George Forsythe and the Development of Computer Science

by Donald E. Knuth

The sudden death of George Forsythe this spring was a serious loss to everyone associated with computing. When we recall the many things he contributed to the field during his lifetime, we consider ourselves fortunate that computer science has had such an able leader.

My purpose in this article is to review George Forsythe's contributions to the establishment of Computer Science as a recognized discipline. It is generally agreed that he, more than any other man, is responsible for the rapid development of computer science in the world's colleges and universities. His foresight, combined with his untiring efforts to spread the gospel of computing, have had a significant and lasting impact; one might almost regard him as the Martin Luther of the Computer Reformation!

Since George's publications express these ideas so well, I believe the best way to summarize his work is to repeat many of the things he said, in his own words. This article consists mainly of the quotations that particularly struck me as I reread his papers recently. Indeed, much of what follows belongs in a computer-science supplement to Bartlett's *Familiar Quotations.*

From Numerical Analysis to Computer Science

George's early training and research in numerical analysis was a good blend of theory and practice:

> The fact that the CPC was generally wrong when I knew the answer made me wonder what it was like for someone who didn't know what to expect. [76, p. 5]

Starting in 1948 he worked for the National Bureau of Standards' Institute for Numerical Analysis in Los Angeles, California, where he did extensive programming for the SWAC computer. In 1954 this Institute became part of U.C.L.A., and he put a great deal of energy into the teaching of mathematics and numerical analysis. He also worked on nonnumerical problems, such as the tabulation of all possible semigroups on four elements; at this time, he considered such combinatorial algorithms to be a part of numerical analysis [46, p. 7], and he regarded automatic programming as another branch [49, p. 655]. He began to foresee the less obvious implications of programming:

> The use of practically any computing technique itself raises a number of mathematical problems. There is thus a very considerable impact of computation on mathematics itself, and this may be expected to influence mathematical research to an increasing degree. [46, p. 5]

> The automatic computer really forces that precision of thinking which is alleged to be a product of any study of mathematics. [49, p. 655]

He also noticed that the rise of computers was being accompanied by an unprecedented demand for young mathematicians:

> The majority of our undergraduate mathematics majors are lured at once into the marketplace, where they are greatly in demand as servants of the fast-multiplying family of fast-multiplying computers. [49, p. 651]

Therefore he began to argue that computers should play a prominent role in undergraduate mathematics education. At this time he felt that only one new course was needed for undergraduates, namely an introduction to programming; he stressed that the best way to teach it would be to combine computer programming with the traditional courses, instead of having separate training in numerical analysis. His paper "The Role of Numerical Analysis in an Undergraduate Program" [49] suggests over 50 good ways to mix computing into other courses; these suggestions ought to be required reading for all teachers today, since they are now perhaps even more relevant than they were in 1959. Indeed, the adaptation of traditional courses has been painfully slow (probably because professors of the older generation have not wanted to dirty their hands with the newfangled machines); in 1970 Forsythe was still strongly urging mathematics teachers to bend a little:

> Compared with most undergraduate subjects, mathematics courses

> are very easy to prepare for, because they change so slowly. The computing part of it is probably the only part that changes much. Why not devote time to learning that? [80, p. 23]

In 1961 we find him using the term "computer science" for the first time in his writing:

> [Computers] are developing so rapidly that even computer scientists cannot keep up with them. It must be bewildering to most mathematicians and engineers...In spite of the diversity of the applications, the methods of attacking the difficult problems with computers show a great unity, and the name of Computer Sciences is being attached to the discipline as it emerges. It must be understood, however, that this is still a young field whose structure is still nebulous. The student will find a great many more problems than answers. [59, p. 177]

He identified the "computer sciences" as the theory of programming, numerical analysis, data processing, and the design of computer systems, and observed that the latter three were better understood than the theory of programming, and more available in courses.

The Establishment of Computer Science

By that time Forsythe knew that numerical analysis was destined to be only a part of the computing milieu; a new discipline was crystallizing which cried out to be taught. He had come to Stanford as a professor of mathematics in 1957, but now he and Professor John Herriot wanted to hire colleagues interested in programming, artificial intelligence, and such topics, which are not considered mathematics. Stanford's administration, especially Dean Bowker (who is now Chancellor at Berkeley), also became convinced that computing is important; so George was able to found the Division of Computer Science within the Mathematics Department in 1961.

During that academic year he lectured on "Educational Implications of the Computer Revolution" at Brown University:

> "Machine-held strings of binary digits can simulate a great many *kinds* of things, of which numbers are just one kind. For example, they can simulate automobiles on a freeway, chess pieces, electrons in a box, musical notes, Russian words, patterns on a paper, human cells, colors, electrical circuits, and so on. To think of a computer as made up essentially of numbers is simply a carry-over from the successful use of mathematical analysis in studying models...Enough is known already of the diverse applications of computing for us to recognize the birth of a coherent body of technique, which I call *computer science*...Whether computers are used for engineering design, medical data processing, composing music, or other purposes, the structure of computing is much the same. We are extremely short of talented people in this field, and so we need departments, curricula, and research and degree programs in computer science...I think of the Computer Science Department as eventually including experts in Programming, Numerical Analysis, Automata Theory, Data Processing, Business Games, Adaptive Systems, Information Theory, Information Retrieval, Recursive Function Theory, Computer Linguistics, etc., as these fields emerge in structure...Universities must respond [to the computer revolution] with far-reaching changes in the educational structure. [60]

At this time there were comparatively few graduate computer science programs available in American colleges; and they had other names, like Systems and Communication Sciences (Carnegie), Computer and Information Sciences (University of Pennsylvania), Communication Science (University of Michigan). Forsythe did not invent the term "computer science," which had gradually been working its way into the English language, but his influence was an important factor in the present widespread acceptance of the term.

A brief digression into the history of computer science education seems appropriate at this point. Apparently computing courses got started in universities largely because IBM donated about 100 "free" computers during the 1950s, with the stipulation that programming courses must be taught. This strategy made it possible for computing to get its foot in the academic door. Naturally there were many students and a few members of the faculty who were intrigued and became involved. Engineering departments, especially at schools like M.I.T., Pennsylvania, and Illinois, where computers were being built, also had a head start. Many ideas were exchanged during special summer school sessions at the University of Michigan, and later the Ford Foundation sponsored a project there on the use of computers in engineering education. A good survey of these developments has been given by Howard E. Tompkins in *Advances in Computers Vol. 4,* Academic Press, New York, 1963, pp. 135–168.

But these early stages hardly represented computer science as it is understood today, nor did many people regard it as the germ of a genuine discipline worthy of study on a par with other subjects. I myself was a graduate student in mathematics who enjoyed programming as a hobby; I had written two compilers, but I had no idea that I would someday be teaching about data structures and relating all this to mathematics. A few people, like George Forsythe and Alan Perlis and Richard Hamming, had no such mental blocks. Louis Fein had also perceived the eventual rise of computer science; he had recommended in 1957 that Stanford establish a Graduate School of Computer Science, analogous to the Harvard Business School. (cf. reference [B] below.)

George argued the case for computer science long and loud, and he won; at Stanford he was in fact "the producer and director, author, scene designer, and casting manager of this hit show." [A] Several more faculty members were carefully selected, and the Division became a separate academic department in January 1965.

Since this was one of the first such departments, it naturally came under very close scrutiny. Now we realize that eventually every university will have such a department. Although this development is inevitable in the long run, it will happen sooner than might be expected largely because George was such an effective spokesman, especially to mathematicians and to people in the government.

Here are some important points he has made, in addition to those quoted earlier:

> The most valuable acquisitions in a scientific or technical education are the general-purpose mental tools which remain serviceable for a lifetime. I rate natural language and mathematics as the most important of these tools, and computer science as a third... The learning of mathematics and computer science together has pedagogical advantages, for the basic concepts of each reinforce the learning of the other. [71, p. 456–457]

> The question "What can be automated?" is one of the most inspir-

> ing philosophical and practical questions of contemporary civilization. [75, p. 92]

The last sentence is taken from the introduction to an invited address on Computer Science and Education at the IFIP Congress 1968; I wish I could quote the entire article.

Forsythe frequently stressed the value of *experimental* computer science, as well as the theoretical:

> To a modern mathematician, design seems to be a second-rate intellectual activity. But in the most mathematical of the sciences, physics, the role of design is highly appreciated...If experimental work can win half the laurels in physics, then good experimental work in computer science must be rated very high indeed. [68, p. 4]

Intense Activity

The primary reason George's views have been so influential is that he continually poured so much energy into all aspects of his work. One way to illustrate this is to focus on a randomly-selected period of his life and to look more deeply into his daily activity; therefore I studied his correspondence file for the months of January and February 1964.

At this time his Division of Computer Science contained two faculty members besides himself (John Herriot and John McCarthy), plus two young "visiting assistant professors" for whom regular appointments were being arranged (Gene Golub and Niklaus Wirth), and an instructor (Harold Van Zoeren). As the correspondence shows he was actively trying to build up the faculty, and I suspect that every computer scientist in America was approached at least twice during the early 1960s with a potential offer of employment at Stanford! George was also the director of Stanford's Computation Center, and a member of several national advisory panels and committees. In addition, he had just been appointed editor of the Algorithms section of *Communications*.

During this two-month period he wrote a total of 195 letters, which may be grouped as follows:

1. Recruiting faculty, 48 letters (including two addressed to me).
2. Algorithms section, editorial work, 43 letters.
3. Recommendations of policy to outside groups, 36 letters.
4. Departmental correspondence with graduate students, 35 letters.
5. Research interests, 11 letters.
6. Miscellaneous, 22 letters.

Many of these letters were two pages long; some were even longer.

Several letters described the current status of computer science at Stanford:

> We are a bit separate from the Mathematics Department, and have responsibility for courses in numerical analysis, programming, artificial intelligence, and any other areas of Computer Science which we can manage. [January 3, 1964]

> The role of the Computer Science Division is likely to be increasingly divergent from that of Mathematics. It is important to acquire people with strong mathematics backgrounds, who are nevertheless prepared to follow Computer Science into its new directions. [January 7, 1964]

> We have a master's degree program with about 40 graduate students, and a number of students headed for interdepartmental Ph.D.'s in Computer Science. [January 8, 1964]

One thing which enabled computer science to grow was that other universities could point to Stanford's example. Conversely, George was able to make use of other universities' activities; in a memo to the dean on January 30, he said:

> I enclose copies of two letters...which indicate in and between the lines that [the University of Wisconsin in] Madison is putting on a really major effort in Computer Science. They are even calling it Computer Science at last!

On June 5, having been elected president of the ACM, George wrote:

> Votes have strange outcomes in California. Goldwater and Forsythe.

By July 2, he was really feeling the increased responsibilities:

> The pile of undigested mail on my desk is staggering.

His two years as ACM President were in general a rather happy and prosperous time for that organization. He published regular letters to the members [65] in *Communications,* and these letters are worth rereading today because in them he discussed many of his own feelings, as well as ACM business. His letter in the March 1965 issue contains an excellent account of how he grappled with the problems of a new Computer Science Department:

> We must now turn our attention from the battle for recognition to the struggle to recognize the identity of our new discipline ...One of my personal concerns with our Computer Science Department is to assess the future of numerical analysis...The core of Computer Science has become and will remain a field of its own, concerned with the forefront of new ideas...I conclude that the computer and information sciences badly need an association of people to study them, improve them, and render them better understood and thus more useful.

But the intended introduction to his President's Letter for September 1965, had to be changed. He had written:

> I am delighted that you have voted to change our name to the *Association for Computing and Information Sciences*...I think it gives a much clearer picture of who we are and what we do.

A two-thirds majority was necessary for such a name change, and the actual vote was only 3794–2203. I must confess that I was one of the 2203 who opposed making a change; this was one of the few disagreements I ever had with George.

Algorithms

The major thing which distinguishes computer science from other disciplines is its emphasis on algorithms, and in this field George Forsythe made several vital contributions. He inaugurated a new area of scholarly work: refereeing and editing algorithms.

His point of view was nicely expressed in the "Forum on Algorithms" in *Communications,* April 1966:

> There are few problems for which a good algorithm of probable permanent value is known...Small details are of the greatest importance...The development of excellent algorithms requires a long time, from discovery of a basic idea to the perfection of the method...A useful algorithm is a substantial contribution to knowledge. Its publication constitutes an important piece of scholarship. [67]

He was fond of pointing out how much remains to be done, since even the solution to $ax^2+bx+c=0$ is at the frontier of well-understood problems:

> Hardly anyone knows how to solve even a quadratic equation on a computer without unnecessarily risking loss of precision or overflow or underflow! [68, p. 4]

As an indication of his behind-the-scenes activities, here are some more excerpts from letters he wrote during January and February 1964:

> The program is really in poor style, and I'm peeved with the referee for not saying so. You use a switch and a mass of **goto**'s where straightforward ALGOL would use conditional expressions. You even **goto** *"here"* from the line above *"here"*!! [January 8, 1964]
>
> I am sorry that refereeing increases the time between submittal and publication, but I am confident that the net result of refereeing will be a large gain in the quality of our algorithms. [January 13, 1964]
>
> It is very hard to find matching **begin**s and **end**s, which should be above each other or on the same line. [January 29, 1964]
>
> We are punching cards from the galleys and running them as a check. [February 24, 1964]
>
> I believe that our algorithms must have enough substantial content to save a programmer at least an hour's thought. [February 26, 1964]

At that time approximately 180 algorithms per year were being submitted to *Communications.*

George also contributed to ACM publications in other ways: In 1966 he became the first editor of the Education department of *Communications;* he had been an editor of the *Journal* from 1955 to 1959; and he was chairman of the Editorial Board from 1960 to 1962.

The Permanence of Computer Science

How did George view these developments from a historical perspective? He set down his long-range views in the following memorandum, written at Stanford in 1970 just after Edsger Dijkstra had visited our department and stimulated some thought-provoking discussions:

> My feeling since 1962 has been that, even if Computer Science should turn out to be fully developed and fairly static by 1985, it will have been very important for universities to have created Computer Science Departments in the years 1960–1970. For, given the departmental structure of universities (which I deplore), I don't see how universities could otherwise have got rolling on research in this area. And without this research, much of the quality of computer usage in universities would be frozen at the level of Early FORTRAN.
>
> I don't mean that I do in fact forecast an end to the development of computer science by 1985. Being the study of computers, Computer Science can't begin to settle down until years after the hardware developments level off. This is not yet in sight.
>
> However, Dijkstra did set me to thinking about how long Computer Science will last. It may be that its difficult applications (like robotry and problem solving) will move off into various other disciplines. And the difficult problems in the core of Computer Science may get merged into discrete mathematics, as mathematicians get interested in them.
>
> On the other hand, there is very little evidence at present that mathematicians are taking any interest at all in the important questions of the mathematical theory of computation. (Speed, optimality, data structures, storage requirements, proofs of correctness, etc., etc.) If they do not, then maybe these core computer scientists may absorb all of discrete mathematics themselves into a still unnamed discipline.
>
> Most of all, I'd like to see universities able to restructure themselves into task forces able to attack new disciplines as they arise. [April 14, 1970]

He also had made another prediction:

> In years to come we may expect a department of computer science to mix with departments of pure mathematics, operations research, statistics, applied mathematics, and so on, inside a school of mathematical sciences. We can hope for some weakening of the autonomy of individual departments, and a concomitant strengthening of the ability of a university to found and carry out interdisciplinary programs. [68, p. 6]

Conclusion

I have tried to summarize our debt to George Forsythe by quoting from the extensive writings in which he expressed important ideas so clearly. But this is only part of the story. The accompanying article by John Herriot describes the more personal side of George's life—his selfless assistance and counsel to his students and colleagues, and the real qualities of leadership for which we are especially grateful.

Since I am not competent to write about numerical analysis, I have not been able to describe George's respected contributions to research. A short summary of this aspect of his work is being prepared by A.S. Householder for publication in the *SIAM Journal on Numerical Analysis* later this year. George knew that he would have to sacrifice much of the time he wanted to spend on his main research interests, for the cause of Computer Science. He quipped:

> In the past 15 years many numerical analysts have progressed from being queer people in mathematics departments to being queer people in computer science departments! [71, p. 456]

Nevertheless he continued to stress the important connections between numerical analysis and the other aspects of computer science.

He was a Fellow of both the British Computer Society and the American Association for the Advancement of Science. He was a council member of the American Mathematical Society, 1960–63, and a Trustee of the Society for Industrial and Applied Mathematics, 1971–72.

A bibliography of his publications appears below. In addition to these works, he published many shorter book reviews, letters to the editor, etc. He was especially concerned about the need for good books on computer science, so he served as the editor of Prentice-Hall's prestigious Series in Automatic Computation, encompassing more than 75 titles. This is a "fifteen-foot-shelf" to be compared with the books he listed in [26].

He took notes at every lecture he attended and kept them in beautifully organized files. This material, together with his correspondence, has been deposited in the Stanford University archives for the use of future historians.

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79. The maximum and minimum of a positive definite quadratic polynomial on a sphere are convex functions of the radius. *SIAM J. Appl. Math. 19* (1970), 551–554.
80. Computer science and mathematics. *SIGCSE Bull. 2,* 4 (Sept.–Oct. 1970), 20–23.
81. Recent references on solving elliptic partial differential equations by finite differences or finite elements," *SIGNUM Newsletter, 6,* 1 (Jan. 1971), 99, 32–56.
82. Variational study of nonlinear spline curves (with E. H. Lee). To appear in *SIAM Review.*
83. von Neumann's comparison method for random sampling from the normal and other distributions. To appear in *Math. of Computation.*

Ph.D. Students

(A) Ph.D. in Mathematics with specialty in Numerical Analysis
(B) Interdepartmental Ph.D.
(C) Ph.D. in Computer Science

Eldon Hansen (Forsythe, 1960). On Jacobi methods and block-Jacobi methods for computing matrix eigenvalues. (A)

James Ortega (Forsythe, 1962). An error analysis of Householder's method for the symmetric eigenvalue problem. (A)

Betty Jane Stone (Forsythe, 1962). 1. Best possible ratios of certain matrix norms. 2. Lower bounds for the eigenvalues of a fixed membrane. (A)

Beresford Parlett (Forsythe, 1962). Applications of Laguerre's method to the matrix eigenvalue problem. (A)

Donald Fisher (Forsythe and Gilbarg, 1962). Calculation of subsonic cavities with sonic free streamlines. (A)

Ramon E. Moore (Forsythe and McGregor, 1963). Interval arithmetic and automatic error analysis in digital computing. (A)

Robert Causey (Forsythe, 1964). On closest normal matrices. (A)

Cleve B. Moler (Forsythe, 1965). Finite difference methods for the eigenvalues of Laplace's operator. (A)

James Daniel (Forsythe and Schiffer, 1965). The conjugate gradient method for linear and nonlinear operator equations. (A)

Donald W. Grace (Forsythe and Polya, 1965). Computer search for nonisomorphic convex polyhedra. (B)

James M. Varah (Forsythe, 1966). The computation of bounds for the invariant subspaces of a general matrix operator. (A)

Roger W. Hockney (Buneman, Forsythe, Golub, 1966). The computer simulation of anomalous plasma diffusion and the numerical solution of Poisson's equation. (B)

Paul Richman (Forsythe and Herriot, 1968). 1. ε-Calculus. 2. Transonic fluid flow and the approximation of the iterated integrals of a singular function. (C)

J. Alan George (Forsythe and Dorr, 1971). Computer implementation of the finite element method. (C)

Richard P. Brent (Forsythe, Dorr, and Moler, 1971). Algorithms for finding zeros and extrema of functions without calculating derivatives. (C)

David R. Stoutemyer (Forsythe, 1972). Numerical implementation of the Schwarz alternating procedure for elliptic partial differential equations. (C)

Student Paper Competition Awards

On the following pages are the winning papers in the first annual ACM Communications Student Paper Competition. We, the Student Editorial Committee, started work on this issue in January 1971, learning each step of the process as we went. The hardest part for us (other than waiting for the first entry to arrive) was making the final decision *not* to publish a given paper—each time we found ourselves delaying this decision, hoping to make it easier.

We are very pleased with the three winning papers; we hope that their depth and diversity will encourage the professional world to seek student participation, and inspire students to contribute their own ideas. In addition to the recognition received by having their papers published, the authors' awards are:

First place. "Generating Parsers for Affix Grammars" by David R. Crowe of the University of British Columbia. $250 cash, a trip to ACM 72 to receive the award in person, and a three-year subscription to the ACM serial publication of his choice.

Second place. "Political Redistricting by Computer" by Robert E. Helbig, Patrick K. Orr, and Robert R. Roediger of Washington University. $150 cash, and for each author a three-year subscription to the ACM serial publication of his choice.

Third place. "An Extensible Editor for a Small Machine with Disk Storage" by Arthur J. Benjamin of Brandeis University. $100 cash, and a three-year subscription to the ACM serial publication of his choice.

(The number of papers that will be published and the pattern of awards may not be the same in subsequent years.)

All of the refereeing of Competition papers was done by graduate students at various colleges and universities. Our thanks are extended to the referees listed below (and a few others we may have omitted) for their efforts in writing careful, detailed critiques of the papers. Both they and the authors have learned from the work that went into the excellent two- and three-page reports.

Susan Bloch
Ashok Chandra
Clark Crane
Robert Crawford
Alan Davis
Michael S. Doyle
Carl D. Farrell
Alan Filipski
Roger G. Frey
T. Furugori
Gunnar R. Grape
Michael Hanau
William H. Harrison
Alan B. Hayes
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Gabriele Ricci
Harry Saal
Michael Saunders
Daniel P. Siewiorek
David C. Smith
Edward Syrett
James W. Welsch
Nelson Wiederman

We are also grateful to those authors listed below whose papers we were unable to publish, but whose efforts were good enough to make our decisions very difficult. Without the many months of work they put into their papers, the Competition could not have been a success.

Wilfred S. Ageno, University of Hawaii
Todd Allen, University of Delaware
Wayne F. Bialas and David J. Decker, Clarkson College of Technology
Ronald J. Brachman, Princeton University
Donald Cohen, Carnegie-Mellon University
Patricia R. Cox and Cheryl J. Whitford, University of New Mexico
Ola-Olu Adeniyi Daini, Ohio Wesleyan University
Dennis J. Eaglestone, Arizona State University
William A. Gates, University of Wisconsin
Randall Glissmann, Northwestern University
Gary Gorsline, Blacksburg High School (Va.)
Joseph W. Guderjohn, University of Colorado
Jewell M. Harwood, State University College at Plattsburgh (N.Y.)
James R. Heath, Purdue University
Douglas H. Hoffman and Alan R. Schwartz, University of California (Santa Barbara)
Joan Marie Hrenko, North Carolina State University
Robert A. Kelley, Cubberley High School (Palo Alto, Calif.)
Gerard F. Lameiro, Colorado State University
David Misunas, Massachusetts Institute of Technology
Randall B. Neff, Rice University
John R. Odden, California Institute of Technology
Richard A. Page, San Jose State College
Donald C. Pierantozzi, Drexel University
Joseph P. Sambataro Jr., Fordham University
Lee J. Scheffler, Massachusetts Institute of Technology
Thomas A. Schultz, Johns Hopkins University
Douglas R. Spence, Florida Institute of Technology
Edwin Thanhouser, Trinity University
William W. Thomas III, PMC Colleges (Pa.)
Mark Tomizawa, Kenwood High School (Chicago)
Ronald W. Van Orne Jr. and William H. Walker IV, US Air Force Academy
Nicholan F. Vitulli and David Woods, Colgate University

Finally, we wish to thank all those in the ACM who have made our job fun and interesting, particularly Elliott Organick, Myrtle Kellington, M. Stuart Lynn and George Capsis.

As students at Stanford University, we wish to voice our gratitude for the encouragement and inspiration we received from our late department chairman, George E. Forsythe, whom we all miss so deeply.

1971-72 ACM Communications
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