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Optimization and Learning with Zeroth-order Stochastic Oracles

By Stefan M. Wild

Mathematical optimization is a foundational technology for machine learning and the solution of design, decision, and control problems. In most optimization applications, the principal assumption is the availability of at least the first-order derivatives of objective and constraint functions. This assumption is often nonrestrictive, since researchers can use techniques such as automatic differentiation and differentiable programming to obtain derivatives from the mathematical equations that underlie these functions. Derivative-free (or "zeroth-order") optimization addresses settings wherein such derivatives are not available [5].

Given the pervasiveness of sensors and other experimental and observational data, these types of settings are arising in increasingly more science and engineering domains. For example, consider the ongoing search for novel materials for energy storage. In order to create viable new materials, we must move beyond pure theory and account for the actual processes that occur during materials synthesis. A necessary consequence is that material properties are only available via *in situ* and *in operando* characterization. In the context of optimization, this scenario is called a "zeroth-order oracle" — our knowledge about a particular system or property is data driven and limited by the black-box nature of measurement procurement. An additional challenge is that such measurements are subject to random variations, meaning that researchers are dealing with zeroth-order *stochastic* oracles.

We can compactly express this type of optimization problem as

$$\min_{\mathbf{x}\in\mathbf{R}^n} \mathbb{E}_\xi\left[f(\mathbf{x};\xi)\right],$$

where $\mathbf{x}$ denotes the vector of n decision variables and ξ is a random variable (e.g., a variable that is associated with the stochastic synthesis and measurement processes). The zeroth-order stochastic oracle is $f(\mathbf{x};\xi)$. We can specify values for the random variable only in certain problem settings; in others—such as the laboratory environment in Figure 1—doing so is impossible.

Figure 1 displays an instantiation of a data-driven optimization setting in a chemistry lab at Argonne National Laboratory. An optimization solver specifies a particular composition of solvents and bases, an operating temperature, and reaction times; this combination is then run through a continuous flow reactor. The material that exits the reactor is then automatically characterized through an inline nuclear magnetic resonance detector that illuminates properties of the synthesized materials. These stochastic, zeroth-order oracle outputs return to the solver in a closed-loop setting that

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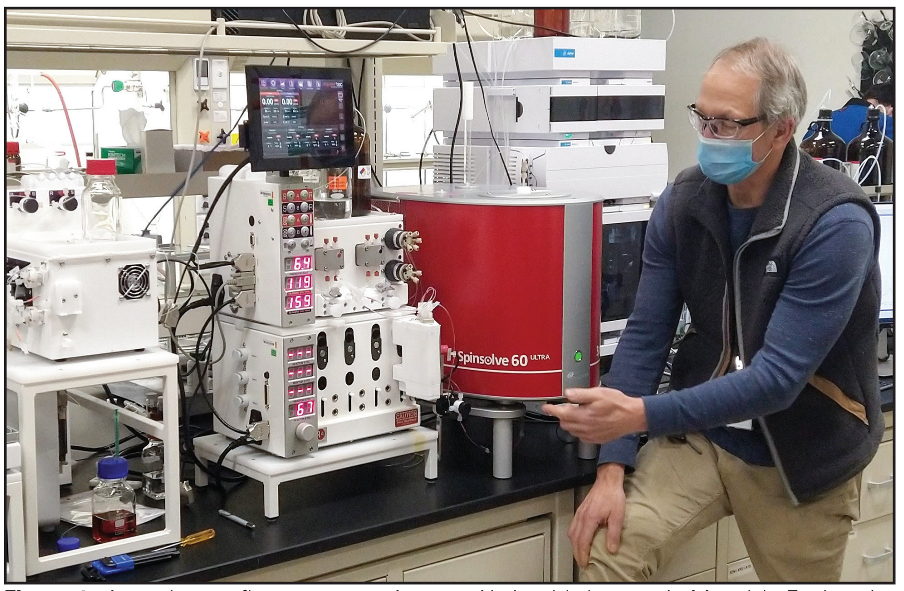

Figure 1. *A continuous flow reactor at Argonne National Laboratory's Materials Engineering Research Facility uses the optimization solver ParMOO to perform autonomous discovery [2]. Photo courtesy of Stefan Wild.*

Resilient Data-driven Dynamical Systems with Koopman: An Infinite-dimensional Numerical Analysis Perspective

By Steven L. Brunton and Matthew J. Colbrook

Dynamical systems, which describe the evolution of systems in time, are ubiquitous in modern science and engineering. They find use in a wide variety of applications, from mechanics and circuits to climatology, neuroscience, and epidemiology. Consider a discrete-time dynamical system with state $\boldsymbol{x}$ in a state space $\Omega\subset\mathbb{R}^d$ that is governed by an unknown and typically nonlinear function $\boldsymbol{F}:\Omega\to\Omega$:

$$\boldsymbol{x}_{n+1}=\boldsymbol{F}(\boldsymbol{x}_n), \qquad n\geq 0. \qquad (1)$$

The classical, geometric way to analyze such systems—which dates back to the seminal work of Henri Poincaré—is based on the local analysis of fixed points, periodic orbits, stable or unstable manifolds, and so forth. Although Poincaré's framework has revolutionized our understanding of dynamical systems, this approach has at least two challenges in many modern applications: (i) Obtaining a global understanding of the nonlinear dynamics and (ii) handling systems that are either too complex to analyze or offer incomplete information about the evolution (i.e., unknown, high-dimensional, and highly nonlinear $\boldsymbol{F}$).

Koopman operator theory, which originated with Bernard Koopman and John von Neumann [6, 7], provides a powerful alternative to the classical geometric view of dynamical systems because it addresses nonlinearity: the fundamental issue that underlies the aforementioned challenges. We lift the nonlinear system (1) into an infinite-dimensional space of observable functions $g:\Omega\to\mathbb{C}$ via a Koopman operator $\mathcal{K}$:

$$\mathcal{K}g(\boldsymbol{x}_n)=g(\boldsymbol{x}_{n+1}).$$

The evolution dynamics thus become linear, allowing us to utilize generic solution techniques that are based on spectral decompositions. In recent decades, Koopman operators have captivated researchers because of emerging data-driven and numerical implementations that coincide with the rise of machine learning and high-performance computing [2].

One major goal of modern Koopman operator theory is to find a coordinate transformation with which a linear system may approximate even strongly nonlinear dynamics; this coordinate system relates to the spectrum of the Koopman operator. In 2005, Igor Mezić introduced the Koopman mode decomposition [8], which provided a theoretical basis for connecting the dynamic mode decomposition (DMD) with the Koopman operator [9, 10]. DMD quickly became the workhorse algorithm for computational approximations of the Koopman operator due to its simple and highly extensible formulation in terms of linear algebra, and the fact that it applies equally well to data-driven modeling when no governing equations are available. However, researchers soon realized that simply building linear models in terms of the primitive measured variables cannot sufficiently capture nonlinear dynamics beyond periodic and quasi-periodic phenomena. A major breakthrough occurred with the introduction of *extended* DMD (EDMD), which generalizes DMD to a broader class of basis functions in which to expand eigenfunctions of the Koopman operator [11].

See **Dynamical Systems** *on page 4*

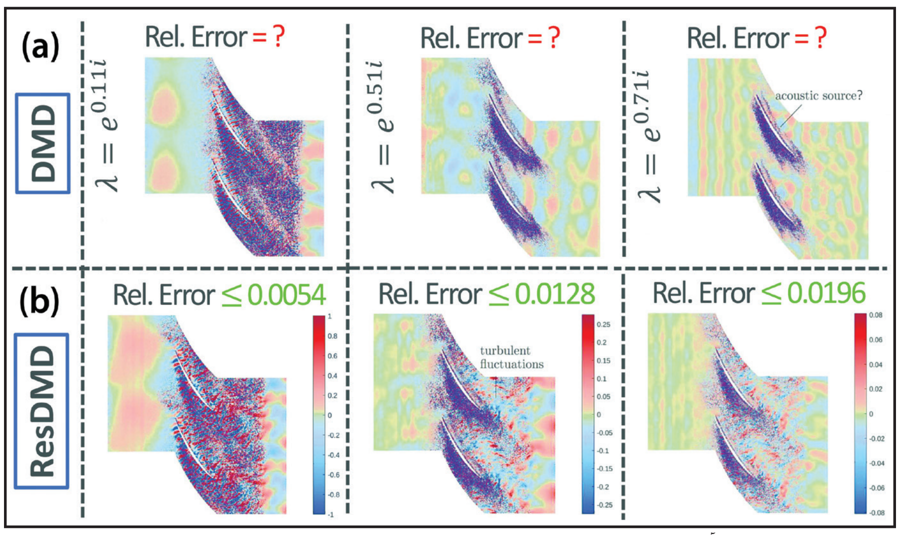

Figure 1. *Koopman modes of a turbulent flow (Reynolds number 3.9×10^5) past a cascade of airfoils that are computed from trajectory data ($d\approx300{,}000$). Koopman modes are projections of the physical field onto eigenfunctions of $\mathcal{K}$; they provide the collective motion of the fluid that occurs at the same spatial frequency, growth, or decay rate according to an approximate eigenvalue λ.* **1a.** *Koopman modes that were computed via existing state-of-the-art techniques. Note the lack of error bounds.* **1b.** *Koopman modes that were computed using residual dynamic mode decomposition (ResDMD). The physical picture in 1b is different from 1a, but we know that it is correct because of the guaranteed relative error bounds (green text). This outcome illustrates the importance of verification. Figure courtesy of Matthew Colbrook.*

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Welcoming the Newest Electees to the SIAM Board of Trustees and Council

By Lina Sorg

In late 2022, the SIAM community voted to elect/re-elect[1] three members to the SIAM Board of Trustees and four members to the SIAM Council. These seven individuals took office on January 1, 2023, and will serve until December 31, 2025.

The Board manages the Society, accounting for its scientific and professional policies and objectives. It also maintains complete legal control of SIAM's financial assets, including budgets, funds, and investments. The Council is responsible for reviewing and formulating SIAM's scientific policies, monitoring its technical activities, proposing new initiatives, and recommending actions to the Board when necessary.

Here, the newly elected leadership—all of whom have a rich history of SIAM involvement—share their reactions, ambitions, and intentions for their time in office. Their full candidate statements are available online.[2]

SIAM Board of Trustees

Ricardo Cortez (Tulane University): "I was pleasantly surprised to find out that I had been elected to the SIAM Board of Trustees. SIAM membership had excellent candidate options and I am grateful for their support. In the last few years, the disruptions created by the pandemic have continued to affect our community, from the ways in which students learn mathematics to the development and communication of research results. As we address the lasting consequences of these disruptions, it is an important time for SIAM to lead creative efforts that promote the growth and exchange of ideas. I look forward to working with SIAM leadership to implement initiatives that provide support to the applied mathematics community and attract new members."

Bonita V. Saunders* (National Institute of Standards and Technology): "I am very honored to have been elected for a second term on the SIAM Board of Trustees. I look forward to continuing the Board's work by striving to make informed decisions that promote and support applied and computational scientists and their research. I will also continue efforts to keep the lines of communication more open between SIAM leadership and SIAM Activity Groups or SIAM Sections, where fiscally sound decisions may not be appreciated as such. Additional transparency might lead to outcomes that work for both sides — or at the very least, help the sides better understand each other."

Ulrike Meier Yang (Lawrence Livermore National Laboratory): "I am honored and delighted to have been elected to the SIAM Board of Trustees, and I appreciate the support of the SIAM membership. SIAM is an important society that focuses on the continued development of applied mathematical and computational research that is necessary for the solution of many real-world problems. I look forward to working with other Board members to advance SIAM's continued growth and learn more about relevant issues. Some of my areas of interest include increasing diversity and creating effective hybrid conferences."

SIAM Council

Alicia Dickenstein* (University of Buenos Aires): "I am honored to have been re-elected to the SIAM Council and am very grateful to the members for their support. I am happy to serve the entire SIAM community and particularly look forward to finding ways to more internationally replicate certain initiatives that are naturally aimed at U.S.-based members. We have many challenges to address, including the role of applied mathematics in new areas; the interaction between data-driven algorithms and modeling; funding, underrepresentation, publishing, industry engagement, education, and outreach; and the consolidation of hybrid participation."

Heike Faßbender* (Technische Universität Braunschweig): "I am delighted to have been re-elected to the SIAM Council and am very grateful to the membership for their support. As I said in my candidate statement, I would like to help strengthen the "I" in SIAM, as it seems even more relevant today than ever before to open new channels of communication between researchers and potential users of mathematical tools. Another important issue is the continued development of SIAM conferences. We must find a good balance between in-person attendance and online participation to reconcile the burden of travel with the value of personal exchange."

Johnny Guzmán (Brown University): "I am very grateful and honored to have been elected by my colleagues to serve on the SIAM Council. Through its journals, meetings, and programs, SIAM plays a key role in fostering collaborations that lead to breakthroughs in applied mathematics. SIAM has made huge strides in making our organization inclusive, diverse, and accessible. I look forward to continuing to improve these efforts."

Valeria Simoncini* (Università di Bologna): "This is an uninterrupted period of new research challenges that require computer science, statistics, and engineering expertise to join efforts with the mathematical community. In this exciting and fast-changing setting, I believe that SIAM should continue to testify and strengthen the role of applied mathematics in innovative application areas such as data science—where new mathematics is being created at incredible speeds—and through publications, conferences, and social media exchanges with researchers in new and well-established disciplines. SIAM should also continue to be inclusive, encourage and support participation, and create research and networking opportunities for all mathematicians."

The dedication of SIAM's elected leadership contributes to the continued growth and success of the Society. SIAM is therefore greatly appreciative of the entire slate of candidates, as well as the members who cast their votes in the 2022 election. Thank you for your willingness to serve and advance the community.

Lina Sorg is the managing editor of SIAM News.

[1] * indicates an incumbent member
[2] https://sinews.siam.org/Details-Page/introducing-siams-newest-leadership

The newly elected members of the SIAM Board of Trustees and SIAM Council. Top row, left to right: Board electees Ricardo Cortez (Tulane University), Bonita Saunders (National Institute of Standards and Technology), and Ulrike Meier Yang (Lawrence Livermore National Laboratory). Bottom row, left to right: Council electees Alicia Dickenstein* (University of Buenos Aires), Heike Faßbender* (Technische Universität Braunschweig), Johnny Guzmán (Brown University), and Valeria Simoncini* (Università di Bologna). Photos courtesy of the elected individuals.*

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Obituary: Seymour Victor Parter

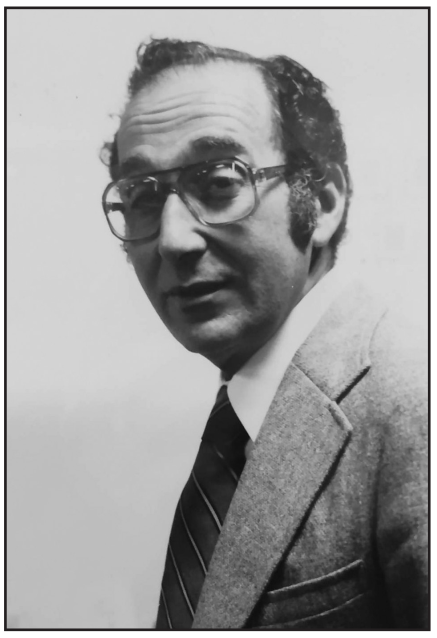
By Michael Steuerwalt

Seymour Victor Parter, professor emeritus of mathematics and computer science at the University of Wisconsin–Madison and a past president of SIAM, died peacefully at home in Madison, Wis., on October 21, 2022. He was 95 years old.

Seymour's career did not follow the usual track, in that he worked full time while earning his degrees. His father died early, so he and his mother ran the family restaurant; he worked there for 30 or more hours each week until it was sold in 1951. During that period, Seymour graduated from the Illinois Institute of Technology with a bachelor's degree in mathematics and a minor in physics (in 1949), followed by a master's degree in mathematics (in 1951). Karl Menger directed his master's thesis in topology, which focused on generalized metric spaces.

Upon Menger's recommendation, Seymour applied for a position at Los Alamos Scientific Laboratory (now Los Alamos National Laboratory), excited by the prospect of working on physics and math problems in the mountains. He was hired by Preston Hammer in March 1951. As a staff member, Seymour programmed numerical algorithms for machines like the IBM CPC and IBM 602A. Doing so introduced him to the type of serious scientific computing work that he would continue at Los Alamos, then later at the National Bureau of Standards (now the National Institute of Standards and Technology) and New York University (NYU). Through these efforts, Seymour befriended accomplished mathematicians and physicists such as Hans Bethe, Mark Kac, Peter Lax, Robert Richtmyer, Marshall Rosenbluth, Garrett Birkhoff, Stanislaw Ulam, John von Neumann, Edward Teller, Kurt Otto Friedrichs, and Louis Nirenberg.

In 1951, SEAC (Standards Eastern Automatic Computer)—a new computer that was designed and built by the National Bureau of Standards—became available to Los Alamos scientists. Seymour received a SEAC manual in October of that year and traveled to Washington, D.C., to run calculations on this more powerful machine. In May 1952, he returned to Los Alamos to work under Richtmyer in the Theoretical Division, where he programmed and ran important defense codes on a variety of machines. Staff member Lester Barnhoff taught Seymour how to be a human do loop for card-programmed computers when the computer memory couldn't hold all program instructions simultaneously, or when the computer lacked a loop register. Seymour would read the computer program into the card reader until finding a colored card, which revealed how many times he had to run the next set of cards through the reader; to carefully count the number of times, he pushed pennies across a table.



Seymour Victor Parter, 1927-2022. SIAM photo.

In May 1953, Seymour was sent to NYU to work on the UNIVAC (Universal Automatic Computer), which had been recently installed by the U.S. Atomic Energy Commission. When Richtmyer told him that his stay would continue through the spring of 1954, Seymour enrolled in the graduate program at NYU's Department of Mathematics (now the Courant Institute of Mathematical Sciences). He performed well, and Los Alamos agreed to assign him to UNIVAC projects each fall and spring so he could continue his classwork at NYU. Seymour was always grateful to Carson Mark, head of Los Alamos' Theoretical Division at the time, for allowing him to complete his Ph.D. while maintaining employment.

Seymour wrote his graduate thesis, "On Mappings of Multiply Connected Domains by Solutions of Partial Differential Equations," under the direction of Lipman Bers [1]. Although he finished his thesis in 1956, Seymour did not receive his degree until January 1958, as he had not yet completed the language requirement. Because the tests only occurred once a year and had to be passed six months before the degree was granted, Seymour had time for extracurricular activities while meeting this final obligation. He spent the 1957-1958 academic year at the Massachusetts Institute of Technology in what was essentially a postdoctoral appointment. Seymour considered this year to be his most important; he learned to ski and met his wife Ruth while horseback riding near Boulder, Colo. They married in October 1957.

Meanwhile, Seymour's mathematical interests shifted from pure to applied and computational mathematics. The growing national enthusiasm for science, aerospace, and computation increased the demand in industry and academia for individuals with both mathematical and computational skills. Seymour became an assistant professor in mathematics and associate director of the Research Computing Center at Indiana University from 1958-1960, then moved to Cornell University from 1960-1962 and Stanford University from 1962-1963. In the fall of 1963, he accepted an associate professorship at UW–Madison with a joint appointment in the Department of Mathematics and Department of Numerical Analysis (now the Department of Computer Sciences). He remained there for 36 years but maintained his relationship with Los Alamos, partly because the Laboratory continued to generate interesting research problems and partly because he and Ruth had friends in Los Alamos and Santa Fe. He also oversaw the Ph.D. theses of 15 graduate students, at least five of whom worked at or visited the Laboratory.

Seymour's research was broad, influential, and imbued with an awareness of associated computational issues and practical consequences. It involved the modeling, analysis, and computational solution of various physical problems, as well as the design and analysis of computational methods. Seymour was interested in complex analysis, singular perturbations, sparse matrix theory and its connection to graphs, numerical methods for partial differential

See **Seymour Victor Parter** *on page 5*

Optimization

Continued from page 1

minimizes wasted product and accelerates materials discovery. Figure 2 illustrates this closed-loop (or "online") optimization.

One of the main techniques in derivative-free optimization is the use of model-based methods, which utilize zeroth-order outputs to form surrogate models that are expressly built and adaptively updated for optimization [3]. Users can perform new queries of the oracle based on these models, which model-based algorithms then employ to evolve the trust region, i.e., the area in which a model is presumed to be trustworthy for optimization purposes. Such techniques are becoming progressively more commonplace when the oracle outputs are deterministic and optimization takes place over no more than a few dozen decision variables.

When the oracle is stochastic, we must reconsider the typical interpolation-based surrogate models and algorithmic dynamics. Stochastic settings also reduce the decision variable dimensions that one can effectively address when compared to deterministic, noise-free oracles. As the number of variables grows, optimization incurs an increasingly large overhead—in terms of both the linear algebraic operations and the number of oracle queries—that is associated with the creation and maintenance of surrogate models in high-dimensional spaces.

Randomized strategies for deterministic optimization problems, like Coralia Cartis and Lindon Roberts' approach [1], enable work in substantially lower-dimensional spaces. These methods typically use ideas from sketching to provide a dimension reduction at each iteration that results in significantly smaller overhead. By applying results such as the Johnson–Lindenstrauss lemma, we can show that—with large probability—a reduced gradient will be small in magnitude only if the full-space gradient is small as well. Consequently, the performance of model-based, trust-region iterations in reduced spaces has provable implications for the full space wherein the optimization problem resides. Because of this randomized dimension reduction, algorithmic convergence is now based on probabilistic analysis.

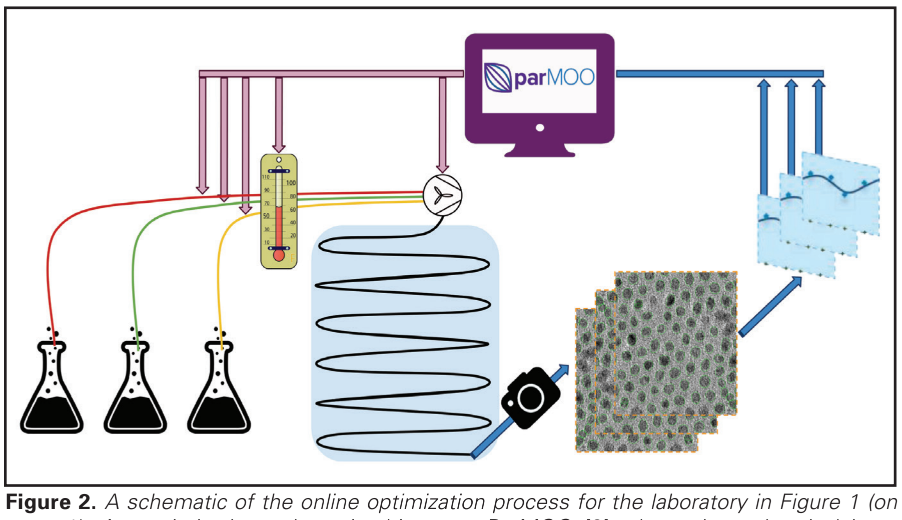


Figure 2. *A schematic of the online optimization process for the laboratory in Figure 1 (on page 1). An optimization solver—in this case, ParMOO [2]—determines chemical input flow rates and residence temperature before the corresponding material is synthesized in a continuous flow reactor. Synthesized material—in this case, for a fuel cell—flows through characterization devices that report material property measurements back to the optimization solver. Figure courtesy of Stefan Wild.*

Such techniques can greatly increase the range of decision variable dimensions for which zeroth-order deterministic problems are solvable in practice. For example, Figure 3 depicts the way in which a subproblem that would have been posed in a three-dimensional trust region is now posed in a one-dimensional trust region that is defined by a randomized sketching matrix Q_k.

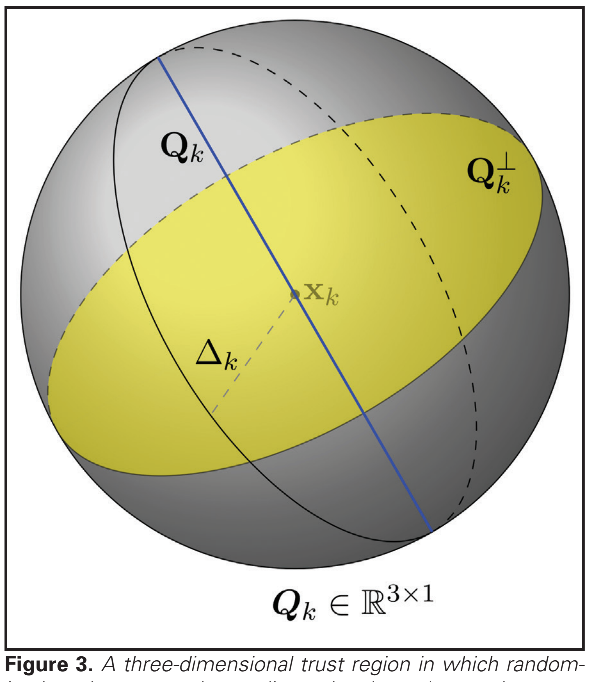


Figure 3. *A three-dimensional trust region in which randomized variants use lower-dimensional random subspaces. Figure courtesy of Xiaoqian Liu and Stefan Wild.*

When the zeroth-order oracle is stochastic, two sources of randomness occur in algorithms: (i) Randomness due to the algorithm's sketching and (ii) randomness from realizations of the stochastic oracle. We must carefully separate these two sources, but it is again possible to show that extensions of such zeroth-order algorithms are convergent on stochastic optimization problems [4].

This result allows researchers to address stochastic optimization problems with hundreds of decision variables, rather than mere handfuls. It also expands the scope for the solution of complex stochastic data-driven problems, including the tuning of variational algorithms on emerging quantum computers.

Acknowledgments: This work is partially based on efforts that are supported by the Applied Mathematics Program in the Office of Advanced Scientific Computing Research at the U.S. Department of Energy's Office of Science.

References

[1] Cartis, C., & Roberts, L. (2022). Scalable subspace methods for derivative-free nonlinear least-squares optimization. *Math. Program.*

[2] Chang, T.H., & Wild, S.M. (2022). *ParMOO: Python library for parallel multiobjective simulation optimization*. Retrieved from https://parmoo.readthedocs.io.

[3] Conn, A.R., Scheinberg, K., & Vicente, L.N. (2009). *Introduction to derivative-free optimization*. In *MOS-SIAM series on optimization*. Philadelphia, PA: Society for Industrial and Applied Mathematics.

[4] Dzahini, K.J., & Wild, S.M. (2022). Stochastic trust-region algorithm in random subspaces with convergence and expected complexity analyses. Preprint, *arXiv:2207.06452*.

[5] Larson, J., Menickelly, M., & Wild, S.M. (2019). Derivative-free optimization methods. *Acta Numer.*, *28*, 287-404.

Stefan M. Wild is director of the Applied Mathematics and Computational Research Division at Lawrence Berkeley National Laboratory. He was formerly a senior computational mathematician at Argonne National Laboratory. His website is https://wildsm.github.io.

Dynamical Systems

Continued from page 1

One may think of EDMD as a Galerkin method to approximate the Koopman operator by a finite matrix $\mathbf{K}\in\mathbb{C}^{N\times N}$.

However, practical realities have tempered much of the promise of Koopman theory — infinite-dimensional spectral problems are difficult! So difficult, in fact, that sometimes a computer cannot even *approximately* solve them. Two of the biggest challenges that currently face data-driven Koopman theory are as follows [2]:

(i) Spectral pollution (i.e., spurious modes) that results from the approximation of infinite-dimensional dynamics in a chosen finite-dimensional computational basis

(ii) Systems with continuous eigenvalue spectrums, such as a simple pendulum that oscillates at a continuous range of frequencies for different energies.

Moreover, if $\mathcal{K}$ preserves a key structure (e.g., a measure), can we ensure that $\mathbf{K}$ does so as well? Here, we summarize these significant challenges and describe new advances that offer resilient solutions that are based on rigorous, infinite-dimensional numerical analysis [3-5].

Addressing Spectral Pollution: The Power of Residuals

We want to approximate functions g in terms of a finite set of basis functions $\psi_1,\ldots,\psi_N$, $\psi_j:\Omega\rightarrow\mathbb{C}$. In turn, EDMD approximates $\mathcal{K}$ by a finite matrix $\mathbf{K}\in\mathbb{C}^{N\times N}$. Due to this truncation, eigenvalues of $\mathbf{K}$ may be spurious and have no relationship to the spectrum of $\mathcal{K}$. Consider trajectory data $\{\boldsymbol{x}^{(m)},\boldsymbol{y}^{(m)}=\boldsymbol{F}(\boldsymbol{x}^{(m)})\}_{m=1}^{M}$ and define the matrices

$$M_X=\sqrt{W}\begin{pmatrix}\psi_1(\boldsymbol{x}^{(1)}) & \cdots & \psi_N(\boldsymbol{x}^{(1)})\\ & \vdots & \\ \psi_1(\boldsymbol{x}^{(M)}) & \cdots & \psi_N(\boldsymbol{x}^{(M)})\end{pmatrix},$$

$$M_Y=\sqrt{W}\begin{pmatrix}\psi_1(\boldsymbol{y}^{(1)}) & \cdots & \psi_N(\boldsymbol{y}^{(1)})\\ & \vdots & \\ \psi_1(\boldsymbol{y}^{(M)}) & \cdots & \psi_N(\boldsymbol{y}^{(M)})\end{pmatrix},$$

where $W=\text{diag}(w_1,\ldots w_M)$. The parameters w_m, which we interpret as quadrature weights, measure the relative importance of each snapshot $(\boldsymbol{x}^{(m)},\boldsymbol{y}^{(m)})$ and $\mathbf{K}=(M_X{}^*M_X)^{\dagger}M_X{}^*M_Y$. How can we assess the accuracy of a candidate eigenfunction $\varphi(x)=\sum_{j=1}^{N}\boldsymbol{v}_j\psi_j(x)$ of $\mathcal{K}$ with $\boldsymbol{v}\in\mathbb{C}^N$ and a corresponding candidate eigenvalue λ? (Note that we may compute such approximate eigenpairs from $\mathbf{K}$ or some other means). One solution is to approximate relative residuals via the equation

$$\frac{||\mathcal{K}\varphi-\lambda\varphi||^2}{||\varphi||^2}\approx\left(\boldsymbol{v}^*\left[M_Y{}^*M_Y-\lambda(M_X{}^*M_Y)^*-\bar{\lambda}M_X{}^*M_Y+|\lambda|^2M_X{}^*M_X\right]\boldsymbol{v}\right)/\boldsymbol{v}^*\left[M_X{}^*M_X\right]\boldsymbol{v}.$$

Under generic conditions, this approximation becomes exact in the large data limit $M\rightarrow\infty$. Using the additional matrix $M_Y{}^*M_Y$ provides access to an *infinite-dimensional* residual, even with *finite matrices*. We can therefore turn this idea into an algorithm—*residual* DMD (ResDMD) [5]—at no extra computational or data cost beyond that of EDMD. By either discarding eigenpairs of $\mathbf{K}$ with large residuals or using the residual itself to search for local minima, we can compute spectra of $\mathcal{K}$ without spectral pollution. For example, Figure 1 (on page 1) illustrates Koopman modes that are computed for a turbulent flow; ResDMD provides error bounds and hence allows us to compute a picture that is physically correct. Because ResDMD verifies spectral computations, we can also verify Koopman mode decompositions and learned choices of ψ_j.

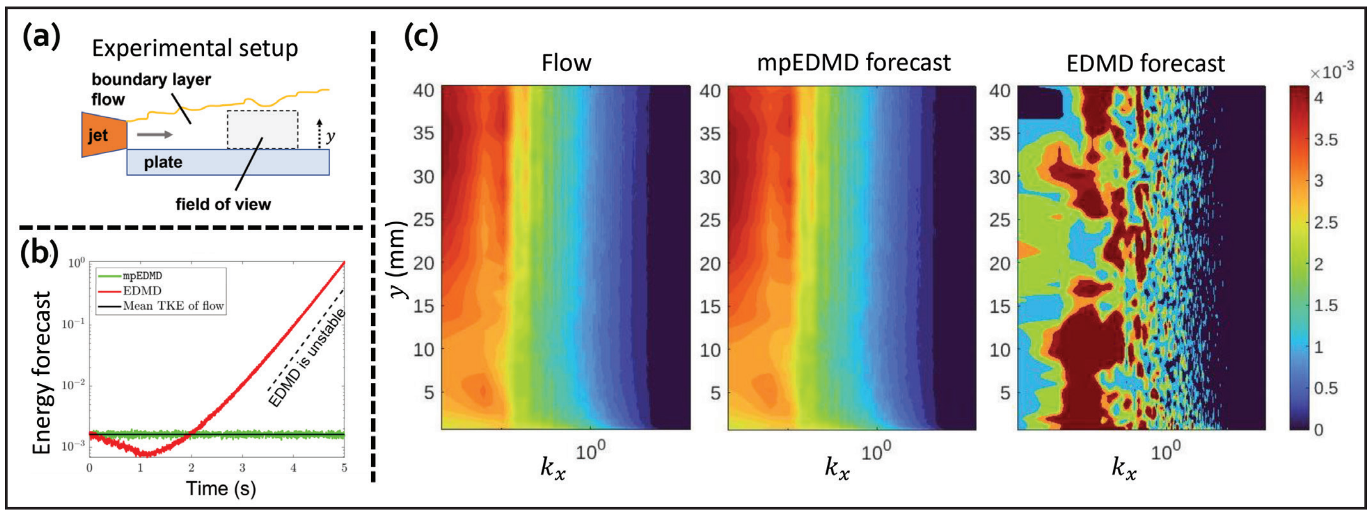


Figure 3. *The advantage of structure-preserving discretizations, such as the measure-preserving extended dynamic mode decomposition (mpEDMD).* **3a.** *Experimental setup of wall-jet boundary layer flow with Reynolds number* 6.4×10^4. **3b.** *Horizontal averages of the forecasts for turbulent kinetic energy, which show stability of mpEDMD.* **3c.** *Wavenumber spectra measure the energy content of various turbulent structures as a function of their size, thus providing an efficient measure of a flow reconstruction method's performance over various spatial scales. Figure courtesy of Matthew Colbrook.*

Computing Continuous Spectra: Smoothing with Rational Kernels

Many operators in infinite dimensions can have continuous spectra and thus may not be diagonalized by eigenfunctions alone. However, truncating to a finite matrix $\mathbf{K}$ destroys continuous spectra. We wish to compute so-called *spectral measures*, as doing so allows us to provide a diagonalization of $\mathcal{K}$. If the dynamical system preserves a measure, we can expand a function $g:\Omega\rightarrow\mathbb{C}$ in terms of eigenfunctions φ_j and generalized eigenfunctions $\phi_{\theta,g}$ of $\mathcal{K}$ [8]:

$$g(\boldsymbol{x})=\sum_{\text{eigs. }\lambda_j}c_j\varphi_j(\boldsymbol{x})+\underbrace{\int_{-\pi}^{\pi}\phi_{\theta,g}(\boldsymbol{x})d\theta}_{\text{continuous spectra}}.$$

This decomposition is characterized by spectral measures ν_g that are supported on the unit circle. Just as a prism splits white light into its different frequencies (see Figure 2a), ν_g splits the signal $\{g(\boldsymbol{x}_n)\}$ into simpler parts with corresponding spectral frequencies:

$$g(\boldsymbol{x}_n)=[\mathcal{K}^n g](\boldsymbol{x}_0)=$$

$$\sum_{\text{eigs. }\lambda_j}c_j\lambda_j^n\varphi_j(\boldsymbol{x}_0)+\int_{-\pi}^{\pi}e^{in\theta}\phi_{\theta,g}(\boldsymbol{x}_0)d\theta.$$

We can compute smoothed approximations ν_g^{ϵ} that correspond to the convolution of ν_g with a smoothing kernel of smoothing parameter ϵ [5]. A judicious choice of *rational* kernels leads to an exact representation of ν_g^{ϵ} in terms of the resolvent operator, i.e., solutions of linear systems $(\mathcal{K}-z)^{-1}g$. We must adaptively select the truncation size $N=N(\epsilon)$ to compute the solutions of these systems for a given smoothing parameter ϵ. This action yields an algorithm that computes spectral measures of generic Koopman operators [5] with explicit convergence rates as $\epsilon\downarrow 0$, which allows us to compute continuous spectra of Koopman operators. Figure 2 depicts this algorithm in action for the nonlinear pendulum, which is readily analyzable via Poincaré's geometric approach but remained a canonical open problem in Koopman analysis for several years.

Structure-preserving Discretizations

We can also enforce structure preservation in approximations of Koopman operators. For example, if the system in (1) is measure preserving, then $\mathcal{K}$ is an isometry. When $G=M_X{}^*M_X$, $\boldsymbol{g}^*\mathbf{K}^*G\mathbf{K}\boldsymbol{g}\approx\|\mathcal{K}g\|^2=\|g\|^2\approx\boldsymbol{g}^*G\boldsymbol{g}$, which becomes exact in the large data limit. *Measure-preserving* EDMD (mpEDMD) [3] enforces $G=\mathbf{K}^*G\mathbf{K}$ and leads to an orthogonal Procrustes problem:

$$\mathbf{K}\in\underset{\substack{B\in\mathbb{C}^{N\times N}\\ B^*GB=G}}{\operatorname{argmin}}\left\|M_YG^{-\frac{1}{2}}-M_XBG^{-\frac{1}{2}}\right\|_F^2.\quad(2)$$

Using the singular value decomposition, we can compute a solution; this solution combines a Galerkin projection with a polar decomposition. For information about incorporating other types of constraints in DMD via Procrustes problems, see [1]. Figure 3 shows key benefits of mpEDMD when capturing the behavior of a turbulent boundary-layer flow. Moreover, mpEDMD utilizes a discretization matrix that is normal in a suitable Hilbert space, thus allowing us to tackle the two aforementioned challenges and causing the convergence of key spectral properties and even convergence rates in system sizes N. The problem in (2) is also equivalent to the corresponding constrained total least-squares problem and hence provides a strongly consistent estimation that is robust to noise in M_X and M_Y.

The Need for Infinite-dimensional Numerical Analysis

These examples demonstrate the way in which an infinite-dimensional numerical analysis view of spectral computations led to breakthroughs in the use of Koopman operators. But this is by no means the end of the story, as future directions involve establishing connections to infinite-dimensional control theory and optimizing feature spaces based on measures of a subspace's invariance. However, any theory that seeks to understand the convergence of algorithms for Koopman operators—and any algorithm that is based on finite-dimensional approximations and seeks to be robust—must be aware of the infinite-dimensional nature of Koopman operators and the associated pitfalls.

Given the rich history of spectral computations, it is natural to turn to infinite-dimensional numerical analysis for methods and solutions. However, we cannot solve all infinite-dimensional spectral problems computationally, and the same is undoubtedly true for data-driven dynamical systems. The establishment of methodological boundaries—i.e., proving impossibility results that shine a light on limitations and guide us in feasible directions—will be a key future direction in this field. A formidable question is, "What are the foundations of data-driven dynamical systems and computing spectral properties of Koopman operators?" The answer will help us realize Koopman's 90-year-old perspective as a powerful tool in the 21st century.

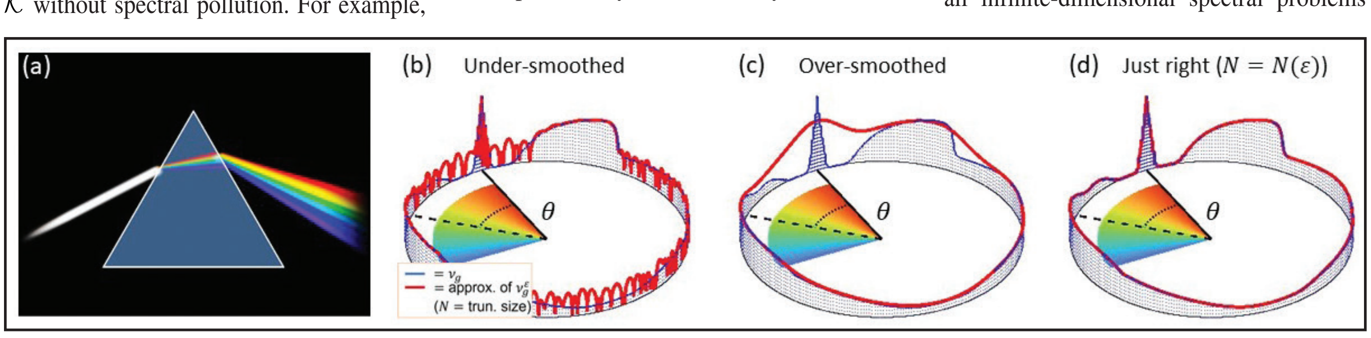


Figure 2. *Spectral measures (supported on the unit circle) that are computed from trajectory data for the fully nonlinear pendulum.* **2a.** *Spectral measures decompose a system into simpler parts, just like a prism splits up light.* **2b.** *The outcome when the selected* N *is not large enough.* **2c.** *The consequence of over-smoothing.* **2d.** *The adaptive method, which converges, demonstrates that we can now compute spectral measures and continuous spectra. Figure courtesy of the authors.*

References

[1] Baddoo, P.J., Herrmann, B., McKeon, B.J., Kutz, J.N., & Brunton, S.L. (2021). Physics-informed dynamic mode decomposition (piDMD). To appear in *Proc. Royal Soc. A*.

[2] Brunton, S.L., Budišić, M., Kaiser, E., & Kutz, J.N. (2022). Modern Koopman theory for dynamical systems. *SIAM Rev.*, *64*(2), 229-340.

[3] Colbrook, M.J. (2022). The mpEDMD algorithm for data-driven computations of measure-preserving dynamical systems. Preprint, *arXiv:2209.02244*.

[4] Colbrook, M.J., Ayton, L.J., & Szőke, M. (2022). Residual dynamic mode decomposition: Robust and verified Koopmanism. Preprint, *arXiv:2205.09779*.

[5] Colbrook, M.J., & Townsend, A. (2021). Rigorous data-driven computation of spectral properties of Koopman operators for dynamical systems. Preprint, *arXiv:2111.14889*.

[6] Koopman, B.O. (1931). Hamiltonian systems and transformation in Hilbert space. *Proc. Nat. Acad. Sci.*, *17*(5), 315-318.

[7] Koopman, B.O., & Von Neumann, J. (1932). Dynamical systems of continuous spectra. *Proc. Nat. Acad. Sci.*, *18*(3), 255-263.

[8] Mezić, I. (2005). Spectral properties of dynamical systems, model reduction and decompositions. *Nonlin. Dyn.*, *41*(1), 309-325.

[9] Rowley, C.W., Mezić, I., Bagheri, S., Schlatter, P., & Henningson, D.S. (2009). Spectral analysis of nonlinear flows. *J. Fluid Mech.*, *641*, 115-127.

[10] Schmid, P.J. (2010). Dynamic mode decomposition of numerical and experimental data. *J. Fluid Mech.*, *656*, 5-28.

[11] Williams, M.O., Kevrekidis, I.G., & Rowley, C.W. (2015). A data-driven approximation of the Koopman operator: Extending dynamic mode decomposition. *J. Nonlin. Sci.*, *25*(6), 1307-1346.

Steven L. Brunton is a professor of mechanical engineering at the University of Washington (UW). He is also an adjunct professor of applied mathematics and computer science, and a Data Science Fellow at UW's eScience Institute. His research combines machine learning with dynamical systems to model and control systems in fluid dynamics, biolocomotion, optics, energy systems, and manufacturing. Matthew J. Colbrook is an assistant professor at the University of Cambridge. He studies the analysis and development of algorithms in the context of approximation theory, spectral theory, solutions of partial differential equations, neural networks, data-driven dynamical systems, optimization, inverse problems, and the solvability complexity index.

2022 Gene Golub SIAM Summer School Explores Financial Analytics

By Agostino Capponi, Francesca Biagini, Sebastian Jaimungal, and Stephan Sturm

The 2022 Gene Golub SIAM Summer School[1] (G2S3) took place at the Gran Sasso Science Institute in L'Aquila, Italy, from August 1-12, 2022. SIAM founded the program[2]—which offers schools in applied mathematics, computational science, and industrial mathematics for graduate students in mathematics and computer science—after a generous bequest from former SIAM President Gene Golub, a pioneer in the field of numerical analysis. The theme of the 2022 school, which was organized by the SIAM Activity Group on Financial Mathematics and Engineering,[3] was "Financial Analytics: Networks, Learning, and High-Performance Computing."

Nearly 40 students from 12 different countries took part in the 2022 iteration of G2S3. The Gran Sasso Science Institute's wonderful hospitality facilitated the students' active participation in an intensive study program that featured the most recent advancements in mathematical finance and computation. The schedule included four invited lecturers, whose two-day talks and activities built upon each other and effectively integrated theory and practice problems, including programming exercises.

[1] https://siam2022.gssi.it
[2] https://www.siam.org/students-education/programs-initiatives/gene-golub-siam-summer-school
[3] https://www.siam.org/membership/activity-groups/detail/financial-mathematics-and-engineering

The invited speakers and their areas of expertise were as follows:

- Ludovic Tangpi (Princeton University): Quantitative Risk Management in Finance
- Mike Ludkovski (University of California, Santa Barbara): Energy and Commodity Markets
- Matthew Dixon (Illinois Institute of Technology): Machine Learning and Financial Technology
- Roxana Dumitrescu (King's College London): Mean Field Games.

These lecturers represent the scientific quality and diversity that comprised the core of G2S3's immersive experience.

Throughout the course of the summer school, attendees grew their networks and interacted with peers from all over the world. A highlight of 2022's G2S3 was the "Student's Day." After a brief introduction on presentation skills, students split into groups and prepared short presentations based on previously-covered material from the school. Each group then delivered their presentations and received feedback from the four G2S3 lecturers and their fellow participants. To further enhance the students' involvement, several poster sessions allowed them to share and discuss their own research with one another.

The 2022 G2S3 organizers placed a special emphasis on preparation for professional careers in the finance and financial technology sectors. One evening, market practitioner Marco Bianchetti (Intesa Sanpaolo) visited the group and offered personal insights, skills, and tips on how to effectively prepare for a career in industry. His talk was followed by a question-and-answer session about academic careers, during which assistant professors and senior postdoctoral researchers shared their stories.

Participants of the 2022 Gene Golub SIAM Summer School (G2S3)—which took place in L'Aquila, Italy, in August 2022—gather for a group photo outside of the Gran Sasso Science Institute. Photo courtesy of Fabio Paolucci.

To foster group spirit and take advantage of L'Aquila's beautiful mountains, the summer school organizers coordinated a wonderful excursion to Santo Stefano di Sessanio that involved a short hike to the Castle of Rocca Calascio, with lunch and a guided tour for all students. The 12-day program offered numerous other opportunities to taste delicious Italian food and experience Italian art and culture as well.

The latest rendition of G2S3 was a great success thanks to support and engagement from multiple parties. In particular, we wish to acknowledge SIAM for its generous financial support, the Gran Sasso Science Institute for its organization and hospitality, and Stephan Sturm (Worcester Polytechnic Institute) and Katharina Oberpriller (University of Freiburg) for assisting the participants with an incredible level of devotion throughout the program's entire duration. These contributors collectively made it possible for us to organize a first-class event with intellectual activities and valuable social interactions. We highly recommend that other SIAM Activity Groups[4] organize summer schools in the future, as such programs successfully train and guide the next generation of applied mathematicians who are preparing to embark on their professional careers.

*The 2023 Gene Golub SIAM Summer School on Quantum Computing and Optimization[5] will take place at Lehigh University in Bethlehem, Pa., from July 30 to August 11, 2023. Applications are currently being accepted; the deadline to apply for the 2023 program is **February 15, 2023**. Please reach out to **g2s3quantum-list@lehigh.edu** with any questions.*

*Interested in organizing a future school? Letters of intent that propose topics and organizers for the 2024 iteration of G2S3 are due to Richard Moore, SIAM's Director of Programs and Services, at **moore@siam.org** by **January 31, 2023**. Visit the G2S3 website to learn more.[6]*

Student participants enjoy a hiking excursion to Santo Stefano di Sessanio and the Castle of Rocca Calascio during the 2022 Gene Golub SIAM Summer School (G2S3), which took place in L'Aquila, Italy, in August 2022. Photo courtesy of Lingyi Yang.

[4] https://www.siam.org/membership/activity-groups
[5] https://wordpress.lehigh.edu/siamquantum

Agostino Capponi, Francesca Biagini, Sebastian Jaimungal, and Stephan Sturm were the organizers of the 2022 iteration of G2S3. Agostino Capponi is an associate professor in the Department of Industrial Engineering and Operations Research at Columbia University, where he is also the founding director of the Center for Digital Finance and Technologies. He served as chair of the SIAM Activity Group on Financial Mathematics and Engineering (SIAG/FME) from 2019 to 2021. Francesca Biagini is a full professor at the University of Munich, where she is also Vice President for International Affairs and Diversity. She served as the secretary of SIAG/FME from 2017 to 2019. Sebastian Jaimungal is a full professor of mathematical finance at the University of Toronto and a fellow of the Fields Institute for Research in Mathematical Sciences. He has served SIAG/FME in various roles, most recently as its chair from 2017 to 2019. Stephan Sturm is an associate professor of applied mathematics at Worcester Polytechnic Institute who specializes in the field of financial mathematics and engineering. He served as the secretary of SIAG/FME from 2020 to 2022.

[6] https://www.siam.org/students-education/programs-initiatives/gene-golub-siam-summer-school

Seymour Victor Parter

Continued from page 3

equations (PDEs), iterative methods, and preconditioners for numerical solutions of matrix equations. Though he did not consider himself a specialist, Seymour made significant advances in multiple areas. For instance, he wrote several papers that linked graph theory to sparse elimination — including an early paper that was published in *SIAM Review* in 1961 [2]. Researchers still used the paper's key lemma to design and analyze sparse elimination methods three decades later.

Seymour also conducted significant analysis on Toeplitz forms and the eigenvectors and singular values of Toeplitz matrices, which pertain to error estimation and preconditioning. His work in singular perturbations and bifurcation theory expanded to the study of chemical reactors and fluid flows between rotating disks. He authored several influential series of papers about block iterative methods for finite difference and finite element matrices, the convergence of multigrid schemes, and the norm and spectral equivalence of elliptic PDEs.

Seymour was active in the broader mathematical community and sat on numerous panels and committees, including an advisory panel to the National Academy of Sciences. He was also a prominent, engaged member of SIAM. He served on the Joint Projects Committee of the American Mathematical Society, Mathematical Association of America, and SIAM from 1978-1980; the SIAM Council from 1978-1981; and as SIAM President from 1981-1982. Seymour was also the managing editor of the *SIAM Journal on Numerical Analysis* from 1977-1980 and served on its editorial board from 1981-1997. In addition, he was on the editorial board for the *SIAM Journal on Applied Mathematics* from 1976-1979.

Beyond SIAM, Seymour became chairman of the Conference Board of Mathematical Sciences from 1983-1985. Furthermore, he edited books on numerical methods for PDEs, large-scale scientific computation, and (with Richard Meyer) singular perturbations and asymptotics. He was elected as a SIAM Fellow in 2009 and a fellow of the American Association for the Advancement of Science in 1992.

Seymour officially retired from UW–Madison in 1996, though he continued post-retirement service for three years and remained involved in probability seminars and topics courses for even longer. He and Ruth loved to travel and visited Germany, Australia, and New Zealand. Seymour kept attending conferences, giving lectures at universities, and conferring with other researchers about exciting problems. He also maintained two long-standing habits during retirement: enthusiastically participating in reading clubs and running with a group of friends along the lakefront near UW–Madison's campus (slow enough for conversation but steady enough to reach an interesting destination, a practice that lasted until the runners were well into their 80s and 90s).

Seymour's family—his wife Ruth, sons Paul and David, daughter-in-law Susan, and grandchildren Alicia, Ezra, and Danielle—as well as his intersecting circles of friends, colleagues, and students all agree that he was attentive, kind, caring, competent, and accomplished. He will be sorely missed.

References

[1] Parter, S.V. (1960). On mappings of multiply connected domains by solutions of partial differential equations. *Commun. Pure Appl. Math.*, *13*(2), 167-182.

[2] Parter, S. (1961). The use of linear graphs in Gauss elimination. *SIAM Rev.*, *3*(2), 119-130.

Michael Steuerwalt holds a B.E.E. and M.S. from the University of Dayton and a Ph.D. from the University of Wisconsin–Madison. He worked as a student and staff member at Los Alamos National Laboratory and was program director of the computational mathematics and applied mathematics programs in the National Science Foundation's Division of Mathematical Sciences.

Anticipating the 2023 COMAP Modeling Contests

By Guangming Yao, Kelly Black, Amanda Beecher, Kathleen Kavanagh, and Steve Horton

Are you looking for an opportunity to help your undergraduate students solve real-world problems with applied mathematics and computational methodologies? Consider forming a team and participating in one of the Consortium for Mathematics and Its Applications[1] (COMAP) international modeling contests[2] — and potentially winning one of six SIAM Awards in the Mathematical Contest in Modeling and Interdisciplinary Contest in Modeling.[3]

COMAP's annual contests promote mathematical modeling and creative problem-solving. Participating students work together in groups to tackle a complex, open-ended problem that does not have one distinct solution. COMAP sponsors several types of contests, including the Mathematical Contest in Modeling (MCM) and Interdisciplinary Contest in Modeling[4] (ICM) for high school and undergraduate students, the Middle and High School Mathematical Contests in Modeling,[5] and the International Mathematical Modeling Challenge for middle and high school students.[6]

Each team must have an advisor, though the responsibilities of this individual are minimal. Nevertheless, working with a team can be a rewarding experience for advisors because it provides them with a rare chance to interact with a small group of students and focus on aspects of problem-solving that are rarely addressed in the classroom. During the competition, teams progress through a full range of interesting activities. For instance, they must decide how to best scale back the problem in question while still capturing the phenomena of interest; conduct a basic analysis of their model and explore its sensitivity and assumptions; and submit a full written report that describes the model, analysis, and results. These contests thus facilitate the type of personal growth that might otherwise occur over a much longer time span.

Students who take part in MCM and ICM gain a level of experience that is atypical for undergraduates. Participants can use—and have used—their involvement as talking points in job interviews; discussing one's efforts to solve a complex problem in a group setting will certainly interest potential employers. The same is true for graduate school applications. Every student, regardless of whether they win a top contest award, receives this benefit.

Each submitted contest paper is reviewed at least twice by professional mathematicians and/or scientists, and we invite interested *SIAM News* readers to get involved by volunteering to score student papers. The judgment process directly supports our students and profession, and judges experience the triumph of student successes firsthand.

MCM was founded in 1985 and ICM began in 2015. The contests' current format—which consists of three problems each for MCM and ICM—was first implemented in 2018. MCM and ICM problems address continuous and discrete mathematics, data insights, operations research, network science, sustainability, and policy. Nearly 500 U.S. teams and over 20,000 teams from across the globe compete in the competitions every year. A total of 27,205 teams from more than 1,400 institutions participated in 2022, ultimately providing 80,000+ students with an authentic, real-world modeling marathon experience.

SIAM supports MCM and ICM by recognizing six teams who are ranked as "Outstanding" during judging—one for each problem—with a SIAM Award.[7] Each winning team member receives a complimentary one-year SIAM student membership, and the faculty advisor is sent a certificate that recognizes the team. COMAP also offers a number of other awards[8] for MCM and ICM, including the Ben Fusaro Award, Frank R.

See **Modeling Contests** *on page 8*

1 https://www.comap.com
2 https://www.comap.com/contests
3 https://www.siam.org/prizes-recognition/student-prizes/detail/siam-award-in-the-mathematical-contest-in-modeling
4 https://www.contest.comap.com/undergraduate/contests/index.html
5 https://www.comap.com/contests/himcm-midmcm
6 http://www.immchallenge.org
7 https://www.siam.org/prizes-recognition/student-prizes/detail/full-prize-specifications/siam-award-in-the-mathematical-contest-in-modeling
8 https://www.contest.comap.com/undergraduate/contests/mcm/instructions.php#VIII

SIAM Establishes Postdoctoral Support Fund

SIAM is excited to announce that it has established the SIAM Postdoctoral Support Fund. This new fund is made possible with the backing of longtime members and respected advocates of SIAM and the applied mathematics community, Dr. Martin (Marty) Golubitsky and Dr. Barbara L. Keyfitz. SIAM is incredibly grateful for their generous gift, which will be used to directly support postdoctoral researchers by offering them much-needed mentorship and direct research experience opportunities.

The SIAM Postdoctoral Support Fund will establish a unique and important program that provides postdoctoral scholars with resources, mentorship, and career advancement opportunities that are often difficult to obtain. The fund will support up to four postdocs and their mentors per year, and each mentor/mentee pair will receive up to $15,000 of support. The first group of postdocs will be selected in the summer of 2023 from multiple disciplines within academia, business, and industry. Read more about the fund—as well as Dr. Golubitsky and Dr. Keyfitz's robust engagement with SIAM programs, publications, and events over the years—in the full online announcement.[1]


Martin (Marty) Golubitsky and Barbara Keyfitz.

"We are fortunate that in our careers, we have frequently had the opportunity to mentor postdoctoral researchers," Dr. Golubitsky and Dr. Keyfitz said. "Our own research programs have benefitted greatly from these interactions. We believe that the new SIAM Postdoctoral Support Fund will help expand unusual postdoctoral research and networking opportunities for new Ph.D.s during a pivotal time in their careers."

Many thanks to Dr. Golubitsky and Dr. Keyfitz for helping to fund this new program! SIAM is deeply appreciative of their philanthropy.

1 https://sinews.siam.org/Details-Page/siam-establishes-postdoctoral-support-fund

A Successful Revival of the SIAM Washington-Baltimore Section

By Harbir Antil and Ratna Khatri

The 2022 SIAM Washington, D.C.-Baltimore Section Annual Meeting[1] took place at the Virginia Tech Research Center in Arlington, Va., on November 4, 2022. This gathering marked the resurrection of the SIAM Washington-Baltimore Section,[2] which serves members in Washington, D.C., Maryland, Virginia, and Delaware and had previously remained dormant for several years. Section vice president Harbir Antil (George Mason University), secretary Ratna Khatri (U.S. Naval Research Laboratory), and president Andrey Rukhin organized the in-person meeting, with generous support from SIAM, the Center for Mathematics and Artificial Intelligence[3] at George Mason University, and the Interdisciplinary Center for Applied Mathematics[4] at Virginia Tech.

[1] https://www.siam.org/conferences/cm/conference/dc-balt22
[2] https://www.siam.org/membership/sections/detail/siam-washington-baltimore-section
[3] https://cmai.gmu.edu
[4] https://vtechworks.lib.vt.edu/handle/10919/47107

The SIAM Washington-Baltimore Section was formerly inactive due to leadership complications and the COVID-19 pandemic. Rukhin, Antil, and Khatri assumed leadership in January 2022 and immediately sought to revive the section and unite the Washington-Baltimore community again. In May 2022, the board decided to coordinate an in-person section meeting for local SIAM members at all career stages (students, faculty members, and researchers/scientists) and from all sectors (academia, business, industry, and government).

The conference[5] comprised two plenary talks, presentations and a panel discussion with program officers, a poster session for students and early-career researchers, and various opportunities for networking. Stefan Wild (Lawrence Berkeley National Laboratory) and Howard Elman (University of Maryland, College Park) served as the plenary speakers. Program officers Warren P. Adams and Fariba Fahroo (Air Force Office of Scientific Research); Yuliya Gorb, Leland M. Jameson, and Stacey Levine (National Science Foundation); and Reza Malek-Madani (Office of Naval Research) offered useful insights into their respective funding agencies. Furthermore, 13 attendees from a variety of backgrounds took part in the poster session: one undergraduate student, three graduate students, six postdoctoral researchers, two faculty members, and one staff scientist.

[5] https://math.gmu.edu/~hantil/SIAM/Fall2022

While the organizers received an overwhelming amount of interest in the meeting, its size was ultimately limited by room capacity. Even after registration closed,

See **Washington-Baltimore** *on page 10*

Howard Elman (University of Maryland, College Park) delivers an engaging plenary talk during the 2022 SIAM Washington, D.C.-Baltimore Section Annual Meeting, which took place in Arlington, Va., in November 2022. Photo courtesy of Ratna Khatri.

SIAM Publications: Stronger After the Pandemic

By Kivmars Bowling

2022 saw the world finally begin to emerge from the COVID-19 pandemic. The SIAM Publications team was once again able to meet face-to-face with our communities—including SIAM book authors, journal editors, and conference attendees—after several years of virtual interactions. The virtual Zoom world persists and will surely continue to do so, as it enables greater attendance for some meetings. Nevertheless, the valuable in-person conversations over the last year reminded us of what we've been missing during lockdown (even if some social skills had to be relearned…).

Following a surge in 2020 and 2021 journal submissions that was likely driven by researchers who finished writing papers while they were stuck at home, 2022 saw a return to the pre-pandemic submission levels of 2019 — though some SIAM journals still experienced increases.

As always, we thankfully acknowledge the tireless work of our journal editors and editorial support staff, who carefully handle the healthy flow of submissions and ensure that SIAM journals maintain their prestigious publication standard. The high regard in which SIAM journals are held is again reflected in the strong increase of article downloads; this number was up 12 percent in 2022, following a 10 percent increase in 2021. The continually growing demand for SIAM journals is fantastic to see.

The SIAM Publications Library[1]—which hosts SIAM journal, e-book, and proceedings content—received an upgrade in early 2022 (see Figure 1). This renovation was the culmination of a three-year project that involved an army of internal staff, vendor staff, volunteers, and SIAM members; thank you to everyone who provided feedback and input.

New features on the modernized platform include a responsive design, improved search (with typeahead functionality), and related content recommendations. The upgrade will also allow us to begin publishing Extensible Markup Language (XML) full-text versions of SIAM content (in addition to PDFs), launch a new integrated online bookstore, and offer single sign-on for SIAM members. We hope that you've been enjoying the new platform thus far; if you have any feedback or ideas for further development, please email us at **service@siam.org**. Community input will help guide future iterations.

2023 brings editor-in-chief (EIC) transitions for two of SIAM's journals (see Figure 2). We extend our sincere thanks to the outgoing EICs, Desmond Higham (University of Edinburgh) and Daniel Král (Masaryk University), for their excellent leadership over the past six years and welcome their successors. Stanislav Živný (University of Oxford) assumed the role of EIC for the *SIAM Journal on Discrete Mathematics* (*SIDMA*) on January 1, while

[1] https://epubs.siam.org

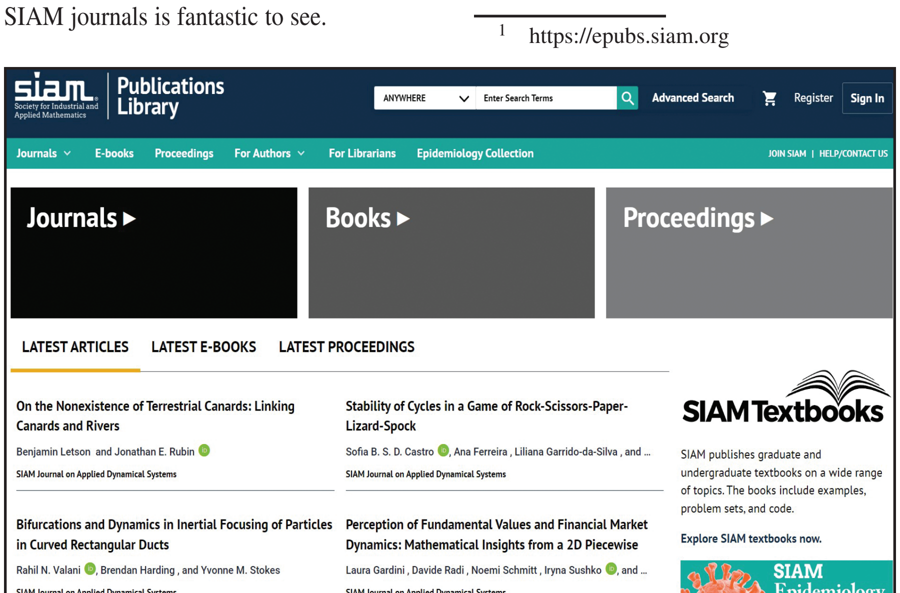


Figure 1. *The upgraded SIAM Publications Library is available at https://epubs.siam.org.*

Publication	Outgoing Editor-in-Chief	Incoming Editor-in-Chief
SIDMA	Daniel Král	Stanislav Živný
SIREV	Desmond Higham	Carola-Bibiane Schönlieb

Figure 2. *The outgoing and incoming editors-in-chief for the SIAM Journal on Discrete Mathematics (SIDMA) and SIAM Review (SIREV).*

Carola-Bibiane Schönlieb (University of Cambridge) will take the reins at *SIAM Review* (*SIREV*) on April 1.

The SIAM Books program published at a robust rate in 2022, despite the ongoing industry-wide issues with paper shortages and printing. Last year's noteworthy titles included *An Applied Mathematician's Apology*[2] by Nick Trefethen and *How to Be Creative: A Practical Guide for the Mathematical Sciences*[3] by Nicholas Higham and Dennis Sherwood. The latter text offers ideas and strategies[4] for maximizing creativity in a variety of contexts. These titles reflect SIAM's goal to publish more general interest books, in addition to our many high-quality monographs and textbooks. If you have an idea for a book project, please contact Elizabeth Greenspan (executive editor of SIAM Books) at **greenspan@siam.org**.

SIAM Journals and Open Access Funder Mandates

As a reminder, all SIAM journals are already fully compliant with the European Plan S and U.K. Research and Innovation (UKRI) funder mandates via the green open access routes. More information is available online.[5]

2022 saw the announcement of another significant funder mandate; the U.S. Office of Science and Technology Policy released a new public access memo called the Nelson Memo.[6] A key change from the 2013 Holdren Memo[7] is the elimination of the 12-month embargo for federally funded work. Each U.S. federal agency must now draft an updated public access policy that will go into effect by the end of December 2025, but SIAM authors will likely be able to comply via a green open access route. We will provide confirmation once the federal policies are published.

[2] https://my.siam.org/Store/Product/viewproduct/?ProductId=42813032
[3] https://my.siam.org/Store/Product/viewproduct/?ProductId=42453396
[4] https://sinews.siam.org/Details-Page/how-to-boost-your-creativity
[5] https://epubs.siam.org/journal-authors#openaccess
[6] https://www.whitehouse.gov/wp-content/uploads/2022/08/08-2022-OSTP-Public-Access-Memo.pdf
[7] https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/ostp_public_access_memo_2013.pdf

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Faculty support for SIAM journals and e-books is absolutely vital when libraries select resources to renew or add to their holdings. Since library budgets are under pressure and increasingly dominated by large commercial publishers, *your voice as a faculty member matters*. If you feel comfortable doing so, please talk to your institution's librarian and emphasize the importance of SIAM journals and e-books for your research and teaching endeavors. SIAM is a proud independent nonprofit society publisher, and library support is critical to ensuring that SIAM publications remain in strong health and maintain the highest standards of quality and service for the applied mathematics, computational science, and data science community.

Your own usage of SIAM journals also matters. Librarians monitor article downloads when deciding whether to renew resources, so please encourage your students and colleagues to always download SIAM articles from the SIAM Publications Library[8] when they are logged into their institutions (whether remotely or by IP address when on campus). Every SIAM article download demonstrates the value of SIAM resources at all institutions.

I look forward to more opportunities to meet many of you at SIAM conferences this year. In the meantime, feel free to reach out to me at **bowling@siam.org** with any questions or comments.

Kivmars Bowling is the Director of Publications at SIAM.

[8] https://epubs.siam.org

Key Epidemiological Parameters for SARS-CoV-2 Outbreaks and Variant Selection From Noisy Data

By Ruian Ke and Ethan Romero-Severson

The COVID-19 pandemic changed the work strategies of epidemiologists. Instead of iteratively refining models for a fixed data set over the course of months or years, researchers experienced an insatiable demand for definitive knowledge about a new pathogen. Suddenly, preliminary predictions based on noisy and often incomplete data became elements of a real-time, public discussion in a politically charged atmosphere. Conducting scientific studies that influence public decision-making is difficult, but it is not impossible. Here we discuss some of the key takeaways from our work with both noisy data and a high demand for certainty during an ongoing pandemic.

R_0 and r for Initial Outbreaks

At the beginning of the SARS-CoV-2 outbreak in Wuhan, China, in late 2019, researchers around the world wanted to estimate two fundamental epidemiological parameters: the early exponential growth rate (r) and the basic reproductive number (R_0). The former describes the rate at which an outbreak grows in size and provides an epidemic doubling time (expressed as $\log_e(2)/r$), while the latter is defined as the average number of secondary infections that result from an index case in a fully susceptible population. One typically derives R_0 from estimates of r and the estimated distribution of the generation interval, i.e., the time interval from the moment the virus infects the donor to when it infects the recipient in a transmission pair [5]. Broadly speaking, larger values of r indicate a more rapidly growing epidemic, while larger values of R_0 indicate an epidemic that is harder to control.

The earliest estimates of r and R_0 came from case report data in Wuhan [4]. By fitting an exponential growth model to initial case count data, researchers estimated r to be between 0.1 and 0.15 each day—which translates to an epidemic doubling time of five to seven days—and R_0 to be between 2.2 and 3. These approximations were very similar to the estimates for SARS-CoV-1 in 2003, leading to initial optimism that SARS-CoV-2 would not pose a global threat and would ultimately succumb to regional interventions — much like SARS-CoV-1. As we now know, this view was far too conservative. The problem was that the rapidly changing technological and clinical landscape made the data from Wuhan unreliable; any method that assumed those early data were robust generated misleading results.

Our team approached this problem in January 2020 not by trying to "fix" the noisy data from Wuhan, but by collecting extensive case reports and travel data for people who moved from Wuhan to other provinces. Focusing on individuals who were *infected* in Wuhan but *detected* outside of Hubei province (where Wuhan is located) sidestepped the issue of unreliable data that came directly from Wuhan. Unlike those at the epicenter of the pandemic, provincial health systems were prepared for incoming cases and began to rigorously test everyone who entered each province.

To further isolate potential sources of bias in different data collection systems, we designed two inference approaches to reconstruct the preliminary dynamics of SARS-CoV-2 in Wuhan [6]. We found that the early epidemic in Wuhan doubled every 2.4 days, suggesting an extremely rapid spread that progressed much more quickly than previously thought. We further estimated R_0 to be between 4.7 and 6.6 — also significantly higher than previous approximations, even when we incorporated the substantial uncertainty in other epidemiological parameters that influence R_0. When we reached this conclusion in early 2020, it was initially met with extensive criticism and disbelief, especially since no major outbreaks outside of China were occurring at the time. However, subsequent outbreaks in Europe and the U.S. suggested that our estimates of the two fundamental parameters were accurate [1, 2].

Using simulations to connect our results to real-world implications, we found that incorporating the possibility of asymptomatic transmission—which was not yet evident at the time—meant that even extensive quarantine and contact tracing of symptomatic individuals would not control the epidemic locally. Instead, early and strong control measures like social distancing were required to stop the virus' spread [6].

Retrospectively, we realized that inaccuracies in the earliest estimates of R_0 and r arose from large uncertainties in the case count data that were collected in Wuhan in late 2019. Low surveillance intensity, a lack of validated diagnostic tools for SARS-CoV-2, heterogeneity in symptoms, and so forth—issues that are often associated with a novel pathogen outbreak—were responsible for these uncertainties. Unfortunately, many forecasting models and public health policy

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Modeling Contests

Continued from page 6

Giordano Award, Leonhard Euler Award, Rachel Carson Award, Vilfredo Pareto Award, and several COMAP Scholarship Awards. Organizations such as the American Statistical Association, Mathematical Association of America, Institute for Operations Research and the Management Sciences, and American Mathematical Society also sponsor additional prizes.

MCM and ICM are rewarding pathways for SIAM undergraduate members and SIAM student chapters. Two free modeling handbooks—*Math Modeling: Getting Started and Getting Solutions*[9] [1] and *Math Modeling: Computing and Communicating*[10] [2], both written by SIAM members who are involved in the MathWorks Math Modeling Challenge[11]—are great starting points for participating student teams. SIAM's free Math Modeling Reference Cards[12] are another valuable resource (see Figure 1).

Registration is now open for COMAP's 2023 international math modeling contests. Participating MCM/ICM teams will tackle the problems over a long weekend from **Thursday, February 16** at **5 p.m. EST** to **Monday, February 20** at **8 p.m. EST** with the hope of winning one of the $10,000 COMAP Scholarship Awards.

Learn more online[13] and register[14] by **February 16** at **3 p.m. EST**. Follow @COMAPMath on Twitter for up-to-date contest information, and visit the COMAP website for free modeling resources and study materials.[15] Encourage your students to form a team and sign up for this highly impactful experience today!

References

[1] Bliss, K.M., Fowler, K.R., & Galluzzo, B.J. (2014). *Math modeling: Getting started and getting solutions*. Philadelphia, PA: Society for Industrial and Applied Mathematics.

[2] Bliss, K.M., Galluzzo, B.J., Kavanagh, K.R., & Levy, R. (2018). *Math modeling: Computing and communicating*. Philadelphia, PA: Society for Industrial and Applied Mathematics.

Guangming Yao is an associate professor of mathematics at Clarkson University. She has served as a judge for MathWorks Math Modeling Challenge and the Consortium for Mathematics and Its Applications (COMAP) Mathematical Contest in Modeling (MCM) for years. Kelly Black is an academic professional at the University of Georgia. He has been involved with MCM for nearly 30 years and is currently the lead judge for "Problem A," as well as a member of the problem writing committee. Amanda Beecher is an associate professor of mathematics at Ramapo College of New Jersey, where she also serves as the founding department head of the Data Science undergraduate program and program director of the Master of Science in Applied Mathematics program. She is the Director of Undergraduate Contests at COMAP. Kathleen Kavanagh is a professor of mathematics at Clarkson University and the Vice President for Education at SIAM. Steve Horton is a professor emeritus and former head of the Department of Mathematical Sciences at West Point.

[9] https://m3challenge.siam.org/sites/default/files/uploads/siam-guidebook-final-press.pdf

[10] https://m3challenge.siam.org/sites/default/files/uploads/siam-technical-guidebook-web.pdf

[11] https://m3challenge.siam.org

[12] https://m3challenge.siam.org/sites/default/files/uploads/siam-cards-final-press.pdf

[13] https://www.contest.comap.com/undergraduate/contests/index.html

[14] https://www.contest.comap.com/undergraduate/contests/mcm/register.php

[15] https://www.comap.com/resources/free-materials

Figure 1. *Students can use these Math Modeling Reference Cards, which are freely available from SIAM,[12] to prepare for contests such as the Mathematical Contest in Modeling (MCM), Interdisciplinary Contest in Modeling (ICM), and MathWorks Math Modeling Challenge.*

SARS-CoV-2

Continued from page 8

decisions throughout 2020 integrated the initial conservative estimates of R_0 and epidemic doubling time, largely ignoring the later (and often more accurate) estimates that were based on better data. It is impossible to know exactly what we could have done to avoid this scenario; however, a critical examination of the appropriateness of standard methods for the unique situation would certainly have helped frame the discussion in terms of how noise and uncertainty shaped the early data.

Selection Coefficient for SARS-CoV-2 Variants

As COVID-19 spread globally, researchers began to worry about viral evolution and selection. Bette Korber of Los Alamos National Laboratory was the first person to identify positive selection in SARS-CoV-2 in the D614G mutation by tracking the change in frequency over time [3]. At first, her discovery faced widespread incredulity; critics wondered how a single amino acid could change the phenotype so drastically. Other studies around that time employed phylogenetic-based methods and found limited evidence of selection at D614G [9], thus framing an apparent controversy surrounding SARS-CoV-2's possible evolution towards higher levels of contagiousness.

We approached this issue from a different perspective. Rather than attempting to track the places at which D614G emerged globally, we considered its first entry into a country as a unique trial and modeled the time to extinction or fixation (when all sampled viruses have the D614G mutation) [7]. By treating countries like pseudo-independent units, we explicitly modeled the heterogeneity in selection effects due to differences in the ways in which various countries collected SARS-CoV-2 data. This method ultimately led to a more stable estimate of the danger of new variants.

After our attempts to estimate r, we tried several different types of models—from a complex stochastic model to a simple statistical model—under the assumption that knowing the validity of different model structures was as important as the inferences themselves. We found unambiguous evidence for selection, which suggested an increase in contagiousness for D614G and several other variants — even in the presence of very high levels of migration [7]. We later extended this work to prove that increases in recent infections by a previous variant (e.g., Delta) consequently heighten the selection effect for a new incoming variant (e.g., Omicron) [8]. However, heterogeneity in measured selection effects at the country level was very large. If we had used noisy data from only one country or ignored the data's natural hierarchical structure, we easily could have significantly under- or overestimated the selection effects for new variants.

Lessons Learned

Ultimately, we concluded that applied epidemiology during an ongoing pandemic is severely complicated by the noisy and incomplete data that stem from a novel pathogen outbreak. Even simple tasks, such as estimating an exponential growth rate, become challenging if auxiliary assumptions are left unexamined and subsequently unmet. While we do not have an immediate solution to these problems, we attempted to implement workflows that acknowledge early data's potential inaccuracies and the helpfulness of analytical methods—like novel data cleaning techniques and explicit modeling of random effects—when accounting for data uncertainty. We can therefore collectively prepare for the next pandemic by developing a body of knowledge that encompasses strategies to best handle potentially unreliable data, realistic standards for the integration of uncertainty in epidemiological parameters, and statistical software that incorporates those concerns.

More broadly, our experiences during the beginning stages of the COVID-19 pandemic clearly demonstrate that uncertainties in early data collection for a novel outbreak can yield diverse or opposing conclusions from different research groups. As scientists, we should resist the urge to quickly settle scientific issues and form consensuses too prematurely; the rigorous discussion and evaluation of different findings will presumably lead to more accurate knowledge and better public health policies. According to theoretical physicist Richard Feynman, "The first principle is that you must not fool yourself, and you are the easiest person to fool." This is a good reminder, especially when the stakes are high.

References

[1] Ke, R., Romero-Severson, E., Sanche, S., & Hengartner, N. (2021). Estimating the reproductive number R_0 of SARS-CoV-2 in the United States and eight European countries and implications for vaccination. *J. Theor. Biol.*, *517*, 110621.

[2] Ke, R., Sanche, S., Romero-Severson, E., & Hengartner, N. (2020). Fast spread of COVID-19 in Europe and the US suggests the necessity of early, strong and comprehensive interventions. Preprint, *medRxiv*.

[3] Korber, B., Fischer, W.M., Gnanakaran, S., Yoon, H., Theiler, J., Abfalterer, W., … Montefiori, D.C. (2020). Tracking changes in SARS-CoV-2 spike: Evidence that D614G increases infectivity of the COVID-19 virus. *Cell*, *182*(4), 812-827.e19.

[4] Li, Q., Guan, X., Wu, P., Wang, X., Zhou, L., Tong, Y., … Feng, Z. (2020). Early transmission dynamics in Wuhan, China, of novel coronavirus-infected pneumonia. *New Engl. J. Med.*, *382*(13), 1199-1207.

[5] Park, S.W., Bolker, B.M., Champredon, D., Earn, D.J.D., Li, M., Weitz, J.S., … Dushoff, J. (2020). Reconciling early-outbreak estimates of the basic reproductive number and its uncertainty: Framework and applications to the novel coronavirus (SARS-CoV-2) outbreak. *J. R. Soc. Interface*, *17*(168).

[6] Sanche, S., Lin, Y.T., Xu, C., Romero-Severson, E., Hengartner, N., & Ke, R. (2020). High contagiousness and rapid spread of severe acute respiratory syndrome coronavirus 2. *Emerg. Infect. Dis.*, *26*(7), 1470-1477.

[7] Van Dorp, C.H., Goldberg, E.E., Hengartner, N., Ke, R., & Romero-Severson, E.O. (2021). Estimating the strength of selection for new SARS-CoV-2 variants. *Nat. Commun.*, *12*, 7239.

[8] Van Dorp, C., Goldberg, E., Ke, R., Hengartner, N., & Romero-Severson, E. (2022). Global estimates of the fitness advantage of SARS-CoV-2 variant Omicron. *Virus Evol.*, *8*(2), veac089.

[9] Volz, E., Hill, V., McCrone, J.T., Price, A., Jorgensen, D., O'Toole, Á., … Connor, T.R. (2021). Evaluating the effects of SARS-CoV-2 spike mutation D614G on transmissibility and pathogenicity. *Cell*, *184*(1), 64-75.

Ruian Ke is a staff scientist at Los Alamos National Laboratory whose research centers on modeling the dynamics and evolution of viral pathogens, including HIV, influenza, and HCV. Since late 2019, his research has focused heavily on the use of mathematical modeling and machine learning approaches to understand the transmission, infection, and evolution dynamics of SARS-CoV-2. Ethan Romero-Severson is a computational epidemiologist in the Theoretical Biology and Biophysics group at Los Alamos National Laboratory. His work on infectious disease epidemiology bridges the evolutionary biology and mathematical modeling of viral pathogens like HIV, HCV, and bunyaviruses.

A Whirlwind Tour of Mathematics and Its History

The Story of Proof: Logic and the History of Mathematics. *By John Stillwell. Princeton University Press, Princeton, NJ, November 2022. 456 pages, $45.00.*

BOOK REVIEW
By Ernest Davis

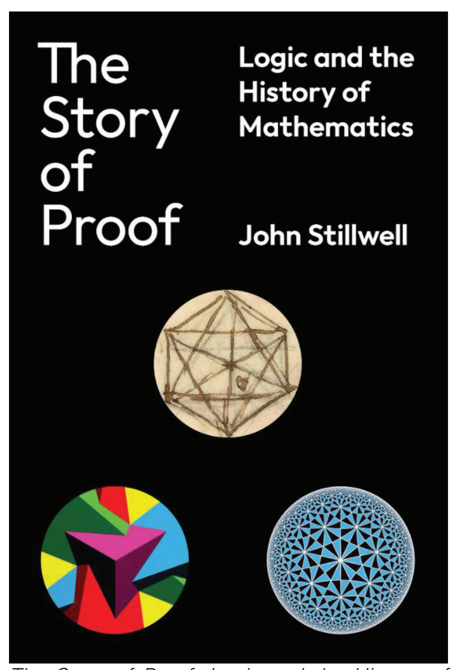
Mathematician John Stillwell is both a historian and philosopher of math. He is a remarkably prolific author of textbooks on subjects such as the geometry of surfaces, Lie theory, number theory, and the relation of set theory to analysis, as well as several rather advanced popular math books. Within the last five years, he published *Reverse Mathematics: Proofs from the Inside Out* (2018); *A Concise History of Mathematics for Philosophers* (2019); *Algebraic Number Theory for Beginners: Following a Path from Euclid to Noether* (2022); and his newest book, *The Story of Proof: Logic and the History of Mathematics*.

In the preface, Stillwell states his purpose in writing *The Story of Proof*:

> It is about proof — not just about what proof is but about where it came from, and perhaps where it is going.…Even professional mathematicians will be enlightened, I believe, by seeing the evolution of proof in mathematics, because advances in mathematics are often advances in the concept of proof.

This is an ambitious goal, and I will soon return to the question of how well Stillwell achieves it. First, however, let me describe the book's contents.

Stillwell offers a whirlwind tour across a huge panorama that encompasses most topics in undergraduate mathematics. Over the course of more than 400 pages, he covers the following subjects: the Pythagorean theorem and its proofs; the discovery of irrational numbers and the subsequent response of Greek mathematics; Euclid's axiomatization of geometry, Moritz Pasch's betweenness axioms, and David Hilbert's axiomatization; projective geometry; quadratic and cubic equations; quaternions and octonions; groups, fields, rings, vector spaces, and Galois theory; algebraic geometry, conic sections, and cubic curves; infinite series and power series; differential and integral calculus; integrals of algebraic curves and elliptic integrals; number theory, Gaussian integers, and prime ideals; the fundamental theorem of algebra; non-Euclidean geometry; graph theory; Leonhard Euler's polyhedron formula, the Euler characteristic of surfaces, and knot theory; the rigorous formulations of the real line, continuity, convergence, and the Riemann and Lebesgue integrals; Cantorian set theory, infinite ordinals and cardinals, the continuum hypothesis, and inaccessible cardinals; axiomatizations of the integers, reals, and set theory; the axiom of choice and its implications; propositional logic, predicate calculus, Kurt Gödel's completeness theory, and Turing machines; Gödel's incompleteness theorem; and the proof of the consistency of Peano arithmetic via ϵ_0 induction. These are just the major headings; many other topics appear more briefly.



The Story of Proof: Logic and the History of Mathematics. By John Stillwell. Courtesy of Princeton University Press.

Stillwell provides a myriad of proofs throughout the book, mostly in their original or early forms. He gives Pappus' proof of the isosceles triangle theorem, Bonaventura Cavalieri's proof of the volume of the sphere, Isaac Newton's derivation of the power series for the inverse of the natural logarithm (i.e., e^x), Pierre-Simon Laplace's proof of the fundamental theorem of algebra, Pierre de Fermat's proof of Fermat's last theorem for $n=4$, and many others. Finally, Stillwell includes some discussion of the evolution of fundamental mathematical concepts throughout the centuries. His commentary on infinity and continuity is particularly well done.

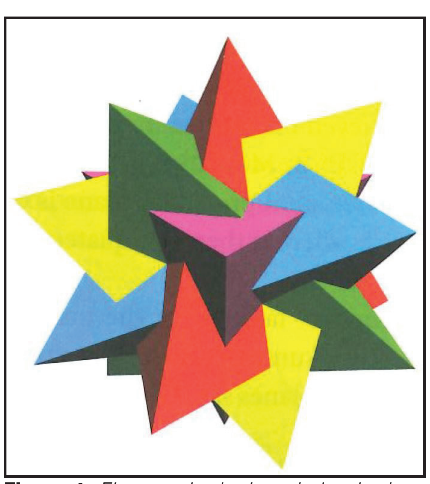


Figure 1. *Five tetrahedra in a dodecahedron. Figure courtesy of Princeton University Press.*

The book strictly adheres to pure mathematics and contains almost no consideration of applications. The only biographical information is birth and death years, and Stillwell does not discuss any general or intellectual history outside of mathematics. As such, there is an awful lot of math and mathematical history in *The Story of Proof*. Stillwell is profoundly knowledgeable, and his writing is careful and clear. The book is also physically beautiful, with many vibrant figures and a pleasing use of color within the text (see Figures 1 and 2). Kudos to the publisher's production staff.

Nonetheless, I found *The Story of Proof* less enjoyable and less satisfying than Stillwell's earlier books. The problem with whirlwind tours is that they are rushed, which manifests in a number of general issues. First, Stillwell's presentation is often so compressed that it will be unintelligible to readers who do not already know the subject, and useless to those who do. I do not see how anyone can glean many takeaways from a two-page presentation of Galois theory, a two-paragraph discussion of Felix Hausdorff's definition of a topological space and continuity, or a two-page description of the Lebesgue measure and integral. Though Stillwell's account of these items is logically complete and self-contained, true understanding requires more motivation, exposition, and examples.

Second, Stillwell skips important aspects of certain fields. It seems odd to write a chapter about the fundamental theorem of algebra for polynomials with real coefficients without mentioning that it also applies to polynomials with complex coefficients, and that the complex numbers are therefore algebraically closed — especially since Stillwell discusses algebraic closure in other contexts. Equally strange is his decision to write about projective geometry while barely mentioning projective transformations, and to write about linear algebra without referencing linear transformations or matrices. Stillwell describes Newton and others' *ad hoc* derivation of the power series for specific functions without mentioning Brook Taylor's 1715 discovery of the Taylor series, which subsumed them all. Finally, it is odd that Stillwell covers the axiomatization of set theory without naming Russell's paradox, which was a large stumbling block in the process of axiomatization and necessitated a variety of workarounds.

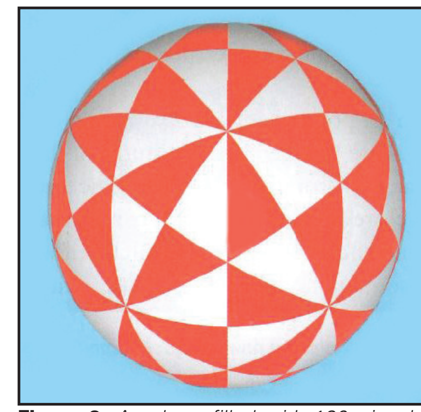


Figure 2. *A sphere filled with 120 triangles. Figure courtesy of Princeton University Press.*

On a larger scale, some important areas of math are excluded — even Stillwell can't squeeze *all* of mathematics into less than 500 pages. I am personally more interested in probability theory and functions of a complex variable than some of the subjects in the text, but that is a matter of taste. However, the nearly complete omission of dynamical systems of every kind seems much less acceptable. The characterization of change and motion over time has been a major theme of mathematics for 350 years, and ignoring that entire field seriously distorts the history of math — particularly in the 17th and 18th centuries.

In terms of the book's stated intentions, the examination of conceptual evolution is shortchanged. As I noted previously, Stillwell's treatment of the evolution of the concept of infinity is excellent (he did this at greater length and detail in his 2010 book, *Roads to Infinity: The Mathematics of Truth and Proof*). His treatment of the real line, continuity, and integration is also good. However, his presentation of the history of differentiation, groups, functions, and axiomatization has major gaps.

The evolution of the concept of a *proof* is especially elusive and difficult to trace; it would require a much deeper and more careful historical analysis than Stillwell provides here. He describes many specific proofs across a range of historical periods, but these examples do not in themselves make a case for conceptual change. Proofs from 300 years ago look different from

See **Tour of Mathematics** *on page 12*

Washington-Baltimore

Continued from page 7

the waitlist continued to grow. This inspiring response further reinforces the SIAM community's desire to come together and demonstrates the instrumental role of section leadership in facilitating such interactions. Nevertheless, anyone who has ever organized a conference knows that doing so is not an easy task. Coordinators must solicit speakers, find a venue, create a corresponding webpage, manage registrations, arrange food and giveaways, and secure independent funding sources to offset costs for attendees. Leadership of the SIAM Washington-Baltimore Section successfully handled all of these challenges and diligently worked to make this meeting a reality.

In response, the gathering was a huge success. Applied mathematicians from academia, the national laboratories, government agencies, and industry assembled at the daylong event. Attendees appreciated the in-person format; in fact, this was the first in-person meeting for many individuals since the onset of COVID-19 three years ago. The program officers' presentations and the consequent panel session were particularly well-received — especially by early-career researchers who had missed out on crucial networking and growth opportunities during the pandemic. The audience also enjoyed the plenary talks and embraced the opportunity to catch up with old friends and get to know many young and well-established researchers from both their own fields and other sectors. Participants praised the speaker and program officer selection and commented that the meeting was "interesting," "very enjoyable," "very productive," "quite well organized," and "valuable and helpful."

Overall, the conference represented a highly successful comeback for the SIAM Washington-Baltimore Section. The organizers are grateful to Suzanne Weekes (Executive Director of SIAM) and Annie Imperatrice (Senior Assistant to the Executive Director) for their strong and generous support. Section leadership hopes to maintain activity within the Washington-Baltimore Section and continue to connect the local SIAM community of applied mathematicians, computational scientists, and data scientists.

Harbir Antil is head of the Center for Mathematics and Artificial Intelligence and a professor of mathematics at George Mason University. His areas of interest include optimization, calculus of variations, partial differential equations, numerical analysis, and scientific computing with applications in optimal control, shape optimization, free boundary problems, dimensional reduction, inverse problems, and deep learning. He is the vice president of the SIAM Washington-Baltimore Section. Ratna Khatri is the Jerome and Isabella Karle Distinguished Scholar Fellow in the Optical Sciences Division at the U.S. Naval Research Laboratory. Her research interests include partial differential equation-constrained optimization, deep learning, and inverse problems in imaging science. She is the secretary of the SIAM Washington-Baltimore Section.

Program officers from the National Science Foundation, Air Force Office of Scientific Research, and Office of Naval Research discuss useful funding opportunities and answer audience questions at the 2022 SIAM Washington, D.C.-Baltimore Section Annual Meeting, which was held in Arlington, Va., in November 2022. Photo courtesy of Ratna Khatri.

SIAM Conferences: More Resilient Than Ever

By Richard Moore

Several words come to mind when I reflect on 2022, but the one that seems to best describe the current state of SIAM conferences is "resilient." That resilience begins with good governance, as SIAM leadership made the bold commitment in the fall of 2021 to run all possible 2022 conferences in a hybrid format. This crucial and prescient decision meant that SIAM was able to respond with minimal disruption as COVID-19's Omicron variant swept across the world just a few weeks later, necessitating a switch of all conferences in early 2022 to a strictly virtual format.

SIAM conference staff bolstered this resilience in their efficient execution of the additional and complex workload that is associated with hybrid events, including vendor exploration and integration of external systems; renegotiation of site contracts; communication with co-chairs, speakers, registrants, and the broader community; and contingency planning and consideration of downstream consequences. And most important of all is the resilience of the entire SIAM community of researchers, teachers, and practitioners across all walks of life, career stages, and corners of the globe who have shared in this grand experiment. SIAM has done its best to provide venues—both physical and virtual—that allow participants to share their research and best practices, form and nurture collaborations, build their careers, and meet with friends and colleagues.

So, what does 2023 have in store? Most conferences are scheduled to take place in person, as the widespread availability of effective vaccines provides strong protection against COVID-19. Of course, SIAM will continue to trust the science by following recommendations from the World Health Organization and U.S. Centers for Disease Control and Prevention. A hybrid option has been made available to attendees of the ACM-SIAM Symposium on Discrete Algorithms[1] in Florence, Italy, from January 22-25, though speakers were strongly encouraged to take part in person.

Highlights of this year's conference calendar include the 2023 SIAM Conference on Computational Science and Engineering[2] (CSE23), which will take place in Amsterdam, the Netherlands, from February 26 to March 3. It is the first CSE conference outside the U.S., and the current number of submissions indicates that it will be SIAM's largest in-person conference to date. Several months later, the 2023 SIAM Conference on Applications of Dynamical Systems[3] (DS23) will be held from May 14-18 in Portland, Ore. — its first iteration outside of Snowbird, Utah, since 1990. Early information suggests that DS23 will also be the largest-ever in-person conference in its series. Submissions are similarly robust for the co-located SIAM Conference on Optimization[4] and SIAM Conference on Applied and Computational Discrete Algorithms,[5] both of which will take place in Seattle, Wash., from May 31 to June 3.

Many additional exciting events are forthcoming in 2023 as part of SIAM conferences and as standalone activities. The SIAM Hackathon[6] is scheduled for February 25 and 26 in Amsterdam—immediately prior to CSE23—while the SIAM International Meshing Roundtable Workshop[7] will follow CSE23 from March 6-9. DS23 will include the Workshop Celebrating Diversity,[8] and the SIAM Conference on Financial Mathematics and Engineering[9]—which will be held in Philadelphia, Pa., from June 6-9—will again feature a student programming competition.[10] SIAM will provide logistical and financial assistance to the Graduate Student Mathematical Modeling Camp at the University of Delaware from June 7-10 and the Mathematical Problems in Industry Workshop at the New Jersey Institute of Technology from June 12-16.[11] And virtual SIAM Career Fairs will occur on April 4 and October 11.

In addition, the now-international MathWorks Math Modeling Challenge[12] (M3 Challenge) continues to inspire the next generation to apply their mathematical modeling skills to problems of societal importance. Registration closes February 24 for Challenge Weekend, which kicks off on March 3. The M3 finalist teams and Technical Computing awardees will present their solutions to a panel of judges on April 24 in New York City. Note that many of these programs are meant for students: the segment of our community whose professional opportunities were most impacted by the pandemic. It is incumbent upon all of us to spend the coming months connecting students with activities that will shape their careers as mathematicians.

Attendees of the 2022 SIAM Annual Meeting, which took place in a hybrid format in Pittsburgh, Pa., in July 2022, network and mingle during the Poster Session. SIAM photo.

This year, the quadrennial International Congress on Industrial and Applied Mathematics[13] (ICIAM 2023) will take place in Tokyo, Japan, from August 20-25. As is customary during ICIAM years, SIAM will not hold its Annual Meeting in 2023; instead, we throw our support behind this major international conference. Monitor your email and **www.siam.org** for information about travel awards for U.S. scholars who are attending ICIAM 2023.

Looking beyond 2023, SIAM staff and leadership are currently planning the next iteration of hybrid SIAM conferences. The fully synchronous hybrid model that we adopted in 2022 acknowledged the uncertainty of the pandemic and reflected SIAM's commitment to enabling the complete participation of all registrants, even if they were not able to be physically present at the conference venue. Such a labor-intensive and costly version of the hybrid modality is no longer necessary; discussions are underway to better understand how we can preserve positive hybrid takeaways while rethinking the more problematic aspects to sustainably deliver SIAM conferences that are as inclusive, accessible, and environmentally responsible as possible. Your survey responses and suggestions to SIAM staff and leadership will be invaluable in this endeavor.

The collective efforts of many individuals and organizations make SIAM conferences the esteemed gatherings that they are, and we are thankful to all of them. First and foremost are conference co-chairs, who set their meetings' themes and lead the selection of plenary speakers. Support from funding agencies—most notably the U.S. National Science Foundation (NSF) and U.S. Department of Energy—as well as corporate sponsors helps keep registration fees as low as possible. In addition, donors and authors make SIAM conferences more accessible through their donations to the SIAM Student Travel Fund, which contributes to the Student Travel Awards.[14] A grant from the NSF also supports travel awards for students and early-career researchers[15] at U.S.-based institutions.

Finally, I would like to end this piece with heartfelt thanks to Connie Young, SIAM's longstanding conference director who retired at the end of 2022. Connie's 23-year tenure saw many evolutions in SIAM conferences, none more abrupt and challenging than those prompted by the pandemic. We wish her good health and happiness in her retirement. SIAM's new conference director, Lisa Dyson, brings a wealth of experience to the role and has hit the ground running; please say hi if you see her at an upcoming meeting!

Richard Moore is the Director of Programs and Services at SIAM.

1 https://www.siam.org/conferences/cm/conference/soda23
2 https://www.siam.org/conferences/cm/conference/cse23
3 https://www.siam.org/conferences/cm/conference/ds23
4 https://www.siam.org/conferences/cm/conference/op23
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11 https://www.siam.org/students-education/programs-initiatives/gsmmc-and-mpi
12 https://m3challenge.siam.org
13 https://iciam2023.org
14 https://www.siam.org/conferences/conference-support/siam-student-travel-awards
15 https://www.siam.org/conferences/conference-support/siam-early-career-travel-awards

Marketing and Communications: A Resource Roundup

By Becky Kerner

SIAM is proud to offer an abundance of resources and programs that support and serve the applied mathematics community. Most of these resources—which are developed with valuable input from member volunteers—are freely available as part of our mission to provide media for the exchange of information and ultimately grow the pipeline of future applied mathematicians, computational scientists, and data scientists. We create these resources to support three main groups: individuals who already work in or study the applied mathematical sciences, educators who introduce students to these areas, and students who are beginning to learn about modeling, programming, and potential careers in science, technology, engineering, and mathematics (STEM). The SIAM Marketing and Communications Department has been involved in the creation of many of our most important resources over the years, and it has been gratifying and rewarding to witness the usefulness of these offerings. Below are some examples of SIAM resources that are available to you, your students, and your colleagues.

> "We had an especially challenging and specific job requirement. We posted the position and sent the targeted mass email through the SIAM Job Board; it was extremely effective! Now whenever I have open positions, I always recommend the SIAM Job Board to hiring managers and technical recruiters." — *Holly Smith, former recruiter for Siemens Digital Industries Software*

Careers in the Mathematical Sciences Brochure

Every five years, SIAM produces a new Careers Brochure — a popular resource that spotlights applied mathematicians who work in various facets of the mathematical sciences, with a focus on industrial careers. The recently updated edition features more than 20 new profiles, and we also plan to add a video component in the near future. We are very appreciative of the SIAM Career Opportunities, Diversity Advisory, Education, and Industry Committees for helping to identify community members to be featured, and for reviewing pertinent career information. The brochure is available for free download on SIAM's website[1] and purchase at the SIAM Bookstore.[2] We will also have print copies at the SIAM booth during most 2023 SIAM conferences — stop by and pick one up!

SIAM Job Board

The SIAM Job Board offers job seekers and employers an easy way to connect. In 2022, we provided a platform that connected 120 companies with qualified candidates. These companies posted 325+ jobs on the SIAM Job Board that received 650+ applications, with a total of nearly 100,000 views. Visit **jobs.siam.org** to browse available positions or advertise your organization's openings; sign up for email alerts and follow the SIAM Job Board on Twitter[3] to be notified whenever a new opportunity is added.

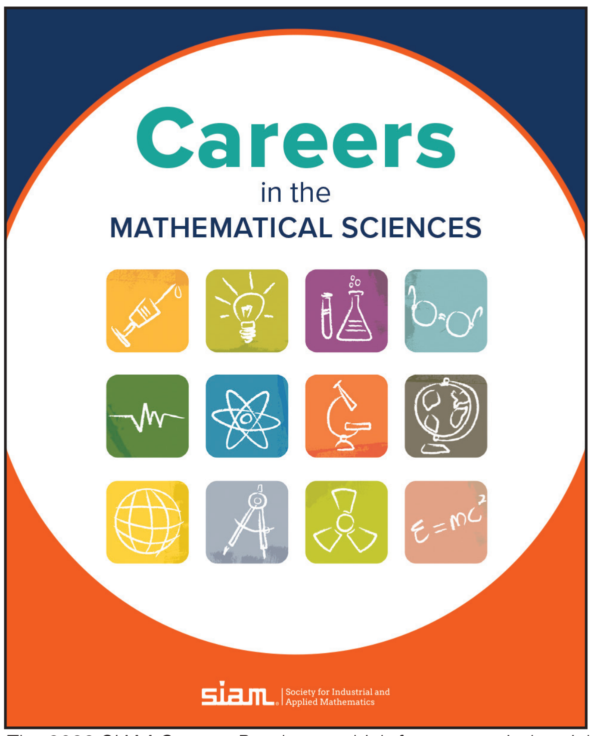
1 https://www.siam.org/students-education/programs-initiatives/thinking-of-a-career-in-applied-mathematics
2 https://my.siam.org/Store/Product/viewproduct/?ProductId=661

SIAM Videos

We uploaded 75 educational videos to SIAM's YouTube channel[4] in 2022, largely from conference talks, seminars, workshops, and panels. We now have an impressive 500 videos on our YouTube channel, which collectively received 173,000 views last year with a total watch time of 5,500 hours. SIAM works with many of our activity group organizers to host webinars that are shared freely on YouTube. Most recently, we posted the presentations[5] from the SIAM Convening on Climate Science, Sustainability, and Clean Energy,[6] which took place in October 2022 in Tysons, Va. This National Science Foundation-funded multidisciplinary scoping workshop focused on six main goal areas and produced a report[7] and nine recommendations[8] for research funding around climate science, clean energy, and sustainability.

In 2022, the Marketing and Communications Department worked with a professional video team to produce eight new videos that will be shared with the community over the next six months. Some of the videos were filmed at Oak Ridge National Laboratory, where we interviewed SIAM members Katherine Evans, Juan Restrepo, and Slaven Peles on the topics of climate, renewable energy, and supercomputing. The other videos were filmed during the 2022 SIAM Conference on Mathematics of Data Science,[9] which took place in San Diego, Calif., in September 2022. While there, we interviewed more than 15 attendees who ranged from undergraduate students to established researchers. Look for these videos throughout 2023!

3 https://twitter.com/SIAMJobBoard
4 https://www.youtube.com/@SIAMConnect
5 https://go.siam.org/HJb4X5
6 https://www.siam.org/publications/reports/siam-convening-on-climate-science-sustainability-and-clean-energy
7 https://www.siam.org/Portals/0/Programs/climate_convening/Report_SIAMClimateConvening.pdf
8 https://www.siam.org/Portals/0/Programs/climate_convening/Recommendations_SIAMClimateConvening.pdf
9 https://www.siam.org/conferences/cm/conference/mds22



The 2022 SIAM Careers Brochure, which focuses on industrial careers, features more than 20 new profiles of SIAM community members. It is freely available on the SIAM website and can otherwise be purchased from the SIAM Bookstore.

SIAM.org Website

From career[10] and student[11] materials to in-depth reports[12] and updates on educational issues, science policy, and advocacy, the SIAM website is a hub of useful information that spans the past several decades. In the coming year, we'll be making big changes and improvements to **www.siam.org** to ensure that it is as useful and accessible as possible. We are working with the SIAM Education, Industry, and Science Policy Committees to add new resource sections to the website as well. Stay tuned!

MathWorks Math Modeling Challenge

Now in its 18th year, SIAM's MathWorks Math Modeling Challenge[13] (M3 Challenge) spotlights applied mathematics and technical computing as powerful problem-solving tools and viable, exciting professions. Nearly 55,000 high school and sixth form students have participated in M3 Challenge to date, which has awarded $1.75 million in scholarships. This incredibly impactful program also offers free educator and student resources, including handbooks[14] about math modeling and modeling with computing; the "What is Math Modeling?" video series[15] (which has been watched nearly 500,000 times) and "Essentials of Math Modeling" video series[16] (featuring MATLAB); and the *Guidelines for Assessment and Instruction in Mathematical Modeling Education*[17] (GAIMME), a report that helps educators understand and teach the modeling process as a basic tool for problem-solving and logical thinking in STEM. Visit the M3 Challenge website to learn more and find out how you can serve as a judge or submit a problem topic.

> "The content [in the GAIMME report] not only helps teachers incorporate mathematical modeling problems into classes, but also makes the curious and diligent ones want to do so, or even to teach a whole course in modeling." — *Jan Holly, professor of mathematics and statistics at Colby College*

We are grateful to the organizations and companies that supported SIAM in 2022 and made our continued resource and program development possible. We are always seeking collaborative partners to help us create new resources and programs and sustain or refresh existing ones. If your company is interested in partnering with SIAM, email us at **marketing@siam.org** to explore the possibilities.

Thank you to the SIAM volunteers and members who have contributed to this vast portfolio of resources, and to those of you who put them to good use! Are there additional resources that would be helpful but don't yet exist? Let us know at **marketing@siam.org**.

Becky Kerner is the Director of Marketing and Communications at SIAM.

10 https://www.siam.org/careers/resources
11 https://www.siam.org/students-education/resources
12 https://www.siam.org/publications/reports
13 https://m3challenge.siam.org
14 https://m3challenge.siam.org/resources/modeling-handbook
15 https://go.siam.org/jqMfUC
16 https://go.siam.org/n7M4VS
17 https://m3challenge.siam.org/resources/teaching-modeling

SIAM staff pose at the 2022 MathWorks Math Modeling Challenge (M3 Challenge) Final Event, which took place in New York City in April 2022. From left to right: Eliana Zimet, Programs Coordinator; Michelle Montgomery, M3 Challenge Project Director; Becky Kerner, Director of Marketing and Communications; Adrianne Ali, Marketing and Communications Manager; and Taylor Johnson, Digital Communications and Content Coordinator. SIAM photo.

Tour of Mathematics

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today's proofs for a number of reasons; for instance, the available mathematical toolbox has expanded enormously, writing styles and terminologies have changed, and specific mathematical concepts have advanced. The concept of a proof itself has also undoubtedly transformed over time, but such change is particularly hard to tease out from the historical record.

The introduction of the purely symbolic proof in formal logic in Alfred North Whitehead and Bertrand Russell's *Principia Mathematica* (and other works of that time) represented a major extension to the concept of proof at the start of the 20th century. Otherwise, the concept has remained remarkably constant over the last 2,000 years, especially when compared to other mathematical categories like number and function. Some of Euclid's proofs had technical gaps (which Stillwell discusses), and some of the things that Euler did with infinite series make current mathematicians seasick (which he does not discuss). Even so, what these historical mathematicians considered to be proofs are, by and large, still recognizable as such to us. Identifying how the concept of proof *has* changed would be both interesting and valuable, but doing so would require a much more careful analysis and comparison than what Stillwell has carried out.

All in all, I think that *The Story of Proof* would have been better if Stillwell had covered fewer subjects in greater depth and analyzed conceptual change more carefully. But even though he has not quite accomplished the goal that he set for himself, many readers will learn a lot from this book. The ideal reader is likely a bright mathematics college student who has broad interests in both math and math history — a student who would enjoy learning that the theory of conics attains its most unified form when viewed in the context of the complex projective plane, and seeing how Euler solved the Basel problem of computing $\sum_{n=1}^{\infty} 1/n^2$. If Stillwell's brief account inspires such a reader to seek out a fuller treatment in some other book, then so much the better.

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