from the Computer Science Division of the Mathematics Department): Stanford was one of the first places to form such a department. People like John Herriot, John McCarthy and Donald Knuth came early on. Visitors like Jim Wilkinson, Peter Henrici, Germund Dahlquist and many others would come often, made life interesting and formed collaborations.

Gene went on to have a remarkable career. In three separate interviews and several hours of face to face and phone conversations, he vividly recalled many milestones. The success of his work on semi-iterative methods with Varga in the early 1960s, the computation of the SVD with Kahan in the mid-1960s and the fast Poisson solver in the early 1970s, followed with several milestone papers that have made an impact not only on the field of numerical linear algebra but on the broad areas of science and engineering in a variety of disciplines. His work on the preconditioned conjugate gradient method in the late 1970s (joint work with Paul Concus and Dianne O'Leary) helped popularize the method among large circles of scientists and practitioners. He put the total least squares problem on the map (joint work with Charlie Van Loan, after introducing the problem earlier in his work with Christian Reinsch). He worked on moments and quadrature rules with a variety of collaborators, work of great mathematical beauty. One of his latest contributions is his work on Google's PageRank algorithm; a technique for accelerating the convergence of the algorithm (joint work with Sep Kamvar, Taher Haveliwala and Christopher Manning) has received much attention.

The Birth of Papers

Gene has many anecdotes to offer on how some of his strongest papers came to life, and makes interesting connections that illustrate how some of his most important work started almost accidentally, just by way of paying attention to a comment, or resurrecting ideas that he had earlier in a different context.

An intriguing story is how the project on the computation of SVD came to life. We mentioned earlier that while in England Gene heard Lanczos speak on the SVD and kept it at a corner of his mind. Much later, in 1963, Ben Rosen talked at Stanford about computing pseudo-inverses via projections. At the end of the talk Forsythe got up and said, "Well, will somebody please figure out how to compute the pseudo-inverse of a matrix?!" Gene remembered Lanczos's lecture in this context. And it got him interested in the SVD. The combination of having heard Lanczos years earlier, and those stirring words, *marching orders*, by Forsythe, began an important component of Gene's career. He worked with Peter Businger, who was a research assistant, and he asked Peter to compute the eigenvalues of

$$\begin{bmatrix} 0 & A \\ A^T & 0 \end{bmatrix}.$$

The absolute values of the eigenvalues of this matrix are indeed the singular values of A. Peter put that into an eigenvalue routine and they saw zeros on the diagonal of the tridiagonal matrix that was generated. From studying David Young's work on Property A and from his own work on cyclic reduction Gene knew that one could reorder the matrix, and get a bidiagonal matrix. So Gene started thinking hard about ways to bidiagonalize the matrix, and figured out how to do it using left and right orthogonal transformations, while he visited Boeing in Seattle in the summer of 1963. Perhaps the fresh Pacific Northwest air helped with it.

In October 1963 there was a meeting at the University of Wisconsin. Gene saw Kahan and told him about the work he had been doing. Kahan was working on similar ideas, and they decided to collaborate. Kahan came to visit Stanford with Forsythe's support, and the famous Golub and Kahan paper was written.

Computing the singular values of a bidiagonal matrix efficiently came a little later. Gene thought that Householder transformations could do the trick. He and Christian Reinsch worked on this problem independently around the same time, and eventually an algorithm using QR with double shifts was published under joint authorship. In their paper the total least squares problem was also introduced. (The catchy name was given to it much later, by Charlie Van Loan.)

Years after the seminal work on the SVD, Paul Van Dooren was at Stanford and was scheduled to give a talk. In the audience were Wilkinson, Dahlquist, and Gene. At some point during the talk Paul asked, a little nervously: "Do you know what the SVD is?" The immediate answer came: "You are at the SVD Headquarters!" Nick Trefethen later designed a T-shirt with "SVD HQ" written on it.

The story of how the Fast Poisson Solver was born is also fascinating. Roger Hockney came as a research fellow to Stanford. He was working for Forsythe and the plasma physicist and engineer Oscar Buneman. He told Gene about the problems he was working on, that required solving a sequence of tridiagonal matrices. Gene remembered his playing with cyclic reduction as a graduate student. It was possible to apply cyclic reduction to a tridiagonal matrix, to get another tridiagonal matrix. Gene and Hockney realized that in fact a block

version could be derived, as long as the blocks commute. Hockney programmed it but it seemed unstable if more than one step of cyclic reduction was carried out. Later on, Buneman gave a talk at Los Alamos and showed how to form the full procedure of cyclic reduction. He provided a two-page long program for doing it. This caused excitement. When Gene visited a little later, he and Buzbee were discussing it, when Clair Nielson came in and said he would like to use the method, but with different boundary conditions. This forced the three to sit down and deeply understand the method. Nielson came up with a way to solve the resulting difference equations. Later on, Alan George was very helpful and showed how to modify the right-hand side so that the method is stable. The paper of Buzbee, Golub and Nielson was at one point the most cited mathematics paper in the *SIAM Journal on Numerical Analysis*.

Buzbee, Dorr, George, and Golub went on to write their well-known paper on applying the solver to irregular domains. A package called FISHPACK, based on these ideas, was written by Paul Schwarztrauber and Roland Sweet. (Why "FISHPACK"? Translating the word "Poisson" from French might shed light on this mystery!)

The above mentioned work, along with an earlier paper of Gene with David Mayers at a conference in INRIA, have been an important part of the early advances of domain decomposition, and embedding techniques (fictitious domains). The rise of parallel computing at the time, and the attractive concept of subdividing a complex domain into simple subdomains, caught on thanks to work of Gene and many other people who played a pivotal role, such as Olof Widlund.

Another important work that followed was Gene's joint work with Concus and O'Leary on the preconditioned conjugate gradient (CG) method. In an earlier paper, Gene and Concus used the Chebyshev method for solving the Poisson equation as a means to solve the Helmholtz equation on a rectangular domain. Paul, Gene and Dianne presented the idea of using CG in its preconditioned version, and derived an elegant short algorithm that worked extremely well. In their paper the term "generalized CG" is actually used. The term "preconditioned CG" caught on later.

The Fast Poisson Solver and what followed it is a nice example of the serendipity of science: you never know where your research may take you. This work made a contribution to advances in domain decomposition techniques and in preconditioned iterative solvers, merely due to the need to find ways to overcome difficulties that arose in applying the solver, either due to a complicated computational domain, or due to a difficult underlying partial differential equation.

Finally, we mention the "accidental birth" of the work on moments and quadrature. Gene spent a year in 1965–66 at the Courant Institute. He arrived there shortly after meeting Dahlquist in Sweden and learning from him about the topic. Interestingly, a talk of Hans Weinberger given at Maryland that Gene had missed (and heard about from colleagues) about error bounds using residuals, stimulated his interest in error estimates, and he thought of ways to put it in the framework of moments. One day, he was sitting in Peter Lax's

office. His mind started wandering. He picked up a book of Herbert Wilf, and started reading the section about Gaussian Quadrature. It was then and there that Gene realized that the weights were the squares of the first elements of the eigenvectors of the Jacobi matrix, obtained from orthogonal polynomials. (The eigenvalues were the nodes.) These mathematical facts may have been known to some experts, but Gene figured out how to do the computation: compute the weights by reorganizing the QR method. When recalling this story, Gene smiles and says that sometimes being "semibored" is all that it takes to make a discovery...

Service and the Book

Gene has a tremendous record of service to the scientific computing community. He served as President of SIAM, and played a central role in forming the International Council for Industrial and Applied Mathematics. He is the founding editor of two important SIAM journals – *SIAM Journal on Scientific Computing* and *SIAM Journal on Matrix Analysis* and *Applications*, and has been on a large number of advisory boards and committees. It's hard to imagine the community without the journals he founded, but their formation was not trivial and came after careful thought, taking into account the nature of existing journals in the field. Gene mentions a few little-known anecdotes. For example, he was influenced by Bellman when making the choice "matrix analysis." We should also mention that Gene founded the NA-NET and the NA-Digest, indispensable working and networking tools for many in the community for years to come.

Gene's devotion to his community has been demonstrated many times throughout the years in terms of time, energy and financial support. For his work on acceleration of the PageRank algorithm Gene received Google stock; he donated most of these funds to found the Paul and Cindy Saylor Chair at the University of Illinois. Gene says his gift is a way for him to acknowledge the important part that the university played in his life, and at the same time it was an opportunity to give tribute to Paul and Cindy for being such supportive friends that do so much for the academic community. Previous to this, Gene funded the Hohn/Nash student fellowship at the University of Illinois to honor two of his early mentors.

And how did the Golub and Van Loan book come about? Roger Horn was the founder of the Department of Mathematical Sciences at Johns Hopkins. In cooperation with Johns Hopkins Press, he held a series of short courses each documented in a monograph. He had invited Gene to teach one of these courses. Charlie Van Loan was there. They decided to try to write a monograph. As the book was being written, they wrote several papers together. The book now has three editions, has sold over 50,000 copies and has been cited over 10,000 times. According to Gene, Charlie Van Loan was the principal writer of the book and the force behind it, and Gene remembers the period of working with Van Loan on the book as a wonderful one.

People

When asked what has defined his career, Gene does not point out this or that paper, but rather he talks about people. He praises his students and says they have made him a better person. He admires their personalities, behavior, scholarship, and integrity, and says he feels fortunate to have met many of them. He attributes his hospitality and the endless number of parties he hosted at his home and back yard to the welcoming and open culture he had experienced at Illinois as a graduate student decades earlier. He also says that part of his success has to do with geography: people like coming to Stanford, they like the climate and the food and all the small pleasures that the area offers, and as a result the traffic of visitors has never stopped for over 40 years. There has been a lot of collaboration and a lot of scientific matchmaking at Stanford.

Gene has many anecdotes about his interaction with his colleagues and his students. Some of them are not necessarily related to inverting a matrix or computing eigenvalues but have made a great impact on Gene's life. Take email, for example. As the Computer Science Department grew, the numerical analysis group moved to the ground floor of Serra House, a building that had served as the home of the University President. The terminals were in the kitchen. "The person who shamed me into using email was Dan Boley," recalls Gene with a laugh. He came by and said "You are the only professor in the department who doesn't use email actively." Gene smiles and says that this statement was slightly exaggerated, but the seed was planted and there was no way back. Email became a big part of Gene's life.

Many of the first students who took Gene's courses are now very familiar names and great forces in the numerical community: Richard Bartels, Richard Brent, Jim Daniel, Alan George, Roger Horn, Victor Pereyra, Michael Saunders, Jim Varah, Margaret Wright, and others. He gives them credit for forcing him to "dot the i's and cross the t's" when he taught his first advanced numerical analysis course: this later helped in setting the stage for the Golub and Van Loan book.

Gene was married for a few years in the 1990s to Barbara Morris, whom he had met in England approximately 40 years earlier. His brother lives in Chicago (with a convenient escape route to Phoenix when winter hits). Most of Gene's waking hours in the last 50 or so years have been devoted to being with members of his extended family of the numerical linear algebra community.

Conclusion

This book's theme is about the impact that Gene's work has made in our field. Many more pages would be necessary to describe in full Gene's contributions. He has written many excellent papers, has become a member of the National Academy of Sciences and the National Academy of Engineers, founded *SIAM Journal on Scientific Computing* and *SIAM Journal on Matrix Analysis and*

Applications, was President of SIAM, founded the Scientific Computation and Computational Mathematics Program at Stanford, and has received ten honorary doctorates. But beyond all his honors, what makes Gene special is his dedication and his commitment to promoting numerical analysis and scientific computing, and his great support of young people.

In the last few years Gene has traveled a lot, being in many ways an ambassador of our community. We cherish the impact that Gene has had on our careers in so many ways: by hearing him give a talk that has made an impact in terms of selecting a research direction (or even a research career!), by accepting Gene's cordial invitation to visit at Stanford and experiencing that feeling of being at the "headquarters", or by meeting via Gene a colleague who has later become an important collaborator.

It is appropriate to close by going back to the roots: the "founding fathers" of numerical linear algebra. Gene has a lot of kind words to say about them. He singles out two seminal figures: Wilkinson and Householder. In particular, he takes time to talk about the role Jim Wilkinson had played. Wilkinson laid the foundations for pure numerical linear algebra, says Gene. He extracted the basic numerical problems and showed how to construct good numerical algorithms. Gene always felt that his own area of interest was in applied numerical linear algebra and that he was trying to take the lessons taught by Wilkinson and use them in different applications. That would include, for example, working out the stabilized version of the LU factorization for use in the simplex method (joint work with Richard Bartels). This work showed that one can get a reliable solution, and it is based on principles worked out by Wilkinson. "I see myself as an *applied Wilkinsonian*," says Gene. "Wilkinson is the one who really led the way for many in terms of error analysis, and by pointing out the important issues in matrix computations."

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