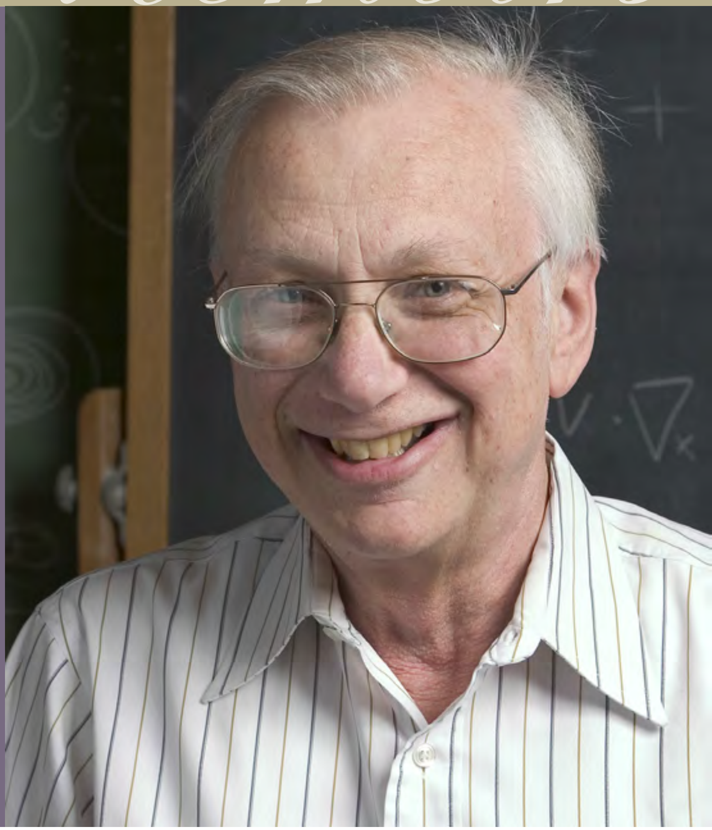
David I. Gottlieb

1944–2008

BIOGRAPHICAL *Memoirs*



A Biographical Memoir by
Saul Abarbanel,
Sigal Gottlieb,
Jan S. Hesthaven,
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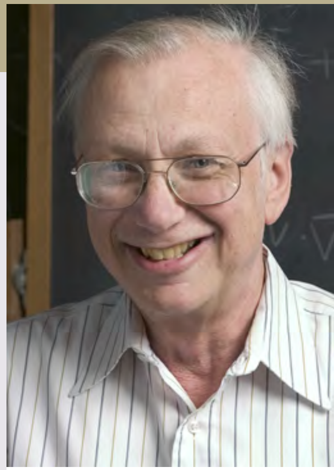
NATIONAL ACADEMY OF SCIENCES

DAVID I. **GOTTLIEB**

November 14, 1944–December 6, 2008

Elected to the NAS, 2006



By Saul Abarbanel, Sigal Gottlieb, Jan S. Hesthaven, and Chi-Wang Shu

David Gottlieb was born in Tel Aviv, Israel, to Yaffa and Yitzhak Gottlieb. He attended the Zeitlin High School, where he was in the mathematical and physical sciences track, though he had other fields in mind for his higher education. Gottlieb enjoyed telling the story of how he had come to study mathematics by pure chance. His first loves were literature and, even more, history—they were passions he maintained for his entire life. It was therefore natural that, while serving as a sergeant in the Israeli army, Gottlieb sought admission to Tel Aviv University to pursue studies in history. He was sorely disappointed to learn that he had missed the registration deadline for the School of Humanities. As he walked through the university campus on his way home, an elderly gentleman approached him and asked about the reason for the sad face. Soon identifying himself as Professor Posner, chair of the university's Department of Mathematics, he invited Gottlieb to join that department to explore and develop his talents in mathematics. The rest, as they say, is history.

Gottlieb graduated with an M.Sc. in 1969, having worked under the guidance of mathematician Shlomo Breuer; and with a Ph.D. in mathematics in 1972 as the first student of Saul Abarbanel and indeed as the department's very first Ph.D.

For his postdoctoral work, Gottlieb went to MIT to work with Gilbert Strang. Also at MIT at the time was a young researcher, Steven Orszag, who had initiated some exciting work on the use and analysis of spectral methods for the numerical solution of partial differential equations. Strang proposed that Gottlieb talk to Orszag to explore possible areas of common interest. This marked the beginning of a very productive collaboration, culminating in their classic monograph, Numerical Analysis of Spectral Methods, published by the Society for Industrial and Applied Mathematics (SIAM) (Gottlieb and Orszag 1977).

This was also the time of a new initiative—the creation of the Institute for Computer Applications in Science and Engineering (ICASE) at NASA Langley Research Center in 1972—that would come to play a central role in Gottlieb's scientific life. He became an associate member in 1974 and would visit annually for the next 28 years, until ICASE closed in 2002. During its relatively short history, ICASE became a global focal point for many of the major developments in computational fluid dynamics and in related areas such as computational mathematics for partial differential equations, optimization, and scientific visualization. The summer program in particular was legendary for bringing together an outstanding group of leading researchers from throughout the world. Gottlieb was in the midst of it, continuing his work on high-order and spectral methods, demonstrating to the NASA community the effectiveness of these methods on complex problems, and enjoying the spirit and collegial atmosphere tremendously.

At the blackboard Gottlieb would show his unique ability to penetrate a complex problem and condense it to its essence, thereby producing a much simpler problem that would be amenable to analysis and insight.

In 1975, while maintaining a close connection to ICASE and continuing to spend every summer there, Gottlieb returned to Tel Aviv University as a senior lecturer in applied mathematics. He rapidly rose to the rank of full professor (in 1982) and served as chairman of the department from 1983 to 1985. This was a period of intense scientific activity because of the rapid growth and broad interest in spectral methods following the 1977 monograph.

Around 1980, Gottlieb was invited to France to give a series of lectures on his work related to the analysis and application of spectral methods. These lectures were to mark the beginning of intense activities in France and Italy that would result in the development of a rigorous approximation theory for spectral methods and the infusion of modern functional analysis into the topic. While not a major contributor to this approach, Gottlieb understood its value and provided consistent encouragement to a group of young mathematicians, mainly in France and Italy, who would lay the foundation for rigorous error analysis of spectral methods during this decade.

In 1982, Peter Lax led an investigation for the U.S. National Science Board, culminating in the report Large Scale Computing in Science and Engineering. This document is now recognized as the first major study to predict the future importance and impact of large-scale computing on computational sciences, and on science in general. It prompted Brown University's Division of Applied Mathematics to seek to create a new activity area in scientific computing and numerical analysis. At Lax's recommendation, the principals invited Gottlieb to come to Brown to develop and lead this new initiative and related research activities.


With his wife, Esty, at Brown.

From 1985 until his death in 2008, Gottlieb was a member of the Brown faculty. He was awarded the Ford Foundation Chair in 1993, and from 1996 to 1999 he was chairman of the Division of Applied Mathematics. He built a world-renowned program at Brown that focused on high-order methods for the solution of time-dependent partial differential equations—a topic that is now more relevant and important than ever. Most of the world's leading experts in this area visited with Gottlieb and his Brown colleagues at one point or another. Among the many major efforts he led at Brown were fundamental advances in shock capturing through the use of spectral methods, the Gegenbauer polynomial-based approach for overcoming the Gibbs phenomenon, the development of a stability theory for compact finite-difference schemes, a novel analysis of perfectly matched layer methods for absorbing boundary conditions, and the development of penalty methods for the weak imposition of boundary conditions.

Gottlieb's research style was legendary: He preferred to work at the blackboard, addressing questions one by one and often discussing out loud how to take the next step. Many offices were left coated in thick layers of chalk dust after such sessions. Gottlieb rarely took notes during or after these discussions, relying on his memory and insight and insisting that the effort be repeated during the following session. At the blackboard Gottlieb would show his unique ability to penetrate a complex problem and condense it to its essence, thereby producing a much simpler problem that would be amenable to analysis and insight. Because this approach often enabled progress on problems otherwise believed to be out of reach, its value was most impressive to his students and collaborators.

Gottlieb's informal and insightful style was also evident in the classroom. He had the ability to approach a complex proof by explaining the heart of it in a straightforward and relevant manner, along with plenty of examples. True to his lifelong love of history, his lecture topics were often presented not only within their scientific context but within their historical context as well. His lectures were often interspersed with jokes, making an often difficult and serious subject seem light and enjoyable. He was mindful of the fact that this approach could mislead students into thinking the subject was simpler than it was, and he would often warn them, "If you think this is simple, you are not understanding it." Gottlieb loved teaching and firmly believed that the thorough understanding of core material was superior to superficial knowledge of a vast body of material. For this reason his classes would sometimes appear to progress slowly. Some young and ambitious students were surprised at first, coming to appreciate only later the depth of understanding he had given them through this teaching approach. Gottlieb formed close relationships with his students and welcomed them to his office, and to his home as well. The respect and friendship between Gottlieb and his students can be seen in the words of former-student Leland Jameson, now a program director at the National Science Foundation:

> *The one thing that impressed me so much about David was not only his ability to be a good scientist but also his ability to live a life balanced with research, family, and religion. This is not easy to do but he seemed to do it very well. Without exception, David was loved by all his students. This is an amazing compliment because it is not rare for Ph.D. students to state that graduate school was the most miserable time of their lives. But I believe that all of David's students, including myself, consider our time as his student as one of the most rewarding times in our lives. In fact, I really have not enjoyed any job as much as I enjoyed the three years as his student.*

Over the course of his career, Gottlieb supervised 22 Ph.D. students (three in Tel Aviv, one at the Université de Paris-Sud, and 18 at Brown) and served as a mentor for numerous postdoctoral researchers, many of whom went on to become leaders in their fields both domestically and internationally.

With his daughter at her 1999 graduation from Brown.

Gottlieb's impact extended beyond the students and colleagues at his home institution to the broader scientific community. His service to this community took many forms. He served on the editorial boards of numerous journals over the years, including the *Journal of Computational Physics, Journal of Scientific Computing, SIAM Journal on Numerical Analysis, and SIAM Journal on Scientific Computing.* As a member of numerous review and visiting committees for universities, funding agencies, and national laboratories, Gottlieb played a central role in the development of computational mathematics and science as a discipline in the United States. He was one of the founders of the International Conference of Spectral and High-Order Methods (ICOSAHOM)—a series of symposia that have been running successfully since 1989 and continue to be the primary venue for the growing community of people working in these areas.

While the scientific value and long-term impact of Gottlieb's body of work are universally recognized, his qualities as a human being have had an equally profound impact on the large community that developed around him. This combination was expressed by Peter Lax at a conference celebrating Gottlieb's 60th birthday: "master of scientific computation, subtle numerical analyst, [and] mensch extraordinaire."

The Yiddish word "mensch" denotes a person of integrity and honor, combining responsibility, dignity, and kindness. Those of us who were fortunate enough to get to know Gottlieb came to appreciate his sincerity, his openness, his insightfulness, and above all his genuine interest in the well-being of others.

In May 1997, Gottlieb was diagnosed with kidney cancer—for which the forms of treatment available at the time were very limited and the chances of survival poor. When the disease returned in late 1999, his life expectancy was reduced to eight months. But Gottlieb defied his illness and prognosis for 11 years with the gentle persistence and quiet humor so characteristic of him. He devoted himself to his family and his work, developing new areas of research (such as mathematical models of tumors and tumor diagnosis) and nurturing the new generation—his grandchildren.

The illness and the many experimental forms of treatment he underwent took a tremendous toll on his physical well-being, yet Gottlieb always gave the impression that all of this was secondary. He always had time for people seeking his help, advice, or comfort. A couple of months before his passing, while he was hospitalized for a week for observation, two graduate students from Brown's Division of Applied Mathematics were scheduled for an oral preliminary examination. In consideration of the students regarding the stress they might experience by postponing the exam, he offered to administer it from his hospital bed, and he did so with his usual insight, encouragement, and humor. During the 11 years after his diagnosis, Gottlieb's accomplishments included publishing close to 40 peer-reviewed publications, coauthoring a book (Hesthaven, Gottlieb, and Gottlieb 2007), advising nine doctoral students, and generally influencing the course of his field. His courage in his long fight with his illness serves as an inspiration to all of us as we face hardship in our own lives.

In recognition of his originality and scientific impact, Gottlieb was awarded a NASA Group Achievement Award in 1992 as a core member of ICASE, and he received honorary doctorates from the University of Paris VI (1994) and Uppsala University (1996). He was elected to the U.S. National Academy of Sciences in 2006 and to the American Academy of Arts and Sciences in 2007. In July 2008 he gave the SIAM John von Neumann Lecture ("The Effect of Local Features on Global Expansions") at the 2008 SIAM annual meeting. It was to be his last public lecture.

On December 6, 2008, the worldwide community of computational mathematicians and scientists lost one of its most respected and original members when Gottlieb passed away at the age of 64. He was survived by his wife Esty, their three children Sigal, Yitzchak (Zuki), and Lee-Ad (Adi), and four grandchildren.

On January 25, 2009, Gottlieb's close colleagues, friends, and former students gathered with his family at the Brown Hillel Center to celebrate his life with a memorial service. Many took advantage of the opportunity to pay tribute to him and his legacy, expressing their deep respect and appreciation for his scientific achievements, his kindness, his complete lack of selfishness, his courage, and his total devotion to his family.

In December 2009, an International Conference on Advances in Scientific Computing was held at Brown University to honor Gottlieb's memory and to review recent advances and explore exciting new directions in areas that were so central to his research: scientific computing and related numerical solutions of partial differential equations; and mathematical modeling for time-dependent problems and its applications.

At least three journal special issues—of *Communications in Computational Physics, ESAIM: Mathematical Modeling and Numerical Analysis, and Journal of Scientific Computing*—also have been published in Gottlieb's memory. In 2010, the Gottlieb Memorial Award was established at Brown. It is awarded annually by the Division of Applied Mathematics, to one or more graduating students, on the basis of excellence in graduate studies as evidenced by their doctoral dissertation.

With his deep interest in history, David Gottlieb often wished he had more time to study this subject in greater depth. He never expected that his fortuitous departure into computational mathematics would allow him to shape history itself through his work and his qualities as a human being.

Research Achievements

In addition to the classic monograph (Gottlieb and Orszag 1977) and book (Hesthaven, Gottlieb, and Gottlieb 2007) mentioned above, Gottlieb published more than 125 papers on a wide range of topics. We have grouped his contributions into several categories, listed in approximate chronological order. In some cases we refer to papers in the attached selected bibliography, which constitute some of his most significant work.

Analytic techniques for ordinary differential equations and boundary-value problems

Gottlieb's first major research activities, based on his M.Sc. work at Tel Aviv University under his advisor Shlomo Breuer, were focused on problems originating in the theory of ordinary differential equations (ODEs). Some of his earliest efforts in this area were devoted to the development of: (1) exact solutions to certain classes of ODEs; and (2) necessary and sufficient conditions on the coefficients of ODEs that would allow for the existence of a transformation to an equivalent system with constant coefficients. These activities also included contributions to the understanding of the behavior of solutions to large classes of ordinary differential equations and boundary-value problems.

Finite-difference schemes for partial differential equations

A major line of Gottlieb's research , starting from his Ph.D. thesis and continuing until his death, was the design of high-order finite-difference schemes (in the broad sense, including compact schemes, Galerkin schemes, stable treatment of boundary conditions, and semi-discrete and fully discrete schemes, for example) and the analysis of their stability, accuracy, and convergence. Within this broad topic, many of the papers of Gottlieb and his collaborators were in the tradition of classical numerical analysis, using deep mathematical tools to obtain rigorous stability properties of highly efficient numerical methods. Other papers involved discussions on implementations and applications. Either way, many of the results contained in these papers have been very influential in the numerical analysis community and in the fields of application alike.

Time-stepping techniques for partial differential equations

Throughout his career, Gottlieb also contributed substantially to the analysis and improved understanding of time-stepping methods when used in the context of solving partial differential equations in a methods-of-lines approach. In his early work, he and his collaborators developed a rigorous understanding of widely used methods such as splitting methods (e.g., Abarbanel and Gottlieb 1981), time-stepping techniques developed specifically for spectral methods (e.g., Gottlieb and Turkel 1980), and various specialized schemes.

A significant advancement in the understanding of the widely used Runge-Kutta methods resulted from work by Gottlieb and his collaborators in the mid-1990s. In Abarbanel, Gottlieb, and Carpenter 1996 and in Carpenter, Gottlieb, Abarbanel, and Don 1995 they highlighted and explained problems specific to Runge-Kutta methods when used in the context of solving initial boundary-value problems and they showed how standard approaches lead to a loss of accuracy. These two papers also included a detailed discussion on the sources of these problems as well as on the development of techniques to overcome them. These techniques have since then been widely employed by other practitioners. Another Gottlieb contribution to the use of Runge-Kutta methods was a combination of explicit and implicit schemes to overcome issues with fine grids.

Gottlieb and his collaborators also developed methods for multi-scale problems, based on two-level techniques, to improve time-integration. These nonlinear Galerkin methods are still of interest, and the early papers by Gottlieb et al. (such as Dettori, Gottlieb, and Temam 1996) continue to inspire researchers in the field.

Spectral methods

Gottlieb is perhaps the best known as one of the pioneers in the design, analysis, and application of spectral methods as efficient and accurate techniques for solving general partial differential equations. These methods, which use global polynomial or trigonometric polynomial expansions, can achieve very fast convergence—up to exponential convergence for analytic solutions. Gottlieb's two books (Hesthaven, Gottlieb, and Gottlieb 2007; Gottlieb and Orszag 1977) are both devoted to the analysis and application of spectral methods. Throughout his career he also wrote numerous papers on this subject.

Gottlieb's work on this subject included papers on traditional numerical analysis, centered on mathematical techniques to obtain rigorous stability properties of highly efficient numerical methods, as well as applications of spectral methods. Much of his early work was devoted to developing the first rigorous and systematic treatment of the semi-discrete and fully discrete stability of spectral methods applied to time-dependent problems. Some of his notable papers on this topic include Carpenter, Gottlieb, and Shu 2003; Gottlieb and Hesthaven 2001; Don and Gottlieb 1998; Carpenter and Gottlieb 1996; Don and Gottlieb 1990; Gottlieb, Lustman, and Tadmor 1987; Gottlieb and Turkel 1985; Gottlieb 1981; Gottlieb 1978; and many others.

Many of the papers on penalty-type methods and on uncertainty, statistics, and stochastics described in the above section on "finite-difference schemes for partial differential equations" also involve spectral methods. Moreover, Gottlieb's work addressed the issue of the optimal number of subdomains for hyperbolic problems on parallel computers as well as general issues related to parallel computing.

He and his collaborators also studied the combination, or hybridization, of spectral methods and high-order accurate non-oscillatory finite-difference methods for shock-wave calculations. The goal was a suitable hybridization that retained the advantage of both methods while eliminating their relative weaknesses.

The Gibbs phenomenon

In the early 1990s, Gottlieb and his collaborators began a systematic study of strategies to overcome "the Gibbs phenomenon," which refers to the fact that when a high-order method, such as a spectral or a finite-difference method, is used to solve a problem with solutions that are piecewise smooth but may contain discontinuities, the accuracy is greatly reduced. In fact, there is no convergence in the maximum norm near the discontinuity, as there are always oscillations (overshoots and undershoots) near a discontinuity with a fixed relative size. The convergence rate away from the discontinuity is also seriously deteriorated to at most first-order. However, the high-order accuracy information is not lost but instead is hidden—in the moments against smooth functions or in the negative norms.

Previous efforts used this observation to recover accuracy away from the discontinuity. However, accuracy at or near the discontinuity was still low, thereby posing a philosophical question: Does the partial spectral sum contain enough information, for a discontinuous and piecewise smooth function, to extract high-order accuracy in the maximum norm everywhere, including at the discontinuity? Using Gegenbauer polynomials with increasing powers in the weight function and by carefully balancing the truncation errors and the regularization errors, Gottlieb and his collaborators were able to construct uniformly accurate series based on the spectral partial sum or on other finite dimensional information. These series can be proved to converge exponentially fast, in the maximum norm, to the piecewise analytic discontinuous solutions of the partial differential equations. Such convergence is uniform, including at the discontinuity point itself, thus answering affirmatively the philosophical question raised above and completely removing the difficulty caused by the Gibbs phenomenon. Consequently, this technique has been generalized and applied by many authors.

Gottlieb's early work on this topic (Gottlieb 1998) led to a large number of papers, culminating in the SIAM Review article (Gottlieb and Shu 1997). His last public lecture, the John von Neumann Lecture given at the 2008 SIAM annual meeting, was devoted to the topic.

Boundary conditions

Problems involving boundary conditions were of significant interest to Gottlieb throughout his career. He recognized that the boundary conditions were an integral part of the solution to all differential equations, both partial and ordinary. His work in this area focused on three issues:

Boundary errors in time integration.

These contributions, mentioned above in the section on "time-stepping techniques for partial differential equations," involved the analysis and removal of errors in time integration resulting from the boundary conditions.

Penalty boundary conditions.

Gottlieb and his collaborators performed extensive research on penalty-type boundary treatments, including both for physical boundaries and for the internal artificial boundaries that arise when multi-domain finite-difference or spectral methods are used. These methods, when formulated and implemented correctly, have the advantage of simplicity in implementation and of conferring provable stability properties for the resulting schemes. Gottlieb's last paper (Carpenter, Nordstrom, and Gottlieb 2010), published in the *Journal of Scientific Computing* special issue in his memory, was related to this topic.

Absorbing boundary conditions.

In the mid 1990s, Gottlieb took an interest in absorbing boundary conditions for open-domain wave problems. The development of the perfectly matched layer methods (PML) in 1995 by J.-P. Berenger inspired Gottlieb and collaborators to look at these techniques from a more mathematical point of view. This led to the development of several influential papers that discussed: (1) the well-posedness of the widely used PML methods (Abarbanel and Gottlieb 1997); and (2) the development of a novel constructive ansatz-driven approach for PML methods (Abarbanel and Gottlieb 1998) in electromagnetics and, later, in acoustics. The analysis also helped explain problems that practitioners had observed in applications, consequently leading to the final development of an entirely new class of nonlinear absorbing boundary conditions (Abarbanel, Gottlieb, and Hesthaven 2006).

Model reduction

Later in his career, Gottlieb and his collaborators paid attention to statistical techniques for dealing with problems of model reduction. This activity included a paper, with an uncertainty analysis following the research of A. J. Chorin et al., on steady-state flow in a dual throat nozzle (Chen, Gottlieb, and Hesthaven 2005). Gottlieb's efforts also included subsequent work on the influence of stochastics in the solution of hyperbolic problems (including boundary conditions); and work on an optimal prediction technique applied to a particle-method problem published the month before his death (Chertock, Gottlieb, and Solomonoff 2008).

Other work

Throughout his career, Gottlieb collaborated extensively with engineers and other applied scientists to develop mathematical models for specific applications, to analyze the models in order to understand their properties (such as well-posedness), and to design efficient numerical methods for solving them. Examples of these joint efforts were his work with colleagues on optimization of chemical vapor infiltration in materials science, wind set-down relaxation on a sloping beach, and secondary frequencies in the wake of a circular-cylinder with vortex shedding (Abarbanel et al. 1991).

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