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Mathematics for Medicine: Changing Patients' Lives with Systems Modeling

By Richard Allen, Rohit Rao, and C.J. Musante

The full emergence of the SARS-CoV-2 pandemic in early 2020 presented a medical and scientific challenge that spanned disciplines across academia and industry. In response to this challenge, we—a team of applied mathematicians in the Quantitative Systems Pharmacology (QSP) group at Pfizer[1]—worked alongside colleagues in other domains to understand, model, and react to the pandemic.

Pfizer's QSP group uses mathematics (typically ordinary differential equations) to mechanistically describe the dynamics of disease and treatment. We have supported the development of novel programs for many different conditions, including type 2 diabetes, obesity, nonalcoholic steatohepatitis, cancer, and inflammatory diseases. Because medicines typically take years to advance from concept to approval, we usually generate models alongside a drug development program in a *learn and confirm* paradigm and utilize emerging data to continuously improve them. For SARS-CoV-2, however, it was immediately clear that historic treatment development cycles and typical modeling approaches would not be helpful. To put it simply, we—like so many others in numerous fields—had to move quickly.

As the SARS-CoV-2 pandemic gained traction, we realized that our skillset could potentially accelerate the development of effective treatments for patients. In April 2020, we thus began to build a QSP model of COVID-19 that captured both viral dynamics and immune response to infection. QSP models that support drug discovery and development follow one of two general approaches: a *fit-for-purpose model* or a *platform model*. The fit-for-purpose model focuses on a particular question, target, or mechanism but might not have much additional applicability, while the platform model is scoped to capture all pertinent aspects of a disease. In the context of COVID-19, we had to pick an approach before any information about treatment efficacy was available. As such, we wanted to be ready to address a wide range of possible model-related questions when they arose and hence decided to include viral dynamics, cellular damage, and immune response in our model.

We designed the model's desired behavior in accordance with our early understanding of viral dynamics and severe reactions to SARS-CoV-2 infection. One method of model development requires assembling relevant data and using optimization techniques to match that data, thereby ensuring that the model captures the necessary dynamics. However, such data was not accessible at the onset of the pandemic. To quickly develop the model, we defined key properties called *unit tests* in place of a full dataset (see Figure 1). If we could not find reasonable parameters that passed these tests, we would know that our model could not capture the observed biology and was structurally incorrect.

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Unit Test	Criteria	Rationale
Innate immune system activation and typical mild/moderate pathogenesis of COVID-19	Simulated viral peak at approximately four days and engagement of innate immunity; model returns to pre-infection baselines	The model should be able to elicit transient peak dynamics for viral load and immune response on the time scale of infection
The innate immune response can clear the virus	Without innate immunity, viral load peak is higher and clearance is slower	The immune response is crucial to controlling SARS-CoV-2 infection
Damaged cells also induce an immune response	An immune response occurs in the absence of the virus but with an initial condition of damaged cells	Even if no virus is present, damaged cells should elicit an inflammatory response
Hyperinflammatory response	Sustained immune response after virus clearance leads to alveolar cell damage	Hyperinflammatory response is associated with the hospitalization of COVID-19 patients and can persist after the virus has cleared

Figure 1. *Original unit tests that enabled the rapid development of a quantitative systems pharmacology model of COVID-19. Figure courtesy of the authors.*

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

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Stochastic Rounding 2.0, With a View Towards Complexity Analysis

By Petros Drineas and Ilse C.F. Ipsen

Stochastic rounding (SR) is a probabilistic rounding mode that is surprisingly effective in large-scale computations and low-precision arithmetic [3]. Its random nature promotes error cancellation rather than error accumulation, resulting in a slower growth of roundoff errors as the problem size increases — especially when compared to traditional deterministic rounding methods like rounding-to-nearest. Here, we advocate for SR as a foundational tool in the complexity analysis of algorithms and suggest several research directions.

Stochastic Rounding 1.0

George Forsythe introduced SR in 1950 with a one-paragraph abstract for the 52nd meeting of the American Mathematical Society that was subsequently reprinted in *SIAM Review* [5]. In the context of numerical integration under rounding-to-nearest, Forsythe was concerned about modeling individual roundoff errors as random variables, as was first suggested by John von Neumann and Herman Goldstine in 1947. Forsythe observed that individual roundoff errors at times "had a biased distribution which caused unexpectedly large accumulations of the [total] rounding-off error," and that "in the integration of smooth functions the ordinary rounding-off errors will frequently not be distributed like independent random variables" [5]. Hence Forsythe's proposal of SR to make an individual roundoff error look like a "true random variable."

Stochastic Rounding 2.0

Despite its illustrious beginnings, SR has since been largely overlooked by the numerical analysis community. Yet, the hardware design landscape exhibits a strong momentum towards SR implementations on graphics processing units (GPUs) and intelligence processing units (IPUs).

Commercial hardware—such as the Graphcore IPU, IBM floating-point adders and multipliers, AMD mixed-precision adders, and even NVIDIA's implementations of deterministic rounding—already incorporate SR in various forms, as do Tesla D1 and Amazon Web Services Trainium chips. SR promotes efficient hardware integration and precision management, which are crucial for machine learning (ML) and artificial intelligence (AI). The advent of digital neuromorphic processors like Intel's Loihi chip and SpiNNaker2, both of which feature SR, further underscores the readiness and even *necessity* of the widespread adoption of SR in hardware. The time is ripe for the adoption of SR as a standard feature in GPU and IPU architectures to optimize performance and accuracy across diverse applications.

Another reason to adopt SR is the emergence of deep neural networks (DNNs) and their implications for AI. Indeed, SR is primed to be a game-changer in training neural networks with low-precision arithmetic. It tends to avoid stagnation problems that are typical of traditional deterministic rounding modes, thereby allowing efficient training with minimal accuracy loss.

Prior work has demonstrated the successful training of DNNs on 16-bit and even 8-bit fixed-point arithmetic with SR, with the added benefit of significantly reducing energy costs. The performance of SR-based hardware compares favorably with that of higher-precision formats like binary32, but it comes with a lower computational overhead. SR's application extends to dynamic fixed-point arithmetic and innovative hardware designs, such as in-memory computations and block floating-point numbers. SR has the ability to support training at various levels of arithmetic precision and enhance convergence speeds while maintaining training accuracy. These capabilities make it particularly attractive for AI applications, where computational efficiency and resource minimization are critical.

Our piece discusses challenges and opportunities for SR in numerical linear algebra. We propose SR as a model for algorithm complexity analysis that is *natively* implemented in hardware and discuss future research directions to alleviate its drawbacks.

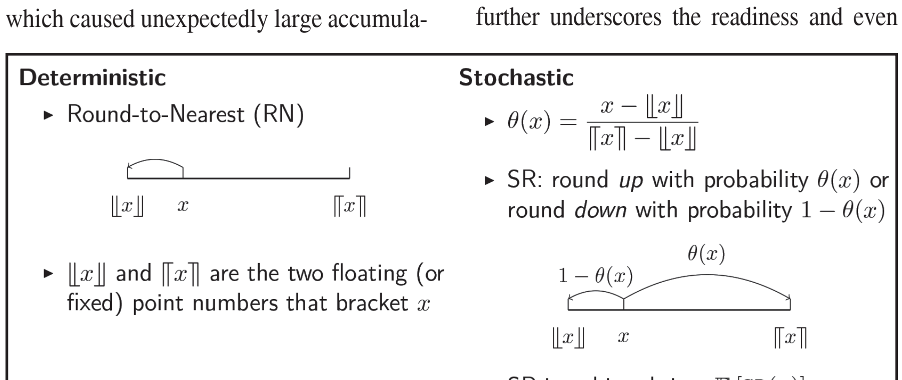

Figure 1. *Deterministic rounding versus stochastic rounding (SR). Given a real number x that is bracketed by two numbers $\lfloor\!\lfloor x \rfloor\!\rfloor$ and $\lceil\!\lceil x \rceil\!\rceil$, the deterministic rounding-to-nearest method always rounds to the nearest bracketing number. In contrast, SR picks one of the two bracketing numbers with a probability that is proportional to its distance from x and returns an unbiased estimator of x. Figure courtesy of the authors.*

SR Explained

Suppose we want to round the number 0.7 to a single bit: either 0 or 1. Traditional deterministic rounding-to-nearest rounds 0.7 to the nearest option, which is 1. In contrast,

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Reflections from the 2024 SIAM EDGE Fellow

By Nikira Walter

My first introduction to Enhancing Diversity in Graduate Education[1] (EDGE) was in the summer of 2022 when my alma mater, Spelman College, hosted the annual EDGE reunion. As a rising junior, I was spending the summer at Spelman to work as a mentor for the Women in STEM Summer Bridge Accelerator[2] (WiSTEM) and conduct numerical analysis research through the Louis Stokes Alliances for Minority Participation[3] (LSAMP) program. When I received the Department of Mathematics' call for volunteers to help host our EDGE guests, I readily accepted. It was then that I officially met Sylvia Bozeman—Spelman emerita and EDGE co-founder—who encouraged my fellow mentors and me to apply to the EDGE Summer Program[4] when the time came. I had already known that I wanted to attend graduate school, and at that moment I decided that I would apply to EDGE as well.

Throughout my undergraduate years, I pursued multiple other mathematics research opportunities in addition to the aforementioned WiSTEM and LSAMP endeavors. Immediately before my freshman year, I took part in WiSTEM myself and jumpstarted my college career from my bedroom during the height of the COVID-19 pandemic in 2020. I later became a mentor and teaching assistant for Calculus 1 and participated in the Keeping the STEM Gate Open[5] project. In the summer of 2021, I participated in the Casualty Actuarial Society Student Central Summer Program[6] and learned more about the seemingly foreign topic of actuarial science (I didn't know it at the time, but this marked the start of my shift from mathematics to statistics). And as a rising senior during the summer of 2023, I worked as an actuarial intern for Allstate. This collection of wonderful experiences helped to shape my mind and encouraged me to pursue a higher degree with the goal of ultimately serving the community that so generously served me.

Nikira Walter, a first-year Ph.D. student in statistics at Columbia University, is the 2024 SIAM EDGE Fellow. She attended the 2024 EDGE Summer Program, which took place in June at the University of Tennessee, Knoxville. Photo courtesy of Braven, Inc.

To achieve this goal, I of course had to apply to graduate school. While readying my grad school application materials, I also applied to EDGE: a program that would prepare me for my subsequent years in higher education. Ever since my encounter with Dr. Bozeman, I had heard nothing but good things about the EDGE Summer Program from previous students and former instructors. I was thrilled to learn that I was accepted to the 2024 program and couldn't have been happier to join a legacy of brilliant women in math.

As the program began to heat up, I held on to this joy to keep myself feeling positive when the work became increasingly difficult. The 2024 EDGE Summer Program[7] took place at the University of Tennessee, Knoxville, from June 2-29. Over the course of a month, we took four classes that focused on linear algebra, real analysis, measure theory, and applied mathematics and statistics. As a part of our daily schedule, we attended group problem sessions; group lunches; colloquium talks; "difficult dialogue" sessions; and a sprinkling of fun bonding activities, including a zipline and ropes course and a weekend barbeque. My cohort and I also organized some fun outings on our own, such as kayak adventures, time at the pool, and a trip to the movies to see *Inside Out 2*. Needless to say, we were really busy all month!

I think all EDGE participants would agree that the curriculum and framework is truly well designed. We learned a lot from our instructors, directors, peer mentors, and each other — not only academically, but also personally. One of the biggest gifts of EDGE is the resulting network of kind, intelligent, motivated, and supportive ladies who remain in your corner for the challenging grad school journey that lies ahead. At this year's reunion, which took place during the Summer Program, members of the 2023 cohort returned and offered much-needed advice about graduate school and EDGE itself. I was overjoyed to reconnect with a fellow Spelman alumna and make the acquaintance of our reunion colloquium speaker, Michelle Craddock Guinn of Belmont University, who was also a Spelman alum! Coming from a sweet sisterhood like Spelman, I was—and continue to be—fully aware of the value of the EDGE sisterhood. Through the 2024 cohort, I've gained 12 new friends who will understand my experiences as a Ph.D. student and serve as resources to help me reach the finish line. And at the end of the month, I was honored to be named the 2024 SIAM Edge Fellow by the EDGE co-directors and faculty.

Now that I'm a graduate student at Columbia University, I can affirm that the volume and pace of the EDGE program accurately simulates graduate school. The heavy EDGE workload, which moved quickly through the material with a fast turnaround for homework, prepared me for graduate-level assignments. As an introvert, I don't always position myself to work with others in my studies; however, the collaborative problem sessions this summer opened my mind to the possibilities that stem from groupwork. Trying to balance studies, self-care, and community is a real challenge, and EDGE provided me with a blueprint that I can mold and model as I establish my routine at Columbia.

I am currently two months into my Ph.D. program in statistics and can already see why no one says that grad school is easy. To be completely transparent, I struggled a bit with imposter syndrome during EDGE, and it has resurfaced twice as harshly at Columbia. It's a reality that so many people face, and it brings me some comfort to know that I'm not the first—and will surely not be the last—to experience these feelings. I'm an optimist at heart, so I always try to look on the bright side of things. When doing so proves difficult, I gain strength from my community — which now includes the other EDGE participants. I am constantly reminded that I am here for a reason and am strong enough to succeed; this outpouring of love and support keeps me going and helps me see the beauty and potential in my struggles. I aspire to become a professor and a change agent within the sphere of academia. I wish to apply statistics to educational problems throughout the

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[1] https://www.edgeforwomen.org
[2] https://www.spelman.edu/academics/summer-programs/wistem.html
[3] https://new.nsf.gov/funding/opportunities/lsamp-louis-stokes-alliances-minority-participation
[4] https://www.edgeforwomen.org/summer-session
[5] https://mathvoices.ams.org/teachingandlearning/kstem-go-keeping-the-stem-gate-open-by-broadening-approaches-to-assessment
[6] https://www.casstudentcentral.org/cassummerprogram
[7] https://www.edgeforwomen.org/summer-session/edge-2024-participants

Participants, mentors, and faculty of the 2024 EDGE Summer Program—which was held in June at the University of Tennessee, Knoxville—gather for a group photo. The month-long program familiarized students with concepts in linear algebra, real analysis, measure theory, and applied mathematics and statistics. Photo courtesy of the EDGE Foundation.

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Systems Modeling

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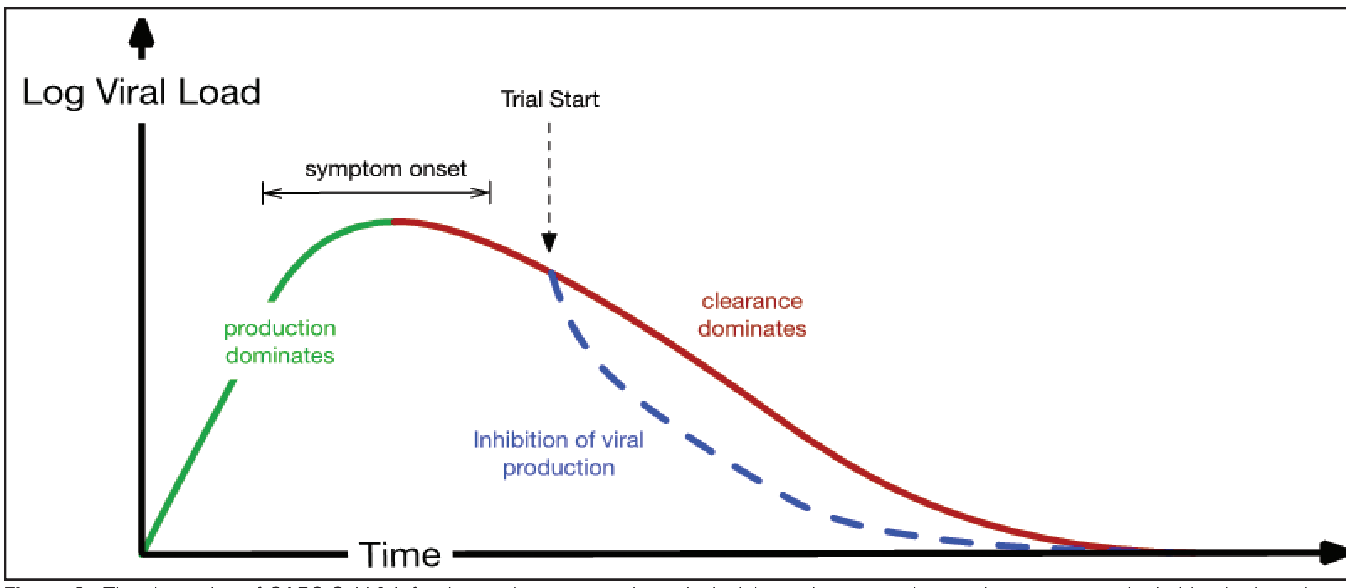

Figure 3. *The dynamics of SARS-CoV-2 infection and treatment. In typical trials, patients are almost always post-peak viral load when the trial begins (based on the timing of symptom onset, positive test results, and recruitment into the trial). Figure courtesy of the authors.*

Our team utilized components of prior models to quickly assemble a version 0.1 of our model [2, 6, 9]. Once this model satisfied our unit tests, we established some early insights about the interplay between the strength and sensitivity of immune response versus the biomarkers of cell damage. We published our complete prototype (including all code) to bolster other comparable modeling or drug discovery/development efforts in academia or industry [4].

In theory, this model would support drug development programs that target any aspect of COVID-19. By the time our prototype version was published in full [4], a key Pfizer program was creating an antiviral therapeutic called nirmatrelvir/ritonavir that targets M^{pro}: a required protease in the SARS-CoV-2 replication process [7]. Once our model was calibrated to a wider array of data, it could make several key predictions with a clear impact on the possible pursuit of this investigational therapeutic and the optimization of clinical trial design [8]. Figure 2 summarizes the early questions that influenced our model and its ultimate outcomes.

One key question is as follows: At what point after initial infection (in clinical trials and real life) should patients start taking medication? Based on other clinical trial data and the incubation period of SARS-CoV-2, we were confident that this point would usually occur post-peak viral load (see Figure 3). The first query in Figure 2 may appear straightforward, but some situations (and models) exhibit *target-cell limited dynamics* where viral load peaks when virion production ceases due to the infection of all potential target cells. In this scenario, a medication that inhibits viral production cannot be efficacious because there is no viral production; in Figure 3, a lack of production would occur at the "clearance dominates" portion of the curve. Our unit test guaranteed that this circumstance was not *necessarily* true for our model. Once it was calibrated with data, the model clearly predicted that COVID-19's peak was driven by a balance of production and clearance of the virus, with immune response driving the latter. Our model also predicted that five days of treatment (and the inhibition of viral production) sufficiently allows the immune system to clear the remainder of the virus in nearly all patients.

Of course, this is not to say that we got everything right. We slightly overpredicted the amount by which the viral load would decrease (see Figure 2), as translating *in vitro* drug potency to clinical potency is always challenging. In this case, the changing nature of the COVID-19 pandemic (e.g., the emergence of new variants) and an increased prevalence of seropositivity meant that our clinical trial participants had lower baseline viral loads when they entered the trial than we expected (based on older trials). In both our model and real life, these factors are correlated with reduced viral load, which lowers treatment efficacy.

We were least confident in our prediction of the relative risk reduction of hospitalization or death for treated patients versus the placebo group. This uncertainty stemmed partly from the fact that the methodology was based on observational data of interleukin-6 levels in patients; we did not know whether this relationship would hold in treated clinical trial participants and/or cohorts with large variability in response to infection. But excitingly, our model predicted that the medication would be highly efficacious in preventing hospitalization — a result that only increased our anticipation of the clinical trial's outcome.

Learning that the investigational therapeutic was efficacious [5] was certainly a career highlight for everyone involved. It was incredibly gratifying to know that our model predictions, to a very large degree, were borne out in the clinical trial. However, our story does not end there. With this pivotal data in hand, we updated the model to precisely match the clinical trial and used it to inform discussions with regulatory agencies about this promising investigational therapeutic. For example, we shared our model with the U.S. Food and Drug Administration to support their review[2] [3] and subsequent approval of nirmatrelvir/ritonavir tablets (commercially known as PAXLOVID™).

To enable robust predictions, we developed representative virtual populations [1, 8] whose viral dynamics and risk of hospitalization or death (predicted based on immune response) matched available data. While constructing these virtual populations, we realized that some virtual patients in both untreated and treated groups would often experience a second viral load peak after a certain time period. We could not identify a scientific reason for excluding these patients from our virtual populations and thus retained them, even though we were unsure of the likelihood of this observation. As more data emerged, we began to comprehend that this phenomenon—now known as *viral load rebound*—is very real. Moreover, we could use the model to understand its relative occurrence in different populations (e.g., immunocompromised patients) and the impact of longer dosing.

Accelerating the development of novel medications while simultaneously generating appropriate safety and efficacy data and maintaining regulatory compliance is undoubtedly difficult. Building a QSP model in the midst of a global pandemic was sometimes stressful, sometimes frustrating, and sometimes of uncertain value. We therefore greatly appreciate the support and collaboration of our many colleagues who worked tirelessly and innovatively to mitigate and ultimately remove all obstacles and make nirmatrelvir/ritonavir (commercially knowns as PAXLOVID™) available to eligible patients. Our positive outcome serves as a broad reminder to trust your models and listen to the mathematics.

[2] https://www.fda.gov/advisory-committees/advisory-committee-calendar/updated-information-march-16-2023-antimicrobial-drugs-advisory-committee-meeting-announcement

Question	Model Prediction	Observed Outcome in EPIC-HR Clinical Trial [5]
Can an antiviral drug that is dosed post-peak viral load be efficacious in COVID-19?	Yes	Efficacy was observed when subjects were dosed post-peak viral load
What is an effective treatment duration for most patients?	Five days of dosing	Five days of dosing was efficacious
What is the effect on viral load?	~ 1 log10 copies/mL lower	~ mean -0.87 [95 percent confidence interval: -1.07, -0.66] log10 copies/mL lower viral load
How will this benefit patients?	~ 60-90 percent relative reduction of risk when treatment begins within five days of symptoms	~ 88 percent relative reduction of risk

Figure 2. *Key predictions of the COVID-19 model and comparison to outcomes in the EPIC-HR clinical trial [5]. Figure courtesy of the authors.*

PAXLOVID has been approved for the treatment of mild-to-moderate coronavirus disease 2019 (COVID-19) in adults who are at high risk for progression to severe COVID-19, including hospitalization or death. PAXLOVID has not been approved, but has been authorized for emergency use by FDA under an EUA, for the treatment of mild-to-moderate COVID-19 in pediatric patients (12 years of age and older weighing at least 40 kg) who are at high risk for progression to severe COVID-19, including hospitalization or death; and the emergency use of PAXLOVID is only authorized for the duration of the declaration that circumstances exist justifying the authorization of the emergency use of drugs and biological products during the COVID-19 pandemic under Section 564(b)(1) of the Act, 21 U.S.C. § 360bbb-3(b)(1), unless the declaration is terminated or authorization revoked sooner. For additional information, please refer to the product's U.S. Prescribing Information (including BOXED WARNING).[3]

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[3] https://labeling.pfizer.com/ShowLabeling.aspx?id=19599

Richard Allen has been supporting drug discovery and development with mechanistic modeling at Pfizer for the past 12 years. He holds a Ph.D. in applied mathematics from University College London and was a postdoctoral fellow at the University of North Carolina at Chapel Hill. Rohit Rao has been supporting mechanistic modeling efforts at Pfizer for the past five years. He holds a Ph.D. in chemical and biochemical engineering from Rutgers University and completed a postdoctoral fellowship at Harvard University. C.J. Musante has been supporting drug discovery and development with mechanistic modeling at Pfizer for the past 15 years. She holds a Ph.D. in applied mathematics from North Carolina State University and was a postdoctoral fellow at the University of North Carolina at Chapel Hill.

Stochastic Rounding

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SR rounds 0.7 to 1 with probability 0.7 and to 0 with probability $1-0.7=0.3$. The outcome of SR rounding is a *random variable* with expectation $0.7\cdot 1+0.3\cdot 0=0.7$. In statistical parlance, the rounded number is an *unbiased estimator* of the exact number. This simple statement has significant positive implications for the behavior of SR when analyzing the numerical accuracy of arithmetic operations.

The formal definition of the stochastically rounded version $\mathrm{SR}(x)$ of a real number x first appeared in [8]. Let $\mathcal{F}\subset\mathbb{R}$ be a finite set of floating-point or fixed-point numbers, and assume that x is in the interval $[\min\mathcal{F},\, \max\mathcal{F}]$. Identify the two adjacent numbers in $\mathcal{F}$ that bracket x:

$$\lceil\lceil x\rceil\rceil=\min\{y\in\mathcal{F}: y\geq x\} \quad \text{and} \quad \lfloor\lfloor x\rfloor\rfloor=\max\{y\in\mathcal{F}: y\leq x\}. \tag{1}$$

Thus, $\lfloor\lfloor x\rfloor\rfloor\leq x\leq\lceil\lceil x\rceil\rceil$. If $\lfloor\lfloor x\rfloor\rfloor=\lceil\lceil x\rceil\rceil$, then $\mathrm{SR}(x)=x$. Otherwise, SR rounds with higher probability to the closer of the two numbers:

$$\mathrm{SR}(x)=\begin{cases}\lceil\lceil x\rceil\rceil \text{ with probability } p(x)\equiv\dfrac{x-\lfloor\lfloor x\rfloor\rfloor}{\lceil\lceil x\rceil\rceil-\lfloor\lfloor x\rfloor\rfloor},\\ \lfloor\lfloor x\rfloor\rfloor \text{ with probability } 1-p(x)\end{cases}$$

(see Figure 1, on page 1). An alternative is the *SR up-or-down mode* [3, 10], where rounding up or down happens independently of x with probability $p(x)=1/2$.

Advantages of SR

Early SR work [7] described probabilistic models for roundoff error analysis and concluded that such models are generally very good in both theory and practice. The recent renaissance of SR makes a strong case for randomization in the rounding process:

• SR produces roundoff errors with zero mean, thereby encouraging cancellation (rather than accumulation) of errors. In contrast, rounding-to-nearest can accumulate large roundoff errors whenever the individual errors have the same sign.

• SR tends to avoid *stagnation*. This phenomenon is associated with rounding-to-nearest [2, 3], where many tiny updates to a large quantity get lost in the rounding process. Suppose that we want to compute the sum $s_0+\sum_{j=1}^{k}s_j$, where $s_0\in\mathcal{F}$ and the magnitude of the summands $|s_j|$ is sufficiently small compared to $|s_0|$ (i.e., smaller than half of the distance from s_0 to the closest numbers in $\mathcal{F}$). Then the rounding-to-nearest operation $\mathrm{fl}(\cdot)$ produces $\mathrm{fl}(s_0+\sum_{j=1}^{k}s_j)=s_0$. This means that the addition of s_j does not change the sum, and the sum stagnates.

• The total roundoff error from SR tends to grow more slowly with the problem size than the one from rounding-to-nearest. Specifically, the total roundoff error from the summation of n numbers under SR has, with high probability, a bound proportional to $\sqrt{n}u$, where u is the unit roundoff [6]. This is in contrast to rounding-to-nearest, where the bound is proportional to nu. The proofs in [6] rely on measure of concentration inequalities for sums of random variables—such as Bernstein, Chernoff, and Hoeffding inequalities—and corroborate the bound empirically.

• SR increases the smallest singular value of tall-and-thin matrices, thereby improving their conditioning for the solution of least squares/regression problems. We demonstrated [4] that SR implicitly regularizes such matrices in theory and practice, therefore improving their behavior in downstream ML and data analysis applications. Our proofs rely on non-asymptotic random matrix theory results, which unfortunately lack tightness and intuition.

Limitations of SR

Here we summarize several drawbacks of SR when compared to rounding-to-nearest:

• *Lack of reproducibility:* SR introduces randomness in rounding decisions, leading to nondeterministic results across different runs of the same computation.

• *Inability to use true randomness:* Because implementing SR with true randomness is impossible, one must resort to pseudorandom number generators (PRNGs). This creates an additional layer of complexity in both theoretical analysis and practical applications.

• *Increased computational overhead:* SR requires additional computational resources to generate pseudorandom numbers and perform the rounding operation, which can slow performance.

• *Limited adoption in legacy systems:* Existing numerical libraries and systems may not be able to support SR, limiting its adoption in legacy codes and applications. A detailed discussion of SR implementations in hardware and software is available in [3].

Our Proposal: SR for Complexity Analysis

The most ambitious research agenda for SR, from a numerical linear algebra and theoretical computer science perspective, is the opportunity to establish a complexity analysis of algorithms in its presence.

Existing methodologies for assessing the performance of algorithms include the following four. *Worst-case analysis* upper bounds the maximum time (or space) that an algorithm could possibly require, thus ensuring performance guarantees in even the most challenging scenarios. *Average-case analysis* assesses expected performance over a distribution of all possible inputs and offers a measure of efficiency for typical cases. *Amortized analysis* evaluates the average performance of each operation in a sequence and spreads the cost of expensive operations over many cheaper ones, ultimately providing a balanced perspective of overall efficiency. And *smoothed complexity*, introduced in the early 2000s, aims to bridge the gap between worst- and average-case analyses by evaluating algorithm performance under slight Gaussian random perturbations of worst-case inputs [9], thus reflecting practical scenarios where inputs are not perfectly adversarial. Smoothed complexity has gained significant recognition for its profound impact on the analysis of algorithms. Its importance is underscored by prestigious awards, including the 2008 Gödel Prize, 2009 Delbert Ray Fulkerson Prize, and 2010 Rolf Nevanlinna Prize.

In contrast, we propose the use of *complexity analysis under SR* to analyze the performance of algorithms whose operations are performed with SR. The small, random perturbations that are inflicted by each SR operation should, one hopes, move algorithms away from worst-case instances. In this sense, complexity analysis under SR is reminiscent of smoothed complexity but has the major advantage of being *natively* implemented in modern hardware, which accurately reflects algorithm performance *in silico*. Therefore, SR complexity analysis is a potentially viable and realistic alternative to worst-case and smoothed analysis because it offers a comprehensive understanding of algorithmic behavior on modern hardware.

We envision several research directions to exploit the unique advantages of SR as a foundation for complexity analysis. First, there is a need for a theoretical framework that can rigorously define and evaluate the effect of SR on algorithm performance. A straightforward initial approach could consist of a perturbation analysis of SR's impact when applied solely to the original input, with computations in exact arithmetic. This approach parallels smoothed complexity analysis, but a more advanced framework would also evaluate the influence of SR on computations within the algorithm.

Second, it is crucial to establish empirical benchmarks and compare SR to traditional deterministic rounding modes across a wide range of real-world applications. Doing so would help understand its practical benefits and limitations, particularly for computations on large-scale data sets in low-precision arithmetic (e.g., ML and AI applications). These research directions could solidify SR's role as a foundational tool in complexity analysis — akin to the role of smoothed complexity in bridging theoretical and practical perspectives in algorithm performance assessment.

Other Research Directions for SR

Finally, we urge the scientific community to focus on the following research directions.

• Reproducibility in the context of SR requires the employment of PRNGs with fixed seeds. While PRNGs are not truly random, they offer a well-studied, repeatable source of randomness [1]. As such, the design of PRNGs that balance performance and randomness quality and are optimized for hardware integration would be particularly useful. SR could also be selectively applied in critical parts of the algorithm or on inputs that are far from rounding boundaries. More precisely, SR could be selectively employed for inputs x that deviate significantly from $\lfloor\lfloor x\rfloor\rfloor$ and $\lceil\lceil x\rceil\rceil$, as these cases result in larger perturbations and a more pronounced impact on the outcome.

• The development of practical non-asymptotic random matrix theory tools could significantly enhance our knowledge of SR's behavior in numerical linear algebra computations. User-friendly bounds for SR would allow for a better understanding of the effect of SR on standard numerical algorithms and could lead to proofs that SR is a potent approach to reducing error propagation and increasing numerical accuracy.

• A *gradual* integration of SR into widely-used numerical libraries and standards—combined with clear guidelines and tools for the adaption of legacy systems—could help its incorporation into existing software libraries without the need for extensive rewrites.

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Petros Drineas is a professor and head of the Department of Computer Science at Purdue University. His work focuses on randomization in numerical linear algebra (RandNLA), and he has applied RandNLA techniques extensively to data science, particularly the analysis of genomic data. Ilse C.F. Ipsen is a Distinguished Professor of Mathematics at North Carolina State University. Her research interests include numerical linear algebra, randomized algorithms, and probabilistic numerics.

Finding My Passion: A Mathematical Journey from Academia to Industry

By Vrushaly Shinglot

Like many other students, I had a complicated relationship with mathematics in my elementary and middle school years. In high school, however, I began to develop an aptitude for the subject with the help of a couple of teachers who dramatically changed my perspective. I started to view mathematics as a subject of logic and reasoning, rather than a mere set of abstract concepts. Therefore, my decision to pursue a B.S. in mathematics from the Maharaja Sayajirao University of Baroda in India came naturally. Unfortunately, the basic sciences—unlike engineering and medicine—were not popular areas of study among my peers because they provided limited career opportunities within India at the time. As a result, there was very little societal awareness of the varied career pathways that the basic sciences could offer beyond academia. Nevertheless, the support of my parents motivated me to carve my own path and find a career that centered on my passion for mathematics.

My undergraduate courses allowed me to explore the diversity of mathematics and better understand math as a language with which to interpret the world. I marveled at the beauty of mathematics and its significance in various areas of study, including the use of optimization in operations research, cryptography's relevance to debit cards, and the application of linear algebra in many aspects of physics and engineering. During these college years, I also began to appreciate both the connections and distinctions between pure and applied math. I ultimately determined that I was more drawn towards applied mathematics, as I wanted to specifically work on real-world problems. Having narrowed my interest, I decided to seek an M.S. in applied mathematics from my undergraduate institution.

In the initial year of my continuing studies, I secured the first rank in my class; doing so enabled me to pursue a specialization in industrial mathematics that, in hindsight, became a pivotal milestone in my career path. As part of this track, I studied a unique set of subjects—such as fuzzy logic, wavelets, and finite volume analysis—that are commonplace in multiple industrial organizations. The curriculum also involved hands-on projects in a variety of real-world engineering disciplines, from flood prediction (civil engineering) to temperature distribution in power transformers (electrical engineering). These invaluable experiences revealed the magnificence of computational mathematics within the context of engineering. At the culmination of my master's degree, I felt that I had fulfilled at least part of my quest by solidifying my interest in computational mathematics within engineering settings. However, a long expedition stretched ahead during which I had to build a research skillset and discern career options in this area.

The next step was a Ph.D. My sister, who had moved to the U.S. to advance her own career, told me that a Ph.D. from a U.S. institution would offer me the necessary qualifications to succeed. As I began to prepare for the move, I also took some time to explore several teaching opportunities. I served as an assistant professor at the Sardar Vallabhbhai Patel Institute of Technology in India and later worked as a visiting lecturer at my alma mater. Regardless of one's position, I believe that teaching is an integral part of a career trajectory; it strengthens existing skills and aids in the effective communication of ideas and concepts. I therefore view all of my teaching experiences—including my time as a teaching assistant during my Ph.D.—as essential components of my professional journey.

Upon arriving in the U.S. to pursue my Ph.D. at the University of Texas at Dallas, I was committed to learning more about the art of problem solving. I was instantly drawn to the work of my advisor, John Zweck, who studies nonlinear optical dynamical systems and their varied applications in medicine, astronomy, and optics. I jumped at the opportunity to perform my dissertation research under his guidance, as it seemed to perfectly align with my mathematical interests and had motivating real-world applications. My dissertation used adjoint-state optimization to numerically compute periodically stationary pulses in a short pulse laser and investigate their stability. My Ph.D. was certainly a comprehensive experience in that I acquired technical skills but also developed important research attributes such as patience, curiosity, organization, and analytical thinking.

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As my educational crusade drew to a close and my professional odyssey loomed in the immediate future, I found myself at a crucial inflection point. While applying for jobs towards the end of my Ph.D., I was still undecided on whether to continue my journey in academia or find a job in industry. I ultimately accepted a postdoctoral position within the Mathematics in Medicine Program at the Houston Methodist Research Institute, knowing that I would still have a chance to transition to industry at the conclusion of the appointment. While there, I developed mathematical models to test the efficacy of different cancer treatments. This project strengthened my aptitude as a computational mathematician and fostered new proficiencies, like modeling physical systems and utilizing statistical analysis to interpret real-world data. At Houston Methodist, I realized that I am highly motivated by environments that allow me to explore tangible applications and immediately witness their practical implementations.

As a circuit simulation engineer at Cadence Design Systems in San Jose, Calif., Vrushaly Shinglot develops, optimizes, and codes mathematical algorithms for a leading circuit simulation software. Photo courtesy of the author.

Though I greatly enjoyed my postdoctoral research, I recognized my propensity towards the use of computational mathematics in optics or related fields. I thus began to actively seek employment in a relevant area of industry. During this time, my husband—who was already working in the semiconductor industry as a mechanical engineer—introduced me to the applications of computational mathematics in semiconductors, from circuit simulation to thermal analysis of data centers. I was fascinated by the advanced role of semiconductors in high-performance computing, biomedical devices, and satellite communication. My search for a job within the semiconductor industry ended successfully in May 2023 when I joined Cadence Design Systems[1] in San Jose, Calif., as a circuit simulation engineer.

Cadence is primarily a software company that services the area of systems design automation, with a core focus on electronic design automation (EDA). I mainly work on the research and development team for a leading circuit simulation software called the Spectre Simulation Platform.[2] Specifically, I develop, optimize, and code mathematical algorithms that simulate radio frequency and optical circuits, and I regularly utilize numerical methods for differential equations, linear algebra, and control theory.

I was both excited and anxious upon joining Cadence, as I had spent more than six years in academia and did not have any sort of background in circuit simulation. However, Cadence's Career Catalyst Program[3] for recent graduates ensured a smooth transition by offering various educational sessions about the fundamentals of EDA, collaboration, networking, and so forth. Cadence also hosted informal gaming events to expand our networks and foster inclusivity among employees. And although I was concerned about work-life balance in industry (I had seen a few friends struggle with this in their own careers), I've found that Cadence actually favors and advocates for work-life balance with global recharge days. Overall, I am quite content in my current position; developing commercial software allows me to showcase my existing skills while garnering new proficiencies in mathematics and computer programming.

My expedition with applied mathematics has been undoubtedly fulfilling thus far. As I explored different directions in both academia and industry, I learned to enjoy the journey more than the destination. Support from my advisors, teachers, and family has played a crucial role in making this adventure as smooth as possible, and I am grateful to have found a career that satisfies my passion. However, my most important takeaway is to always maintain a healthy level of curiosity. In light of emerging areas like artificial intelligence and quantum computing—and their significant applications in healthcare, communication, energy, etc.—I am excited to see what new types of mathematical challenges and opportunities may arise in the field of circuit simulation.

Unfortunately, a widespread perception that mathematics is mostly about numbers still persists in today's world. Given my experience, I would like to inform all students (from elementary to graduate school) that mathematics—with its abundant applications in fields such as real analysis and topology (pure mathematics) and numerical analysis and dynamical systems (applied mathematics)—has much more to offer than just numbers.

Vrushaly Shinglot is a circuit simulation engineer at Cadence Design Systems. She received her Ph.D. in applied mathematics from the University of Texas at Dallas.

1 https://www.cadence.com
2 https://www.cadence.com/en_US/home/tools/custom-ic-analog-rf-design/circuit-simulation.html
3 https://www.cadence.com/en_US/home/company/careers/interns-and-new-grads.html


Vrushaly Shinglot (third from left) gathers with her family to celebrate her graduation from the University of Texas at Dallas with a Ph.D. in applied mathematics. Photo courtesy of the author.

EDGE Fellow

Continued from page 2

world and solve issues that pertain to the access and quality of education for underrepresented groups. With the help of EDGE, I know I will succeed in my purpose.

I want to thank the EDGE Program and SIAM for selecting me as this year's EDGE Fellow, a recognition that further affirms my good performance. When I enrolled in the EDGE Summer Program, I had no idea that becoming a SIAM EDGE Fellow was even a possibility. I approached the experience with the goal of bettering myself, and it has been rewarding to have my efforts noticed. And to any students who may be reading this article, keep going! Remind yourself that you deserve to be in the room. Sometimes the journey may not look like how you imagined, but that doesn't change the fact that you are capable of achieving your goals. If you are a woman who intends to pursue a Ph.D. in a mathematical field, I strongly encourage you to apply to EDGE. We need more women math warriors, and you won't regret it! And if you are a professional in the field, I look forward to working beside you soon.

To learn more about the 2025 EDGE Summer Program—which will take place from June 1-28, 2025, at the University of Tennessee, Knoxville—see page 6.

Nikira Walter is a first-year Ph.D. student in statistics at Columbia University. She graduated magna cum laude from Spelman College with a B.S. in mathematics. Walter's passion for education and social justice drives her academic and career goals, and she aspires to become a professor in the future.

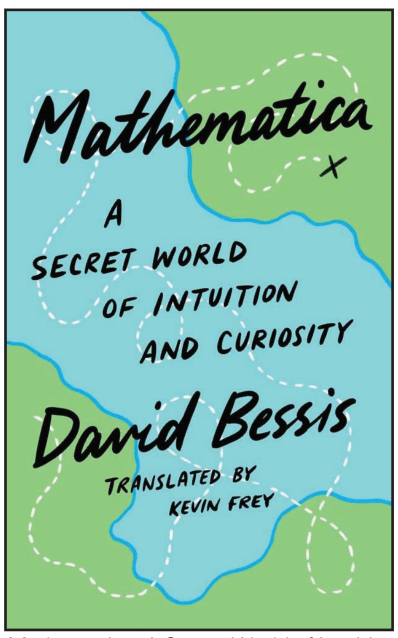
A Self-help Book for Aspiring Mathematicians

Mathematica: A Secret World of Intuition and Curiosity. *By David Bessis. Translated by Kevin Frey. Yale University Press, New Haven, CT, May 2024. 344 pages, $30.00.*

BOOK REVIEW
By Ernest Davis

David Bessis first published *Mathematica: Une aventure au coeur de nous-mêmes* in 2022 through French publishing house Éditions du Seuil. Now, two years later, it has been translated by Kevin Frey and released in English under the title *Mathematica: A Secret World of Intuition and Curiosity*.

Mathematica is primarily a self-help book and thus exhibits the characteristic features of that genre. The tone is proselytizing and the claims are extravagant. Bessis writes long sections in the second person and repeatedly assures "you," the reader, that you have the potential to transform your mind and your life generally—and your mathematical comprehension and abilities more specifically—through the use of an astonishingly simple method that will soon be explained. In fact, this technique is so simple that no one has ever dared to write it down before — though mathematicians secretly pass it down as occult knowledge from generation to generation.



Mathematica: A Secret World of Intuition and Curiosity. By David Bessis, translated by Kevin Frey. Courtesy of Yale University Press.

The following quotations reflect the overall tone and outlook of the text:

- "The aim of this book is to change the way you see the world."
- "Developing good mental habits, adopting the right psychological attitude, can make you *a billion* [Bessis' emphasis] times better at math. But the method for becoming good at math has never been taught in schools. You can reach it only by accident."
- "The basic principle is simple yet revolutionary. It's the kind of idea that almost no one thinks of because it's too simple and it goes against our instincts. The kind of idea, precisely, that has the potential to change everything, at all levels of math learning, including the absolute beginners and the self-professed lousy at math."
- "While the official knowledge has been transcribed in textbooks, the secret art of mathematicians has remained an oral tradition passed down from generation to generation. It reveals what no one dares write down in books because it doesn't seem serious enough, because it's not science, and because it resembles self-improvement too much."

Bessis' method comprises several components. One is the conquest of fear, both

See **Self-help Book** *on page 7*

Application Portal for the 2025 EDGE Summer Program Now Open

The Sylvia Bozeman and Rhonda Hughes Enhancing Diversity in Graduate Education (EDGE) Foundation is delighted to announce that the application portal for the 2025 EDGE Summer Program[1] is now open! The EDGE Summer Program is a four-week residential session that is designed to prepare a cohort of women and gender nonconforming individuals to thrive in their Ph.D. programs in the mathematical sciences.

The 2025 EDGE Summer Program will take place from June 1-28, 2025, at the University of Tennessee, Knoxville. Program activities include the following:

- Four core workshops in courses such as algebra, analysis, measure theory, and machine learning
- Daily collaborative problem sessions with advanced graduate student mentors
- Regular office hours and highly personalized feedback from facilitators
- Weekly colloquia on a variety of research topics
- Special discussions about equity and identity in mathematics, teaching practices, and other professional development skills.

The EDGE Foundation will cover all travel, room, and board expenses that relate to the Summer Program. Participants will also receive a modest stipend.

Program applicants should be women or gender nonconforming individuals who (i) are applying to Ph.D. programs in the mathematical sciences or (ii) have just completed their first year in a Ph.D. program in the mathematical sciences. Students from underrepresented minority groups are especially encouraged to apply.

Apply online today through MathPrograms;[2] applications are due **February 14, 2025**. Please direct any questions to **edgestaff@edgeforwomen.org**.

[1] https://www.edgeforwomen.org/summer-session
[2] https://www.mathprograms.org/db/programs/1670

Self-help Book

Continued from page 6

in social settings and your own mind. The social advice is that when a colleague is explaining their work to you, you should be frank about—or even exaggerate—your lack of understanding. And the personal advice is that you should allow yourself to fail in your initial attempts to understand a subject but remain persistent, like a child who falls when they first try to walk or an athlete who repeatedly practices a skill (Bessis' analogies). This guidance is certainly sensible but not very remarkable.

However, Bessis primarily advocates for a process of consciously training one's own mathematical intuition so that it works more effectively — an approach to mental improvement that he developed in high school and honed before his doctoral studies. He reports that this tactic has enormously improved both his mathematical abilities and his broader intellectual capacities. Bessis calls this process "System 3," as a continuation of psychologist Daniel Kahneman's well-known division of cognitive activities into System 1 (automatic, unconscious abilities such as vision or understanding a native language) and System 2 (problem solving and other types of conscious methodical reasoning).

The issue with this notion is that the word "intuition" and the phrase "mathematical intuition" are hopelessly vague and encompass many very different cognitive processes (Kahneman's distinction between "System 1" and "System 2" is also problematic). I find it extremely regrettable that these descriptions have become common at all levels of scientific rigor in publications about the human mind and people who do mathematics. Bessis says completely contradictory things about intuition. Most of the time, he seems to mean "spatial visualization," which he has practiced assiduously and performs very well. Even here, though, his usage is inconsistent. For instance, he attributes the ease with which most people can solve the problem "1 billion minus 1" to their ability to visualize the nine-digit number 999,999,999, which is not spatial visualization. At another point, Bessis declares that "[m]athematical intuition is so banal, simple, and stupid that you need a lot of self-confidence not to throw it in the trash ... The shy little voice that's telling you that you don't understand, that's your mathematical intuition." I'm not sure what to make of that "shy little voice," but it's certainly not visualization.

Toward the end of the book, Bessis writes that "[t]his intuition might have been primarily visual, or of an entirely different nature. In the end it doesn't matter that much. All mathematicians approach mathematical objects intuitively, but intuitions come in many shapes and forms. My weakest point is my inability to find my way in complicated notations, to follow without stumbling reasonings that contain a lot of symbols and formulas. Entire areas of mathematics put me off because of this, especially analysis. It's only gotten worse over time as I've lost patience with it."

This statement is admirably honest; Bessis' musings are often best when he is saying something that undermines his entire thesis, as in this case. For if Bessis himself cannot adapt his own method to analysis or number theory (which he mentions elsewhere), why should he assume that the method will allow the public to learn whatever variety of math they want? If he has no patience for analysis, why does he suppose that other people will have patience for any type of advanced math? If "mathematical intuition" is not primarily visual, why does he spend multiple chapters advocating for visualization? And why does he wait until page 216 to inform readers that different areas of math may require entirely different kinds of "intuition"?

Bessis provides only two concrete examples of his own use of mathematical intuition, and neither are very interesting. The first involves his ability to avoid being tricked by a problem that Kahneman studied. "A ball and a bat cost a total of $1.10," he writes. "The bat costs $1 more than the ball. How much does the ball cost?" Bessis spends several pages on this scenario, explaining how you can see that the answer is 5 cents with the right kind of diagram. The second example is how he came to understand the relation between the dimensions of a vector space and the rank of a linear mapping by visualizing the vector spaces as barrels of varying size and the mappings as pipes of varying diameters.

Like many mathematicians, Bessis is under the illusion that everyone would get the same pleasure out of mathematics that he does if they could only get over their fears and inhibitions that stem from bad math teachers in elementary school. He thus makes absurd pronouncements like "Learning to write math is learning to have clear ideas. Wouldn't it be a shame to deprive yourself of that?"

Mathematica is perhaps most usefully read as an intellectual autobiography. Bessis has an unusual mind, which he has examined with careful introspection over the course of many years. He has put himself through some odd mental exercises and vividly describes some of his more atypical experiences.

Bessis devotes individual chapters to three great mathematicians—William Thurston, René Descartes, and Alexander Grothendieck—who he claims wrote about their mental methods in similar ways to himself. These are among the best chapters in the book, though they are marred by a hectoring tone. Decartes, Grothendieck, and even Albert Einstein maintained that they had no special abilities, just a good method of thought. Bessis quotes Einstein's assertion that "I have no special talent. I am only passionately curious." He writes charmingly about this, noting that "When I was fifteen, I hated this quote from Einstein. To me it sounded phony, insincere, like a supermodel saying that what really counts is inner beauty." However, the more mature Bessis urges readers to seriously consider this and other comparable pronouncements by Descartes and Grothendieck. This direction is not very convincing, and Bessis cannot actually maintain the attitude. In fact, he is very much prone to hero worship and carefully lists all of the prizes that his idols have won each time he introduces them. In the end, he admits that "[p]roving theorems like those of Tom Hales and Maryna Viazovska is obviously not within reach of everyone." Hmm, so much for the idea that you too can be a great mathematician if you conquer your fears and practice a method of mental discipline so simple that no one dares to write it down.

Despite Bessis' interest in the mental processes that influence learning and mathematical thought, he is seemingly unaware of the large body of research on this very subject by math educationalists and cognitive psychologists such as Stanislas Dehaene and Rochel Gelman. He also fails to mention any of the numerous popular and semi-popular math books that do successfully present math in understandable and engaging ways.

Additionally, one common feature of self-help books is missing: the claim that many adherents have achieved success by following the author's method. Although Bessis has taught at both Yale University and École Normale Supérieure, he gives no indication that any of his students have successfully learned his method, or that he has tried to teach it to them.

Let me conclude by pointing out that in general, *Mathematica* has been favorably received and praised by distinguished mathematicians like Terence Tao, Steven Strogatz, and Hugo Duminil-Copin. My negative opinion is a minority one, and you may well find the book more congenial than I did.

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

Industry Panel at AN24 Considers Career Opportunities Outside of Academia

By Jillian Kunze

Researchers in industry and the national laboratories routinely utilize a wide variety of mathematical tools, leading to a high demand for applied mathematicians and computational scientists in these spaces. During the 2024 SIAM Annual Meeting[1]—which took place in Spokane, Wash., this past July—Sharon Arroyo of The Boeing Company[2] moderated an industry career panel[3] that explored the realities of non-academic positions and outlined the various routes to these roles. Panelists Amanda Howard of Pacific Northwest National Laboratory;[4] Nicole Jackson of Sandia National Laboratories;[5] John-Paul Sabino of The Boeing Company; Gwen Spencer of Netflix;[6] and Wotao Yin of Alibaba Group[7]/Academy for Discovery, Adventure, Momentum and Outlook shared their insights with an engaged audience.

Spencer explained that she was initially drawn to industry for the chance to work on applied topics with interesting collaborators. "There was really an aspect of wanting to test my training," she said. "I wanted to have access to people who know completely different things, and I heard from lots of people that industry was the place to do this." Yin likewise acknowledged the diversity of projects in industry, noting that he appreciates the progression from finding a core initial idea to delving into the related literature and ultimately outputting a finished product that customers will pay to use. Similarly, Sabino enjoys the gratification of watching what he visualizes come to life through coding and development. "To me, that's one of the best aspects of what I'm able to do — to scratch that creative itch," he said. "It's as close to real-life magic as we get. This is a highly creative profession, which the vast majority of people outside of our field don't appreciate."

Jackson, who works within the national laboratory ecosystem, values the opportunities to collaborate with colleagues in academia. "I get to oscillate quite nicely from doing fundamental research to bringing it back to the really applied setting," she said. As such, scientists in national labs often divide their attention between several different pursuits at once. "You can find a portfolio of projects that are interesting to you and that build skills for each other," Howard said.

When conversation turned to daily life at a national lab, Howard explained that her workplace is still highly virtual and she often works from home when programming, writing grants and papers, or meeting with collaborators. As a senior machine learning scientist at Netflix, Spencer purposely plans her schedule to accommodate multiple work streams. "I spend at least 60 to 70 percent of my day doing technical work, and some amount of time developing slide decks and going to meetings," she said. The panelists collectively utilize a multitude of mathematical techniques in their roles, including geometric data structures, partial differential equation-constrained optimization, physics-informed machine learning, linear programming, and generative adversarial networks.

All jobs almost always involve both stimulating tasks and some inevitably frustrating aspects. One potential source of strain is that industry researchers cannot disclose, publish, or discuss trade secrets, which means that some important accomplishments cannot be shared. And like other professionals, industry employees must also deal with monetary uncertainty at times. "You usually have more ideas about what you want to do than reliable and predictable income streams to fund them," Sabino said.

CAREERS IN MATHEMATICAL SCIENCES

Jackson's favorite parts of her position at Sandia National Laboratories include the "a-ha" moment when uncertainty turns into an exciting result, and the process of receiving feedback from industry partners. In contrast, one of the most vexing aspects is funding rejection. "One of the things that I've learned over the years is that rejection is going to happen, and you have to figure out how to move on," she said. Because each funding opportunity receives a huge number of proposals, Howard tries to not take rejection too personally. And fortunately, applied mathematics is relevant to a wide variety of research pursuits. "I don't ever have a shortage of projects because I can fit into a lot of different ones," Howard said. While working within these types of cross-cutting collaborations, mathematicians can learn more about the priorities of different funding offices and grow their connections with individuals in an assortment of roles. "A lot of it comes down to forming a network of people within your organization," Jackson said.

From left to right: panelists John-Paul Sabino (The Boeing Company), Amanda Howard (Pacific Northwest National Laboratory), Gwen Spencer (Netflix), Nicole Jackson (Sandia National Laboratories), and Wotao Yin (Alibaba Group/Academy for Discovery, Adventure, Momentum and Outlook) discuss careers in mathematics beyond the academic sphere during the 2024 SIAM Annual Meeting, which took place in Spokane, Wash., in July. SIAM photo.

Explaining mathematical concepts in general terms is an essential skill in both industry and the national laboratories. "In terms of communicating mathematics to a less technical audience, we rely on the tried-and-true analogy," Sabino said. Knowing the audience is key — are they technical experts in a different field or managers who probably do not want to see a lot of equations? "I like to think of it as 'what is the story I'm going to tell?' and hopefully bring people along on that journey," Jackson said. "What are the takeaways that the people listening are hopefully going to walk away with? How can I communicate this in a highly visual way?"

Mathematicians in application-focused workplaces must also occasionally make peace with inelegant solutions. "There are all kinds of businesses," Yin said. "Some businesses do not worry as much about accuracy." For instance, financial institutions usually recognize the challenges that accompany their very noisy data. Spencer stated that she enjoys the simplicity that comes from conquering a problem with just one or two features — perhaps via an approach that provides 80 percent of the value with 20 percent of the effort. "You develop different ways of thinking about how you triumphed over a problem," she said. Howard similarly reframes her processes when necessary. "I think an effective approximation is often the elegant and harder solution," she said.

As discussion turned to career path options, the panelists urged students to explore many different possibilities through projects, coursework, or internships. "What makes you excited to do the technical work that you're interested in?" Jackson said. "If you have a large problem space, what part of that space are you intrinsically motivated by? I encourage you to think about what makes you excited, and what could make you want to get up to do the work."

Additionally, it is important to consider whether the market for a certain type of role is emerging, stable, or growing, and whether companies will likely continue to value that role; all of these factors will determine the number of available opportunities in the future. Concentrating on a very niche field could cause trouble if the associated skillset becomes less relevant over time. "If you master two different techniques, you have a much better chance," Yin said, adding that one should also contemplate the long-term growth potential of multiple career pathways. "Let's say that you do algorithms. You can choose between places where an algorithm makes decisions, or where an algorithm supports human decision-makers."

LinkedIn is a good platform on which to maintain personal networks while establishing new connections across different organizations. "If you know people who like the companies they work at, it can help to ask to be referred," Spencer said. "Lots of companies offer referral bonuses." Furthermore, meeting employees at conferences and during job interviews is a great way to get to know an organization. "I think that there's a lot of heterogeneity in how companies understand the role of science in their potential," Spencer added.

When applying for jobs after graduating with a Ph.D., an applicant's thesis does not need to directly relate to the job description in question. In fact, Sabino recalled one interviewer who told him not to be disappointed if he never worked on his thesis topic again. "Mathematicians are highly versatile," he said. "They can solve a variety of problems, as this panel has demonstrated. There's relatively few applied mathematicians, and they can work in a wide variety of areas." But if early-career scientists are hoping to make a major transition after graduate school, some interstitial experience may nonetheless be helpful. "Postdocs are a really good option if you're looking to transition away from your thesis topic," Howard said. "Pick something that bridges the two."

For individuals with Ph.D.s in pure mathematics who are interested in the applied world, additional experiences—like internships at national laboratories that span pure and applied math—are particularly essential. "If you can add a sentence [in your resume] on the area of research, those key words are really important," Yin said. Hard skills like programming and soft skills like collaboration are likewise crucial in many job application processes. "A big question mark we have for any candidate is whether they are going to be able to transition well into working with teams," Sabino said.

As their final advice, the panelists reemphasized the value of exploring different domains as a student, developing a toolbelt with a range of mathematical techniques, and maintaining a strong network. "If you want something, don't be afraid to let people know," Sabino said. "Making connections with people—just talking with people—can help build those little networks that lead to a job."

Jillian Kunze is the associate editor of SIAM News.

A career panel at the 2024 SIAM Annual Meeting, which was held this July in Spokane, Wash., explored mathematical research in industry and the national laboratories. From left to right: panelists John-Paul Sabino (The Boeing Company), Amanda Howard (Pacific Northwest National Laboratory), Gwen Spencer (Netflix), Nicole Jackson (Sandia National Laboratories), and Wotao Yin (Alibaba Group/Academy for Discovery, Adventure, Momentum and Outlook), as well as moderator Sharon Arroyo (The Boeing Company). SIAM photo.

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1 https://www.siam.org/conferences-events/siam-conferences/an24
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SIAM | CONFERENCES

A Place to Network and Exchange Ideas

Upcoming Deadlines

ACM-SIAM Symposium on Discrete Algorithms (SODA25)

January 12–15, 2025 | New Orleans, Louisiana, U.S.
go.siam.org/soda25 | #SIAMDA25

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Yossi Azar, *Tel-Aviv University, Israel*
Debmalya Panigrahi, *Duke University, U.S*

SODA will be held jointly with:
SIAM Symposium on Algorithm Engineering and Experiments (ALENEX)
SIAM Symposium on Simplicity in Algorithms (SOSA)

EARLY REGISTRATION RATE and HOTEL RESERVATION DEADLINE: December 9, 2024

SIAM Conference on Financial Mathematics and Engineering (FM25)

July 15–18, 2025 | Miami, Florida, U.S.
go.siam.org/fm25 | #SIAMFM25

ORGANIZING COMMITTEE CO-CHAIRS
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Luitgard Veraart, *London School of Economics and Political Science, United Kingdom*

SUBMISSION AND TRAVEL AWARD DEADLINES
December 17, 2024: Minisymposium Proposal Submissions
January 13, 2025: Contributed Lecture, Poster, and Minisymposium Presentation Abstracts
April 15, 2025: Travel Fund Applications

The Third Joint SIAM/CAIMS Annual Meetings (AN25)

July 28–August 1, 2025 | Montréal, Québec, Canada
go.siam.org/an25 | #SIAMAN25

ORGANIZING COMMITTEE CO-CHAIRS
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Arvind K. Saibaba, *North Carolina State University, U.S.*

SUBMISSION AND TRAVEL AWARD DEADLINES
January 13, 2025: Minisymposium Proposal Submissions
February 10, 2025: Contributed Lecture, Poster, Miniposterium and Minisymposium Presentation Abstracts
April 28, 2025: Travel Fund Applications

SIAM Conference on Control and Its Applications (CT25)

July 28–30, 2025 | Montréal, Québec, Canada
go.siam.org/ct25 | #SIAMCT25

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SUBMISSION AND TRAVEL AWARD DEADLINES
January 13, 2025: Minisymposium Proposal Submissions
January 27, 2025: Contributed Lecture, Poster, Minisymposium Presentation Abstracts, and Proceedings Papers
April 28, 2025: Travel Fund Applications

SIAM Conference on Computational Geometric Design (GD25)

July 28–30, 2025 | Montréal, Québec, Canada
go.siam.org/gd25 | #SIAMGD25

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January 27, 2025: Contributed Lecture, Poster, and Minisymposium Presentation Abstracts
April 28, 2025: Travel Fund Applications

Information is current as of October 11, 2024. Visit *siam.org/conferences* for the most up-to-date information.

Upcoming SIAM Events

Bulgarian Section of SIAM Annual Meeting 2024
December 9–11, 2024
Sofia, Bulgaria

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

SIAM Symposium on Algorithm Engineering and Experiments
January 12–13, 2025
New Orleans, Louisiana, U.S.

SIAM Symposium on Simplicity in Algorithms
January 13–14, 2025
New Orleans, Louisiana, U.S.

SIAM Conference on Computational Science and Engineering
March 3–7, 2025
Fort Worth, Texas, U.S.
Sponsored by the SIAM Activity Group on Computational Science and Engineering

SIAM International Conference on Data Mining
May 1–3, 2025
Alexandria, Virginia, U.S.
Sponsored by the SIAM Activity Group on Data Science

SIAM Conference on Applications of Dynamical Systems
May 11–15, 2025
Denver, Colorado, U.S.
Sponsored by the SIAM Activity Group on Dynamical Systems

SIAM Conference on Applied Algebraic Geometry
July 7–11, 2025
Madison, Wisconsin, U.S.
Sponsored by the SIAM Activity Group on Algebraic Geometry

SIAM Conference on Financial Mathematics and Engineering
July 15–18, 2025
Miami, Florida, U.S.
Sponsored by the SIAM Activity Group on Financial Mathematics and Engineering

The Third Joint SIAM/CAIMS Annual Meetings
July 28–August 1, 2025
Montréal, Québec, Canada

SIAM Conference on Control and Its Applications
July 28–30, 2025
Montréal, Québec, Canada
Sponsored by the SIAM Activity Group on Control and Systems Theory

SIAM Conference on Computational Geometric Design
July 28–30, 2025
Montréal, Québec, Canada
Sponsored by the SIAM Activity Group on Geometric Design

SIAM Conference on Applied and Computational Discrete Algorithms
July 30–August 1, 2025
Montréal, Québec, Canada
Sponsored by the SIAM Activity Group on Applied & Computational Discrete Algorithms

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SIAM Student Chapter Activities and Updates

Regional Student Chapter Events—Many local student chapters come together for regional SIAM student meetings and conferences. During the 2023–2024 academic year, such events included:

Trivia Night
Brown University SIAM Student Chapter hosted an applied math community trivia night. A mix of undergraduate and graduate students, and postdocs attended.

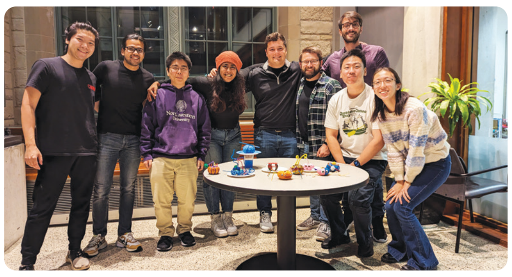
National Oceanic and Atmospheric Administration Visit
The **SIAM Student Chapter at Colorado State University** took a tour of NOAA. They learned about intern opportunities and career pathways for mathematicians in NOAA, and how mathematicians contribute at NOAA.

SIAM End of Year Math Department Barbecue
Eastern Washington University SIAM Student Chapter hosted the annual EWU Math Department BBQ — a social event for students, faculty, and staff to connect and celebrate the year's accomplishments.

Poster Session
Graduate students from the student chapter at the **Schools of Maths and Computer Science at Cardiff University** gave poster presentations. It was an opportunity to ask questions and discuss research with other Ph.D. students and academics.

SIAM Welcomes the Newest Student Chapters

- Loyola University Chicago
- Munich Area
- Nanyang Technical University
- Oklahoma State University
- Texas State University
- Universidad de Costa Rica
- Universidad de Rosario
- Universita di Pavia
- University of Cincinnati Area
- University of Massachusetts Amherst Student Chapter
- University of Leeds
- Wayne State University



Graduate students of applied mathematics and physics in the ***Northwestern University*** *SIAM Student Chapter got together to decorate pumpkins for Halloween.*

Members of the ***Uppsala University*** *SIAM Student Chapter visited Elekta in their beautiful new office in Stockholm. Elekta demonstrated their Leksell Gamma Knife, presented the Cone Beam CT and their work (and collaboration with UU IT department!) from radiation physics to algorithms and patient applications. They also had the pleasure of meeting with the company CEO, Gustaf Salford.*

Mathematics students in the SIAM Student Chapter at ***Pontificia Universidad Catolica de Chile*** *met with professor Elwin van't Wout to discuss and ask questions about academic topics and relaxation topics, and to learn about the teacher's experience.*

Chicago Events
As part of a conference hosted by their university, the **Illinois Institute of Technology SIAM Student Chapter** visited Argonne National Laboratory and Fermilab; hosted student lunches/dinners; participated in lectures with speakers from RUSH, Argonne, and IIT; attended panel discussions; toured IIT; and explored Chicago.

Welcome Event
Imperial College London Student Chapter hosted an event to introduce new Ph.D. students to SIAM and to the university. Current Ph.D. students spoke on their experience of graduate mathematics study, followed by a team-building quiz and drinks and pizza.

Math Quest
The Math Quest, which is hosted by **Nazarbayev University SIAM Student Chapter,** is a week-long challenging team competition with consecutive problems that require creative thinking.

University of Iowa SIAM *Student Chapter organized a girls' night for women math and AMCS graduate students at the university. This was a wonderful chance for female graduate students to bond outside academia.*

Graduate Student Seminar
University of Colorado, Boulder SIAM Student Chapter held a biweekly seminar to allow graduate students the opportunity to present about something they found interesting in front of their peers.

Game Night
University of Utah SIAM Student Chapter participated in a game night co-hosted with their chapter of the AWM, to encourage community within the department.

Elementary School Outreach
University of Washington SIAM Student Chapter went to Lockwood elementary school and gave a few different mathematics demonstrations for their annual math fair.

Apply Now for 2025 SIAM Conference Support

SIAM conference support is available via travel awards, which provide financial assistance. Students and U.S. early career researchers should apply at ***siam.org/conferences/conference-support***.

Nominate two of your students for free membership in 2025!

SIAM members (excluding student members) can nominate up to two students per year for free membership. Go to ***my.siam.org/forms/nominate.htm*** to make your nominations.

Nominate Your Students for the 2025 SIAM Student Paper Prize

The prize will be awarded to the student authors of the three most outstanding papers accepted for publication by SIAM journals between February 15, 2022 and February 14, 2025. Each recipient will present their paper at The Third Joint SIAM/CAIMS Annual Meetings (AN25) and will receive reimbursement up to the value of a SIAM Travel Award. Submit your nominations by February 15, 2025 at ***siam.org/student-paper-prize***.

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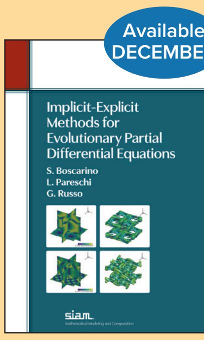
Available DECEMBER



Sebastiano Boscarino, Lorenzo Pareschi, and Giovanni Russo

Implicit-explicit (IMEX) time discretization methods have proven to be highly effective for the numerical solution of a wide class of evolutionary partial differential equations (PDEs) across various contexts. This first book on the subject provides an in-depth yet accessible approach. The authors summarize and illustrate the construction, analysis, and application of IMEX methods using examples, test cases, and implementation details; guide readers through the various methods and teach them how to select and use the one most appropriate for their needs; and demonstrate how to identify stiff terms and effectively implement high-order methods in time for a variety of systems of PDEs.

2024 / x + 324 pages / Softcover / 978-1-61197-819-3
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Data-Driven Methods for Dynamic Systems

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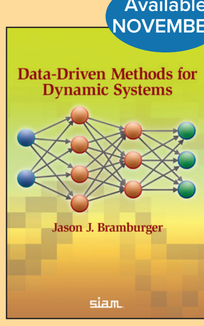

Jason J. Bramburger

As experimental data sets have grown and computational power has increased, new tools have been developed that have the power to model new systems and fundamentally alter how current systems are analyzed. This book brings together modern computational tools to provide an accurate understanding of dynamic data. The techniques build on pencil-and-paper mathematical techniques that go back decades and sometimes even centuries. The result is an introduction to state-of-the-art methods that complement, rather than replace, traditional analysis of time-dependent systems.

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More Computational Methods

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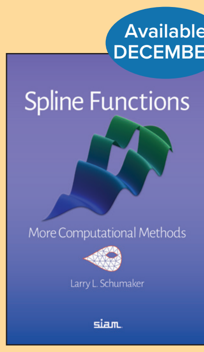

Larry L. Schumaker

This book is a continuation of the author's earlier book *Spline Functions: Computational Methods*, published in 2015 by SIAM. This new book focuses on computational methods developed in the last ten years that make use of splines to approximate functions and data and to solve boundary-value problems.

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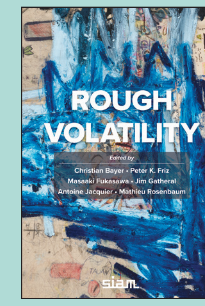
Rough Volatility



Christian Bayer, Peter K. Friz, Masaaki Fukasawa, Jim Gatheral, Antoine Jacquier, and Mathieu Rosenbaum, Editors

Volatility has traditionally been modeled as a semimartingale, with consequent scaling properties, but a new paradigm has emerged, whereby paths of volatility are rougher than those of semimartingales. According to this perspective, volatility behaves as a fractional Brownian motion with a small Hurst parameter. *Rough Volatility* is the first book to offer a comprehensive exploration of the subject. It contributes to the understanding and application of rough volatility models by equipping readers with the tools and insights needed to delve into the topic and explores the motivation for rough volatility modeling and provides a toolbox for its computation and practical implementation.

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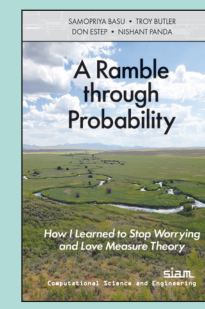
A Ramble through Probability
How I Learned to Stop Worrying and Love Measure Theory



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

Measure theory and measure-theoretic probability are fascinating subjects. Proofs describing profound ways to reason lead to results that are frequently startling, beautiful, and useful. This book traces an eclectic path through the fundamentals of the topic to make the material accessible to a broad range of students. It brings together the key elements and applications in a unified presentation aimed at developing intuition; contains an extensive collection of examples that illustrate, explain, and apply the theories; and is supplemented with videos containing commentary and explanations of select proofs on an ancillary website.

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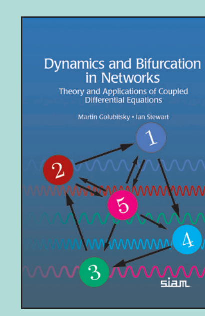
Dynamics and Bifurcation in Networks
Theory and Applications of Coupled Differential Equations

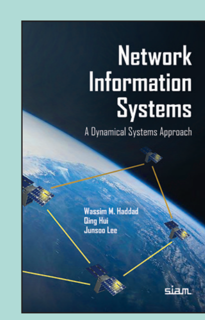


Martin Golubitsky and Ian Stewart

In recent years there has been an explosion of interest in network-based modeling in many branches of science. This book attempts a synthesis of some of the common features of many such models, providing a general framework analogous to the modern theory of nonlinear dynamical systems. How networks lead to behavior not typical in a general dynamical system and how the architecture of the network influences this behavior are the book's main themes. It is the first book to describe the formalism for network dynamics developed over the past 20 years.

2023 / xxx + 834 pages / Hardcover / 978-1-61197-732-5 / List $129.00 / SIAM Member $90.30 / OT185

Network Information Systems
A Dynamical Systems Approach



Wassim M. Haddad, Qing Hui, and Junsoo Lee

This text presents a unique treatment of network control systems. Drawing from fundamental principles of dynamical systems theory and dynamical thermodynamics, the authors develop a continuous-time, discrete-time, and hybrid dynamical system and control framework for linear and nonlinear large-scale network systems. The proposed framework extends the concepts of energy, entropy, and temperature to undirected and directed information networks. Continuous-time, discrete-time, and hybrid thermodynamic principles are used to design distributed control protocol algorithms for static and dynamic networked systems in the face of system uncertainty, exogenous disturbances, imperfect system network communication, and time delays.

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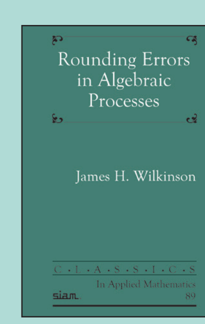
Rounding Errors in Algebraic Processes



James Hardy Wilkinson

This was the first book to give systematic analyses of the effects of rounding errors on a variety of key computations involving polynomials and matrices. A detailed analysis is given of the rounding errors made in the elementary arithmetic operations and inner products, for both floating-point arithmetic and fixed-point arithmetic. The results are then applied in the error analyses of a variety of computations involving polynomials as well as the solution of linear systems, matrix inversion, and eigenvalue computations. The conditioning of these problems is investigated. The aim was to provide a unified method of treatment, and emphasis is placed on the underlying concepts.

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

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Xu He

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