Newsjournal of the Society for Industrial and Applied Mathematics sinews.siam.org

siam news

Volume 57/ Issue 4
May 2024

Special Issue on Quantum Computing

*Part II of this **special issue** highlights research that connects applied mathematics and computational science with quantum computing, and overviews timely developments and trends in the field.*

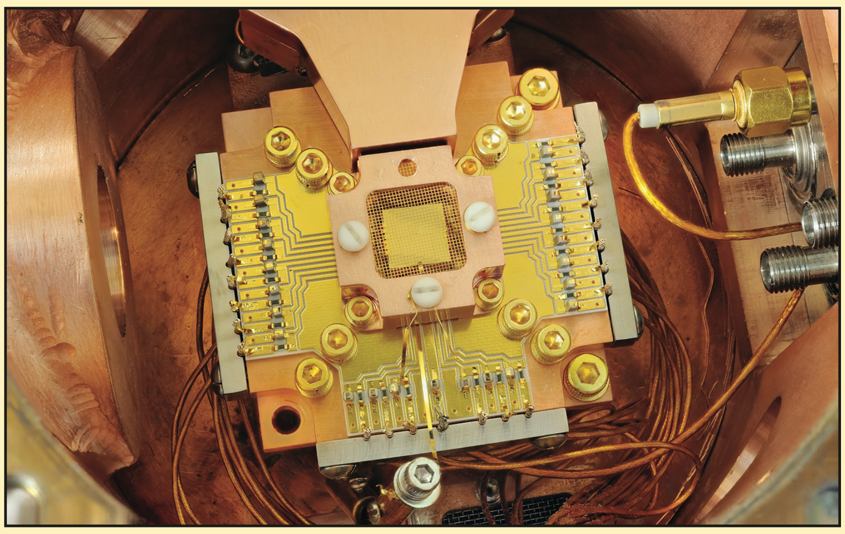


Figure 1. *Ion trap devices induce the transfer of quantum information between ions to enable information processing in quantum computing. Figure courtesy of Y. Colombe/National Institute of Standards and Technology.*

On page 3, David Hyde and Alex Pothen introduce Part II of the SIAM News Special Issue on Quantum Computing and encourage further collaboration between quantum scientists and applied mathematicians.

Fighting Errors with Space

By Shawn X. Cui

The fundamental unit in a quantum computer is a quantum bit (qubit), which is typically the state space of a microscopic particle such as a photon, ion, atom, etc. In quantum computing, qubits should be isolated from their surroundings to minimize noise. Yet by definition, the application of gates and measurements is a form of interaction between qubits and external observers; as such, any quantum computer is inevitably exposed to the environment. A quantum state may unfavorably change to another state at a particular point in time because of *decoherence*. Likewise, a quantum gate may not execute an operation exactly as intended due to technological limitations. These unwanted environmental interactions and operational imprecisions introduce errors to the system; a sufficient accumulation of errors can eradicate all useful information in a quantum state. To become practical, quantum computing must address the issue of errors.

In classical computation, an error is the flip of a bit between 0 and 1. In quantum computing, the analog of a bit flip is the Pauli X operator that switches between $|0\rangle$ and $|1\rangle$. Similarly, a phase flip error corresponds to the Pauli Z operator and multiplies the phase -1 to $|1\rangle$. More "violent" errors can also occur. For example, the environment may entangle with some qubits, evolve for some time, and finally disentangle by measuring itself out. For the purpose of this discussion, let us think of an error as an arbitrary linear operator. It may seem impossible to correct every error at first glance because of the uncountable possibilities. However, a theorem guarantees that if we can correct a set of errors, any operator in the vector space that is spanned by those errors can also be automatically corrected without extra effort. Therefore, correcting the Pauli X, Y, and Z errors sufficiently corrects all 1-qubit errors.

Much like the use of redundancy in classical error correction, a key principle of quantum error correction involves fighting errors with abundant space. Within a space $\mathcal{H}$ of multiple *physical qubits*, we can choose a subspace $\mathcal{L} \subset \mathcal{H}$ as the space of *logical qubits*. Typically, the dimension of $\mathcal{H}$ is several magnitudes larger than that of $\mathcal{L}$. The formulation of subspace $\mathcal{L}$ should allow for the detection of an error that brings a state in $\mathcal{L}$ to somewhere outside, and also permit the distinction of different errors. Error detection usually occurs via measurement, which should be just enough

See **Fighting Errors** *on page 3*

A Practical Introduction to Quantum Computing

By Casey Dowdle and James Whitfield

Quantum theory began as a rather esoteric branch of physics, but its influence spread rapidly throughout the physical sciences. More than a century later, it now contributes to computation, communication, and information applications — resulting in the rise of quantum technology as an industrial pursuit. Here, we introduce the concepts behind quantum theory, quantum technology, and quantum computation, and view quantum theory as an extension of probability in order to connect quantum ideas to well-known concepts in probability theory and statistics. This comparison inspires a discussion about quantum theory's infiltration of the current technological landscape before finally arriving at the notion of quantum computing itself. By examining the major questions within the field of quantum computing, we hope to help direct the influx of industrial and applied mathematicians to the most impactful areas.

Quantum Mechanics

We begin with a probability-first approach to quantum theory. In fact, viewing quantum mechanics as a straightforward extension of probability theory removes much of the surrounding confusion and mystery. In probability theory, a vector of numbers describes the likelihood that a discrete set of events will occur when a random variable is observed or measured. Similarly, the *quantum probability density matrix* describes the likelihood that certain events will occur when a quantum system is observed or measured. The entries of probability vectors are normalized, real, nonnegative coefficients, while the eigenvalues for the density matrix are also normalized, real, and nonnegative.

The connection between the two types of states is perhaps best explained by example. Consider a probability vector

$$p = \begin{bmatrix} 0.25 \\ 0.50 \\ 0.15 \\ 0.10 \end{bmatrix}. \tag{1}$$

The corresponding quantum probability density matrix is then

$$\rho_p = \begin{bmatrix} 0.25 & & & \\ & 0.50 & & \\ & & 0.15 & \\ & & & 0.10 \end{bmatrix}. \tag{2}$$

We can rotate this matrix to change the basis while still preserving the conditions on the eigenvalues. This relation between the two theories can generalize other concepts (such as entropy) almost directly:

$$H(p) = -\sum_k p_k \log p_k \quad \text{and} \quad H(\rho) = -\mathrm{Tr}[\rho \log \rho]. \tag{3}$$

Moreover, the notion of quantum measurement is directly inherited from the underlying probability theory (see Figure 1).

The off-diagonal elements of the density matrix are called *coherences* (coherence is the fundamental difference between quantum and probability theory). The production of modern technological devices is implicitly based on quantum mechanics, but often in nonobvious ways — in contrast with devices whose operation depends on quantum coherence.

Quantum Technology

Realizing the potential of machine learning technology required significant improvements in networking, memory, data availability, software, and hardware. Quantum computing—which is currently in the nascent stages of industrialization—

See **Quantum Computing** *on page 4*

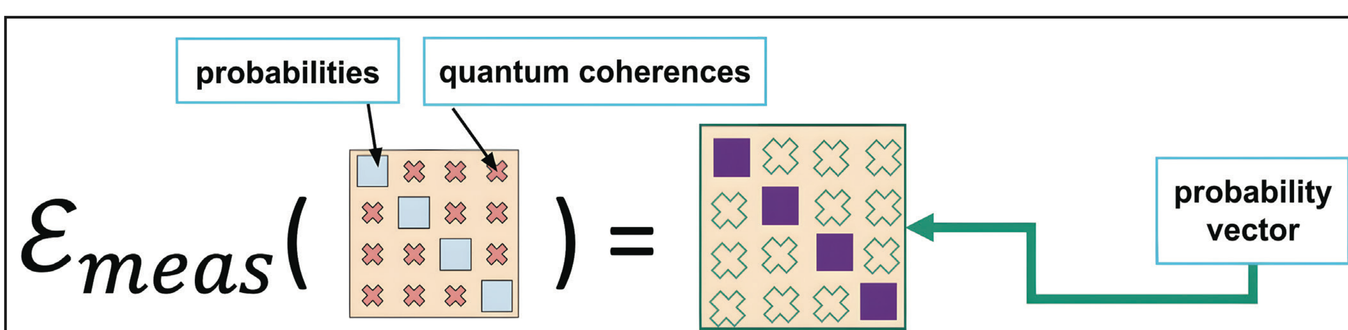


Figure 1. *Quantum aspects of measurement. The quantum channel $\mathcal{E}_{meas}$ transforms a probability density matrix into a probability density vector in the basis of the measurement. From there, the realization of an outcome and its consequences for the probability density vector both remain strictly within the domain of ordinary probability theory. Figure courtesy of James Whitfield.*

Nonprofit Org
U.S. Postage
PAID
Permit No 360
Bellmawr, NJ

siam. SOCIETY for INDUSTRIAL and APPLIED MATHEMATICS
3600 Market Street, 6th Floor
Philadelphia, PA 19104-2688 USA

siam news
Volume 57/ Issue 4/ May 2024

Obituary: Nicholas J. Higham

By Desmond J. Higham and Françoise Tisseur

Nicholas J. Higham—a leading researcher and communicator in computational and applied mathematics and a former president of SIAM—passed away on January 20, 2024, at the age of 62. Nick was born on December 25, 1961, in Eccles, Manchester, in the U.K. Because he was the first baby to be born on Christmas morning, he won a prize — an experience that would later become familiar to him throughout his impressive academic career. Shortly after Nick's birth, a nurse unexpectedly took him away; when she returned with him an hour later, she explained that Nick had played the role of baby Jesus in the hospital's Christmas morning service.

Nick's father, Ken, was highly proficient in Morse code and served as a wireless operator in a tank throughout Europe, Africa, and the Middle East during World War II. His mother, Doris, worked as a secretary and later earned qualifications in English language and literature. Given his parents' respective backgrounds, Nick attributed his mathematical abilities to his father and his writing skills to his mother.


Nicholas J. Higham, 1961-2024. Photo courtesy of Rob Whitrow.

Nick was a talented musician. Beginning at age 14 and continuing into his 40s, he played the keyboard as a resident organist in local social clubs, usually alongside a drummer and visiting artist. He enjoyed long residences at three different clubs, where audience members were typically unaware that "Nick the organist" was also an eminent maths professor. Back when he was an undergraduate student at the University of Manchester, Nick spent his organ earnings on personal computers — an unusual and expensive proposition in the early 1980s. He owned a Commodore PET microcomputer and then upgraded to a Commodore 64 (C64); as a Ph.D. student, he even wrote a piece of commercial software for the C64 that served as a very early and highly prescient version of a digital musical recorder and editor. Nick used a combination of BASIC and 6502 assembler code to convert the computer keyboard into a piano. The manual for this 1985 "Music Master" software is still available online.[1]

After graduating with an honours degree in mathematics and a master's degree in numerical analysis and computing, Nick remained at the University of Manchester to pursue his Ph.D. He more or less chose his own research topic because his supervisor, numerical ordinary differential equation expert George Hall, was confident in his ability to work independently. Before he finished his Ph.D., Nick was offered a permanent academic position at Manchester under the "new blood" scheme, which encouraged U.K. universities to hire promising young academics. He went on to spend the entirety of his career at Manchester, rising to the rank of Richardson Professor of Applied Mathematics (named for mathematician and meteorologist Lewis Fry Richardson) in 1998. Beginning in 2018, he simultaneously held a prestigious Royal Society Research Professorship.

Nick's work as a numerical analyst embraced the full spectrum, from rigorous theory to practical implementation. He quickly became known as the leading expert of rounding error analysis, due in part to his 1996 bestselling 700-page SIAM monograph titled *Accuracy and Stability of Numerical Algorithms*[2] (with a second edition in 2002). His research interests also included linear systems and condition estimation, least-squares problems, eigenvalue problems, matrix functions, and nonlinear matrix equations. Nick's 2008 SIAM book, *Functions of Matrices: Theory and Computation*,[3] was the first text to embrace both theoretical and algorithmic aspects of matrix functions.

In a sequence of articles over the last decade, Nick pioneered two new directions for rigorous floating-point error analysis — revealing the explanatory power of probabilistic rounding models and establishing the effectiveness of mixed-precision arithmetic in high-performance algorithms. In the weeks before his death, he completed the final draft of a 550-page book that brings together concepts and results that he found useful throughout his research career.

Yet another monumental work was Nick's editorship of the authoritative 2015 *Princeton Companion to Applied Mathematics*.[4] During a 2016 interview about this book, Nick was asked, "What is applied mathematics?" [1]. He replied with the following sentiment:

> "My favourite quote is from Lord Rayleigh. He said that applied maths is about using mathematics to solve real world problems 'neither seeking nor avoiding mathematical difficulties.' That means you've got some real world problem in mind and you don't oversimplify it so that you can solve it. You'll do whatever you have to do to come up with either a solution or an approximation. That is a nice way of giving the flavour of applied mathematics."

It is therefore fitting that Nick's most highly cited research paper—"Computing the Nearest Correlation Matrix – A Problem From Finance," which published in the *IMA Journal of Numerical Analysis* [2]—was motivated by a practical query from a member of the financial industry.

The work of numerical analysts is not only recorded in journals and textbooks; it may also be made operational and scalable through software. Nick was passionate about this means of widespread dissemination and impact. In fact, more than 50 of MATLAB's built-in routines are credited directly to him, and his three open-source MATLAB toolboxes—the Matrix Computation Toolbox,[5] Matrix Function Toolbox,[6] and Nonlinear Eigenvalue Problems Toolbox[7]—are routinely cited in the literature. Nick's algorithms for condition estimation, the nearest correlation matrix, and numerous matrix functions and their Fréchet derivatives have been implemented in a wide range of packages and programming languages, including the Linear Algebra PACKage, Python, R, Julia, and the NAG Library. Nick consulted for MathWorks (the maker of MATLAB) for many years and coauthored the popular *MATLAB Guide*[8] with his brother, Desmond Higham, in 2000 (with a second edition in 2005 and a third edition in 2017).

Nick's momentous contributions to the field of applied mathematics have garnered universal recognition. Among other accolades, he received SIAM's George Pólya Prize for Mathematical Exposition[9] in 2021 as well as three awards from the London Mathematical Society: the Naylor Prize and Lectureship in Applied Mathematics in 2019, the Fröhlich Prize in 2008, and a Junior Whitehead Prize in 1999. The Institute of Mathematics and its Applications awarded him their Gold Medal in 2020 and the Leslie Fox Prize for Numerical Analysis in 1988. Nick's roster of awards is bookended by the Alston S. Householder Award in 1987 for his impressive Ph.D. thesis on numerical linear algebra, and the Hans Schneider Prize in Linear Algebra in 2022. He was elected as a Fellow of the Royal Society in 2007 and was named an inaugural Fellow of SIAM in 2009, a Fellow of the Association for Computing Machinery in 2020, a Fellow of the Royal Academy of Engineering in 2022, and an international member of the U.S. National Academy of Engineering in 2023.

Nick was an effective and committed leader. He served on the editorial boards of leading journals in linear algebra and numerical analysis and chaired the SIAM Activity Group on Linear Algebra[10] from 2001 to 2003 and the International Householder Committee from 1999 to 2002. He regularly organized research workshops at venues around the world, including the Schloss Dagstuhl in Germany, the Banff International Research Station in Canada, and the Mathematical Research and Conference Center in Poland.

See **Nicholas J. Higham** *on page 5*

---

1 https://archive.org/details/Music_Master_1985_Supersoft

2 https://nhigham.com/accuracy-and-stability-of-numerical-algorithms

3 https://nhigham.com/functions-of-matrices-theory-and-computation

4 https://nhigham.com/the-princeton-companion-to-applied-mathematics

5 https://www.mathworks.com/matlabcentral/fileexchange/2360-the-matrix-computation-toolbox

6 https://www.mathworks.com/matlabcentral/fileexchange/20820-the-matrix-function-toolbox

7 https://www.mathworks.com/matlabcentral/fileexchange/71064-nlevp

8 https://nhigham.com/matlab-guide

9 https://www.siam.org/prizes-recognition/major-prizes-lectures/detail/george-polya-prize-for-mathematical-exposition

10 https://www.siam.org/membership/activity-groups/detail/linear-algebra

siam news

ISSN 1557–9573. Copyright 2024, all rights reserved, by the Society for Industrial and Applied Mathematics, SIAM, 3600 Market Street, 6th Floor, Philadelphia, PA 19104-2688; (215) 382-9800; siam@siam.org. To be published 10 times in 2024: January/February, March, April, May, June, July/August, September, October, November, and December. The material published herein is not endorsed by SIAM, nor is it intended to reflect SIAM's opinion. The editors reserve the right to select and edit all material submitted for publication.

Advertisers: For display advertising rates and information, contact the Department of Marketing & Communications at marketing@siam.org.

One-year subscription (nonmembers): Electronic-only subscription is free. $73.00 subscription rate worldwide for print copies. SIAM members and subscribers should allow eight weeks for an address change to be effected. Change of address notice should include old and new addresses with zip codes. Please request an address change only if it will last six months or more.

Printed in the USA.

Introducing Part II of the Special Issue on Quantum Computing

By David Hyde and Alex Pothen

In April 2024, *SIAM News* published its first-ever Special Issue on Quantum Computing. The four featured articles connected quantum computing to applied math[1] and addressed a wide variety of topics, from the end-to-end complexity of quantum algorithms[2] to the synergies between quantum computing and machine learning[3] and even applications to financial mathematics.[4] The current edition of *SIAM News* serves as a follow-up to the previous installment and includes a second series of articles by quantum computing experts who continue to explore the intersection of quantum computing, applied mathematics, and computational science (see Figure 1, on page 1). The insights from this two-part Special Issue demonstrate the powerful ability of quantum computers to augment algorithms that pertain to industrial and applied mathematics problems. Additionally, many advances in quantum computing and quantum information science rely on mathematical areas in which SIAM members are the world's leading practitioners. We hope that these thought-provoking articles will encourage further interaction and collaboration between quantum computing and applied mathematics researchers.

In Part II of this Special Issue, Casey Dowdle and James Whitfield introduce quantum computing from a probabilistic point of view; they also comment on available software libraries and hardware for researchers who want to experiment with the field. Shawn Cui then delves into the applied mathematics techniques that enable quantum error correcting codes, which are essential for noisy intermediate-scale quantum (NISQ) devices. Yuri Alexeev, Ankit Kulshrestha, and Ilya Safro conclude the series with a discussion about optimization algorithms and the challenges that are associated with NISQ hardware. These brief, timely articles provide an entry point for quantum computing and highlight several state-of-the-art challenges and opportunities at the intersection of quantum information science and applied mathematics.

We encourage quantum-curious readers to also browse the relevant content in the April issue of *SIAM News*. As quantum computing continues to generate tremendous interest in academia, industry, and government, we look forward to future like-minded projects that connect the SIAM and quantum computing communities.

*SIAM invites quantum-curious mathematical scientists to participate in the upcoming SIAM Quantum Intersections Convening – Integrating Mathematical Scientists Into Quantum Research. This three-day interactive workshop—which will take place from **October 7-9, 2024** in Tysons, Va.—will unite attendees with leading experts in quantum science to promote multidisciplinary collaboration and increase the involvement of mathematicians and statisticians in quantum science research and education.*

*Applications for this convening are now open;[5] the deadline to apply is **June 15th**.*

David Hyde is an assistant professor of computer science at Vanderbilt University. His research interests include computational physics, cloud computing, computer graphics, and quantum computing. Alex Pothen is a professor of computer science at Purdue University. His research interests include combinatorial scientific computing, graph algorithms, and parallel computing. Pothen received SIAM's George Pólya Prize in Applied Combinatorics in 2021 and is a Fellow of SIAM, the American Mathematical Society, and the Association for Computing Machinery.

[1] https://sinews.siam.org/Details-Page/what-can-quantum-computers-do-for-applied-mathematicians

[2] https://sinews.siam.org/Details-Page/quantum-advantages-and-end-to-end-complexity

[3] https://sinews.siam.org/Details-Page/bridging-the-worlds-of-quantum-computing-and-machine-learning

[4] https://sinews.siam.org/Details-Page/quantum-computing-for-financial-mathematics

[5] https://go.siam.org/quantumconvening

Fighting Errors

Continued from page 1

to infer the error without revealing the actual encoded state. Different errors must map $\mathcal{L}$ to pairwise orthogonal subspaces in order to remain unambiguously distinguishable. An extension of this argument leads to the error correction condition: A set of errors $\{E_i\}$ is correctable if and only if $PE_j^\dagger E_i P = \alpha_{ij} P$ for any i, j, where α_{ij} is a scalar and $P:\mathcal{H}\to\mathcal{L}$ is the orthogonal projection onto $\mathcal{L}$. $\mathcal{L}$ is called a quantum error correcting code (QECC).

A large family of QECCs arises as *stabilizer codes* [5]. Let $\mathcal{P}_n$ be the Pauli group on n qubits and $S\subset\mathcal{P}_n$ be an Abelian subgroup that does not contain $-I$. We define the logical subspace as

$$V_S := \{|\psi\rangle\in\mathbb{C}^{2^n} \,|\, P|\psi\rangle=|\psi\rangle,\ \forall P\in S\}.$$

If S has $n-k$ independent generators, the dimension of V_S is 2^k. The distance d is the minimal number of Pauli operator components whose products act on V_S in a nontrivial manner. V_S is a QECC of type $[[n,k,d]]$, which means that it encodes k logical qubits in n physical qubits and has distance d. Using the error correction condition, we can show that such a code corrects arbitrary errors on $\left\lfloor \frac{d-1}{2} \right\rfloor$ qubits. The Shor code [10]—which was the first QECC—is a $[[9,1,3]]$ stabilizer code whose stabilizer S is generated by check operators

$$Z_1Z_2,\ Z_2Z_3,\ Z_4Z_5,\ Z_5Z_6,\ Z_7Z_8,\ Z_8Z_9,$$
$$X_1X_2X_3X_4X_5X_6,\ X_4X_5X_6X_7X_8X_9.$$

V_S thus has the following basis:

$$|0\rangle_L := \frac{1}{2\sqrt{2}}(|000\rangle+|111\rangle)(|000\rangle+|111\rangle)(|000\rangle+|111\rangle),$$

$$|1\rangle_L := \frac{1}{2\sqrt{2}}(|000\rangle-|111\rangle)(|000\rangle-|111\rangle)(|000\rangle-|111\rangle).$$

Another well-known QECC is the toric code [8]. Figure 1 depicts a square lattice wherein a physical qubit lives on each edge. The stabilizer consists of two types of check operators: A_v for each vertex v and B_p for each square p. For a square lattice of size $L\times L$ with a periodic boundary condition, the toric code is of type $[[2L^2,2,L]]$.

Given a QECC that corrects errors on m qubits, consider a stochastic error model where—at each discrete time—an error occurs independently at every qubit with probability p. The error correction process is successful as long as no errors spread more than m qubits; otherwise, a *logical error* is produced. We should therefore perform the correction process frequently and periodically to suppress the likelihood of errors on more than m qubits. According to a fundamental theorem, a threshold p_{th} exists so that as long as $p<p_{th}$, the probability of a logical error can be smaller than that of a physical error [1]. By nesting several layers of the QECC to suppress the logical error rate to be arbitrarily small, we can achieve fault-tolerant quantum computing.

An important class of stabilizer codes is the low-density parity check (LDPC) codes (e.g., toric code), where each qubit participates in a constant number of check operators and each check operator comprises a constant number of qubits [6]. An active area of research involves seeking the ranges of parameters $[[n,k,d]]$ that a QECC can realize. We might also wish to optimize certain parameters over others, such as the encoding rate k/n, distance d, or threshold p_{th}. The toric code has a distance that scales as $\sqrt{n}$. For a long time, scientists believed that the distance in an LDPC code was bounded by $\mathrm{polylog}(n)\sqrt{n}$. But since 2020, researchers have broken this barrier with several methods, including the Hastings-Haah-O'Donnell fiber bundle codes with $d\in\Omega(n^{3/5}/\mathrm{polylog}(n))$ [7] and the Panteleev-Kalachev lifted product codes with $d\in\Omega(n^{1-\alpha/2}/\log(n))$ for $0\le\alpha<1$, which achieve almost linear distance [9]. Although the toric code has a very poor encoding rate of $2/n$, the utilization of tessellations on hyperbolic manifolds can achieve a constant linear encoding rate, even approaching 1 asymptotically.

The actual value of the threshold depends on the assumed error model and can reach as high as 10^{-2} in the toric code [3] (compared to 10^{-7} to 10^{-3} for most other codes' thresholds). LDPC codes are particularly useful in the current noisy intermediate-scale quantum era, when the number of physical qubits in a device ranges from 10^2 to 10^4 and the layout suffers from limited interconnectivity. It is challenging to design a code that optimizes more than one parameter and is simultaneously suitable for hardware implementation. Nevertheless, a recent collaborative project yielded some LDPC codes that outperformed toric code in encoding rate, had a high threshold when compared to toric code, and were potentially implementable on superconducting qubit-based quantum computers [2].

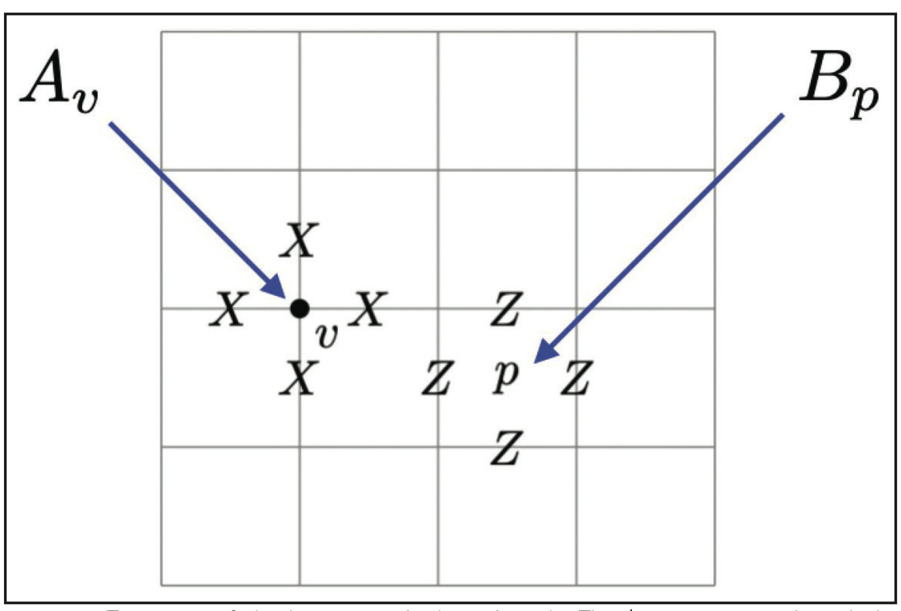


Figure 1. *Two types of check operators in the toric code. The A_v operator acts through the Pauli X operator on each edge adjacent to v, and the B_p operator acts through the Pauli Z operator on each edge on the boundary of p. Figure courtesy of the author.*

Finally, we will briefly mention another method that uses "hardware" to correct errors. Toric code can encode two logical qubits regardless of the lattice size because it represents a two-dimensional topological phase matter (TPM): a gapped quantum spin liquid that hosts quasiparticle excitations (also known as *anyons*). Anyons have a stable degenerate ground space and global degrees of freedom that local perturbations cannot access, which makes the multi-anyon space an ideal location for logical qubit storage. Logical gates, which are realized via the movement of anyons relative to each other, only depend on the isotopy class of the anyons' worldlines. Essentially, the TPM itself is a QECC and error correction occurs at the hardware level. This innovative approach to fault tolerance is called *topological quantum computing* [4, 8]. Though it is a beautiful theory, experimental confirmation of the existence of anyons—especially those that are essential to topological quantum computing—is an extremely difficult task, albeit with high payoffs.

References

[1] Aharonov, D., & Ben-Or, M. (1997). Fault-tolerant quantum computation with constant error. In *STOC '97: Proceedings of the twenty-ninth annual ACM symposium on theory of computing* (pp. 176-188). New York, NY: Association for Computing Machinery.

[2] Bravyi, S., Cross, A.W., Gambetta, J.M., Maslov, D., Rall, P., & Yoder, T.J. (2024). High-threshold and low-overhead fault-tolerant quantum memory. *Nature*, *627*, 778-782.

[3] Fowler, A.G., Stephens, A.M., & Groszkowski, P. (2009). High-threshold universal quantum computation on the surface code. *Phys. Rev. A*, *80*(5), 052312.

[4] Freedman, M.H., Larsen, M., & Wang, Z. (2002). A modular functor which is universal for quantum computation. *Commun. Math. Phys.*, *227*, 605-622.

[5] Gottesman, D. (1996). Class of quantum error-correcting codes saturating the quantum Hamming bound. *Phys. Rev. A*, *54*(3), 1862.

[6] Gottesman, D. (2014). Fault-tolerant quantum computation with constant overhead. *Quantum Inf. Comput.*, *14*(15-16), 1338-1372.

[7] Hastings, M.B., Haah, J., & O'Donnell, R. (2021). Fiber bundle codes: Breaking the $n^{1/2}\mathrm{polylog}(n)$ barrier for quantum LDPC codes. In *STOC 2021: Proceedings of the 53rd annual ACM SIGACT symposium on theory of computing* (pp. 1276-1288). New York, NY: Association for Computing Machinery.

[8] Kitaev, A.Y. (2003). Fault-tolerant quantum computation by anyons. *Ann. Phys.*, *303*(1), 2-30.

[9] Panteleev, P., & Kalachev, G. (2021). Quantum LDPC codes with almost linear minimum distance. *IEEE Trans. Inf. Theory*, *68*(1), 213-229.

[10] Shor, P.W. (1995). Scheme for reducing decoherence in quantum computer memory. *Phys. Rev. A*, *52*(4), R2493.

Shawn X. Cui is an associate professor in the Department of Mathematics and Department of Physics and Astronomy at Purdue University. His research interests include quantum computing, topological quantum field theory, category theory, and low-dimensional topology.

Quantum Computing

Continued from page 1

similarly awaits advancements in theory, implementation, and hardware. Although the full societal impact of quantum technology is not yet actualized, both startup companies and large technology firms have created a variety of early quantum devices. Broadly speaking, there are three key areas of quantum technology: communication, computation, and sensing.

The presence of coherence in the quantum situation expands upon the idea of correlation in probability theory. Quantum correlation—commonly known as *entanglement*—is a stronger type of correlation with cryptographic implications. For example, if two communicators share entanglement, an eavesdropper will be detected when they perturb the correlations of the secure channel; this type of quantum networking has already seen some commercial deployments.

In quantum computing, coherence and entanglement are used to manipulate information. The construction of such a computing device requires the stabilization, manipulation, and readout of quantum information. These conditions present a difficult engineering problem because isolation from the environment often conflicts with responsive experimental controls. For computational purposes, the quantum system should remain in a state where its quantum probability density matrix has only one nonzero eigenspace. Noise from environmental interactions, control errors, or other stochastic processes will cause the density matrix to spread into additional eigenspaces.

While ideal quantum bits (qubits) should be easy to control yet insensitive to the environment, a nonideal qubit that is very sensitive to its environment can effectively serve as a sensor. Among other applications, quantum sensors can detect the presence of small magnetic fields, specific molecules, and even gravitational waves.

Ultimately, the use of coherence is the defining feature of all forms of quantum technology. This characteristic allows for stronger correlations between systems, faster computations, and increased sensitivity to microscopic changes in the environment.

Quantum Computation

The development of quantum computation arose in two major waves; the first wave consisted of quantum algorithms based on formal methods, and the second wave comprised quantum algorithms that were largely based on optimization methods. Quantum error correction evolved during the initial burst of activity. Because questions of quantum noise were considered only formally and shown to be theoretically surmountable, the first wave of quantum algorithms assumed noiseless quantum device operation (or fully quantum error-corrected systems). Two key algorithms emerged from this era: phase estimation and Grover's algorithm. Phase estimation, which constitutes the heart of Peter Shor's factoring algorithm, is largely responsible for driving the early conversation around quantum computing [3].

The availability of noisy intermediate-scale quantum (NISQ) computers inspired the second wave of quantum algorithms, which has yielded quantum tasks that rely on close integration with conventional computing to mitigate noise or extend the range of NISQ devices [2]. The intermediate scale of NISQ computers means that they possess on the order of tens to hundreds of qubits. Decoherence via either unwanted environmental interactions or control errors imposes a noisy functionality on these devices. This lack of control can prevent the full system from being entangled at once — especially as the number of qubits per device increases. Quantum error correction is thus a necessity. Researchers can combine many noisy qubits in an error correcting scheme to form a *logical qubit*. A nearly continuous effort of reading and resetting physical qubits then yields a logical qubit that can maintain its quantum state indefinitely.

Initial interest in the second wave of quantum algorithms centered on adiabatic annealing. Early expectations that adiabatic annealing would be resilient to noise led to optimism about an early quantum computing company called D-Wave Systems.[1] Due to limitations on the form of the final control Hamiltonian, D-Wave's superconducting qubit devices are not universal. However, lifting these limitations would equate adiabatic quantum computing with standard quantum computing models. Since D-Wave computers only solve classical problems, users are fundamentally testing the distinction between simulated and quantum annealing for computational advantages.

Universal quantum computers based on superconducting qubit devices, trapped ion devices, and neutral atom devices are all publicly available via the cloud. The outcomes of these machines are statistically sampled from identically prepared quantum density matrices. Before each sample, the same quantum instructions re-prepare the quantum probability density matrix. Researchers must then use the sampled outcome to solve computational problems based on the corresponding probability density matrix.

Since 2019, there have been several high-profile attempts to demonstrate tasks that quantum computers can perform but conventional computers cannot. Flagship experiments have implemented problems such as random circuit sampling and boson sampling on systems with more than 50 qubits. However, no public claims of quantum advantage have withstood scrutiny thus far.

Efforts to reach the elusive quantum advantage are generally thwarted in two key ways. First, advancements in the simulation of large, noisy quantum systems have enabled counterarguments that are usually based on tensor network methods, which efficiently compress and manipulate quantum states with low entanglement. Second, statistical spoofing has allowed conventional computing to keep pace with the results of flagship experiments. Spoofing algorithms do not attempt to find the right answer for the right reason; instead, they are optimized to exploit adversarial loopholes and obtain the highest statistical score on the defined benchmark.

[1] https://www.dwavesys.com

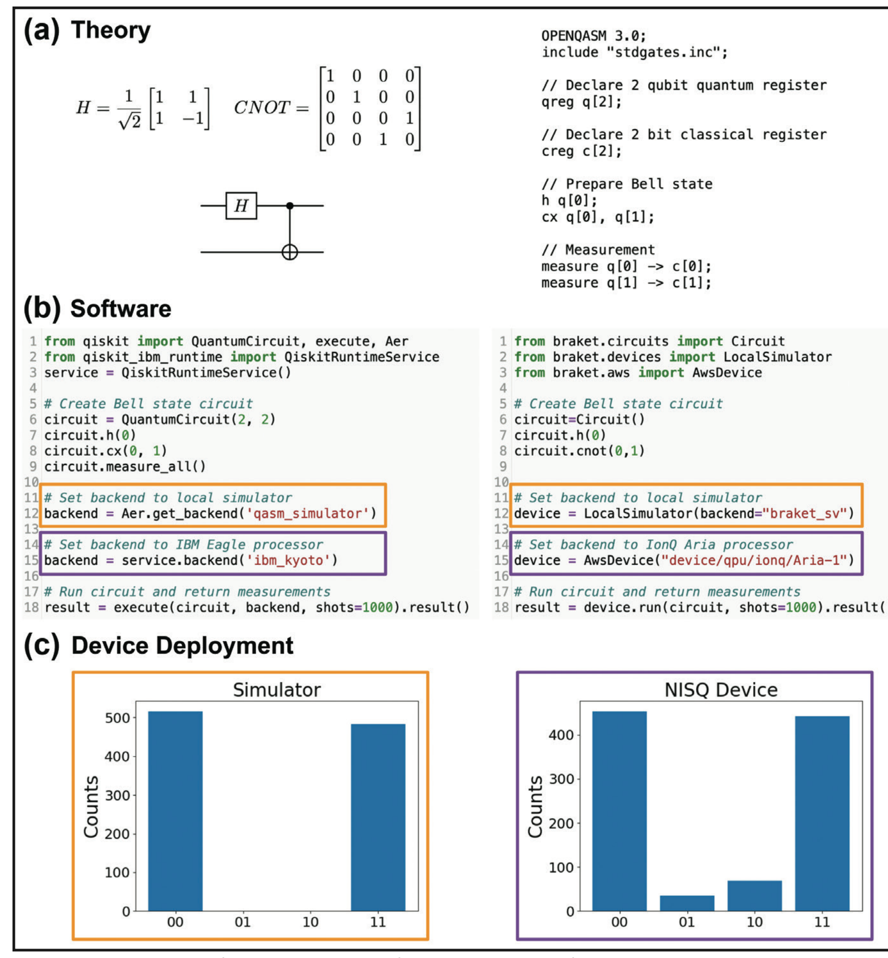


Figure 2. *Example of the progression from theory to software to the eventual deployment of a quantum algorithm that prepares and measures one of the Bell states (four maximally entangled quantum states of two quantum bits).* **2a.** *The first step involves the mathematical representation of quantum gates; a quantum circuit diagram visualizes the gate composition. Open Quantum Assembly Language (OpenQASM) is an intermediate representation of the circuit that is employed by many quantum software packages, such as Qiskit and Amazon Braket.* **2b.** *Possible backends include local simulators (orange box) or real quantum devices (purple box) that are accessed through the cloud.* **2c.** *Finally, practitioners can deploy the algorithm on a simulator or device and analyze the results. Current noisy intermediate-scale quantum devices do not render ideal measurement distributions due to noise. Figure courtesy of Casey Dowdle.*

Applied Mathematics and Quantum Algorithms

As theoretical physicist and mathematician Freeman Dyson once said, "Some mathematicians are birds, others are frogs. Birds fly high in the air and survey broad vistas of mathematics out to the far horizon … Frogs live in the mud below ... delight in the details of particular objects, and they solve problems one at a time" [1]. We need both broad landscape views and intimate knowledge to select and solve difficult problems in a variety of areas, especially as we extend the study of probability to the study of quantum mechanics, advance technology based on coherent quantum systems, and continue to explore the ambitions of quantum computing.

Although quantum theory has existed for an entire century, we still do not fully understand how this extension of probability affects computation and communication (see Figure 2a). As mentioned previously, identifying and demonstrating that a problem is uniquely solvable with quantum technology remains an open concern. This challenge raises questions that pertain to statistical measures, estimation theory, and correlations — all of which appear in applied mathematics. Similarly, the change from probability to quantum deeply affects the fundamentals of cryptography and communication.

The next level is the implementation of theory as software. Numerous software development kits, toolkits, and packages help programmers translate descriptions of algorithms into languages like Julia and Python. Figure 2b provides code snippets from two of the most popular quantum software development kits: Qiskit[2] and Amazon Braket.[3] Many interesting software engineering problems arise at this level of abstraction. For example, certain softwares can now emulate quantum devices via a variety of approaches that range from large matrix-vector multiplication to stochastic sampling methods. Excitingly, current research efforts can move beyond simulation with conventional computers to the utilization of nascent quantum devices.

The subsequent level involves the deployment of today's quantum technology. Cloud computing companies such as Amazon Web Services[4] offer paid access to existing quantum computing devices. The price, connectivity, quality, and physics of these qubit devices vary widely. Their physical qubits are not perfect, and the final result will exhibit physical noise in addition to statistical noise from the finite sample number (see Figure 2c). For this reason, active areas of research include noise mitigation, efficient statistical sampling, and optimal device-level compilation.

The connections between quantum theory, technology, and computation comprise a fantastic ecosystem for both "birds" and "frogs." "Birds" help us make new connections between known ideas in mathematics, engineering, machine learning, and other application areas. At the same time, we need "frogs" that can translate our understanding of quantum mechanics to quantum engineers, thus allowing them to continue their pursuit of practical quantum technology.

References

[1] Dyson, F.J. (2009). Birds and frogs. *Not. Am. Math. Soc.*, *56*(2), 212-223.

[2] Preskill, J. (2018). Quantum computing in the NISQ era and beyond. *Quantum*, *2*, 79.

[3] Shor, P.W. (1994). Algorithms for quantum computation: Discrete logarithms and factoring. In *Proceedings 35th annual symposium on foundations of computer science* (pp. 124-134). Santa Fe, NM: Institute of Electrical and Electronics Engineers.

Casey Dowdle is a Ph.D. student in mathematics at Dartmouth College. His research interests include quantum computing in the context of quantum chemistry, machine learning for many-body physics, and classical dynamics with quantum circuits. James Whitfield is an associate professor in the Department of Physics and Astronomy at Dartmouth. He holds a Ph.D. in chemical physics from Harvard University. For more than a decade, Whitfield has worked at the intersection of quantum chemistry and quantum computing; he currently explores quantum education in his joint appointment as an Amazon Visiting Academic.

[2] https://www.ibm.com/quantum/qiskit

[3] https://aws.amazon.com/braket

[4] https://aws.amazon.com/braket/quantum-computers

Challenges and Opportunities of Scaling Up Quantum Computation and Circuits

By Yuri Alexeev, Ankit Kulshrestha, and Ilya Safro

Rapid advancements in various quantum computing architectures have ignited a sense of cautious optimism about the realization of *quantum advantage*, especially as the field transitions from predominantly theoretical explorations to more applied functionalities. In addition to addressing challenges that pertain to single quantum bit (qubit) noise, fidelity, and decoherence, vendors are now emphasizing the *scalability* of their quantum systems as a critical component of their success. Current architectures—including trapped ions, superconducting circuits, and Rydberg atoms—face scalability hurdles in terms of the number of qubits and their fidelity [1]. These hurdles have inspired both academic and industry researchers to develop scaling strategies that are reminiscent of the early (but still relevant) stages of classical supercomputing. Here, we discuss some of quantum computing's opportunities and challenges in the realms of circuit optimization and scalability.

The design of compact quantum circuits plays an important role in the noisy intermediate-scale quantum (NISQ) computing era and the broader quest for scalable quantum systems. Compact circuits are essential because they enable the efficient use of existing NISQ devices that have a small number of physical qubits, limited connectivity between qubits, and moderate quantum gate fidelity. The design and implementation of compact quantum circuits can maximize the computational power of NISQ devices by permitting users to run larger quantum circuits, thus allowing for the investigation of more realistic problems with the overarching near-term goal of demonstrating quantum advantage. Compact quantum circuits are also crucial for scalability because they reduce the overhead that stems from adding more qubits or gates to a quantum system. Doing so both enables quantum computations on present NISQ devices and paves the way for the eventual construction and deployment of large, fault-tolerant quantum computers — ultimately ushering in a new era of quantum computing that can solve hard optimization problems and address complex challenges across various domains, from cryptography to finance [3].

Current NISQ machines have spawned a class of variational quantum algorithms that aim to solve optimization problems by using an optimization algorithm on a classical computer to adjust the parameters of a quantum circuit. The optimization methods for quantum circuits draw from existing optimization algorithms—such as gradient descent—and require that the quantum devices provide the current state of parameters and the associated gradient vector. In theory, the hybrid quantum-classical algorithm setup should be modular and workable with any optimization algorithm. But in the current era of quantum computing, several issues become apparent when users seek to deploy these systems.

The most challenging component of parameterized quantum circuits (PQCs) is the presence of *barren plateaus*: regions on the optimization surface that yield low-quality solutions and prevent further optimization. For an n-qubit quantum circuit that attempts to minimize a cost function $C(\boldsymbol{\theta})$, the variance of gradient is as follows:

$$\mathrm{Var}\left[\partial_k C(\boldsymbol{\theta})\right] \propto \left(\frac{\mathrm{Tr}\left(U^2\right)}{2^{3n}} - \frac{\mathrm{Tr}(U)^2}{2^{4n}}\right), \tag{1}$$

when any part of the circuit exhibits a unitary t-design [8]. A unitary t-design arises when $U \in \mathbb{U}(d)$ matches the Haar random distribution up to the first t moments. To better understand quantum t-designs, consider the expressiveness superoperator

$$\mathcal{A}^t(.) = \int_{\mathbb{U}(d)} dU_H U^{\otimes t}(.)(U^{\otimes t})^\dagger - \int_{\mathcal{U}} d\mathcal{U} U^{\otimes t}(.)(U^{\otimes t})^\dagger, \tag{2}$$

where the first term is computed over the Haar measure and the second is computed with the given quantum circuit [4, 9].

If $\left|\mathcal{A}^t(.)\right|_2^2 = 0$, the circuit exhibits a t-design. Concerningly, these t-designs occur even for shallow PQCs, and there is no obvious way to alleviate them. Although practitioners have proposed methods like identity initialization or the selection of initial parameters from a better distribution [7], a general solution does not yet exist. The role of optimization algorithms themselves in barren plateaus is an unexplored area of research, and any investigation in this direction could give rise to a proper quantum optimization algorithm and provide insight into the barren plateau phenomenon *during* the optimization process (as opposed to simply studying initial conditions).

Another angle that seems to promise some relief for the barren plateau problem is the design of algorithms for *circuit architecture search* that fit within a given constraint — e.g., better performance and less depth (see Figure 1). These algorithms must search for reusable motifs to help find general quantum circuit designs that perform well on a given task while consuming few resources. Improving circuit architecture search may allow researchers to scale the quantum circuit's processing ability to handle larger, more complex datasets without getting stuck in barren plateaus.

See **Scaling Up Quantum** *on page 7*

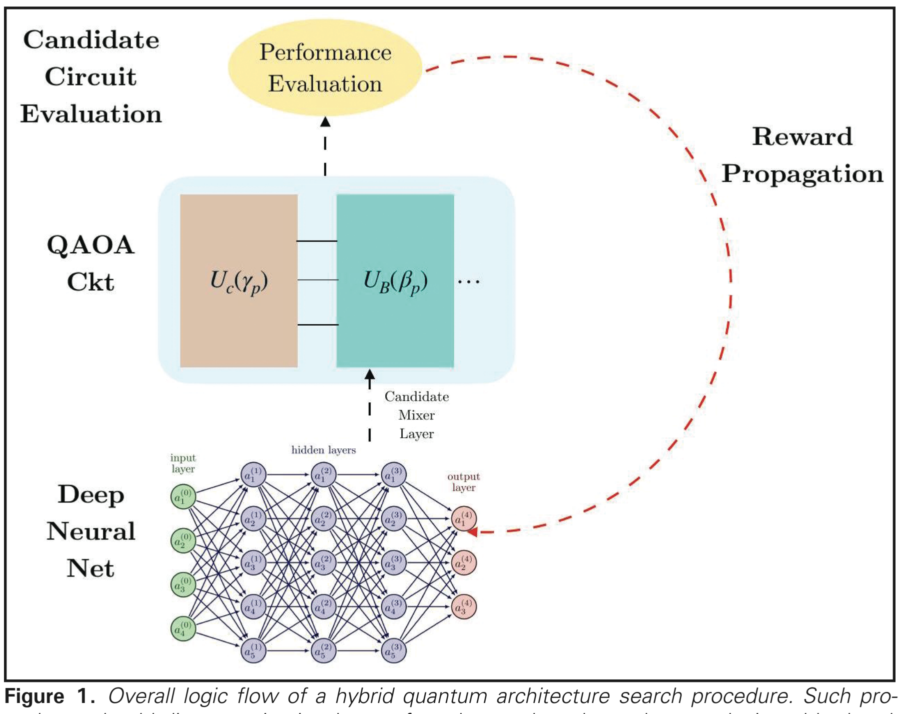


Figure 1. *Overall logic flow of a hybrid quantum architecture search procedure. Such procedures should discover circuits that perform better than those that are designed by hand. Figure courtesy of the authors.*

Nicholas J. Higham

Continued from page 2

Nick's appointment as the first non-U.S.-based member of the SIAM Council—on which he served two terms from 1996 to 2001—reflected his worldwide reputation within the applied mathematics community. He was elected to the SIAM Board of Trustees from 2006 to 2008 and served as SIAM president in 2017 and 2018. During his presidency, he wrote 20 "From the SIAM President" columns for *SIAM News*[11] that addressed a wide range of topics, from Bohemian matrices[12] to the color yellow.[13]

Nick also produced a long-running and hugely popular series of "What Is" blog posts[14] about fundamental areas of mathematics, maintained a widely followed X (formerly Twitter) account, and encouraged SIAM to develop a strong social media presence. He was an ardent proponent of creativity workshops and organized multiple events for both SIAM and his own research group. These experiences inspired his 2022 SIAM book with Dennis Sherwood: *How to Be Creative: A Practical Guide for the Mathematical Sciences*.[15]

Nick met his future wife, Françoise Tisseur, at a conference in Toulouse, France. They started dating in January 1996, got engaged 10 months later, and were married in France in May 1998 after Fran completed a postdoctoral position at the University of Tennessee. Nick and Fran were a perfect match, as they shared common interests within and outside the sphere of mathematics but also complemented one another in many other ways. Their sons Thomas and Freddie were born in 2003 and 2004. Nick was a wonderful father, playing an active role in their upbringing and taking a keen interest in their education. Thomas and Freddie are respectively pursuing degrees in mathematics and computer science at the University of Warwick and the University of York.

Nick's interests—which he always pursued wholeheartedly—extended well beyond the realm of applied math. For example, he and Fran maintained a beautiful garden and a separate allotment for fruits and vegetables. In his 30s, he took up photography — an activity that paired well with his frequent travel. Nick contributed photographs to Alamy,[16] a stock photography agency, and many of his shots have been used by its clients. Another point of enthusiasm for Nick was stationery, ranging from notebooks, pencils, pencil sharpeners, and fountain pens to erasers and blackboard chalk. His scholarship lent itself to a passion for topics such as dictionaries, indexing, punctuation, and typography, which—combined with his communication skills—resulted in his highest-selling SIAM book: 1993's *Handbook of Writing for the Mathematical Sciences*[17] (with a second edition in 1998 and a third edition in 2020).

One of the many remarkable features of Nick's life is that he generated his own momentum. He spent his entire career at the University of Manchester, living across the road from the sixth form (pre-university) college that he attended, and built a research group from scratch in his chosen field. Residing in Eccles also allowed Nick and Fran to spend valuable time with Nick's parents and care for them as they aged. Although it is impossible to sum up Nick's life and contributions in a single sentence, the words that stay with us when we think of Nick are creative, scholarly, humorous, down-to-earth, reliable, determined, and generous. He will be greatly missed by friends, family, colleagues, the SIAM community, and everyone who knew him.

For tributes and reflections from Nick's colleagues and members of SIAM staff, please see "Remembering Nick Higham: 1961-2024" on page 6.

References

[1] Coles, A., & Roell, S. (2016, April 27). The best books on applied mathematics recommended by Nick Higham. *Five Books*. Retrieved from https://fivebooks.com/best-books/nicholas-higham-applied-mathematics.

[2] Higham, N.J. (2002). Computing the nearest correlation matrix—a problem from finance. *IMA J. Numer. Anal.*, *22*(3), 329-343.

Desmond J. Higham is a professor of numerical analysis in the School of Mathematics at the University of Edinburgh. Françoise Tisseur is a professor of numerical analysis in the Department of Mathematics at the University of Manchester.

Nick Higham spends quality time with his wife and sons at a family wedding in 2023. From left to right: Thomas Higham, Françoise Tisseur, Nick Higham, and Freddie Higham. Photo courtesy of Jérémie Laye Photography.

11 https://sinews.siam.org/About-the-Author/nicholas-j-higham
12 https://sinews.siam.org/Details-Page/rhapsodizing-about-bohemian-matrices
13 https://sinews.siam.org/Details-Page/theres-something-about-yellow
14 https://nhigham.com/blog
15 https://nhigham.com/how-to-be-creative-a-practical-guide-for-the-mathematical-sciences
16 https://go.siam.org/AzeQlq
17 https://nhigham.com/handbook-of-writing-for-the-mathematical-sciences

Remembering Nick Higham: 1961-2024

In January 2024, the SIAM community suffered a major loss with the passing of longtime member and former SIAM president Nicholas J. Higham. Nick was an exceptional applied mathematician, communicator, mentor, colleague, and friend. His dedication and contributions to SIAM were unparalleled, and he approached every role, conversation, and research challenge with an intentional level of care that is a testament to his character. Here, a collection of friends, colleagues, and SIAM staff share their reflections, tributes, and memories of Nick.


From left to right: Nick Higham, George Hall of the University of Manchester (Nick's Ph.D. supervisor), and Charlie Van Loan of Cornell University gather for a photo at the conference on "Advances in Numerical Linear Algebra: Celebrating the 60th Birthday of Nick Higham," which was held in July 2022 at the University of Manchester. Nick is wearing a Bohemian matrix eigenvalue tie, which was a gift from Rob Corless of the University of Western Ontario. Photo courtesy of Desmond Higham.

"A former SIAM president once described his role as a "figurehead:" the head of the organization who was elected to represent the SIAM membership. The person in that role should exemplify the best of our discipline in every sense. In that regard, Nick was an ideal president.

Another connotation of the term "figurehead" is a leader without real power. It is true that the SIAM president is but one member of the Board of Trustees: the Society's ultimate authority. But the president also chairs the SIAM Council, speaks with authority as the chief elected officer, and directs the organization through his or her interests and thoughts about what is best for SIAM. In that sense, Nick brought a wealth of experience and a depth of care as president.

Nick cared deeply about SIAM and its publications, communications, and students. Books were one of his major passions, and he worked tirelessly to bolster the SIAM book program and strengthen SIAM journals. He chaired SIAM's Book Committee for seven years and remained a member of the committee until this year.

Nick was also invested in communications. One need only look at his presence on Twitter (now X) to understand his desire to share the wonders of linear algebra with a broad audience, and especially students. His interest in communicating applied mathematics also came to bear on *SIAM News* and the SIAM website, and he often worked with staff to ensure modern and lively communications.

As SIAM president, Nick knew where he wanted to go and what he wanted to do. He even initiated a strategic planning exercise that brought together many SIAM leaders to explore new initiatives and objectives during a weekend retreat. This led to multiple novel ideas for student programs, plans to strengthen industrial representation in SIAM, and several new directions for the SIAM Board and Council.

Nick had already served SIAM in many ways before being elected as president for 2017 and 2018. He was a member of the Committee on Programs and Conferences for six years and served on SIAM's Board of Trustees from 2006 to 2009. He was then elected as SIAM's Vice President-at-Large from 2010 to 2013 and was deeply involved with the Major Awards Committee and various activity groups during his tenure.

Nick's dedicated service to SIAM covered all major activities: books, journals, awards, activity groups, conferences, and *SIAM News*. Of course, this commitment stemmed from Nick's passion for his own research area of numerical linear algebra. He chaired the SIAM Activity Group on Linear Algebra from 2001 to 2003 and was an associate editor for the *SIAM Journal on Matrix Analysis and Applications* from 1989 to 2012; his atypically long stint was no doubt due to his editorial expertise and dedication.

Nick was not just a figurehead; he was a dedicated and major contributor to SIAM throughout his entire career. His presence will be missed by all of us who served with him." – *Jim Crowley, former executive director of SIAM*

"When I think of Manchester, I think of Nick. He loved the city and spent his entire life in its environs. He also loved the university and developed his entire academic career on its campus. There is something poetic and touching about these alignments. The industrial revolution began in Manchester and redefined how we work; Nick took that to a whole new level! The University of Manchester is famous for its role in the history of computing, and Nick has certainly added to that legacy.

This all comes together beautifully as a story, but it doesn't explain Nick's exquisite sense of humor or extraordinary ability to communicate, write, and win arguments with tact and grace. These gifts are the consequence of a very special family and circle of loved ones.

A story that Nick shared with me many years ago speaks to his essential character. As an eight-year-old boy, he was dissatisfied with his enrollment at a distant elementary school. So one day, he simply got off the bus, skipped class, and walked the 15 miles back to his home just to make a statement. Classic NJH!" – *Charlie Van Loan, Cornell University*

"Nick was serving as president when I joined the SIAM staff, and I had the privilege of getting to know him through many SIAM Board and Council meetings, as well as through his committed and generous work on the SIAM books program. I quickly realized that Nick was a rare person indeed — brilliant in his analysis and attention to detail, yet so clear and down-to-earth in his communication style. His deep passion for SIAM—and particularly for the publications program—helped me understand very early on why so many people call the SIAM community their intellectual home.

Nick made many wonderful contributions as a highly successful SIAM book and journal author, a longtime member of the editorial board for the *SIAM Journal on Matrix Analysis and Applications*, and a provider of sound advice on general editorial matters. He wrote two of SIAM's all-time bestsellers, both of which are now in their third editions: *Handbook of Writing for the Mathematical Sciences* and *MATLAB Guide*, the latter of which is fittingly coauthored with his brother, Des Higham. More recently, Nick coauthored a fascinating book with Dennis Sherwood called *How to Be Creative: A Practical Guide for the Mathematical Sciences*.

But the topics of these books reflect something deeper about Nick; he was not just focused on his own research and always had great passion and talent for helping others improve their skills and develop their ideas. In this way, Nick sought to raise all boats, and the SIAM community is stronger for it.

Thank you, Nick, for the many chats over the years. My team and I miss your energy, ideas, and good humour." – *Kivmars Bowling, Director of Publications at SIAM*

"Nick was of course an outstanding research leader in numerical analysis, but he was also a deeply kind man and I am honoured to say something about the brief time that I spent with him.

I can't remember when I first met Nick in person, but we hit it off very quickly. Even though he was a giant in his field, he took great interest in my work as a junior member of academic staff in a different discipline. We had deep technical discussions but also spoke about careers, my role as a school governor, his sons' school, and mathematician Jim Wilkinson's work. Nick and I further bonded over our shared joy of mechanical calculating machines. One of my favourite conference experiences was attending the SIAM Conference on Computational Science and Engineering with Nick.

Nick was also a profoundly practical person. Once I shared some numerical observations with him that he found surprising — a few days later he had coded up an example, verified this behaviour, and written a *SIAM News* column about it! He even sent me LaTeX tips for slides; his own presentations were always a model of clarity and depth.

Nick touched my research life more deeply than most. At some point I had wanted to take a sabbatical leave with him in the future. I thought there would be plenty of time." – *George Constantinides, Imperial College London*

"Nick was dedicated to the SIAM books program, and I interacted with him significantly over the years. After a book published, there was always the chance that he would send a "dreaded email:"

- "I found some more copy-editing problems … it's worrying that they were not caught."
- "There is a major problem … how could this have been allowed to happen?"
- "Disappointed to see … this should have been picked up by the copy editor."

After one such email, he sent a two-page document with "more quibbles!"

But the generous emails far outweighed the dreaded ones:

- "Congratulations! It's a wonderful addition to the literature and to SIAM's catalogue. And a great example to other SIAM book authors of how to produce informative and readable figures."
- "I'm happy to do the panel again any time! If we get one new book as a result, it's worth it."
- "I'm ok with the book … not everything it says … would I fully agree with, but then, I have that feeling about many things I read."

And Nick had a wonderful sense of humor. "If Tim sees this, he'll be off to upgrade his Ferrari," he wrote when my typo increased a book's reported sales by 10,000 copies. He even used emoticons!

I miss Nick for all of the obvious reasons. He was unfailingly generous with his time, advice, and encouragement — I treasure an email from him that ends with "well done!" But I also miss him because of the things unsaid and questions unanswered." – *Elizabeth Greenspan, executive editor, SIAM Book Acquisitions*

"Nick was not just a good friend, colleague, and mentor; he was exceptional in every role he took on. I first crossed paths with him in the usual course of professional engagements: attending meetings, delving into his books and papers, and so forth.

As time progressed, our acquaintance deepened. In 2007, a proposal for a joint position at Manchester—shared between the Department of Mathematics and Department of Computer Science—was put forth by Nick and John Gurd. I found myself aligning more closely with Nick and his wife, Fran, ultimately becoming a Turing Fellow in the Department of

See **Remembering Nick Higham** *on page 8*

Take Advantage of SIAM's Visiting Lecturer Program

Hearing directly from working professionals about research, career opportunities, and general professional development can help students gain a better understanding of the workforce. SIAM facilitates such interactions through its Visiting Lecturer Program (VLP), which provides the SIAM community with a roster of experienced applied mathematicians and computational scientists in academia, industry, and government. Mathematical sciences students and faculty—including SIAM student chapters—can invite VLP speakers to their institutions to present about topics that are of interest to developing professional mathematicians. Talks can be given in person or virtually.

The SIAM Education Committee[1] sponsors the VLP and recognizes the need for all members of our increasingly technological society to familiarize themselves with the achievements and potential of mathematics and computational science.

Points to consider in advance when deciding to host a visiting lecturer include the choice of dates; speakers; topics; and any additional or related activities, such as follow-up discussions. Organizers can reach out directly to speakers and must address these points when communicating with them. It is important to familiarize lecturers with their audience—including special interests or expectations—so they can refine the scope of their talks, but just as crucial to accommodate speakers' suggestions so the audience can capitalize on their experience and expertise. Read more about the program and view the current list of participants online.[2]

[1] https://www.siam.org/about-siam/committees/education-committee
[2] https://www.siam.org/students-education/programs-initiatives/siam-visiting-lecturer-program

Scaling Up Quantum

Continued from page 5

As previously mentioned, a challenging, underexplored direction of variational quantum algorithms is the optimization algorithm's role in addressing the barren plateau and the scalability of quantum circuits. The current theory of barren plateaus is predicated upon the implicit assumption that the optimizer for parameter updates is itself robust to noise; however, this postulation is often not true in practice. For example, optimizers like stochastic gradient descent and adaptive moment estimation produce suboptimal updates when the gradient is noisy [5]. In contrast, the *quantum natural gradient optimizer* [10] exhibits much better performance because it computes the Fubini-Study metric tensor for each step of gradient descent. A pure quantum optimizer would take advantage of the structure in quantum density matrices and unitary gates to update parameters, while also requiring fewer measurements and remaining more robust to any type of noise in quantum circuits; the development of such an optimizer would help address the need for scalability in quantum computing. Furthermore, leveraging gradient-free optimization and learning is another underexplored area that could significantly benefit from the insights of classical gradient-free numerical optimization research [6].

The novel *adaptive approach* to quantum computing allows scientists to design compact quantum algorithms that can adapt to specific problems and NISQ device constraints. This ability is in contrast to traditional quantum algorithms, which are meant to solve general problems and may not be optimal in terms of efficient, compact circuit design. Traditional algorithms often do not account for the shortcomings of NISQ devices, such as the limited number of physical qubits, qubit connectivity, and the fidelity of gate operations.

Although it is still under development, the adaptive approach offers several advantages over traditional quantum algorithms and has been successfully applied in the variational quantum eigensolver and the Quantum Approximate Optimization Algorithm [2, 11]. First, this technique can lead to more efficient and compact algorithms that are tailored to the specific problem at hand. And because the algorithm can adapt to the noise characteristics of the hardware, the adaptive approach is more robust to noise. Users can also modify the algorithm for different hardware constraints, which makes the tactic more flexible than traditional methods. But a downside is that designing compact quantum circuits, which requires an enormous number of gradient evaluations, can be both time consuming and nonscalable.

The scale of problems in the realm of real-life scientific computing, optimization, and machine learning will undoubtedly remain vast, dwarfing even the most optimistic projections for the number of qubits or quantum volume of future architectures. Decomposition algorithms will hence retain their relevance, but the mechanics of communication will likely undergo a transformation. The area of parallelization faces unique challenges and opportunities in this context. The no-cloning theorem states that we cannot create an identical copy of an arbitrary quantum state. Consequently, if a large-scale problem domain is decomposed and separate quantum machines handle its individual parts, the transmittal of information from one quantum processing unit to another via quantum teleportation necessitates the destruction of what has been transmitted at the source. Methods like the EPR pair of qubits for teleportation (named after the Einstein-Podolsky-Rosen paradox) can achieve this transfer with remarkable speed. Consequently, we are on the brink of reimagining parallel computing with the underlying assumption of extremely fast communication, but with the caveat that such communication cannot duplicate arbitrary information. Another largely unexplored area is the use of quantum and hybrid quantum-classical algorithms to initialize classical numerical methods and vice versa. Ultimately, we will continue to encounter new avenues for exploration as we reconsider algorithmic architectures such as multilevel and multiscale algorithms, domain decompositions, domain adaptations, and data reduction.

References

[1] Alexeev, Y., Bacon, D., Brown, K.R., Calderbank, R., Carr, L.D., Chong, F.T., … Thompson, J. (2021). Quantum computer systems for scientific discovery. *PRX Quantum*, *2*(1), 017001.

[2] Grimsley, H.R., Economou, S.E., Barnes, E., & Mayhall, N.J. (2019). An adaptive variational algorithm for exact molecular simulations on a quantum computer. *Nat. Commun.*, *10*(1), 3007.

[3] Herman, D., Googin, C., Liu, X., Sun, Y., Galda, A., Safro, I., … Alexeev, Y. (2023). Quantum computing for finance. *Nat. Rev. Phys.*, *5*, 450-465.

[4] Holmes, Z., Sharma, K., Cerezo, M., & Coles, P.J. (2022). Connecting ansatz expressibility to gradient magnitudes and barren plateaus. *PRX Quantum*, *3*(1), 010313.

[5] Kingma, D.P., & Ba, J. (2014). Adam: A method for stochastic optimization. Preprint, *arXiv:1412.6980*.

[6] Kulshrestha, A., Liu, X., Ushijima-Mwesigwa, H., & Safro, I. (2023). Learning to optimize quantum neural networks without gradients. In *2023 IEEE international conference on quantum computing and engineering (QCE)* (pp. 263-271). Bellevue, WA: IEEE Computer Society.

[7] Kulshrestha, A., & Safro, I. (2022). BEINIT: Avoiding barren plateaus in variational quantum algorithms. In *2022 IEEE international conference on quantum computing and engineering (QCE)* (pp. 197-203). Broomfield, CO: IEEE Computer Society.

[8] McClean, J.R., Boixo, S., Smelyanskiy, V.N., Babbush, R., & Neven, H. (2018). Barren plateaus in quantum neural network training landscapes. *Nat. Commun.*, *9*(1), 4812.

[9] Sim, S., Johnson, P.D., & Aspuru-Guzik, A. (2019). Expressibility and entangling capability of parameterized quantum circuits for hybrid quantum-classical algorithms. *Adv. Quantum Technol.*, *2*(12), 1900070.

[10] Stokes, J., Izaac, J., Killoran, N., & Carleo, G. (2020). Quantum natural gradient. *Quantum*, *4*, 269.

[11] Zhu, L., Tang, H.L., Barron, G.S., Calderon-Vargas, F.A., Mayhall, N.J., Barnes, E., & Economou, S.E. (2022). Adaptive quantum approximate optimization algorithm for solving combinatorial problems on a quantum computer. *Phys. Rev. Res.*, *4*(3), 033029.

Yuri Alexeev is a computational scientist at Argonne National Laboratory, a senior scientist at the University of Chicago, and a principal investigator at Q-NEXT: a National Quantum Information Science Research Center. His current research explores the development of quantum computing algorithms, artificial intelligence for error correction/mitigation, and quantum circuit simulators of quantum systems via high-performance computing for next-generation supercomputers. Ankit Kulshrestha is a senior research scientist at Fujitsu Research of America. His areas of interest include quantum computing and machine learning, with a focus on machine learning techniques to scale the abilities of quantum circuits. Ilya Safro is an associate professor in the Department of Computer and Information Sciences and the Department of Physics and Astronomy at the University of Delaware. His research interests include quantum computing, graph algorithms, large-scale optimization, machine learning, and natural language processing.

Running in the Rain

MATHEMATICAL CURIOSITIES
By Mark Levi

What is the optimal speed of getting from A to B in the rain? By "optimal," I mean picking up as little water as possible. Let's ignore other considerations—such as the duration of discomfort weighted against the pain of running too fast—and assume that everything happens in two dimensions, and that the rain falls vertically. Given these assumptions, our connection to reality is of course tenuous.

After recently getting caught in the rain, I realized that the above question has a clean geometrical answer: *run with the speed at which the endpoints of the wet arc lie on the same vertical* (see Figure 1). To restate this recipe, consider the longest vertical chord (dashed lines in Figure 1) and let m be the common slope of the tangents at the endpoints of this chord (these slopes are the same for the longest chord). The optimal speed is then such that the rain seems to be incoming at slope m. Equivalently,

$$v_{\text{best}} = \frac{v_{\text{rain}}}{m}.$$

Explanation of the Recipe

The amount of water that one picks up while running from A to B is proportional to the shaded area in Figure 2 swept by the "leading arc," which in turn equals the area of the parallelogram LD. Since D is fixed, our goal is to minimize L (see Figure 3). We will now show that L is minimized when the tangency points in Figure 3 lie on the same vertical. To that end, let us differentiate L with respect to θ (see Figure 4):

$$L'(\theta) = y_1' - y_2' = r_1 \cos\theta - r_2 \cos\theta.$$

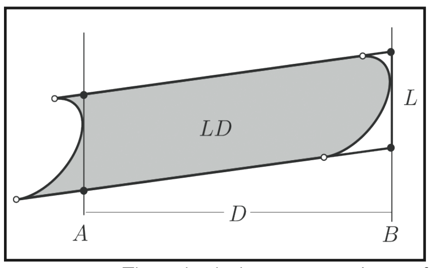


Figure 2. *The shaded area consists of the drops that will hit the runner during the run from A to B. This area equals the area LD of the parallelogram, bounded by the vertical lines and the lines of slope $m = v_{\text{rain}}/v_{\text{run}}$ (the direction of the rain in the runner's frame).*

Figure 4b explains the last equality. The minimal L thus corresponds to $r_1 = r_2$, which is equivalent to the statement that T_1T_2 is vertical. This completes the justification of the recipe for the maximally dry run.

As a concluding remark, one of the standard calculus problems asks the aforementioned question in the case when the runner is a vertical segment. In this case, the contact points[1] with the sloped lines are automatically on the same vertical. This holds for any slope, which means that the amount of water picked up is the same for any speed. Of course, this is clear directly from the fact that L—and thus the area LD of the parallelogram—does not depend on m, and the reference to the recipe is not needed.

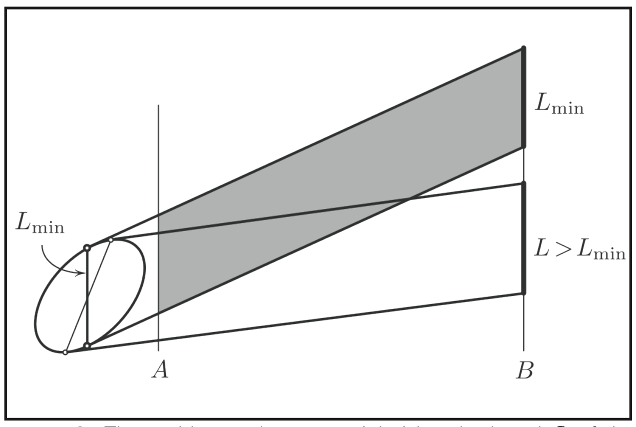


Figure 3. *The problem reduces to minimizing the length L of the "shadow" that is cast on the vertical line by varying the slopes. The smallest slope L corresponds to the smallest area and thus to the least amount of accumulated water.*

The figures in this article were provided by the author.

Mark Levi (levi@math.psu.edu) is a professor of mathematics at the Pennsylvania State University.

[1] Counterparts of tangency points. I could have mentioned that the curve in Figure 1 can have corners, in which case we would speak of supporting lines instead of tangency lines.

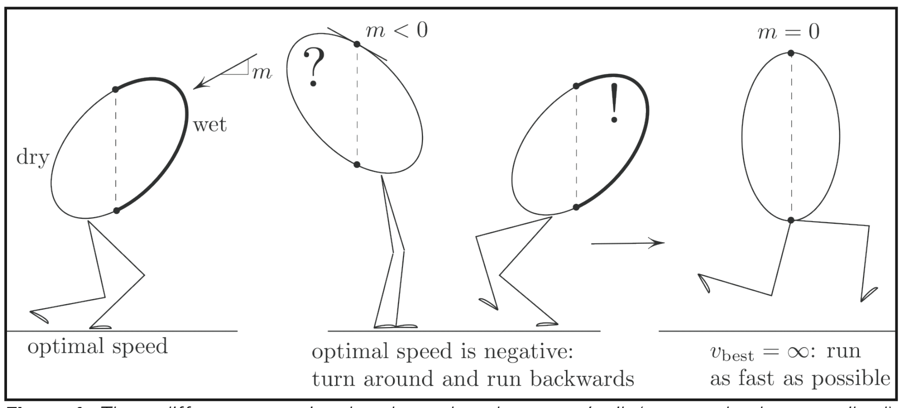


Figure 1. *Three different scenarios that depend on the runner's tilt (assumed to be prescribed).*

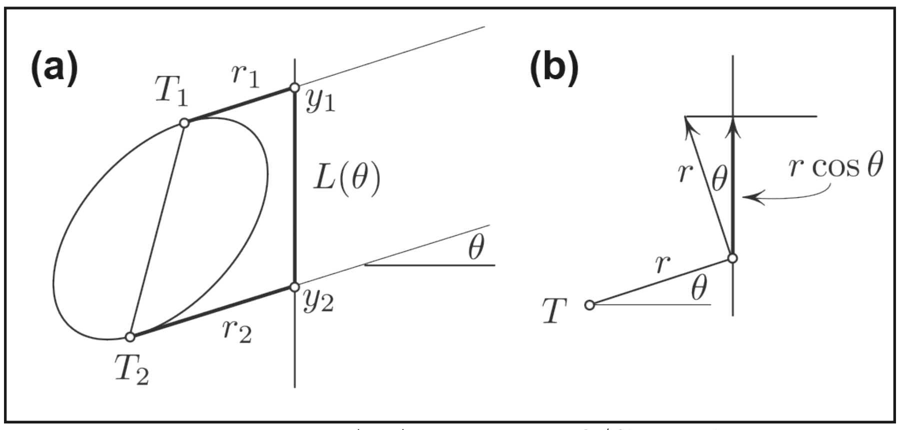


Figure 4. *$r_2 > r_1$ (in **4a**) implies that $y_2' > y_1'$, as follows from $dy/d\theta = r\cos\theta$ (in **4b**).*

Remembering Nick Higham

Continued from page 6

Mathematics. Our collaboration blossomed across numerous projects.

Nick's unwavering dedication to nurturing excellence and supporting others—regardless of their background or career stage—set a standard for community and leadership. He was approachable, insightful, and congenial. Over time, our connection evolved into a partnership that was marked by mutual intellectual curiosity, research collaboration, and mentorship.

Our journey together traversed various technical domains, from numerical linear algebra to high-performance computing and program analysis, and ultimately our exploration of mixed-precision computing. We engaged in spirited debates about complex technical challenges, both of us always enriched by the exchange.

While Nick's research contributions were significant, his leadership within the community was equally remarkable. His dedication to SIAM, including his presidency in 2017 and 2018, was especially notable.

Nick's impact was profound in countless ways. His legacy—in both his work and our friendship—will endure, but his absence will be keenly felt. He was more than a mentor, colleague, and friend; he was an inspiration." – *Jack Dongarra, University of Tennessee*

"Nick established and led a world-leading research group in numerical analysis at Manchester, and we were both lucky to join this group in the early 2010s. At that time, Nick held a European Research Council Advanced Grant that helped create a vibrant research environment and attract many Ph.D. students and postdocs. It is hard to imagine a better place to be a young researcher. Nick ensured that the group's activities were visible and recognized; he co-organized several well-attended international workshops in Manchester that got everyone involved. His 60th birthday conference in 2022 featured more than 30 speakers from around the world — a true recognition of the number of careers he influenced throughout the years. And while much of that activity was due to Nick's reputation and high professional standing, his humble leadership provided room for group members to establish their own research programmes.

But Nick and his wife Fran created more than a successful research group. They nurtured a thriving community of young researchers with enduring friendships that extend across the globe. Thanks to their dedication, Manchester has been a place of warm hospitality and inspiration for generations of students, postdocs, colleagues, and visitors.

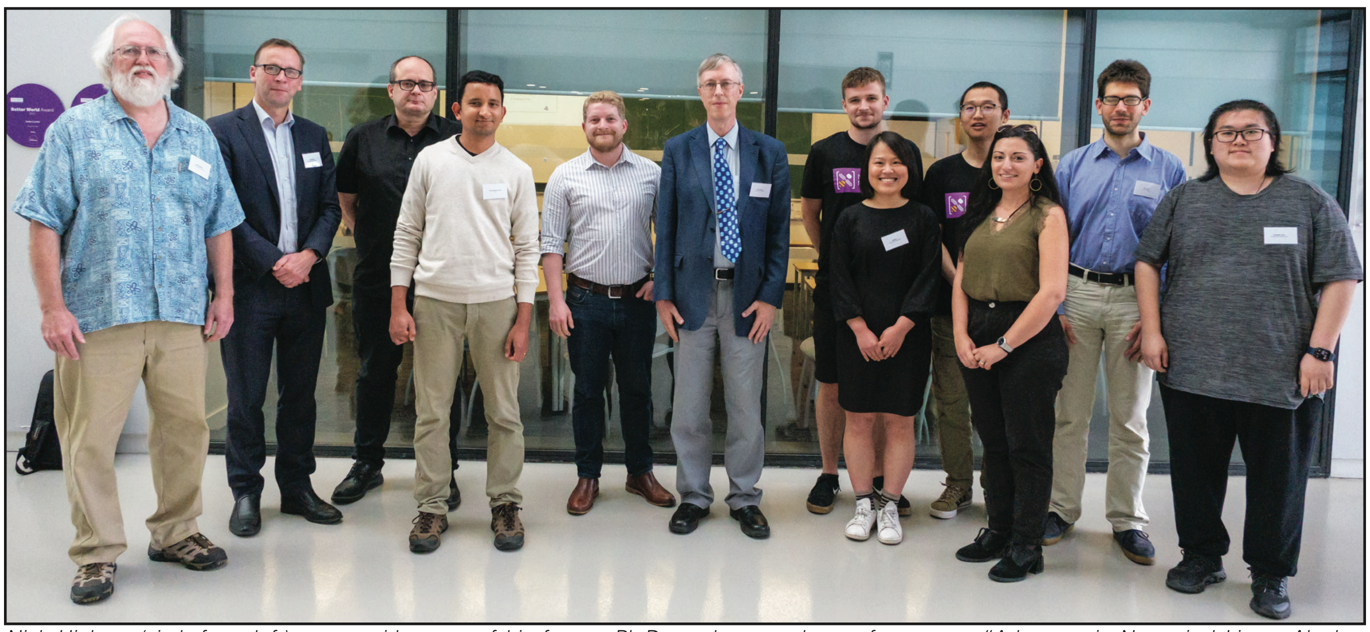
Nick leaves behind a lasting legacy of excellence, generosity, and kindness. His memory will live on in our hearts and minds." – *Stefan Güttel, University of Manchester and Mary Aprahamian Güttel, Slalom*

"Nick was a wonderful friend to SIAM who took a special interest in *SIAM News*. When he visited the Philadelphia office during his presidency—and he did so numerous times—he often had lunch with *SIAM News* staff. He was an excellent conversationalist with broad interests; our chats covered a wide variety of topics, from hobbies and personal anecdotes to the publication process, social media, and the *SIAM News* blog. He wrote 20 "From the SIAM President" columns for *SIAM News* in 2017 and 2018: one for each issue that published while he was president. Working with Nick was an absolute pleasure; his prose communicated his own passions in an accessible manner and he had a keen eye for layout, color, and general aesthetics.

I was always so glad to run into Nick at a SIAM conference. No matter how busy he was, he made time for a quick catch-up session and took a personal interest in everyone with whom he interacted. When he found out that I was engaged to be married, he sent a sweet congratulatory email; he then followed up after the wedding to ask for photos. I felt so touched that he remembered.

It's difficult to wrap my head around the fact that I won't be seeing Nick's friendly face during a coffee break at a future SIAM Annual Meeting. His passing is an enormous loss to both SIAM and the larger applied mathematics community, but the legacy he leaves behind will undoubtedly continue to influence and shape upcoming generations. Nick, you are greatly missed." – *Lina Sorg, managing editor, SIAM News*

On behalf of the entire SIAM community, we extend our sincere condolences to Nick's family. See page 2 for an obituary—written by Nick's brother, Desmond Higham, and his wife, Françoise Tisseur—that overviews Nick's extraordinary career, accomplishments, and personal interests.



Nick Higham (sixth from left) poses with some of his former Ph.D. students at the conference on "Advances in Numerical Linear Algebra: Celebrating the 60th Birthday of Nick Higham," which took place at the University of Manchester in July 2022. Attendees of this international workshop came together to honor Nick's birthday and discuss current developments in the field of numerical linear algebra. Photo © Nick Higham.

Congratulations 2024 SIAM Fellows!

SIAM is pleased to announce the newly selected Class of SIAM Fellows—a group of distinguished members of SIAM who were nominated by their peers for exceptional contributions to the fields of applied mathematics, computational science, and data science. Please join us in congratulating these 26 members of our community.

Peter Ashwin
University of Exeter

Heinz Bauschke
University of British Columbia

David Samuel Bindel
Cornell University

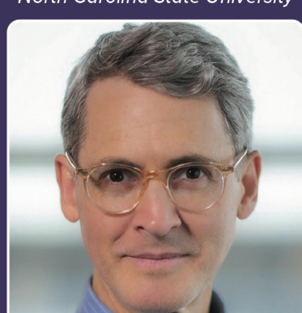
Jie Chen
City University of Hong Kong

Patrick L. Combettes
North Carolina State University

Hans De Sterck
University of Waterloo

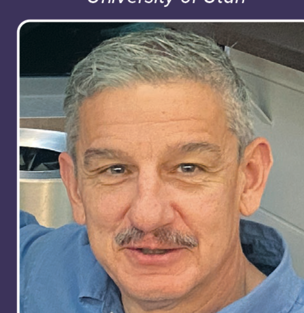
Aaron L. Fogelson
University of Utah

Hélène Frankowska
CNRS and Sorbonne University

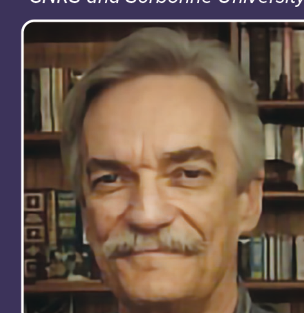


Michael P. Friedlander
University of British Columbia

Daniel Kráľ
Masaryk University



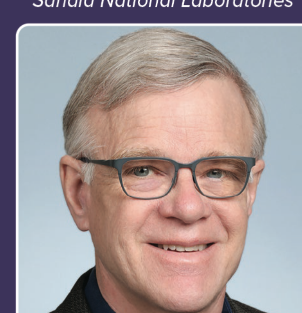
Richard B. Lehoucq
Sandia National Laboratories



José Mario Martínez
State University of Campinas

Deanna Needell
University of California Los Angeles

Cornelis W. Oosterlee
Utrecht University



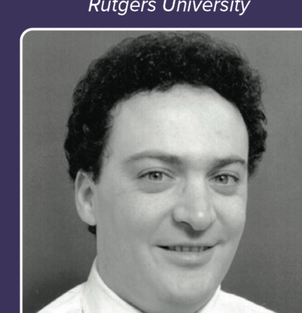
Art B. Owen
Stanford University

Fred S. Roberts
Rutgers University

Joachim Rosenthal
University of Zurich

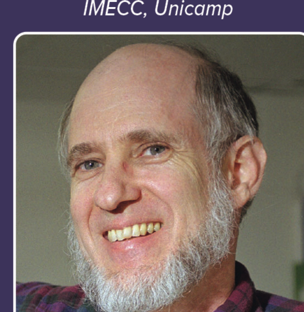
Claudia Sagastizábal
IMECC, Unicamp

Carola-Bibiane Schönlieb
University of Cambridge

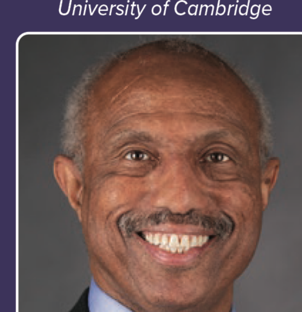


Mark S. Squillante
IBM Thomas J. Watson Research Center

Luis Nunes Vicente
Lehigh University



Layne Terry Watson
Virginia Polytechnic Institute and State University



Nathaniel Whitaker
University of Massachusetts

Chao Yang
Lawrence Berkeley National Laboratory

Ulrike Meier Yang
Lawrence Livermore National Laboratory

Lexing Ying
Stanford University

siam Fellow

Learn more about these esteemed individuals and nominate a colleague by October 16, 2024 for the 2025 Class of SIAM Fellows:

siam.org/prizes-recognition/fellows-program

Moving Memoir by an AI Pioneer

The Worlds I See: Curiosity, Exploration, and Discovery at the Dawn of AI. *By Fei-Fei Li. Flatiron Books, New York, NY, November 2023. 336 pages, $29.99.*

BOOK REVIEW
By Ernest Davis

The extraordinary advances in artificial intelligence (AI) technology over the last decade are largely due to three factors: (i) Improvements in machine learning algorithms, primarily deep learning but also reinforcement learning and transformer architectures; (ii) improvements in computer hardware, particularly graphics processing units; and (iii) the availability of enormous datasets to train AI systems. Fei-Fei Li, a professor of computer science at Stanford University, is a pioneer in the creation of large, high-quality datasets for AI—particularly for computer vision—and the art of building them via crowdsourcing. *The Worlds I See: Curiosity, Exploration, and Discovery at the Dawn of AI* is Li's memoir of her life and labors.

In terms of literary quality, I don't think I've ever read a better-written scientific biography or memoir than *The Worlds I See* (some credit is presumably due to Li's writing partner, Alex Mitchell). Li's portraits of her parents and Bob Sabella—her high school math teacher and close friend until his untimely death—are warmhearted, insightful, moving, and vivid. Equally compelling is her account of the difficulties that she and her family faced immediately after emigrating to the U.S.

The scientific exposition in *The Worlds I See* is always clear and engaging, though not especially deep; in fact, the book is intended for a general readership. A long digression on zoologist Andrew Parker's theory of the centrality of vision in animal evolution during the Precambrian era becomes almost lyrical:

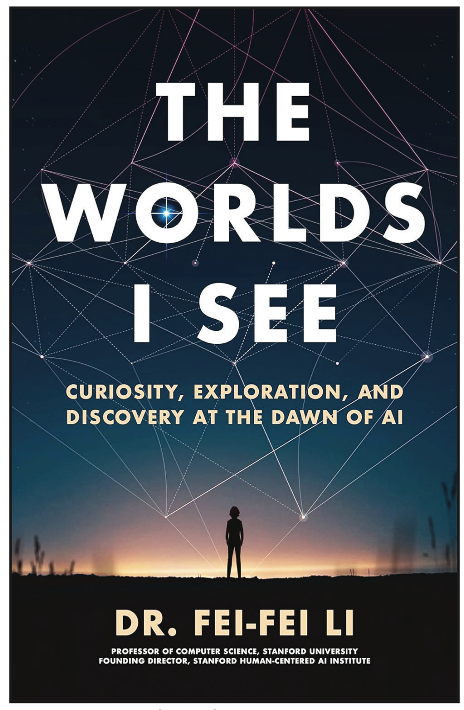
> Photosensitivity was a turning point in the history of life on Earth. By simply letting the light in—to any degree, no matter how dim or formless—our evolutionary predecessors recognized, for the first time, that there was something *beyond* themselves. And, more urgently, they saw that they were engaged in a struggle to survive, with more than one possible outcome. They were awakening to a harsh environment in which threats and opportunities alike abounded, competition for resources was increasing, and their own actions meant the difference between eating and being eaten.

Li wonderfully conveys the atmosphere of scientific study and research and the intense satisfactions, disappointments, thrills, and frustrations that accompany it. She writes without false modesty or self-aggrandizement. She is forthright about her abilities, hard work, and accomplishments but simultaneously upfront regarding her own good fortune and debts to predecessors, teachers, colleagues, and students.

Li was born in Beijing in 1976 and grew up in Chengdu, China. When she was 12, her family emigrated to the U.S. and settled in Parsippany, N.J., where they lived in a cramped apartment on her parents' small incomes as shop assistants. While completing high school and learning English as a second language, Li combined a modest income from a restaurant job with housekeeping and dog walking. Fortunately, she found a mentor and friend in her math teacher, Bob Sabella. In her final year of high school, she was accepted to Princeton University with a near-full scholarship. Although Li felt socially isolated at Princeton—in part because of her classmates' wealth—she enjoyed the academics and majored in physics. Her first experience with scientific research occurred during a summer program at the University of California, Berkeley, where she studied the neuroscience of vision in cats.

While she was in college, Li's parents bought a dry cleaning shop. Li served as a translator between her parents and the customers and worked in the shop on weekends and during breaks. She sometimes considered taking a well-paid job as a "quant" at a financial firm to alleviate some of her family's financial strain, but her mother insisted that she continue her education and pursue her dream of becoming a scientist.

After earning her undergraduate degree, Li pursued her Ph.D. at the California Institute of Technology. She conducted psychological experiments on human vision and built computational models under the direction of Pietro Perona and Christof Koch. While working on her thesis in 2004, Li hand-constructed a dataset that contained more than 9,000 images from 101 categories; at the time, it was the largest image dataset ever built. Upon graduation, she obtained a sequence of faculty positions at the University of Illinois, Princeton, and then Stanford.



The Worlds I See: Curiosity, Exploration, and Discovery at the Dawn of AI. By Fei-Fei Li. Courtesy of Flatiron Books.

In 2006, Li conceived the idea of an image dataset on a much vaster scale: 30,000 categories with a total of several million images. She began to pursue this project with then-Ph.D. student Jia Deng (now an associate professor at Princeton University). It was both a risky and visionary undertaking — the AI community did not foresee the potential impact of large datasets, and "big data" was not yet a buzzword. As such, most of Li's colleagues discouraged the effort. In fact, it initially seemed impossible; a few months into the project, Deng estimated that it would take 19 years to complete. However, a breakthrough came when the duo realized that they could proceed much more quickly by crowdsourcing the work via the Amazon Mechanical Turk[1] platform.

In 2009, Li and Deng released ImageNet:[2] an image database with 22,000 categories of 15 million total images that were divided into a published training set and an unpublished test set. Although ImageNet is currently the gold standard for the training and evaluation of AI vision systems, the research community's initial reaction was tepid. Deng and Li's corresponding paper was accepted at a conference as a poster presentation rather than a talk, and the initial results from systems that trained on ImageNet were not significantly different from those that trained on earlier, much smaller datasets. But the tides turned in 2012 when Alex Krizhevsky, Ilya Sutskever, and Geoffrey Hinton trained their own neural-network-based system (called AlexNet) on ImageNet, achieving dramatically better results than with any competing system. As the saying goes, the rest is history. The deep learning technology that AlexNet pioneered—empowered by enormous datasets of all kinds—has since served as the foundation for almost every noteworthy advance in AI.

Although Li does not discuss it at any length, one of the most striking aspects of ImageNet (and of some of Li's more recent projects, such as the Visual Genome[3] dataset) is the complexity and sophistication of her use of crowdsourcing technology. Li carefully designed and monitored the multi-step process to obtain high-quality tags from crowd workers, refining it through multiple iterations. Some other AI researchers who have utilized crowdsourcing to develop large datasets have been content to give crowd workers a problem and accept their answers at face value — an approach that does not yield results of comparable quality.

Towards the end of *The Worlds I See*, Li describes a series of extended visits to a hospital emergency room to investigate potential uses of AI technology. The book clearly and movingly describes Li's deep admiration for dedicated, overworked, and hurried medical professionals; her empathy for their concerns about cameras with AI technology in their workspaces; and her willingness to learn from them rather than immediately present her own ideas of what they should want. This is a model that all types of computer experts should remember and emulate.

As a memoir, *The Worlds I See* could hardly be better. But as a historical narrative, it does have gaps. There is no index, no bibliography, no footnotes, and the dates of certain events are often unclear. The text offers no guidance for the lay reader who wants to learn more, and no references—often not even titles—for the papers that Li discusses, including her own works. She praises a textbook titled *Vision Science: Photons to Phenomenology*, but I had to google it to learn that the author is Stephen Palmer. There are also no illustrations, which is somewhat astonishing for a book about vision.

I noticed more substantive omissions as well. For example, the text does not mention neuroscientist David Marr of the Massachusetts Institute of Technology, who was a leading figure in both cognitive and AI vision. Perhaps by the time Li entered the field in the late 1990s, Marr's work was too outdated to be useful to her.

See **AI Pioneer** *on page 11*

[1] https://www.mturk.com
[2] https://www.image-net.org
[3] https://homes.cs.washington.edu/~ranjay/visualgenome/index.html

An In-depth Guide to the Methods of Computational Imaging

By Charles A. Bouman

The following is a brief reflection from the author of Foundations of Computational Imaging: A Model-based Approach,[1] which was published by SIAM in 2022. This innovative book defines a common foundation for the mathematical and statistical methods that are associated with computational imaging and addresses a variety of research techniques with applications in multiple disciplines, including applied mathematics, physics, chemistry, optics, and signal processing.

Over the past 20 years, computational imaging has emerged as a multidisciplinary field that focuses on the creation of useful images from raw sensor data. *Foundations of Computational Imaging* presents an essential collection of theoretical materials that can serve as a common language for researchers and practitioners in this new field.

It is commonly believed that images come directly from sensors. For example, people often think that the output of the complementary metal oxide semiconductor (CMOS) sensor in their cell phones is a ready-to-use photograph; this is not true. Instead, the CMOS chip only produces raw data. This data is then processed via a series of complex mathematical algorithms that are implemented on high-performance computational hardware and produce the image we see on the screen. Such computational imaging procedures are required for any imaging system, ranging from cell phone cameras to tomographic imaging systems for medical diagnoses and even the Event Horizon Telescope[2] that generated the first image of the supermassive black hole at the center of the galaxy Messier 87 (which is featured on the front cover of the book).

Any modern imaging system must solve an inverse problem that aims to estimate the desired true image from the available sensor data (see Figure 1). Even if a sensor is able to collect measurements for every pixel in an image, the image must still be denoised, deblurred, and corrected for distortions in geometry and color. And frequently the image must first be reconstructed from indirect, sparse, and nonlinearly distorted sensor measurements that make the formation of the final image computationally challenging and ill posed. In order to design the highest-performing imaging system possible, we must co-design the sensor and computational imaging algorithms/hardware to produce $\hat{X}$: the best estimate of the desired image.

Foundations of Computational Imaging collects a set of algorithms that are commonly used in the implementation of computational imaging systems and arranges them as a single readable reference. The imaging approach is exemplified by the following maximum a posteriori (MAP) estimate:

$$\hat{X} = \arg\min_{x}\{-\log p(Y|x) - \log p(x)\}. \qquad (1)$$

The term $p(Y|x)$ is called the *forward model* because it describes the statistical dependency of the measurements Y with respect to the unknown image x. The term $p(x)$ is the *prior model*, which describes the unknown image that will be reconstructed. Minimizing the sum of these two terms yields a reconstruction that fits the measurements and has a high probability of being the solution. The MAP estimate requires that the solution be both "regular" and consistent with the observed data. In practice, we typically compute the estimate with an iterative algorithm that balances the prior cost function with the forward model cost function. This algorithmic structure—known as model-based iterative reconstruction (MBIR)—is a central theme of computational imaging and appears extensively throughout the text.

Figure 2 illustrates the goal of Bayesian reconstruction algorithms like MBIR. If the measurements are sparse, then the set of reconstructions that fit the observed data intuitively forms a "thin manifold." However, many of these solutions may be completely unrealistic for the application in question. After the prior manifold characterizes the set of images that are probable to have occurred, the MAP estimate finds a reconstruction that is close to both manifolds. Because the prior manifold is essentially a probability density on all naturally occurring images, it is often quite difficult to model. Consequently, the statistical modeling of images and the efficient computation of resulting MBIR reconstructions are major themes of *Foundations of Computational Imaging*.

FROM THE SIAM BOOKSHELF

Chapters 2, 3, and 6 introduce the basic theoretical machinery for image modeling, including autoregressive and Markov random field (MRF) models in both one and two dimensions. The text also generalizes the multidimensional MRF model to the non-Gaussian case to better represent natural images.

Chapters 5 and 7 then explain the basic approaches to high-dimensional quadratic and non-quadratic optimization for MBIR reconstruction. These sections present the strengths and weaknesses of optimization approaches such as gradient descent, coordinate descent, and line search, and outline strategies to achieve the best reconstruction quality with limited computation.

Chapter 8 explores majorization and surrogate functions. We can consider these approaches—which have become mainstays of non-quadratic convex optimization—as a generalization of Newton's method and interpret them as a form of iterative quadratic reweighting. In practice, surrogate functions can dramatically reduce computation without adversely affecting image quality.

Chapter 9 investigates the machinery of constrained optimization, such as the augmented Lagrangian and the alternating direction method of multipliers (ADMM) — essential tools for the efficient solution of large, complex image reconstruction problems. We can use ADMM to break problems into smaller, more modular pieces, which is an important step for practical implementation. Chapter 10 builds upon this foundation by introducing plug-and-play and advanced prior modeling, which provide machinery for the integration of state-of-the-art machine learning algorithms into MBIR reconstruction.

Moving on, chapter 12 offers a systematic, theoretical, and intuitive treatment of the expectation-maximization (EM) algorithm. This algorithm is very useful in a variety of imaging applications because it enables the estimation of model parameters θ even when the reconstruction $\hat{X}$ is unknown. *Foundations of Computational Imaging* assesses the EM algorithm from both an intuitive, theoretical perspective and a more pragmatic, algorithmic point of view.

Chapters 13, 14, and 15 collectively develop the theory of ergodic Markov chains, Hastings-Metropolis samplers, and Gibbs samplers. These approaches frequently contribute to the simulation of stochastic systems that can be formulated to obey the statistics of a Gibbs distribution. Next, chapter 17 develops standard probabilistic machinery that helps to model the Poisson processes that are associated with photon counting detectors. And finally, the four appendices briefly review important topics—like convexity, proximal operators, and Gibbs distributions—that appear throughout the book.

Ultimately, *Foundations of Computational Imaging* can serve as a valuable asset to coursework that centers on model-based or computational imaging, advanced numerical analysis, data science, numerical optimization, and approximation theory. It is also a handy reference for researchers and practitioners who work in medical, scientific, commercial, and industrial imaging.

Enjoy this passage? Visit the SIAM Bookstore[3] to learn more about Foundations of Computational Imaging: A Model-based Approach[4] and browse other SIAM titles.

The 2024 SIAM Conference on Imaging Science[5] will take place from May 28-31 in Atlanta, Ga. Peruse the online program[6] and consider attending the meeting to learn more about computational imaging and additional related areas of study. Bouman's book and other SIAM texts will be available for purchase at conference discounts.

Charles A. Bouman is the Showalter Professor of Electrical and Computer Engineering and Biomedical Engineering at Purdue University. He is a founder of the field of computational imaging and has conducted much research in this area.

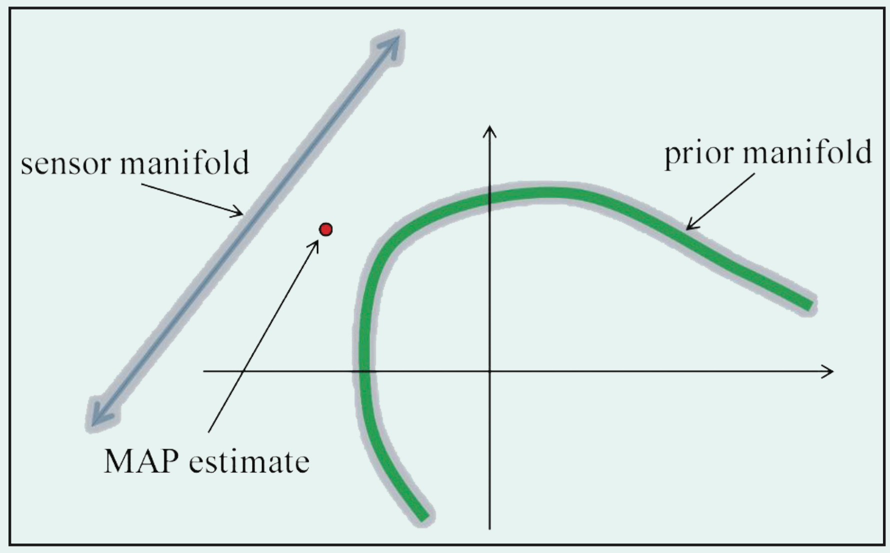


Figure 2. *Graphical illustration of Bayesian estimation. The maximum a posteriori (MAP) reconstruction is the image that is close to both the "thin manifold" of images that fit the data and the "thin manifold" of probable images. Figure courtesy of Foundations of Computational Imaging.*

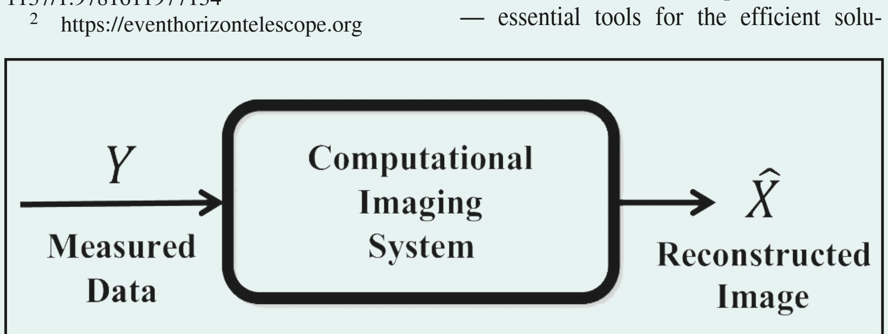


Figure 1. *A computational imaging system obtains data from a sensor and uses advanced algorithms on computing hardware to produce an estimate of the desired image. Figure courtesy of Foundations of Computational Imaging.*

[1] https://epubs.siam.org/doi/book/10.1137/1.9781611977134
[2] https://eventhorizontelescope.org
[3] https://epubs.siam.org
[4] https://epubs.siam.org/doi/book/10.1137/1.9781611977134
[5] https://www.siam.org/conferences/cm/conference/is24
[6] https://meetings.siam.org/program.cfm?CONFCODE=is24

AI Pioneer

Continued from page 10

Closer to home—both Li's home and mine, in different ways—is the exclusion of the first large image dataset that I ever encountered, which marked my initial intimation that large datasets might be central to the future of AI. In 2007, I attended a talk by Antonio Torralba about his forthcoming paper with Rob Fergus (now my colleague at New York University) and William Freeman, titled "80 Million Tiny Images: A Large Data Set for Nonparametric Object and Scene Recognition" [1]. The trio had created a dataset that contained 79 million 32×32 resolution images within 75,000 categories, then demonstrated the sufficiency of nearest-neighbors search for what were fairly good levels of accuracy at the time (this was four times as many images and three times as many categories as ImageNet, which published two years later). The paper began with a dramatic assertion about the value of large datasets: "With overwhelming amounts of data, many problems can be solved without the need for sophisticated algorithms." In the end, the tiny image dataset was much less impactful than ImageNet; the process of tagging images by category was far less precise, and the coarse images were useless for the training of high-quality vision systems. Nevertheless, it certainly deserves a mention in a history of large image datasets for AI vision systems.

Despite these minor flaws, *The Worlds I See* is an extraordinarily valuable and beautiful work. It offers an account of contemporary scientific research at its best and exemplifies the power of scientific memoir.

References

[1] Torralba, A., Fergus, R., & Freeman, W.T. (2008). 80 million tiny images: A large data set for nonparametric object and scene recognition. *IEEE Trans. Pattern Anal. Mach. Intell.*, *30*(11), 1958-1970.

Ernest Davis is a professor of computer science at New York University's Courant Institute of Mathematical Sciences.

SIAM Session at JMM 2024 Addresses Artificial Intelligence in the Education Sector

By Alvaro Ortiz Lugo

The Joint Mathematics Meetings[1] (JMM) have long served as an opportunity for mathematicians, educators, and enthusiasts to convene, exchange ideas, and explore the latest advancements in the field. At JMM 2024,[2] which took place in January in San Francisco, Ca., the SIAM Education Committee[3] organized a comprehensive "Session on Artificial Intelligence and its Uses in Mathematical Education, Research, and Automation in the Industry."[4] The session provided a platform for artificial intelligence (AI) experts and practitioners from various backgrounds to share insights and innovations across four primary domains: research, education, undergraduate experiences, and academic partnerships with industry. Eight individual talks delved into inventive methods, pedagogical techniques, and emerging technologies that are actively revolutionizing the landscape of mathematics.

Education, Course Design, and the Classroom

Alvaro Ortiz of the University of Cincinnati showcased AI's transformative impact in educational environments. Studies show that a large percentage of students now define themselves as AI users and claim that they will not stop utilizing the technology even if university-level restrictions forbid it [1]. But despite this surge in use, a surprisingly small number of institutions are actively establishing policies that address AI and its corresponding academic challenges — often leaving educators to fend for themselves. Ortiz emphasized the necessity of comprehensive professional development that prepares educators to effectively include AI tools in their lesson plans, moderate student interactions with AI, and mitigate AI-related ethical issues. He also exhibited innovative course and instructional design approaches that leverage AI's capabilities, and articulated the importance of personalized, engaging learning experiences that meet diverse student needs.

In addition, Ortiz's presentation briefly explored educational AI tools like intelligent tutoring systems; automated grading platforms; and natural language processors, chatbots, and adaptive learning platforms that may actually augment the learning process without simply providing students with the answer. Ortiz highlighted the potential of these tools to enhance student learning and streamline teaching tasks, but he also acknowledged the inherent complexities and concerns about data privacy, ethics, and algorithmic biases.

Undergraduate Experiences

The JMM 2024 session provided ample time for participants to discuss AI's profound influence on undergraduate research and survey future opportunities for learning and creativity. To begin, Mihhail Berezovski of Embry-Riddle Aeronautical University shared some results from the integration of ChatGPT into the educational landscape, and focused on the chatbot's implementation within Embry-Riddle's project-based classes and Research Experiences for Undergraduates (REU) program. Berezovski recapped student REU experiences over the past two years and explained how the utilization of ChatGPT has created transformative opportunities to boost learning outcomes; foster collaborative experiences; and assist with coding tasks, report writing, and the structure of research publications. Additionally, the incentive of authorship and research ownership made REU students more careful with their use of ChatGPT. To stimulate a sense of transparency in their methods, they only employed it to access public knowledge and technical information for necessary tasks.

Although Berezovski highlighted ChatGPT's advantages as a cutting-edge research tool, ethical considerations are nonetheless paramount. As such, he also examined the moral implications and addressed topics like data privacy, transparency, and possible biases in AI models. Berezovski concluded his talk by reflecting on prospective approaches for AI integration that retain a nuanced understanding of ethical dilemmas and ensure an equitable and inclusive learning environment.

Patricio Gallardo of the University of California, Riverside reported on his experiences with mentoring first- and second-year undergraduate students on the fundamentals of neural networks for mathematical data. Specifically, the students worked with a labeled database of polytopes and their volumes to implement a single-layer rectified linear unit neural network. After learning how to theoretically define the problem and train the corresponding network, they grappled with concepts like equivalence classes and group actions and explored the subject of transfer learning for new databases that are constructed through a change of coordinates — which are advanced topics for the undergraduate level.

In a similar vein, Javier González Anaya of Harvey Mudd College spoke about convolutional neural networks (CNNs), which are prominent in audio, image, and text processing because of their ability to identify characteristic features of complex datasets at a relatively low computational cost. Their success is partly due to the robustness of the pooling layers within CNN architectures. González Anaya then overviewed his role as a co-mentor to three undergraduate students on a project about the combinatorial complexity of max pooling layers, which can serve as piecewise linear functions. To tackle this problem, the students employed a novel technique that relates the linear regions in a max pooling layer to the issue of counting vertices in some concrete polytopes.

All of these presentations emphasized the potential of AI-assisted coding and machine learning methodologies to enhance student productivity by effectively reducing the time of mathematical calculations, which impacts the entire learning and research development process.

AI-assisted Research

The integration of AI technology and mathematical research also holds immense promise in areas like data analysis and theorem-proving methodologies. Lake Bookman of Monash University considered the versatility of Gaussian mixture models (GMMs) in data clustering, acknowledged the challenges of fitting these models to large datasets, and identified the classical expectation-maximization (EM) scheme as an efficient, widely applicable method for GMM fitting. Despite the prevalence of data from multiple underlying models in many scenarios, GMMs' potential for regression remains unknown. Bookman addressed the need for accurate parameter inference in such settings, discussed the extension of EM methods to fully nonlinear models, and noted variations in noise models. He also explored these algorithms' utility in multi-target tracking and image processing applications, which illuminated their broader applicability beyond traditional clustering tasks.

During the SIAM Education Committee's "Session on Artificial Intelligence and its Uses in Mathematical Education, Research, and Automation in the Industry" at the 2024 Joint Mathematics Meetings—which took place in January in San Francisco, Ca.—speakers explored the impact of artificial intelligence on applied mathematics students and educators. Top row, left to right: Mihhail Berezovski (Embry-Riddle Aeronautical University), Lake Bookman (Monash University), and Patricio Gallardo (University of California, Riverside). Middle row, left to right: Sergio García-Morán (Universidad del Rosario), Javier González Anaya (Harvey Mudd College), and Rafael Alberto Méndez-Romero (Universidad del Rosario). Bottom row, left to right: Sudhir Murthy (University of California, Riverside), Alvaro Ortiz (University of Cincinnati), and Yofer Quintanilla-Gómez (Universidad del Rosario). Photos courtesy of the speakers.

Sudhir Murthy of the University of California, Riverside demonstrated how AI might possibly assist with mathematical proofs. For example, he showcased the efficacy of Lean[5]—an interactive theorem prover—in organizing mathematical knowledge and rigorously verifying proofs, ultimately underscoring its versatility across disciplines like number theory, analysis, and algebra. Murthy's talk offered insights into student experiences with the tool, outlined the advantages of interactive theorem-provers in the world of undergraduate mathematics and interdisciplinary curricula, commented on education's relationship with proof automation and AI-generated mathematics, and introduced ongoing endeavors to enrich training data for seamless integration with large language models. AI tools like Lean hint at the imminent arrival of a future where conferences will likely feature AI-proven results.

Academic Partnerships With Industry

The SIAM Education Session at JMM 2024 also included talks by several members of the Colombia Section of SIAM,[6] who illustrated AI's capacity to encourage creative, innovative research and reinvigorate the relationship between industry and academia in Latin America. For instance, the traditional emphasis on disciplinary competencies in Colombian higher education often sidelines crucial industry-academia collaborations and hinders the holistic preparation of students for the workforce. However, the rise of AI has sparked a newfound convergence of interests between academia and industry.

Rafael Alberto Méndez-Romero of Universidad del Rosario spoke about industry's significance as a vital partner in shaping well-rounded technological professionals. He highlighted a successful collaboration between Universidad del Rosario and DevSavant[7] that exemplified the potential of such partnerships to drive gender equity and nurture talent in software engineering. One notable outcome of this collaboration is CodeSavant:[8] a groundbreaking hackathon that leverages generative AI to innovate software development processes. By sharing this paradigmatic success, Méndez-Romero aimed to inspire other institutions and companies to adopt similar collaborative models and foster exceptional young talent in the technology sector.

Yofer Quintanilla-Gómez and Sergio García-Morán, both students at Universidad del Rosario, presented their three-step methodology to establish protocols for emotional support in learning environments. Universities are increasingly prioritizing mental and emotional health within learner-centered frameworks, recognizing its pivotal role in academic success. The intricate relationship between emotions and cognitive processes has thus become a critical research focus in education. While existing literature suggests that peak learning occurs when students are in optimal emotional states, the creation of effective protocols that cultivate such states remains a challenge.

Quintanilla-Gómez and García-Morán's approach encompasses emotional stimulus generation, student response assessment, and educator emotion detection and classification. A specialized center for emotional education at Universidad del Rosario fosters student wellbeing and bolsters this effort, but the speakers want to further refine existing procedures with an automated system that acquires and processes biosignal-based emotional data—such as heart rate and skin conductivity—and utilizes machine learning algorithms to classify emotions. Quintanilla-Gómez and García-Morán aim to advance their university's emotional health protocols and enhance the student body's wellbeing with this innovative emotional acquisition system.

§

Overall, the SIAM Education Session at JMM 2024 comprehensively explored current trends and innovations in education and AI technology — from changes in the classroom to industry collaborations, cutting-edge research, and unique undergraduate experiences. These insights are just a small sample of the many developments that will pave the way for future advancements and collaborations within this landscape.

References

[1] Shaw, C., Yuan, L., Brennan, D., Martin, S., Janson, N., Fox, K., & Bryant, G. (2023, October 23). GenAI in higher education: Fall 2023 update time for class study. *Tyton Partners*. Retrieved from tytonpartners.com/time-for-class-2023/GenAI-Update.

Alvaro Ortiz Lugo is an assistant professor of mathematics at the University of Cincinnati. He was previously a SIAM-sponsored Fellow of Project NExT (New Experiences in Teaching) and is currently a member of the SIAM Education Committee.

1 https://jointmathematicsmeetings.org
2 https://www.jointmathematicsmeetings.org/meetings/national/jmm2024/2300_intro
3 https://www.siam.org/about-siam/committees/education-committee
4 https://www.jointmathematicsmeetings.org/meetings/national/jmm2024/2300_program_siamss8.html#title
5 https://lean-lang.org
6 https://www.siam.org/membership/sections/detail/colombia-section-of-siam-cosiam
7 https://devsavant.com
8 https://noticiasyrespuestas.com/2023/10/02/los-buddies-5-jovenes-ganadores-del-hackathon-de-inteligencia-artificial-generativa-en-colombia

InsideSIAM
Conferences, books, journals, and activities of Society for Industrial and Applied Mathematics

SIAM | CONFERENCES

A Place to Network and Exchange Ideas

Upcoming Deadlines

SIAM Conference on Nonlinear Waves and Coherent Structures (NWCS24)

June 24–27, 2024 | Baltimore, Maryland, U.S.
go.siam.org/nwcs24 | #SIAMNWCS24

ORGANIZING COMMITTEE CO-CHAIRS
Panayotis Kevrekidis, *University of Massachusetts, U.S.*
Anna Vainchtein, *University of Pittsburgh, U.S.*

EARLY REGISTRATION RATE DEADLINE
May 28, 2024

HOTEL RESERVATION DEADLINE
May 28, 2024

THE FOLLOWING CONFERENCES ARE CO-LOCATED:

SIAM Annual Meeting (AN24)

July 8–12, 2024 | Spokane, Washington, U.S.
Online Component July 18–20, 2024
go.siam.org/an24 | #SIAMAN24

ORGANIZING COMMITTEE CO-CHAIRS
Michael P. Friedlander, *University of British Columbia, Canada*
Anna Mazzucato, *Pennsylvania State University, U.S.*

SIAM Conference on Discrete Mathematics (DM24)

July 8–11, 2024 | Spokane, Washington, U.S.
go.siam.org/dm24 | #SIAMDM24

ORGANIZING COMMITTEE CO-CHAIRS
Peter Keevash, *University of Oxford, United Kingdom*
Blair D. Sullivan, *University of Utah, U.S*

SIAM Conference on Applied Mathematics Education (ED24)

July 8–9, 2024 | Spokane, Washington, U.S.
go.siam.org/ed24 | #SIAMED24

ORGANIZING COMMITTEE CO-CHAIRS
Mario Banuelos, *California State University, Fresno, U.S.*
Roummel Marcia, *University of California, Merced, U.S.*

AN24, DM24, and ED24 EARLY REGISTRATION RATE DEADLINE
June 10, 2024

AN24, DM24, and ED24 HOTEL RESERVATION DEADLINE
June 10, 2024

Information is current as of April 17, 2024. Visit *siam.org/conferences* for the most up-to-date information.

Students and Early Career Researchers: Apply Now for Conference Support

SIAM is dedicated to giving students and early career professionals the support they need to be successful. The SIAM Travel Awards Program awards $240,000+ in conference travel funding yearly to these two groups so they can gain the experience and exposure that comes from attending and presenting at SIAM conferences.

Apply now at *siam.smapply.org/prog/travel_awards_program*.

SIAM PRIZE PROGRAM

Nominate a colleague for prizes being awarded at the 2025 SIAM Conference on Computational Science & Engineering.

Submit your nominations at *siam.org/deadline-calendar*

Upcoming SIAM Events

SIAM Conference on Applied Linear Algebra
May 13–17, 2024
Paris, France
Sponsored by the SIAM Activity Group on Linear Algebra

SIAM Conference on Mathematical Aspects of Materials Science
May 19–23, 2024
Pittsburgh, Pennsylvania, U.S.
Sponsored by the SIAM Activity Group on Mathematical Aspects of Materials Science

SIAM Conference on Imaging Science
May 28–31, 2024
Atlanta, Georgia, U.S.
Sponsored by the SIAM Activity Group on Imaging Science

SIAM Conference on the Life Sciences
June 10–13, 2024
Portland, Oregon, U.S.
Sponsored by the SIAM Activity Group on Life Sciences

SIAM Conference on Mathematics of Planet Earth
June 10–12, 2024
Portland, Oregon, U.S.
Sponsored by the SIAM Activity Group on Mathematics of Planet Earth

SIAM Conference on Nonlinear Waves and Coherent Structures
June 24–27, 2024
Baltimore, Maryland, U.S.
Sponsored by the SIAM Activity Group on Nonlinear Waves and Coherent Structures

EASIAM Annual Meeting 2024
June 28–July 1, 2024
University of Macau

2024 SIAM Annual Meeting
July 8–12, 2024
Online Component July 18–20, 2024
Spokane, Washington, U.S.

SIAM Conference on Applied Mathematics Education
July 8–9, 2024
Spokane, Washington, U.S.
Sponsored by the SIAM Activity Group on Applied Mathematics Education

SIAM Conference on Discrete Mathematics
July 8–11, 2024
Spokane, Washington, U.S.
Sponsored by the SIAM Activity Group on Discrete Mathematics

ICERM-SIAM Workshop on Empowering a Diverse Computational Mathematics Research Community
July 22–August 2, 2024
Providence, Rhode Island, U.S.

SIAM Conference on Mathematics of Data Science
October 21–25, 2024
Atlanta, Georgia, U.S.
Sponsored by the SIAM Activity Group on Data Science

ACM-SIAM Symposium on Discrete Algorithms
January 12–15, 2025
New Orleans, Louisiana, U.S.
Sponsored by the SIAM Activity Group on Discrete Mathematics and the ACM Special Interest Group on Algorithms and Computation Theory

FOR MORE INFORMATION ON SIAM CONFERENCES: *siam.org/conferences* siam | MEMBERSHIP

Network | Access | Outreach | Lead

SIAM Section Activities and Updates

Sections are regional or national subgroups of SIAM members that organize lectures, meetings, and other activities to serve members in their region. Here is an update on some of the events that took place throughout 2023:

The **Colombia Section of SIAM** hosted the CoSIAM Math Modeling Challenge (MMC CoSIAM) 2023: Innovation and Collaboration in Action. This challenge was a platform where students and early career mathematicians came together to solve real-world complex problems. In this hackday-style competition, teams of students from prestigious Colombian universities dove into a mathematical modeling challenge, employing tools from mathematics and computer science. Each team, comprising members with diverse specializations and perspectives, faced the task of developing creative and feasible solutions. This experience enriched the participants not only in technical aspects but also in crucial soft skills such as leadership, effective communication, and time management.

The MMC CoSIAM 2023 was hosted by the **Colombia Section of SIAM** on October 20, 2023 at Universidad EIA, Envigado, Antioquia, Colombia.

The 8th annual meeting of the **SIAM Central States Section** was hosted by University of Nebraska-Lincoln October 7–8, 2023. The conference featured 195 registered participants, three plenary talks, 18 minisymposia with 151 talks, one student chapter session with eight talks, 16 contributed talks, and four poster presentations. The conference's goal was to invite, encourage, and support participation from researchers from historically underrepresented groups, and faculty from institutions where opportunities to attend major research conferences might be limited. In addition to their annual meeting, the Central States Section hosted 26 webinars as part of their SIAM Central States Section Computational and Applied Mathematics Forum.

The **SIAM New York–New Jersey–Pennsylvania Section** hosted its inaugural conference on the weekend of October 20, 2023. More than 370 participants attended the conference, which was hosted by New Jersey Institute of Technology. The conference included 26 unique minisymposia, nine contributed sessions, 47 poster presentations, and four plenary speakers. Out of the 375 attendees, 217 were early career mathematicians. The symposium included a special mixer for students that included a dinner, Q & A panel with industry experts, and a digital SIAM scavenger hunt.

The SIAM-NNP Inaugural Conference was hosted by the **SIAM New York–New Jersey–Pennsylvania Section** on October 20–22, 2023 at New Jersey Institute of Technology in Newark, NJ.

The **Argentina Section of SIAM** and the Argentine Association of Applied, Computational, and Industrial Mathematics (ASAMACI) jointly organized the biennial Conference on Industrial, Computational, and Applied Mathematics (MACI). This year, the IX MACI 2023 took place May 8–11, 2023, in Santa Fe, Argentina, hosted by the Universidad Nacional del Litoral. 175 papers were accepted, with 157 presented in person. These papers were categorized into 27 sessions based on their themes and underwent evaluation by anonymous reviewers. The event drew a total of 244 participants. During the conference, 10 plenary talks were held, with six of them being in-person and four virtual, featuring prominent professionals in the field. Additionally, four open roundtable discussions were held for the public which addressed topics such as gender perspectives in the sciences, modeling in the mathematics classroom from different theoretical perspectives, applied mathematics in industry and society, and the intersection of mathematics and machine learning.

The **SIAM Texas-Louisiana Section** held its 6th Annual Meeting (TXLA23) in Lafayette, Louisiana, November 3–5, 2023. The Department of Mathematics at the University of Louisiana at Lafayette hosted the three-day conference, which attracted more than 350 attendees — including 249 speakers and 165 undergraduate and graduate students. The activities of this meeting consisted of a career panel, a mentoring workshop, a poster session, 34 minisymposia, and four plenary lectures. Presenters reported on cutting-edge methodologies and computational algorithms in research areas such as applied algebra, algebraic geometry, biomathematics, computational mathematics, data science, and applications in science and engineering.

The **United Kingdom and Republic of Ireland Section of SIAM** and the Oxford SIAM IMA Student Chapter proudly hosted the SIAM UKIE National Student Chapter 2023 Conference in June. Seventy Ph.D. and master's students attended the event at the Mathematical Institute in Oxford for a two-day event packed full of interesting applied mathematics and ample opportunities for meaningful connections. The event featured 22 student talks, 18 student posters, four plenary speakers, a panel event, and various networking sessions. The student talks and posters covered a wide range of topics and institutions, with a dedicated poster session.

The SIAM UKIE National Student Chapter Conference was hosted by the **United Kingdom and Republic of Ireland Section of SIAM** on June 1–2, 2023 at the Mathematical Institute in Oxford, England.

Get Involved with a SIAM Section!

Want to get involved in your section? Sections are a great way to gain experience in organizing meetings and SIAM leadership. Contact us today to put you in touch with the current leadership in your section. Email *sections@siam.org* with any questions you may have.

For more information, visit: *siam.org/membership/sections*.

FOR MORE INFORMATION ON SIAM MEMBERSHIP: ***siam.org/membership***

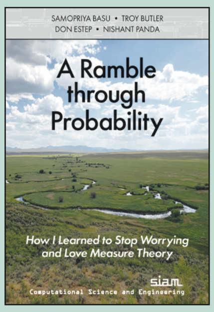
siam BOOKS

Quality and Value in Mathematical Science Literature

New

A Ramble through Probability
How I Learned to Stop Worrying and Love Measure Theory

Samopriya Basu, Troy Butler, Don Estep, and Nishant Panda

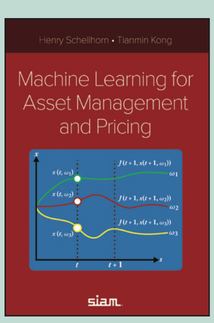


Measure theory and measure-theoretic probability are fascinating subjects that play roles in the development of pure and applied mathematics, statistics, engineering, physics, and finance. This book traces an eclectic path through the fundamentals of the topic to make the material accessible to a broad range of students. It brings together the key elements and applications in a unified presentation aimed at developing intuition; contains an extensive collection of examples that illustrate, explain, and apply the theories; and is supplemented with videos containing commentary and explanations of select proofs on an ancillary website.

2024 / xvi + 603 pp. / Softcover / 978-1-61197-781-3
List $94.00 / SIAM Member $64.80 / CS29

Machine Learning for Asset Management and Pricing

Henry Schellhorn and Tianmin Kong



This textbook covers the latest advances in machine-learning methods for asset management and asset pricing. Recent research in deep learning applied to finance shows that some of the techniques used by asset managers (usually kept confidential) result in better investments than the more standard techniques. Cutting-edge material is integrated with mainstream finance theory and statistical methods to provide a coherent narrative.

2024 / xxiv + 264 pp. / Softcover / 978-1-61197-789-9
List $74.00 / SIAM Member $51.80 / OT195

Order online: *bookstore.siam.org*

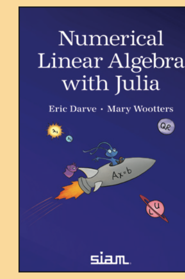
Or call toll-free in U.S. and Canada: 800-447-SIAM; worldwide: +1-215-382-9800

If you live outside North or South America, order from *eurospanbookstore.com/siam* for speedier service and free shipping. Eurospan honors the SIAM member discount. Contact customer service (*service@siam.org*) for the code to use when ordering.

See These Books and More at the SIAM Conference on Applied Linear Algebra in Paris, May 13–17

Numerical Linear Algebra with Julia

Eric Darve and Mary Wootters

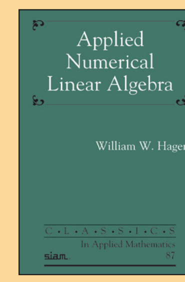


Here is an in-depth coverage of fundamental topics in numerical linear algebra, including how to solve dense and sparse linear systems, compute QR factorizations, compute the eigendecomposition of a matrix, and solve linear systems using iterative methods such as conjugate gradient. Julia code is provided to illustrate concepts and allow readers to explore methods on their own.

2021 / xiv + 406 pages / Softcover / 978-1-611976-54-0 / List $89.00 / SIAM Member $62.30 / OT172

Applied Numerical Linear Algebra

William W. Hager

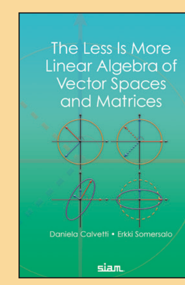


This introduction to numerical issues that arise in linear algebra and its applications touches on a wide range of techniques, including direct and iterative methods, orthogonal factorizations, least squares, eigenproblems, and nonlinear equations. It provides clear and detailed explanations on a wide range of topics from condition numbers to singular value decomposition, as well as material on nonlinear and linear systems.

2022 / xiv + 424 pages / Softcover / 978-1-611976-85-4 / List $89.00 / SIAM Member $62.30 / CL87

The Less Is More Linear Algebra of Vector Spaces and Matrices

Daniela Calvetti and Erkki Somersalo

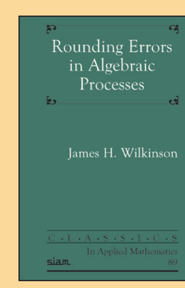


Designed for a proof-based course on linear algebra, this rigorous and concise textbook intentionally introduces vector spaces, inner products, and vector and matrix norms before Gaussian elimination and eigenvalues so students can quickly discover the singular value decomposition (SVD)—arguably the most enlightening and useful of all matrix factorizations.

2022 / xii + 168 pages / Softcover / 978-1-61197-739-4 / List $64.00 / SIAM Member $44.80 / OT187

Rounding Errors in Algebraic Processes

James H. Wilkinson



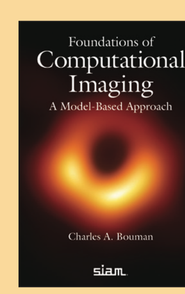
This was the first book to give detailed analyses of the effects of rounding errors on a variety of key computations involving polynomials and matrices. The topics included are still relevant and useful today.

2023 / xiv + 161 pages / Softcover / 978-1-61197-751-6 / List $67.00 / SIAM Member $49.60 / CL89

See These Books and More at the SIAM Conference on Imaging Science in Atlanta, May 28–31

Foundations of Computational Imaging
A Model-Based Approach

Charles A. Bouman

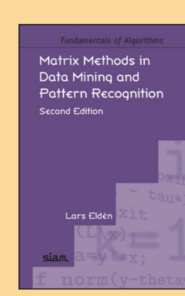


This is the first book to define a common foundation for the mathematical and statistical methods used in computational imaging. It brings together a blend of research with applications in a variety of disciplines to address a collection of problems that can benefit from a common set of methods.

2022 / xii + 337 pages / Softcover / 978-1-611977-12-7 / List $84.00 / SIAM Member $58.80 / OT180

Matrix Methods in Data Mining and Pattern Recognition
Second Edition

Lars Eldén

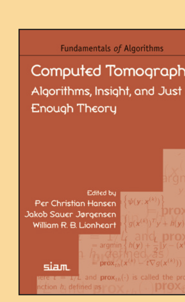


This thoroughly revised second edition provides an updated treatment of numerical linear algebra techniques for solving problems in data mining and pattern recognition. Adopting an application-oriented approach, the author introduces matrix theory and decompositions, describes how modern matrix methods can be applied in real life scenarios, and provides a set of tools that students can modify for a particular application.

2019 / xiv + 229 pages / Softcover / 978-1-611975-85-7 / List $71.50 / SIAM Member $50.05 / FA15

Computed Tomography
Algorithms, Insight, and Just Enough Theory

Edited by Per Christian Hansen, Jakob Sauer Jørgensen, and William R. B. Lionheart



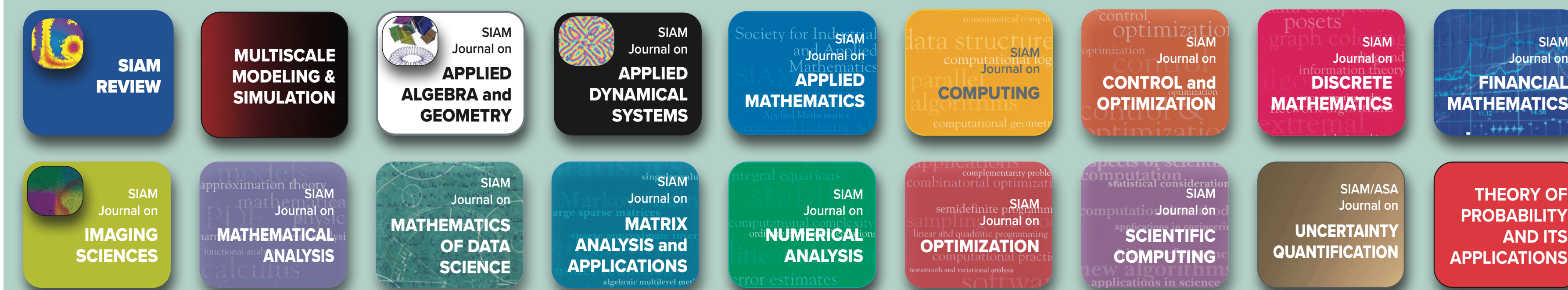
This book describes fundamental computational methods for image reconstruction in computed tomography with a focus on a pedagogical presentation of these methods and their underlying concepts. Insights into the advantages, limitations, and theoretical and computational aspects of the methods are included.

2021 / xviii + 337 pages / Softcover / 978-1-611976-66-3 / List $89.00 / SIAM Member $62.30 / FA18

FOR MORE INFORMATION ON SIAM BOOKS: ***siam.org/books***

SIAM | JOURNALS

Where You Go to Know and Be Known



Recently Posted Articles

SIAM Journal on APPLIED ALGEBRA and GEOMETRY

What Is the Probability That a Random Symmetric Tensor Is Close to Rank-One?
Alberto Cazzaniga, Antonio Lerario, and Andrea Rosana

Erratum: A Counterexample to Comon's Conjecture
Jan Draisma

Harmonic Persistent Homology
Saugata Basu and Nathanael Cox

SIAM Journal on APPLIED DYNAMICAL SYSTEMS

Spectral Submanifolds of the Navier–Stokes Equations
Gergely Buza

Convergence of Weak-SINDy Surrogate Models
Benjamin P. Russo and M. Paul Laiu

Small-Noise-Induced Metastable Transition of Periodically Perturbed Systems
Ying Chao, Jinqiao Duan, and Pingyuan Wei

SIAM Journal on APPLIED MATHEMATICS

Constitutive Relations for Granular Flow That Include the Three Flow Regimes of Chialvo et al.
David G. Schaeffer and Yuhao Hu

Dynamics and Bifurcations in a Nondegenerate Homogeneous Diffusive SIR Rabies Model
Gaoyang She and Fengqi Yi

A Geometric Analysis of the SIRS Model with Secondary Infections
Panagiotis Kaklamanos, Andrea Pugliese, Mattia Sensi, and Sara Sottile

SIAM Journal on COMPUTING

Almost Optimal SuperConstant-Pass Streaming Lower Bounds for Reachability
Lijie Chen, Gillat Kol, Dmitry Paramonov, Raghuvansh R. Saxena, Zhao Song, and Huacheng Yu

Rigid Matrices from Rectangular PCPs
Amey Bhangale, Prahladh Harsha, Orr Paradise, and Avishay Tal

Rounds vs. Communication Tradeoffs for Maximal Independent Sets
Sepehr Assadi, Gillat Kol, and Zhijun Zhang

SIAM Journal on CONTROL and OPTIMIZATION

Local Time Pushed Mixed Equilibrium Strategies for Time-Inconsistent Stopping Problems
Andi Bodnariu, Sören Christensen, and Kristoffer Lindensjö

A Phase Theory of Multi-input Multi-output Linear Time-Invariant Systems
Wei Chen, Dan Wang, Sei Zhen Khong, and Li Qiu

Dynamic Programming in Probability Spaces via Optimal Transport
Antonio Terpin, Nicolas Lanzetti, and Florian Dörfler

SIAM Journal on DISCRETE MATHEMATICS

Rainbow Even Cycles
Zichao Dong and Zijian Xu

The Rainbow Saturation Number Is Linear
Natalie Behague, Tom Johnston, Shoham Letzter, Natasha Morrison, and Shannon Ogden

Spanning Bipartite Quadrangulations of Triangulations of the Projective Plane
Kenta Noguchi

SIAM Journal on FINANCIAL MATHEMATICS

Mortgage Contracts and Underwater Default
Yerkin Kitapbayev and Scott Robertson

Robust Portfolio Selection under Recovery Average Value at Risk
Cosimo Munari, Justin Plückebaum, and Stefan Weber

Generalized Optimized Certainty Equivalent with Applications in the Rank-Dependent Utility Model
Qinyu Wu, Tiantian Mao, and Taizhong Hu

SIAM Journal on IMAGING SCIENCES

NF-ULA: Normalizing Flow-Based Unadjusted Langevin Algorithm for Imaging Inverse Problems
Ziruo Cai, Junqi Tang, Subhadip Mukherjee, Jinglai Li, Carola-Bibiane Schönlieb, and Xiaoqun Zhang

Sliding at First-Order: Higher-Order Momentum Distributions for Discontinuous Image Registration
Lili Bao, Jiahao Lu, Shihui Ying, and Stefan Sommer

Provably Convergent Plug-and-Play Quasi-Newton Methods
Hong Ye Tan, Subhadip Mukherjee, Junqi Tang, and Carola-Bibiane Schönlieb

SIAM Journal on MATHEMATICAL ANALYSIS

Uniqueness and Orbital Stability of Standing Waves for the Nonlinear Schrödinger Equation with a Partial Confinement
Younghun Hong and Sangdon Jin

Linear Elliptic Homogenization for a Class of Highly Oscillating Nonperiodic Potentials
Rémi Goudey and Claude Le Bris

Upper Bound for the Grand Canonical Free Energy of the Bose Gas in the Gross–Pitaevskii Limit
Chiara Boccato, Andreas Deuchert, and David Stocker

SIAM Journal on MATHEMATICS of DATA SCIENCE

Reversible Gromov–Monge Sampler for Simulation-Based Inference
YoonHaeng Hur, Wenxuan Guo, and Tengyuan Liang

Efficiency of ETA Prediction
Chiwei Yan, James Johndrow, Dawn Woodard, and Yanwei Sun

The Sample Complexity of Sparse Multireference Alignment and Single-Particle Cryo-electron Microscopy
Tamir Bendory and Dan Edidin

SIAM Journal on MATRIX ANALYSIS and APPLICATIONS

Explicit Quantum Circuits for Block Encodings of Certain Sparse Matrices
Daan Camps, Lin Lin, Roel Van Beeumen, and Chao Yang

Partial Degeneration of Tensors
Matthias Christandl, Fulvio Gesmundo, Vladimir Lysikov, and Vincent Steffan

SIAM Journal on NUMERICAL ANALYSIS

Sequential Discretization Schemes for a Class of Stochastic Differential Equations and Their Application to Bayesian Filtering
Ö. Deniz Akyildiz, Dan Crisan, and Joaquin Miguez

Singularity Swapping Method for Nearly Singular Integrals Based on Trapezoidal Rule
Gang Bao, Wenmao Hua, Jun Lai, and Jinrui Zhang

A Posteriori Error Control for Fourth-Order Semilinear Problems with Quadratic Nonlinearity
Carsten Carstensen, Benedikt Gräßle, and Neela Nataraj

SIAM Journal on OPTIMIZATION

Generalized Power Cones: Optimal Error Bounds and Automorphisms
Ying Lin, Scott B. Lindstrom, Bruno F. Lourenço, and Ting Kei Pong

Certifying Optimality of Bell Inequality Violations: Noncommutative Polynomial Optimization through Semidefinite Programming and Local Optimization
Timotej Hrga, Igor Klep, and Janez Povh

Parabolic Optimal Control Problems with Combinatorial Switching Constraints, Part II: Outer Approximation Algorithm
Christoph Buchheim, Alexandra Grütering, and Christian Meyer

SIAM Journal on SCIENTIFIC COMPUTING

Approximating the Shape Operator with the Surface Hellan–Herrmann–Johnson Element
Shawn W. Walker

A Direct Probing Method of an Inverse Problem for the Eikonal Equation
Kazufumi Ito and Ying Liang

Computation of Two-Dimensional Stokes Flows via Lightning and AAA Rational Approximation
Yidan Xue, Sarah L. Waters, and Lloyd N. Trefethen

SIAM/ASA Journal on UNCERTAINTY QUANTIFICATION

Subsampling of Parametric Models with Bifidelity Boosting
Nuojin Cheng, Osman Asif Malik, Yiming Xu, Stephen Becker, Alireza Doostan, and Akil Narayan

Calculation of Epidemic First Passage and Peak Time Probability Distributions
Jacob Curran-Sebastian, Lorenzo Pellis, Ian Hall, and Thomas House

A Method of Moments Estimator for Interacting Particle Systems and Their Mean Field Limit
Grigorios A. Pavliotis and Andrea Zanoni

MULTISCALE MODELING & SIMULATION: A SIAM Interdisciplinary Journal

Fluid Models for Kinetic Equations in Swarming Preserving Momentum
Mihaï Bostan and Anh-Tuan VU

A Micro-macro Decomposed Reduced Basis Method for the Time-Dependent Radiative Transfer Equation
Zhichao Peng, Yanlai Chen, Yingda Cheng, and Fengyan Li

Representative Volume Element Approximations in Elastoplastic Spring Networks
Sabine Haberland, Patrick Jaap, Stefan Neukamm, Oliver Sander, and Mario Varga

FOR MORE INFORMATION ON SIAM JOURNALS: *epubs.siam.org/journals*