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A New Computational Method for Nonlinear Filtering

By Hongjiang Qian, George Yin, and Qing Zhang

In numerous applications, noise often corrupts the signals that dynamical systems emit. Users employ a process called *filtering* to remove the noise and restore the original signal. When the underlying dynamics are nonlinear, this process becomes *nonlinear filtering*. Nonlinear noise-removal filters typically examine the input signal and utilize certain stochastic models to make inferences and estimate the most likely value for the original signal. In estimation and control theory, such a process is known as the *filtering problem*. Nonlinear filtering enjoys many applications in the control of partially observed systems, target tracking, signal processing, robotics control, financial engineering, and environmental monitoring.

Here we present a new method that seeks to solve computational nonlinear filtering problems that have persisted for the last 60 years. Unlike the conventional method that approximates conditional means or distributions, this novel technique employs deep filtering with adaptive learning rates. One key computational advantage of this approach is that it generates robust computational results even with changing parameters or noise perturbations. We anticipate that this breakthrough could potentially revive the field of computational nonlinear filtering.

Nonlinear Filtering

Consider a multidimensional stochastic system with state $X(t)$ at continuous time t, for which the precise information of $X(t)$ is unknown; only noise-corrupted observations on $X(t)$ denoted by $Y(t)$ are available. One can describe the dynamics of (state, observation)$=(X(t),Y(t))$ with a pair of stochastic differential equations:

$$\begin{aligned} \mathrm{d}X(t) &= g(X(t))\mathrm{d}t + S(X(t))\mathrm{d}W(t), \\ \mathrm{d}Y(t) &= h(X(t))\mathrm{d}t + H(t)\mathrm{d}V(t). \end{aligned} \tag{1}$$

Here, g and h are suitable vector-valued functions, S and H are suitable matrix-valued functions of their arguments, and $W(t)$ and $V(t)$ are independent noise processes (standard Brownian motions). Nonlinear filtering estimates $X(t)$ based on information from observation Y up to time t. Extensive work on this problem began in the 1960s [1, 3, 6, 8-10]. In 1964, Harold Kushner used Itô calculus to derive the nonlinear filtering equation that is satisfied by a normalized conditional density [3]; this equation is now called the Kushner equation. Subsequently, Tyrone Duncan [1], Richard Mortensen [6], and Moshe Zakai [10] independently derived filtering equations for unnormalized conditional densities; the unnormalized equation is presently known as the Duncan-Mortensen-Zakai (DMZ) equation.

Both the normalized and unnormalized conditional densities comprise partial differential equations of infinite dimensions. A typical approach involves finding a solution to the DMZ equation, then proving that it is indeed the conditional distribution under uniqueness of the solution to the differential equation. In spite of the celebrated results that settled the matter of theoretical nonlinear filtering, finding closed-form solutions is virtually impossible because of this nonlinearity. Researchers have since devoted much effort to the identification of feasible computational methods.

See **Nonlinear Filtering** *on page 4*

function DF(ϑ_0^0, γ_0)
  for $n \leftarrow 0$ to Epoch **do**
    for $k \leftarrow 0$ to $\ell - 1$ **do**
      $\vartheta_{k+1}^{n\ell} = \vartheta_k^{n\ell} - \gamma_n \nabla_\vartheta J(\vartheta_k^{n\ell}, \xi_k^{n\ell})$
    $\vartheta_n^+ = \vartheta_\ell^{n\ell} - (\gamma_n + \Delta)\nabla_\vartheta J(\vartheta_\ell^{n\ell}, \xi_\ell^{n\ell})$
    $\vartheta_n^- = \vartheta_\ell^{n\ell} - (\gamma_n - \Delta)\nabla_\vartheta J(\vartheta_\ell^{n\ell}, \xi_\ell^{n\ell})$
    $\widehat{G}_n = (\chi(\vartheta_n^+, \zeta_n^+) - \chi(\vartheta_n^-, \zeta_n^-))/(2\Delta)$
    $\gamma_{n+1} = \gamma_n - \varepsilon \widehat{G}_n$

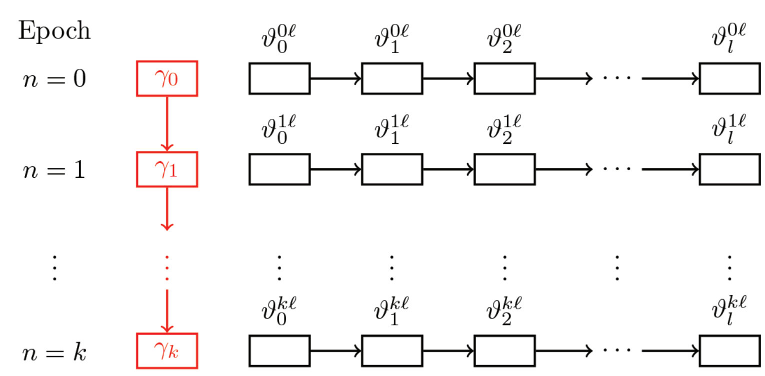

Figure 1. *Algorithm for deep filtering with adaptive learning rates, with a corresponding flow chart. Figure courtesy of the authors.*

Neural Networks May Provide Warnings Ahead of Deadly Heat Waves

By Matthew R. Francis

A series of terrible heat waves struck Europe in the summer of 2022, resulting in more than 20,000 deaths across the continent. In 2021, heat waves led to unprecedented wildfires in both Siberia and the Pacific Northwest, stressing already vulnerable ecosystems. In 2008 and 2010, extreme heat events throughout Asia killed hundreds of thousands of people.

Climate change is increasing both the frequency and severity of deadly heat waves. The most devastating heat events on historical record have all occurred in the past few decades and are unlike anything in the existing paleo-climatological data, which extends back to the dawn of humanity.

"Because of climate change, heat waves that were exceptional [in the past] might become common," Freddy Bouchet, a climate researcher at the Centre National de la Recherche Scientifique and École Normale Supérieure in Paris, France, said. In other words, the human-driven changes in global climate are causing heat waves to happen more often and reach higher temperatures. However, the rarity of previous extreme heat waves makes it difficult for scientists to predict future occurrences — even as they become more common.

"During the last 20 years, only three events [comprise] nearly all of the total [heat-driven] deaths related to climate disaster," Bouchet said. But as the number of heat waves grows, a more robust historical record would be useful for predictive purposes. "It's basically three unprecedented events," Bouchet continued. "It's a serious challenge for scientists, to study something without data."

In a paper that recently published in *Physical Review Fluids* [1], Bouchet and his colleagues approached this problem with a method from statistical physics called *rare event simulation*. They drew on sophisticated climate models that encompass 8,000 years of Earth's history and utilized neural networks to investigate the likelihood that a recorded heat wave would have transpired in the absence of human-created climate change. Using this information, the group then developed a framework that identifies the signs of future heat waves with the hope of predicting them early enough to enable mitigation strategies.

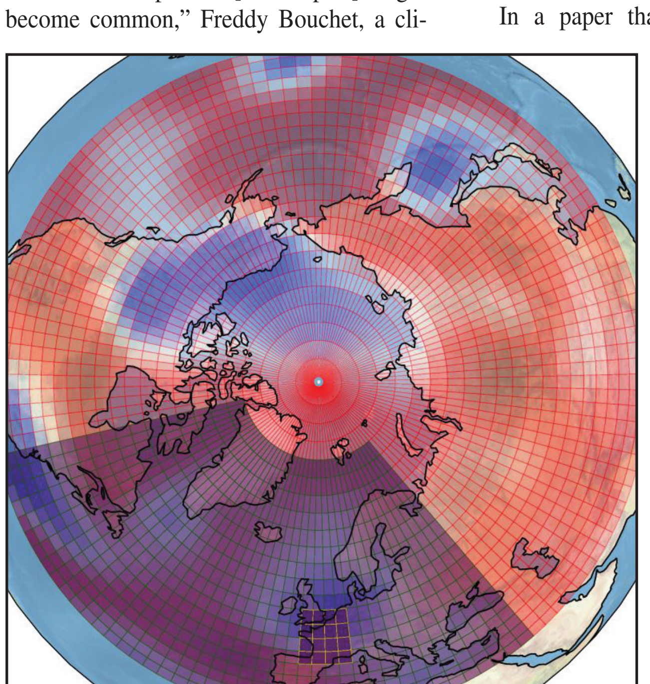

Figure 1. *The grid for the Planet Simulator climate model divides Earth into segments that are roughly 1,000 kilometers wide. The dark purple overlay indicates the North Atlantic region, which was the focus of this particular study. Figure courtesy of [1].*

Isla Simpson, a climate scientist at the U.S. National Center for Atmospheric Research in Boulder, Colo., highlighted the complications of this type of prediction work. "We're dealing with climate change that's driven by greenhouse gases and aerosols and other things, but also just the natural variability of the climate system," she said. "Quantifying how much a heat wave is changing because of greenhouse gases is a big challenge. We need models to help us do that because we have a limited observational record."

However, Simpson clarified that while *specific* predictions are tricky, general conclusions are not. "The planet is warming, so any weather that happens on top of that warming is going to lead to more extreme high temperatures," she said.

Everyone Talks About the Weather

Heat wave prediction faces many of the same problems as local weather forecasting. For instance, the atmosphere is intrinsically chaotic, meaning that small changes in conditions can lead to wildly different outcomes over time. In fact, the Lorenz strange attractor—one of the earliest descriptions of chaos theory—originated from efforts to model the weather. Researchers specifically focus on heat waves that last for more than a few days, since lengthier events can overwhelm a nation's infrastructure. Bouchet noted that the number of deaths during the 2003 European heat wave grew quadratically with time, meaning that extreme temperatures become increasingly deadly the longer they last. Multiple heat waves over the course of a single season therefore constitute an urgent health crisis.

And to cite the cliché, it's not just the heat. "It's a combination of heat and humidity," Bouchet said. "We reach a level where there is a huge nonlinearity in the body's ability to respond." This scenario is

See **Deadly Heat Waves** *on page 3*

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Mathematics, Responsibility, and Joy

By Derek Kane

LETTER TO THE EDITOR

Over the past several years, I have been speaking to students from elementary to graduate school about the importance, beauty, and power of mathematics. These conversations are informed by a watershed moment that occurred nine years ago, when I addressed a group of high school math teachers on my 50th birthday. Confronted with the undeniable proof of my aging and wondering about my place in the world now that my children had left home, I changed the topic of my talk from the general importance of math to *why* it is important that we do math.

The pursuit of beauty is the fundamental motivation for mathematicians. We are all lured in by some particularly elegant argument or radically new way to think about the world; for instance, the Archimedean proof of the existence of irrational numbers forged my personal love of math. The elegance, rigor, and creativity within the field of mathematics can translate into innovative and effective solutions to physical or social issues.

When we apply math to problems that are posed by industry, government, and society, we expect to change people's lives. We make financial transactions safer and more efficient; determine health risks within populations; create robust channels of communication; direct more police to select neighborhoods; identify people as potential terrorists; and determine whether a radar return is a flock of birds, a civilian airliner, or an incoming missile. In short, mathematics' ability to profoundly affect people and communities for both good and ill imposes corresponding moral obligations upon us.

Our first obligation is to predict the impact of our analyses and subsequent decisions on the world. Although the accuracy of these predictions is often limited, the exercise forces us to consider multifarious effects. When submitting a product for approval from the U.S. Food and Drug Administration, for instance, we must describe foreseeable misuse and demonstrate the product's ability to mitigate such harms. In the absence of mitigation, we need to prove that the product's benefits offset the possible damages.

If you want to reflect on your career with satisfaction, you should repeat this exercise for every project that you undertake. What is the *intended* outcome of your work? What are the likely outcomes? How will people actually use your analyses? What technologies and behaviors are you enabling? Do you feel that the benefits of this work outweigh its potential damages?

I began my career by joining the Strategic Defense Initiative (known colloquially as the "*Star Wars* program") to protect the U.S. from missile attacks. I took on this work simply because it was both an interesting engineering challenge and an available job. My regrets about this stage of my career do not stem from my participation in the program, but from the fact that I did not make an informed decision about my involvement by considering the arguments for or against the deployment of an imperfect defense in the face of a nuclear attack. In order to look back without regrets, you have to decide whether you are comfortable with the implications of your present work.

Math is pure and absolute, but physical and social systems are chaotic and uncertain. As such, we must be careful not to translate our models' exact and provable answers into absolute beliefs about machines, natural systems, or societies. Even if *we* acknowledge the world's stochastic nature, those who use the models and tools that we create may consider their predictions to be absolute.

Machine translation between languages is a great triumph of applied math; for instance, I could not have imagined Google Translate when I was a student. However, machine translation is still imperfect. In 2020, an Afghan woman's asylum application was denied in U.S. court because the written submission did not match her initial interviews. This was not a case of the woman attempting to deceive the court, but rather the machine translation changing the personal pronoun "I" to "we" in her written statement [3]. Even good models that are utilized by imperfect systems can cause significant harm.

These imperfect systems are limited by budget or statute and use hard thresholds to determine who will benefit and who will suffer. It is easy to let our algorithms and thresholds disguise our moral choices. For example, a 54-year-old British citizen named Bruce Hardy was undergoing treatment for metastatic kidney cancer in 2008. His doctor recommended a course of Sutent, a new drug that was expected to extend his life for six months at a cost of $54,000. Because British health service policy only valued six months of life at approximately $23,000, the treatment was denied. In the wake of widespread protests, the institute that determined the cost-effectiveness of drugs modified its policy to allow the approval of medications like Sutent [4]. The morally correct position in this case is not obvious, as the same funds that would grant a terminally ill man six more months of life could also fully vaccinate about 50 children [1, 2]. The important lesson is that hard limits and algorithms can obscure the reality of the moral choices at play.

In many cases, the very fact that we are making ethical decisions is opaque. We site a new incinerator near highways and railroads, unaware of its impact on a nearby historic African American community. We segment a city into risk zones for mortgage insurance based on access to emergency services and local crime statistics, not realizing that doing so makes home ownership more inaccessible in a credit-starved neighborhood. Our optimization models incorporate the interests of our employers, the concerns of our coworkers, and our own knowledge and experience. For this reason, meaningful diversity is vital to all workplaces and design processes. One person cannot singlehandedly encompass enough experience to ensure the development of just solutions for all who are affected. I believe that the only way to avoid harming our communities is to guarantee the representation of the entire population throughout every process or project. We need mathematicians who represent all facets of the world, realize the limits of their knowledge, and actively listen to outside concerns and suggestions.

The newly minted Dr. Derek Kane with his daughter, the future Dr. Erin Kane. Photo courtesy of Derek Kane.

Finally, we must find joy and friendship in our pursuits and interactions. The empathy and humanity of our decisions and analyses depend on our engagement with the people around us, and the variety of experiences, knowledge, and insights that we bring to our analyses improve the creativity and value of our solutions. Math is a particularly beautiful way to describe the world, but art, music, literature, and sport offer equally invaluable insights into the human condition and our place therein. Do not begrudge time spent away from your true work and true calling, as this time allows you to translate the rigor and insight of mathematics into a world and community that becomes better through your presence.

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Derek Kane is a mathematician who has worked at DEKA Research and Development since 2000. He received a B.S. in mechanical engineering from the Massachusetts Institute of Technology in 1985 and a Ph.D. in mathematics from the University of Michigan in 1996, for which he studied cohomology of division algebras over p-adic fields.

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Looking to the Future

FROM THE SIAM PRESIDENT
By Sven Leyffer

One of the most rewarding and enjoyable aspects of being SIAM President is the numerous opportunities to meet and interact with students — our future SIAM leaders, as I like to call them. Argonne National Laboratory recently hosted the "Chicagoland" SIAM student chapters, which include the Illinois Institute of Technology, Northwestern University, and the University of Illinois Chicago.

The daylong gathering took place in March and involved survey talks on computational mathematics, science applications, and physics; the obligatory pizza lunch; a panel discussion on career prospects and research projects within the national laboratories; and tours of multiple Argonne facilities. For instance, students visited the Advanced Photon Source,[1] which provides ultra-bright high-energy X-ray beams; the Materials Engineering Research Facility,[2] which serves as a testbed for the advanced manufacture of invented materials; and Aurora,[3] Argonne's new exascale supercomputer. The benefits of such events are twofold; students learn about potential career paths and staff meet prospective interns or postdoctoral researchers. I strongly encourage other SIAM student chapters,[4] laboratories, and research institutions to arrange similar experiences.

Student chapters form the backbone of SIAM's student activities. Last year, SIAM established 19 new student chapters[5] through the dedicated efforts of Tulin Kaman (chair of the SIAM Membership Committee), with assistance from Susanne Brenner (the Past President of SIAM) and Kathleen Kavanagh (SIAM's Vice President for Education). 2021 was also a landmark year, as the number of student chapters surpassed 200.[6] One of my goals as SIAM President is to further increase student participation within the Society and encourage more frequent special events, such as the Argonne lab visit. As such, I do hope that we can continue to grow the student chapter tally in the coming years with the community's help. "We should all encourage young people to establish chapters if they don't already have one at their institutions," Brenner said. "It is easy to make such suggestions when visiting universities or meeting individuals at conferences."

Organizing a SIAM student chapter is not difficult, and the benefits are amazing. SIAM offers plenty of help and provides step-by-step guidance[7] that details the process — all you need are 12 founding members, including two faculty advisers. Maggie Hohenadel (SIAM's Student Chapter and Fellows Coordinator), Tulin Kaman, and I can answer any questions from interested students or faculty. The many advantages of establishing a student chapter include free SIAM membership for full-time students, free membership in two SIAM Activity Groups,[8] SIAM funding for local activities, leadership opportunities, and support for one representative to attend the SIAM Annual Meeting and meet with SIAM leadership and other chapter liaisons over breakfast.

SIAM is currently putting together a special student event for the 2023 International Congress on Industrial and Applied Mathematics,[9] which will take place in Tokyo, Japan, from August 20-25. We plan to sponsor an informal lunch that will allow students to meet the invited speakers and prizewinners, receive career advice, discuss research, and network with each other. Keep an eye out for a forthcoming announcement about how to register for this event. Finally, please reach out to me at **leyffer@anl.gov** if you have ideas for student activities at SIAM.

Sven Leyffer is a senior computational mathematician at Argonne National Laboratory and the current President of SIAM. He holds a Ph.D. from the University of Dundee in Scotland and works on nonlinear and mixed-integer optimization problems.

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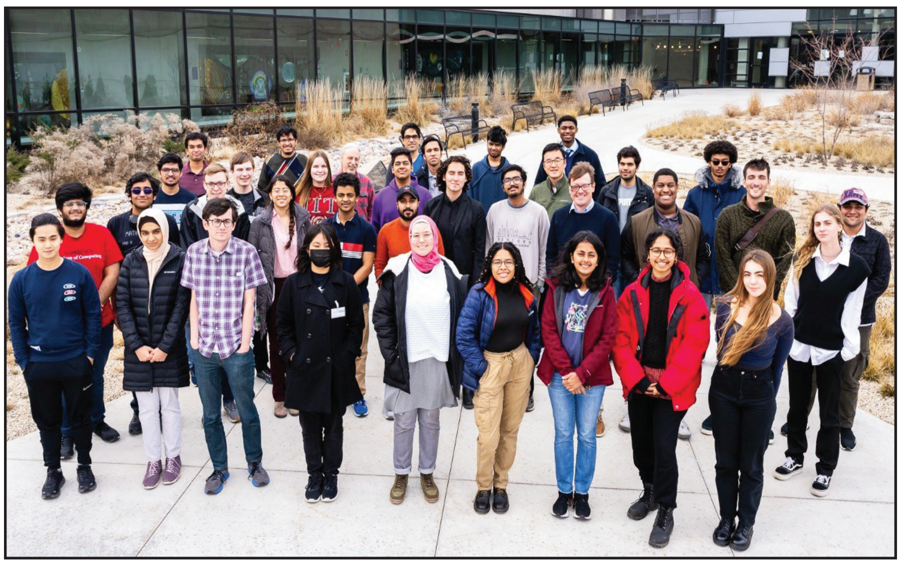

Members of the "Chicagoland" SIAM student chapters at the Illinois Institute of Technology, Northwestern University, and the University of Illinois Chicago gather at Argonne National Laboratory's Theory and Computing Sciences Building during a joint visit in March 2023. Photo courtesy of Argonne National Laboratory.

Deadly Heat Waves

Continued from page 1

particularly salient in humid regions like Southeast Asia and the Indian subcontinent, where wet-bulb temperatures that account for air moisture are progressively exceeding tolerable levels for the human body. In addition, nighttime temperatures do not drop low enough to provide relief.

Arid regions face their own set of issues. "When it gets hot, the evaporation of water can kind of act as a mediator for the temperature," Simpson said. "If you don't have water to evaporate, then you're going to have more extreme heat. Some places are drying out because of climate change, which could alter the nature of land-atmosphere feedbacks and lead to more intense heat waves."

Simulating the Planet

For obvious reasons, heat waves are defined relative to their location. Temperatures over 90 degrees Fahrenheit (32 degrees Celsius) are not extreme in Death Valley, Calif., but could signal a crisis in parts of Alaska or Siberia that are north of the Arctic Circle. Meanwhile, 115 degrees Fahrenheit (46 degrees Celsius) constitutes extreme heat anywhere on the planet. Climate researchers like Bouchet and Simpson look for temperatures that exceed normal local conditions for an extended period of time.

Bouchet and his collaborators calculated temperature anomalies for a given time period by averaging the difference between the statistical mean temperature $\mathbb{E}(\vec{r},t)$ and the temperature $T_{2m}(\vec{r},t)$, which is measured two meters above the surface at time t and a point $\vec{r}$ in space:

$$A(t)=\frac{1}{\tau}\int_t^{t+\tau}\frac{1}{|\mathcal{D}|}\int_{\mathcal{D}}(T_{2m}-\mathbb{E})\,\mathrm{d}\vec{r}\,\mathrm{d}t.$$

Depending on the resolution scale and simulator requirements, the heat wave duration τ can range from one day to the length of an entire season. The researchers used $\tau=14$ days and set $\mathcal{D}$ as a square that is roughly 1,000 kilometers in width — the magnitude of cyclonic atmospheric phenomena (see Figure 1, on page 1).

Modern climate models are extremely sophisticated but computationally expensive to run. For that reason, Bouchet and his coauthors employed the Planet Simulator[1] (PlaSim): a fluid dynamics model of the atmosphere. PlaSim is compatible with Intergovernmental Panel on Climate Change[2] (IPCC) standards, but its lower resolution and fewer parameters allow it to run roughly 100 times faster than other models (albeit at a cost to accuracy). The simulation couples the atmosphere to the planet's surface—ice, land, and water—and outputs important physical quantities like air temperature and pressure.

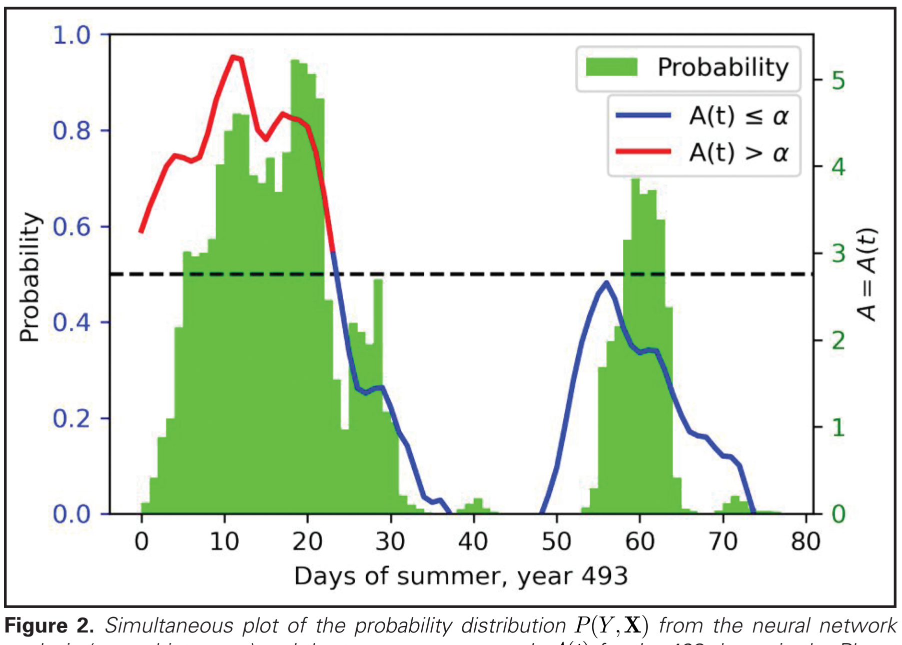

Figure 2. *Simultaneous plot of the probability distribution $P(Y,\mathbf{X})$ from the neural network analysis (green histogram) and the temperature anomaly $A(t)$ for the 493rd year in the Planet Simulator run. When $A(t)$ is greater than the threshold (which is depicted as a dotted line), the region in question experiences a heat wave. Figure courtesy of [1].*

The group ran the simulator 80 times at 100-year intervals to obtain 8,000 years of data, with a temporal resolution of one day. They simulated the atmosphere at a roughly 2.8-degree scale in latitude and longitude and included 10 vertical slices from the surface to the boundary between the troposphere (the lowest layer of the atmosphere, where weather occurs) and the stratosphere.

With these data in hand, the team specified that an extreme heat wave occurs when the temperature anomaly A exceeds a threshold of 2.7 degrees Celsius. Accordingly, they defined a binary variable $Y(t)$ that is equal to 1 during a heat wave and 0 below that limit; they thus aimed to calculate the probability $P(Y=1\,|\,\mathbf{X}=x)$ of a heat wave when the dynamical parameters $\mathbf{X}\in\mathbb{R}^d$ of the atmosphere correspond to a particular state $\boldsymbol{x}$ (see Figure 2). Although this probability function is unknown in principle, the neural network can estimate it via PlaSim's 8,000 years of training data. "[Our] neural network has some predictive power on a timescale of a week to 10 days, which is the weather prediction range," Bouchet said. "Because of chaos, we then lose information about the state of the atmosphere."

But thanks to the slower drivers of atmospheric conditions like ocean properties and soil moisture, the researchers were able to predict heat waves farther out than ordinary weather forecasts. "We have a prediction with a delay of one month for a heat wave that lasted two weeks," Bouchet said, adding that government weather services use similar probabilistic forecasts to help anticipate stresses on electricity production and agriculture.

1 https://www.mi.uni-hamburg.de/en/arbeitsgruppen/theoretische-meteorologie/modelle/plasim.html
2 https://www.ipcc.ch

When the Past Is No Guide

When predicting events that are historically rare, one must identify important properties in the absence of available data. "There's the possibility that the [atmospheric] circulation patterns that induce heat waves are becoming more frequent or more intense," Simpson, who was not involved in Bouchet's neural network research, said. "That's a much more difficult question to address because we don't have a long observational record. Heat waves by definition don't happen that often, so it's hard to pick out a trend as to whether these weather systems are changing."

In other words, disaster preparedness requires more than just the knowledge that heat waves are increasing in frequency, and even more than established correlations between this increase and climate change. Scientists are still trying to determine *how* large-scale atmospheric behaviors—such as monsoon cycles, for example—are changing as the world heats up. These phenomena could have a terrible feedback effect on regional weather, including heat wave occurrence.

One unfortunate irony is that climate researchers like Bouchet will be able to refine their models in the coming years simply due to the growing frequency of deadly weather events. However, effective heat wave prediction mechanisms could save lives if authorities are willing to take action — it is here that neural network forecasting might have its greatest impact.

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Nonlinear Filtering

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The main difficulty is that computational schemes that are based on conditional distributions suffer from the curse of dimensionality. Researchers have made multiple efforts to solve these equations with numerical methods. For example, Sergey Lototsky, Remigijus Mikulevicius, and Boris Rozovskii developed a spectral approach that separated computations involving observations and a system of parameters [5]. Despite significant progress over the years, finding feasible procedures for nonlinear filtering and constructing computable nonlinear filtering algorithms are still extremely challenging.

In contrast to the theoretical work and various attempts to detect conditional means or conditional distributions and their approximations, we do not try to approximate the conditional distribution. Instead, we use machine learning to convert the infinite-dimensional problem into a finite-dimensional parameter optimization problem. In lieu of numerically solving the stochastic partial differential equations, our approach generates Monte Carlo samples for the system states and observations. The problem is then recast as finding a "function" based on the observed random samples. The weights of the neural network parameterize this "function," and a stochastic approximation method proceeds to estimate it [4].

A Machine Learning Approach to Filtering Algorithms

Informed by the rapidly developing field of machine learning, we reformulate the task as a stochastic optimization problem. We extend the traditional diffusion setup and consider the so-called *switching diffusion model*. This model is similar to (1), but f, g, S, and H all depend on a continuous-time Markov chain $\alpha(t)$ that takes values in a finite set and is used to model the hybrid uncertainty that the continuous states do not address. Our approximation procedure is as follows:

(i) Discretize (1) with step size $\delta > 0$ via the Euler-Maruyama method [2] to obtain

$$X_{n+1} = X_n + \delta f(X_n, \alpha_n) + \sqrt{\delta}\, S(X_n, \alpha_n) W_n,$$
$$Y_{n+1} = Y_n + \delta g(X_n, \alpha_n) + \sqrt{\delta}, H(X_n, \alpha_n) V_n. \qquad (2)$$

(ii) Set the number of training samples as N_{sample}, the training window size as n_0, and the total number of steps in the time horizon of the state and observation as N.

(iii) Utilize the Monte Carlo method and (2) to generate data. For a sample point ω, we use (2) to obtain $\{Y_n(\omega), Y_{n+1}(\omega), \ldots, Y_{n+n_0-1}(\omega)\}$—the input of the neural network with fixed sample point ω, $n = n_0, \ldots, N$—and set the corresponding state $X_{n+n_0-1}(\omega)$ as the target.

(iv) Use the least squares error between the target and the calculated output as a loss function for deep neural network (DNN) training to generate a weight vector, denoted by ϑ.

We then apply these weight vectors to another set of Monte Carlo samples of the actual dynamic system. We refer to the corresponding calculated DNN output $\tilde{X}_n$ as the *deep filter*.

We view estimates of X_n as a function of the observation $(Y_0, Y_1, \ldots, Y_n)$ and employ deep learning methods and the artificial neural network to find this function. Contrary to the existing machine learning literature, we propose a systematic approach; while updating the parameter ϑ, we also adaptively update the learning rates and use them in the next step parameter estimation for ϑ. We construct a pair of sequences of estimates for (ϑ, γ) in two loops. The estimate of ϑ requires more iterations than the estimate of γ.

Figure 1 (on page 1) depicts the resulting algorithm for deep filtering with adaptive learning rates, as well as a corresponding flow chart. Under rather broad conditions, γ_n converges to the optimal learning rate γ^* and the approximation error bounds become obtainable [7].

Numerical Examples

We briefly illustrate our approach with a few examples. Further details for these examples—including various nonlinear functions, coefficients, and numerical values—are available on GitHub.[1] Because we can show that the Euler-Maruyama approximations (X_n, α_n) and (Y_n, α_n) converge to the solution of the switching diffusions, we start with the discrete-time approximations rather than the original continuous-time systems.

Example 1: Consider a two-dimensional (2D) nonlinear system with sinusoidal nonlinearity and a Markov switching process; the state and observation variables x and y are both 2D. According to the computational results in Figure 2, the performance in terms of relative errors is robust with respect to the initial learning rates.

Example 2: Motivated by a target tracking problem, consider a six-dimensional dynamical system of a 2D moving particle. In the observation equation for this scenario, the first two components respectively represent the distance and angle. Figure 3 displays the numerical results.

Conclusions

We have presented a new computational method to solve challenging nonlinear filtering problems. Now we conclude with a few observations:

(i) Filtering that involves random switching is difficult. There is no easy way out or ready-made method from the computational toolbox. Our deep filtering algorithm serves as an effective procedure.

(ii) Although the algorithm targets nonlinear filtering, it is applicable to linear systems as well. We have conducted numerical experiments for linear systems and compared them with optimal Kalman filters, noting that the Kalman filters heavily depend on the type of nominal models in question. Such dependence is less pronounced with deep filtering.

(iii) Nonlinear filtering computations often break down when treating functions that involve sinusoidal signals. Deep filters can handle these signals with no substantial difficulty.

(iv) Sparsity in the model may render undesirable outputs. In such a case, one can utilize a deep filter together with several regularization procedures.

(v) In switching diffusions, the use of a deep filter can help devise a computational procedure if the Markov chain is also part of the state to be restored. Though it is currently possible to carry out the computation, the accuracy needs further improvement.

Our computational filtering method, which is based on deep learning techniques, unlocks new avenues for the solution of numerous problems that require the computation and estimation of unknown system signals. This article reports on a straightforward implementation, and we welcome suggestions to improve the overall performance or modify and enhance the basic algorithms.

[1] https://github.com/hongjiang-qian/siam-news/blob/main/examples.pdf

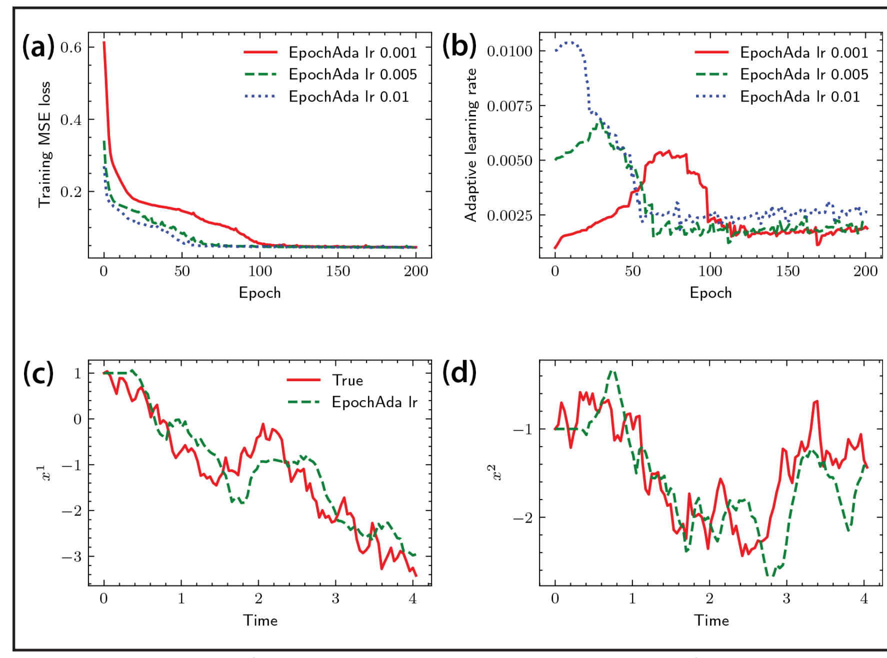

Figure 2. *Visualization of Example 1.* **2a.** *The training loss.* **2b.** *Path of the adaptive learning rate.* **2c–2d.** *Sample paths for the out-of-sample state and corresponding sample paths for the deep filters. Figure courtesy of the authors.*

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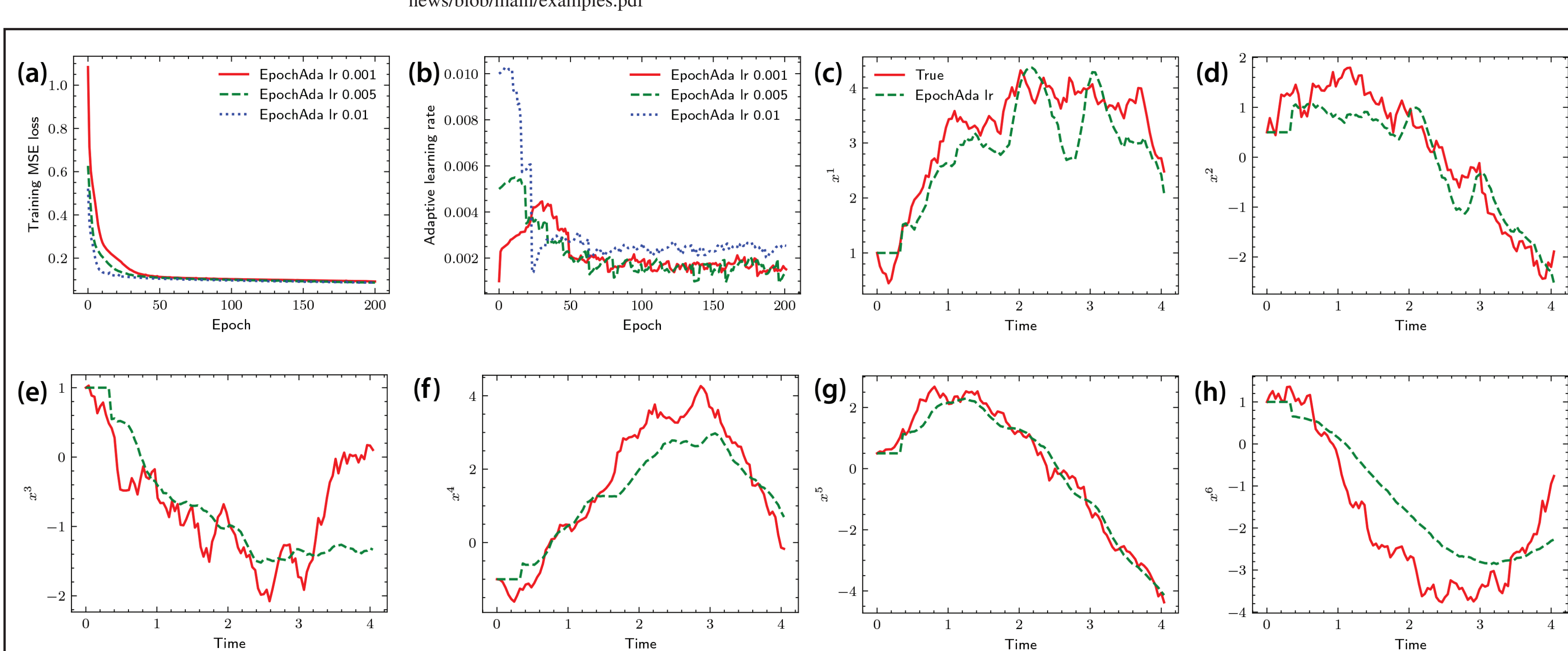


Figure 3. *Visualization of Example 2.* **3a.** *The training loss.* **3b.** *Path of the adaptive learning rate.* **3c–3h.** *Sample paths of the out-of-sample state and the deep filters for each of the components. Figure courtesy of the authors.*

New Book Explores the *Ideas* of Mathematics

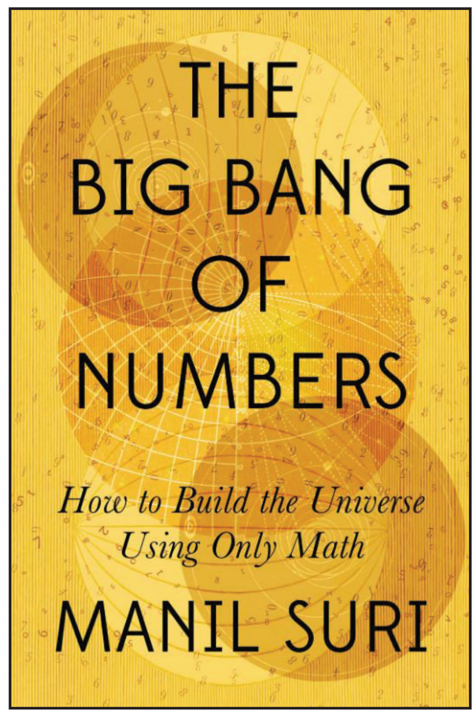
The Big Bang of Numbers: How to Build the Universe Using Only Math. *By Manil Suri. W.W. Norton & Company, New York, NY, September 2022. 384 pages, $32.50.*

BOOK REVIEW
By Paul J. Nahin

Manil Suri, author of *The Big Bang of Numbers* and a professor of mathematics, is also a published novelist. It is therefore no surprise that he is an excellent writer of prose. To be quick to the point, he has produced a coherent book on—in his words—many of the *ideas* of mathematics. That being said, when readers finish Suri's latest book, their ability to *calculate* anything will not be any more developed than before. Realizing this, I could not help but think of Lord Kelvin's famous assertion that, to paraphrase, "we can talk all day about things in general, but until we can *calculate* stuff we really don't know anything" (he actually used the word *measure*, but I think the meaning is the same). In fact, geometry—the most ancient branch of mathematics—takes its very name from this idea (to *measure* the Earth).

To be fair, Suri is not unaware of this concept. In the opening paragraphs, he specifically mentions that *The Big Bang of Numbers* is a reaction to the usual image of mathematics — as simply a tool with which to calculate. Since he then turns away from the notion of calculation, one really can't fault what follows. But to somebody like me, who thinks of mathematics as beautiful precisely *because* it gives us the power to calculate rather than merely pontificate, the text loses some of its allure.

Now, don't take what I've just written the wrong way. Suri tells readers right up front that his goal is to present many of the ideas of math to the general masses in an understandable manner, and he mostly succeeds. The book would be a *great* read for bright youngsters who might otherwise spend too much time on non-academic activities. For readers of SIAM publications, however, there is less about which to be enthusiastic. This tome will surely stimulate some thought in intelligent high school students, but for the SIAM community it is mostly eye candy. Tasty, yes, and briefly fun to "eat," but consumers will ultimately yearn for substance.



The Big Bang of Numbers: How to Build the Universe Using Only Math. By Manil Suri. Courtesy of W.W. Norton & Company.

I write this with a sense of regret because I believe that Suri possesses the skills to have had it both ways. In the introduction, for example, he repeats the words of Rob Fixmer, a former editor at *The New York Times* who asserted that "Mathematics has no emotional impact [compared to physics] … Math doesn't challenge any fundamental beliefs or what it means to be human." Suri doesn't think much of this sentiment (and I bet many SIAM people don't either), but it struck me that such a silly statement provides the opening for an obvious (alas, missed) rebuttal with some discussion of probability — the beautiful branch of math born through the analysis of games of chance.

I am no cultural anthropologist, but I believe that the only creatures on Earth—both past and present—that have ever gambled are humans. Gambling is a unique attribute of being human, and there is *a lot* of emotion in high-stakes betting. The screaming crowds at the local racetrack and the nationwide frenzy whenever a billion-dollar lottery occurs are prime examples of this phenomenon. Probability is bursting with numerous wonderful, nonintuitive *calculations* that only involve arithmetic and could have thus been included in this book. Suri does offer some words on randomness, but none that will give readers the ability to calculate anything.

In addition, the selection of topics in *The Big Bang of Numbers* may strike some people as curious. The text spends a fair amount of space on certain special, important numbers (i.e., $\sqrt{2}$, π, the golden ratio, and $i=\sqrt{-1}$), but of the vastly important e there is only a single sentence telling us that it is "the base of the natural logarithms" — a statement that won't mean much to anybody who isn't already familiar with logarithms. Given that Suri mentions e, π, and i, I also found it surprising that there is no reference—even in passing—to the wonderful $e^{i\pi}+1=0$.

I could continue along this line with my grumbling, but doing so would be mean-spirited. After all, one can criticize just about any book for not covering the topics that the *reviewer* thinks should have been included. As H.G. Wells observed (probably after reading a critical review of one of his bestselling novels), "No passion in the world is equal to the passion to alter someone else's draft." So I will simply end by saying that Suri has done a good job of addressing the topics that he chose to include. For example, there are some interesting mini essays on the complex plane, dimensionality, and the concept of infinity. If you know someone whose math education ended with high school algebra but who is willing to have a second go at *thinking* about math (though is maybe not so interested in actually *doing* math), this book would likely be of interest.

Paul J. Nahin is a professor emeritus of electrical engineering at the University of New Hampshire. He is the author of more than 20 books on mathematics, physics, and electrical engineering; his latest book, The Mathematical Radio, is set to publish through Princeton University Press in early 2024.

U.S. Naval Research Laboratory Offers Myriad Career Opportunities for Applied Mathematicians

By Lina Sorg

Founded in 1923, the U.S. Naval Research Laboratory[1] (NRL) is the corporate research lab of the U.S. Navy[2] and U.S. Marine Corps.[3] As such, it conducts science and engineering research to develop state-of-the-art technologies and approaches that meet both immediate and long-term U.S. defense needs. Many of NRL's divisions employ applied mathematicians and computational scientists who work on a variety of interesting projects, from mapping the sea floor to studying the atmosphere and even outer space.

SIAM News recently chatted with Bruce Danly, Director of Research at NRL, and Tegan Webster, head of the Radar Division's[4] Distributed Sensing Section. During this joint interview, they addressed NRL's research objectives and aims within the larger Department of Defense[5] (DoD) portfolio, spoke about their individual career trajectories and experiences, and offered advice to early-career members of the SIAM community who wish to pursue employment at NRL or similar institutions.

***SIAM News*: How would you describe the mission of NRL?**

Bruce Danly: NRL carries out basic and applied research for the Department of the Navy and, more broadly, the DoD. We also do a little bit of work for non-DoD government customers like the National Oceanic and Atmospheric Administration,[6] Department of Energy,[7] and Department of Homeland Security.[8] Our workforce comes from all of the science, technology, engineering, and mathematics (STEM) disciplines, and our projects focus mainly on the pursuit of innovative ideas that will ultimately benefit the nation by enabling the Navy and Marine Corps with cutting-edge technology. Even so, NRL is largely a civilian organization; only about 100 of our 2,500 employees are active-duty military.

SN: What should *SIAM News* readers know about applied mathematics research at NRL?

BD: Lots of different divisions use mathematics. According to the statistics, we have 11 mathematicians—including Dr. Webster—in the Radar Division alone. Mathematicians are also employed in information technology, electronic warfare, computational fluid dynamics, acoustics, remote sensing, ocean sciences, marine meteorology, and the space divisions. A lot of NRL's applied math work pertains to data assimilation, specifically the assimilation of large datasets that pair with complex computer models. Think weather prediction, for example.

Fundamentally, we're working on most of the disciplines that are buzzing right now in science and engineering. Machine learning, artificial intelligence, quantum sensing, and quantum computing are certainly active areas of research at the lab.

SN: What are some of NRL's current basic research needs?

CAREERS IN MATHEMATICAL SCIENCES

BD: Statistics, data assimilation, signal analysis, and computer science are the most essential basic research needs, though the generation of new algorithms for signal processing is also important. We conduct a great deal of advanced data assimilation work in meteorology and oceanography. Accurately forecasting sonar propagation and sonar operations in the ocean—which is a very complex environment—requires strong ocean models through which the acoustic waves can propagate. This is a key part of a number of our divisions. Another major component at NRL is the Geographic Information System group, which does a lot of global referencing and represents physical data on different reference grids that model the Earth.

Tegan Webster, a mathematician at the U.S. Naval Research Laboratory (NRL) and head of the Radar Division's Distributed Sensing Section, analyzes the graphical user interface of the Multichannel Active Electronically Scanned Array (MAESA) radar testbed in Washington, D.C. The MAESA system transmits, receives, processes, and visualizes data for research and development in radar technology. U.S. Navy photo courtesy of Sarah Peterson.

SN: Tell us about your career trajectories. How did you each end up in your current positions?

Tegan Webster: I earned my undergraduate and master's degrees in applied mathematics and my Ph.D. in mathematics, all at Rensselaer Polytechnic Institute. While in graduate school, I became a student employee in the Radar Division at NRL; the program that I joined is similar to the current STEM Student Employment Program[9] (SSEP). I had done a few internships and the one at NRL was the most interesting, so I stayed on as a full-time employee when I graduated. I spent several years in the Advanced Signal Processing Section, and now I'm the head of the Distributed Sensing Section. I still do technical work in my current position—I specifically work on developing and demonstrating novel radar technologies and concepts—but I also help bring on new hires and student employees.

BD: My background is in physics, and I came to NRL in my late 30s. Prior to NRL, I had spent my entire career at Massachusetts Institute of Technology (MIT) — both in graduate school and on the research staff. I was working on nuclear fusion at MIT, but I wanted to do something with a payoff that I would see in my lifetime. I joined NRL in 1995 and remained in the Electronics Science and Technology Division[10] until 2008, when I became head of the Radar Division. I worked on high-powered millimeter wave amplifiers for radar applications in the Electronics Division, and I built a high-power 94-gigahertz radar with the Radar Division. I don't do research myself anymore, but it's still fun listening to smart people pitch funding proposals.

SN: What does a typical workday look like for each of you?

BD: My workday is that of any administrator in a large organization, from dealing with personnel policy issues and human resource tasks to competing for funding at the lab level. What I'm doing on a given day depends on the time of year. In the fall, I listen to roughly 150 funding proposals, each of which gets 45 minutes. It takes about three months but it's one of the most enjoyable parts of the job. In the spring, I meet with congressional staff members, and on occasion congressional representatives themselves, to defend how we're spending our portion of the Navy's science and technology budget.

I also make connections between our researchers and folks within the Navy and DoD who could integrate an idea or demonstrated advance into something operational. That's another fun part — it involves playing matchmaker between researchers and other customers.

TW: There's a ton of variety and flexibility, so it's hard to get bored. Some days I'll be onsite working on code, running a simulation, analyzing data, or conducting field testing with our testbed systems or operational radar systems. The Radar Division specifically does a lot of work with the Tactical Electronic Warfare Division[11] and the Remote Sensing Division.[12]

Sometimes I create briefs and present them to our sponsors because NRL has to bring in its own funding. We also present many of our projects to our research partners, who are typically other government employees or contractors. I frequently collaborate with a team of about five or six people on multiple undertakings, but there are definitely plenty of independent tasks as well, such as coding or documentation.

SN: What advice would you give to students and early-career researchers who hope to pursue a career with NRL or another government laboratory?

TW: I would suggest trying an internship. When I was an early graduate student, I didn't really think beyond academia because it seemed like the natural path. But internships really changed my perspective, especially the one at NRL because I enjoyed the variety of the work. Every organization—both within and outside of the government—is different and you really won't know what kind of work it involves unless you experience it for yourself. And if someone wants to stay technical, they should pay attention to whether the established, full-time employees are still doing technical work. At a place like NRL, you can absolutely stay technical throughout your career.

SN: What kinds of internship opportunities does NRL offer?

BD: NRL has a number of summer internships and hosts between 100 and 200 students every summer, many of whom return to work for us full time. We offer standard DoD student programs like SSEP, and we even have a Science and Engineering

See **Naval Research Laboratory** *on page 7*

[1] https://www.nrl.navy.mil
[2] https://www.navy.mil
[3] https://www.marines.mil
[4] https://www.nrl.navy.mil/Our-Work/Areas-of-Research/Radar
[5] https://www.defense.gov
[6] https://www.noaa.gov
[7] https://www.energy.gov
[8] https://www.dhs.gov
[9] https://www.nrl.navy.mil/Careers/Students/SSEP
[10] https://www.nrl.navy.mil/Our-Work/Areas-of-Research/Electronics-Science-Technology
[11] https://www.nrl.navy.mil/tewd
[12] https://www.nrl.navy.mil/Our-Work/Areas-of-Research/Remote-Sensing

Naval Research Laboratory

Continued from page 6

Apprenticeship Program[13] for high school students. We have also begun to hire students from several DoD fellowship programs, such as the Science, Mathematics, and Research for Transformation (SMART) Scholarship-for-Service Program.[14] The National Defense Science and Engineering Graduate Fellowship Program[15] awards fellowships to doctoral students in STEM disciplines, and we try to attract these individuals to NRL.

SN: What can you tell us about the hiring process at NRL?

BD: Like many of the defense service laboratories, NRL has direct hire authority; if we find somebody that we want to hire, we can make them an offer without advertising the position. A lot of our hiring is therefore done by word of mouth between hiring managers and people in research divisions who watch graduate students progress in their academic careers and actively recruit them before graduation. However, we're also starting to participate in more virtual job fairs as we come out of the COVID-19 pandemic. Many NRL divisions are actively recruiting now.

[13] https://www.navalsteminterns.us/seap
[14] https://www.smartscholarship.org/smart
[15] https://ndseg.sysplus.com

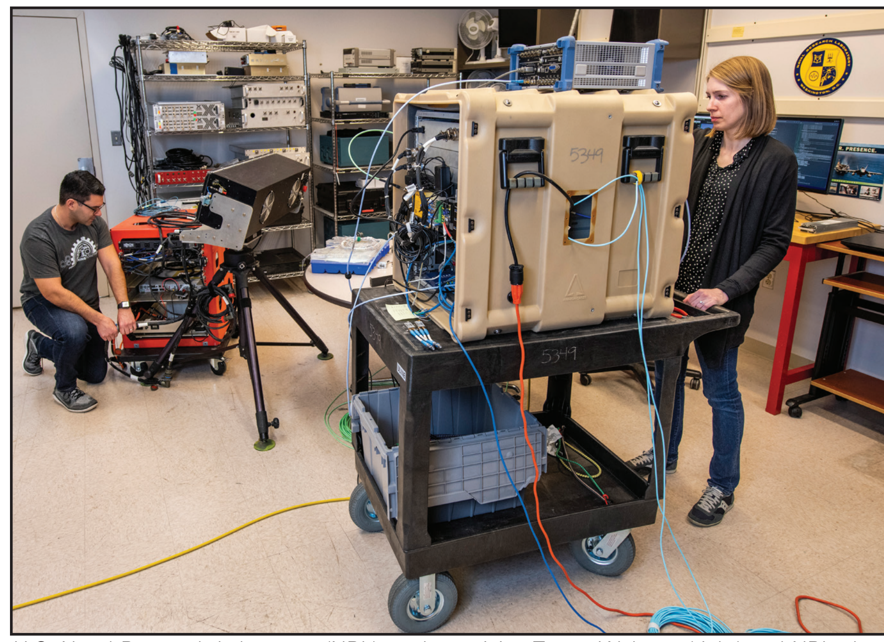
SN: What types of skillsets or particular experiences does NRL look for in prospective employees?

BD: We mainly look for people with master's degrees and Ph.D.s. There is a premium on advanced degrees and innovators who can come up with original solutions for unfamiliar problems. I don't do any of the hiring myself, but those who do—section heads like Dr Webster, branch heads, and even division heads—typically want new hires to fill niche roles in their specific sponsored projects. That being said, NRL is not a place with strict swim lanes. People can change divisions or pursue different directions as long as they are able to find funding for their research and it's germane to something that's relevant to the sponsor.

TW: Specifically in the Radar Division, it's good to have a signal processing background. There's also quite an emphasis on programing, so it really helps to have experience with programming and coding — whether that's Python, MATLAB, or C++. At a minimum, you're going to be doing some type of mathematical modeling.

SN: How can SIAM members get involved with NRL collaborations?

BD: A number of our researchers are already involved in SIAM projects, and Steven Rodriguez of NRL's Material



U.S. Naval Research Laboratory (NRL) mathematician Tegan Webster (right) and NRL electrical engineer Marc Schneider prepare the Multichannel Active Electronically Scanned Array (MAESA) radar testbed for data collection. MAESA handles and visualizes data for research and development in radar technology. U.S. Navy photo courtesy of Sarah Peterson.

Science Division was selected as a 2023 MGB-SIAM Early Career Fellow[16] earlier this year. Anything that SIAM can do to make the existence of NRL known as a good place for mathematicians to work certainly helps, especially since NRL doesn't get an appropriated budget to spend on advertising.

[16] https://sinews.siam.org/Details-Page/siam-announces-the-2023-class-of-mgb-siam-early-career-fellows#Steven

NRL's Technology Transfer Office[17] can establish educational partnership agreements with universities and industry settings, and we have quite a few cooperative research and development agreements with companies and organizations. We also participate in international collaborations through established project agreements with ally countries like the U.K., Australia, Canada, New Zealand, Germany, and Japan. In addition, I serve as the Navy's representative on the Science and Technology board for the North Atlantic Treaty Organization (NATO), and NRL frequently collaborates with NATO nations. We're anything but isolated and we interact with a lot of folks outside of NRL.

SN: What emerging areas of research are a current focus for NRL?

BD: We're not in the business of building quantum computers—we're going to let the commercial world do that—but we are making good use of IBM's existing quantum computers. For the last few years, we've had an agreement with the Air Force Research Laboratory[18] (AFRL) for access to IBM's computers. A previous National Defense Authorization Act and Navy leadership established NRL as the designated quantum center for the Navy, so we recently worked with AFRL, IBM, and the Naval Warfare Centers to come to an agreement that also allows the Naval Warfare Centers to access IBM's quantum computers.[19] We're certainly grateful to AFRL because this agreement is going to expand the capacity for quantum computing research. There's a lot of excitement about quantum computing, which will be very important for certain projects in the future.

SN: Any final thoughts for our readers?

TW: People with a variety of backgrounds can contribute to radar science — you don't necessarily need to have done graduate research in the field. Many individuals with math backgrounds are well suited to the kind of multidisciplinary work that radar research requires.

BD: NRL is a place where careers take all sorts of unique trajectories through different scientific disciplines because no one area of research is likely to yield the fruits of innovation for a person's entire career. People will move from one topic to the next, whether they're physicists or mathematicians or chemists. It's an exciting place to work, and I have certainly enjoyed working here for 27 years and counting.

Lina Sorg is the managing editor of SIAM News.

[17] https://www.nrl.navy.mil/Doing-Business/Technology-Transfer
[18] https://www.afrl.af.mil
[19] https://www.nrl.navy.mil/Media/News/Article/3263682/new-quantum-capabilities-for-naval-warfare-centers

Virginia High School Students Distinguished for Top-notch Model of Electric Biking Habits

2023 MathWorks Math Modeling Challenge Explores Growing Affinity for E-bikes

By Lina Sorg

Despite the rising popularity of electric cars, electric bicycles (e-bikes) are currently the most in-demand electric vehicle on the U.S. market.[1] In fact, the Light Electric Vehicle Association[2] estimated a 70 percent increase in annual U.S. e-bike sales in 2021 — from 463,000 to 790,000 imports.[3] The rising prevalence of e-bikes likely stems from a variety of factors, including affordability; health and environmental benefits; and the chance to avoid the hassle of public transit, parking, and automobile traffic.[4] Many urban businesses have even turned to e-bikes for the delivery of food, groceries, and other merchandise.

"New Yorkers have absolutely embraced e-bikes," Carl Sundstrom, Director of Planning Policy and Innovation at the New York City Department of Transportation (NYC DOT), said. "These devices fit into the city for all the right reasons — they're efficient, small, easy to park, and can carry all sorts of things, from take-out orders and packages to children. NYC DOT is committed to addressing the new opportunities and challenges of the growth of e-bikes by taking their infrastructure and charging needs into account to build a safer, more efficient, and more sustainable city."

[1] https://electrek.co/2022/01/26/electric-bicycles-are-now-outselling-electric-cars-and-plug-in-hybrids-combined-in-the-us
[2] https://levassociation.com
[3] https://electrek.co/2022/07/03/electric-bikes-most-popular-attractive-study
[4] https://www.ebicycles.com/ebike-facts-statistics

Given the recent surge in e-bike popularity and its potential impact on sustainable energy policies, the 2023 MathWorks Math Modeling Challenge[5] (M3 Challenge) focused on the growth of e-bike use. M3 Challenge, a program of SIAM with MathWorks as its title sponsor, is an annual mathematical modeling competition for U.S. high school juniors and seniors and sixth form students in England and Wales. Participating teams of three to five students have 14 consecutive hours to tackle a multifaceted, real-world problem with mathematical modeling techniques and produce a 20-page report that explains and defends their solutions. More than 120 Ph.D.-level applied mathematicians then evaluate all submitted papers during multiple rounds of blind judging and select the top contenders. In late April, the 2023 finalist teams traveled to New York City and presented their solutions to a live panel of judges at Jane Street—a quantitative trading firm—to compete for over $100,000 in scholarship funds.

The 2023 Challenge problem[6] was written by both Chris Musco of New York University—a 2008 M3 Challenge winning alumnus and M3 Challenge Director of Technical Computing Judging—and Neil Nicholson of the University of Notre Dame, with input from the M3 Challenge Problem Development Committee. The three-part question asked students to forecast future e-bike sales, explain the contributing factors, and predict the resulting implications.

[5] https://m3challenge.siam.org
[6] https://m3challenge.siam.org/archives/2023/problem

The 2023 MathWorks Math Modeling Challenge (M3 Challenge) champion team from Thomas Jefferson High School for Science and Technology in Alexandria, Va., received $20,000 in scholarship funds for their first-place models of electric bicycle usage in the U.S. In addition to being named M3 Challenge Champion, the Thomas Jefferson students also earned the runner-up Technical Computing Award and the Outstanding Communication of Results prize, which brought them another $2,500. They presented their winning solution at the M3 Challenge Final Event in New York City on April 24. From left to right: Om Gole, Jerry Sheng, Rishabh Chhabra, Rishabh Prabhu, and Laura Zhang. SIAM photo.

"The Problem Development Committee was interested in learning more about the potential impacts of this technology," Musco said. "There has not been much in-depth analysis of the growth of e-bike usage, its cause, and whether it will continue. The 'unknown' nature of this topic makes e-bikes a strong subject for math modeling and provided an opportunity for students to conduct analysis that was truly new."

The first part of the problem asked teams to create a model that predicts the number of e-bikes that will be sold in 2025 and 2028. They then had to choose one or more factors that might have contributed to recent e-bike popularity—such as environmental awareness, gas prices, personal finance, health and exercise, and/or trendiness—and utilize mathematical modeling to determine whether their selected factors did indeed influence the uptick in e-bike use. Finally, teams quantified the resulting impact of e-bike usage on conditions like carbon emissions, traffic congestion, and general health and wellness.

Members of the first-place team from Thomas Jefferson High School for Science and Technology in Alexandria, Va., were excited by this year's problem topic. "I've used e-bikes before, but I didn't think much of them until I saw their utility through this competition," Rishabh Chhabra said. "When I was younger, one of my neighborhood friends had an electric bike and I got to try it a few times. What I didn't realize, though, is how useful e-bikes can be for long-distance travel or commutes to work." In addition to Chhabra, the Thomas Jefferson team consisted of Om Gole, Rishabh Prabhu, Jerry Sheng, and Laura Zhang.

The group opted for an autoregressive integrated moving average (ARIMA) model to predict the number of U.S. e-bike sales in the next two and five years. "We decided to use an ARIMA model because we wanted to account for the seasonality of monthly e-bike sales, which standard linear and exponential regression don't do," Zhang said. "The ARIMA model is also often used in economics to predict market demand, which fits well with predicting e-bike sales." Since they lacked substantial historic data, the students created an adjustable multiplier for previous years by assuming a ratio between e-bike and plug-in hybrid electric vehicle sales. They then employed a time series to extrapolate monthly e-bike sales from 2018 to 2030. Their model ultimately predicted 1.409 million annual e-bike sales in 2025 and 1.912 million annual e-bike sales in 2028.

Next, the Thomas Jefferson team chose four factors as potential contributors to e-bike popularity: gas prices, median disposable income, transportation distance (measured via monthly vehicle miles), and environmental awareness. The students represented every factor as a time series and relied on the Granger causality test—which measures one time series' ability to predict another—to determine each one's individual significance. "The Granger causality test demonstrates predictive causality and can stagger data to check for delayed effects, which is called lag," Gole said. Using the statsmodels Python library,[7] Gole and his peers executed their model on time series data of monthly e-bikes sales from January 2018 to December 2022. "Our algorithm cleaned the data; ran the Granger causality test; generated F-statistics at lags of one, three, and 12 months; conducted F-tests; and logged p-values," he continued. "It then conducted a significance test on the p-values and highlighted significant results."

The group found that gas prices and environmental awareness can predict a variance in e-bike sales with a one-month lag, meaning that these factors impact sales after only one month. Median disposable income has no substantial influence, and transportation distance can predict variance with a 12-month lag and therefore only impacts e-bikes sales in the long run after one year.

Finally, the students utilized a Markov chain model to quantify the effects of growing e-bike usage on carbon emissions, traffic congestion, and exercise. Specifically, they created a migration matrix to predict the number of people who will use gas cars, electric cars, public transportation, electric bikes, and regular bikes in two and five years. "The standard way of modeling changes in population distribution is via a Markov chain analysis, which primarily consists of matrix algebra," Prabhu said. "Therefore, it made sense to have a matrix method that calculates the impact score, which we implemented by creating a relative effect weighting matrix with relative values to show the impact of a transport mode on each factor." The team determined that carbon emissions will decrease by 3.85 percent in two years and 9.52 percent in five years, traffic congestion will decrease by 0.64 percent in two years and 1.60 percent in five years, and exercise will increase by 0.09 percent in two years and 1.60 percent in five years.

See **Electric Biking** *on page 11*

[7] https://www.statsmodels.org/stable/index.html

COMSATS University Islamabad SIAM Student Chapter Celebrates International Day of Mathematics

By Nimra Yousaf

According to Albert Einstein, "As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality." To celebrate the delight and beauty of math, the COMSATS University Islamabad (CUI) SIAM Student Chapter organized an event in honor of the International Day of Mathematics[1] on March 14, 2023 (Pi Day).

The chapter prepared a variety of activities that included a scavenger hunt, "meme war," and mathematical modeling contest. The scavenger hunt took place before the official start of the event and attracted nearly 20 participants who explored numbers, patterns, and puzzles while sharpening their problem-solving skills and embracing the joy of math. A series of clues led students through the steps of an exciting treasure hunt. The winning group—who called themselves "The Calculators"—consisted of Nimra Yousaf, Amama Fatima, Noor Fatima, and Areeba Salahuddin.

For the meme war, students created math-based memes ahead of the celebration that were then shared via the CUI SIAM Student Chapter's official Instagram page. Followers voted on their favorite posts the day before the event, and Zubair Ahmed—a third-year undergraduate student—won the competition with the most popular meme.

The daylong celebration occurred in the basement of CUI's Junaid Zaidi Library. Yousaf (head of the chapter's content team) and Mohsin Aziz (a chapter volunteer) introduced the International Day of Mathematics, after which Mujtaba Habib (the chapter's vice president) led the recitation of the Holy Quran.

Once the chapter shared the collection of mathematical memes from the previous day, members acknowledged Abdullah Shah — an associate professor at CUI and founder and faculty advisor of the CUI SIAM Student Chapter. He worked hard to establish the first SIAM student chapter in Pakistan and continued to perfect the group after its inauguration in December 2021.

Following a series of pattern-based riddles and puzzles, the mathematical modeling contest commenced. The competition recognized modeling as a powerful tool that helps scientists understand, predict, and optimize complex systems. During the contest, competitors explained difficult problems with societal impacts to the audience in an understandable manner. Fourth-year student Fatima Sehar won the challenge with her excellent commentary.

Volunteers, hosts, speakers, and participants of the COMSATS University Islamabad (CUI) SIAM Student Chapter's International Day of Mathematics celebration pose in front of the Junaid Zaidi Library. Photo courtesy of Mohsin Aziz.

The event's main lecturer was Salman Amin, an assistant professor at CUI, who detailed the importance of mathematics in everyday life and explained the need to celebrate this subject — both during the International Day of Mathematics as well as all year round. Next, CUI assistant professor Zaigham Zia took the stage. He discussed mathematics' many applications to important real-world problems and motivated the students to continue bringing new formulas and ideas to the field.

After Zia's talk, Sohail Iqbal—an assistant professor at CUI who also helped to establish the CUI SIAM Student Chapter—spoke to the crowd. He praised the CUI students' efforts to organize and execute the special celebration in honor of the International Day of Mathematics and wished everyone a "Happy Pi Day." The chapter is extremely grateful for his guidance and assistance during the planning processes for all activities.

Amin, Zia, and Iqbal concluded the gathering with an awards ceremony during which they distributed certificates and prize money to the winners of the scavenger hunt, meme war, and modeling contest. Overall, the event was a fun and successful day for all attendees. The CUI SIAM Student Chapter is incredibly lucky to receive continuous support from CUI faculty. We aim to provide an open platform for students to network and share ideas, and intend to hold more such events in the future.

Nimra Yousaf is a B.S. student of mathematics at COMSATS University Islamabad (CUI) and the content team head for the CUI SIAM Student Chapter.

1 https://www.idm314.org

Attendees and speakers of the COMSATS University Islamabad (CUI) SIAM Student Chapter's recent celebration in honor of the International Day of Mathematics partake in the festivities. From left to right: Zaigham Zia, Salman Amin (the main lecturer for the event), Sohail Iqbal, and Mansoor Shaukat. Photo courtesy of Musharraf.

Take Advantage of SIAM's Visiting Lecturer Program

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

The SIAM Education Committee[1] sponsors the VLP and recognizes the need for all members of our increasingly technological society to familiarize themselves with the achievements and potential of mathematics and computational science. We are grateful to the accomplished individuals who have graciously volunteered to serve as visiting lecturers.

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

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

An Introduction to Game Theory with Engineering Applications

By Dario Bauso

Dario Bauso's Game Theory with Engineering Applications[1] was published by SIAM in 2016. The text describes the foundations of game theory and is intended for both undergraduate and graduate students, industry researchers, and even social scientists, biologists, and physicists. More specifically, it explores the physical intuition of game theory, analyzes design techniques, and addresses emerging cooperation and competition trends in complex distributed systems.

The following excerpt introduces the book and is adapted from the Preface. It has been abridged and edited for clarity.

In the field of systems and control, a key research direction involves *engineering systems*: highly distributed collective systems with humans in the loop. In this context, *highly distributed* indicates that decisions, information, and objectives are distributed throughout the system, and *humans in the loop* implies that the players have bounded rationality and limited computation capabilities. Societal and cultural habits may also influence decisions.

I chose to write *Game Theory with Engineering Applications* because the use of *game theory* within the realm of engineering systems contributes to the design of incentives that obtain socially desirable behaviors from the players. In *demand-side management*, for example, an increase in electricity price may induce a change in prosumer consumption patterns. In *opinion dynamics*, marketing campaigns can influence the market share if we assume that the customers are susceptible players with the same opinions as their neighbors. And in *pedestrian flow*, informing pedestrians of congestion at different locations might redistribute traffic more effectively.

Game theory offers a rich set of model elements, solution concepts, and evolutionary notions for these and other problems. The model elements are the players, action sets, and payoffs; solution concepts include the Nash equilibrium, Stackelberg equilibrium, Pareto optimality, and social optimality. Figure 1 provides a nice summary of the tension that arises in a noncooperative game between two players.

Evolutionary notions demonstrate that equilibria are relevant only if the players can converge to such solutions in a dynamic setting, essentially transforming the game into a kind of dynamic feedback system. But game theory models are *more* than just dynamic feedback systems; each player learns the environment, which in turn learns the player, and so forth. This coupled learning style introduces a higher level of difficulty to the feedback structure.

Much of the book focuses on *games with a large number of players*. In such scenarios, each player uses an aggregate description of the environment that is based on a distribution function for actions or states — which is the main concept in a *mean field game*. If a game consists of a mapping from congestion levels to payoffs, the evolution model is thus a dynamic model that operates in the opposite direction; it maps flows of payoffs to flows of congestion levels. Here, systems and control theory provide a set of sophisticated stabilizability tools for the design of self-organizing and resilient systems that are characterized by cooperation and competition.

FROM THE SIAM BOOKSHELF

Goals of the Book

Game Theory with Engineering Applications aims to integrate game theory with systems and control theory under the unconventional framework of engineering systems. Part I addresses the foundations of the theory of noncooperative and cooperative games—both static and dynamic—while also highlighting new trends in cooperative differential games, learning, approachability (games with vector payoffs), and mean field games (games with many homogeneous players).

Part II seeks to illustrate stylized models of engineered and societal situations. These models deliver fundamental insights into several areas, including individual strategic behaviors, scalability and stability of collective behavior, and the influence of heterogeneity and local interactions. The text also discusses uncertainty and model misspecification, with an emphasis on grand engineering challenges like *resilience* and *big data*.

Structure of the Book

Part I of *Game Theory with Engineering Applications* comprises 12 chapters. Chapters 1 through 4 review the foundations of noncooperative games, chapters 5 and 6 deal with cooperative games, chapter 7 surveys evolutionary games, chapter 8 analyzes the replicator dynamics and succinctly overviews learning in games, chapter 9 handles differential games, and chapter 10 tackles stochastic games. Chapter 11 then pinpoints basic ideas and trends in games with vector payoffs, such as *approachability* and *attainability*, and chapter 12 provides a synopsis of mean field games.

Part II builds upon some of my previous journal articles and contains the remaining content, from chapters 13 to 21. In particular, chapters 14 and 15 both fall under the umbrella of power systems and respectively analyze demand-side management and the synchronization of power generators. Within the realm of socio-physical systems, chapter 13 discusses consensus in multi-agent systems and chapters 16 through 18 illustrate opinion dynamics, bargaining, and pedestrian flow applications. In the context of production/distribution systems, chapters 19 to 21 address supply chains, populations of producers, and cyber-physical systems.

Audience and Coursework

The primary audience for this text comprises students, practitioners, and researchers in different areas of engineering, including industrial, aeronautical, manufacturing, civil, mechanical, and electrical engineering. The topic may also interest scholars in fields like computer science, economics, physics, and biology. Young researchers may especially benefit from reading Part II, and the comprehensive reference list at the end enables further study. The book thus provides a short pathway that allows undergraduate students to become emerging researchers.

In addition, *Game Theory with Engineering Applications* is also suitable as a textbook. For instance, Part I covers information that is appropriate for a first-year graduate class; in fact, it assembles materials from three 2013 graduate courses at the University of Trento, University of Oxford, and Imperial College London. Its tutorial style illustrates the major points in a manner that helps readers quickly grasp the key components of each concept.

Furthermore, an appendix section that covers mathematical review, optimization, Lyapunov stability, the basics of probability theory, and stochastic stability theory contributes to the text's suitability in an undergraduate course. Part II even incorporates a number of simulation algorithms and numerical examples in MATLAB that may improve younger students' coding skills.

Enjoy this passage? Visit the SIAM Bookstore[2] to learn more about Game Theory with Engineering Applications[3] and browse other SIAM titles.

Dario Bauso is a full professor and Chair of Operations Research for Engineering Systems at the University of Groningen in the Netherlands, where he has been a science and engineering faculty member with the Jan C. Willems Center for Systems and Control and the Engineering and Technology Institute Groningen since 2018. Bauso has also been part of the Dipartimento di Ingegneria at the University of Palermo since 2005. His research interests are in optimization, optimal and distributed control, and game theory.

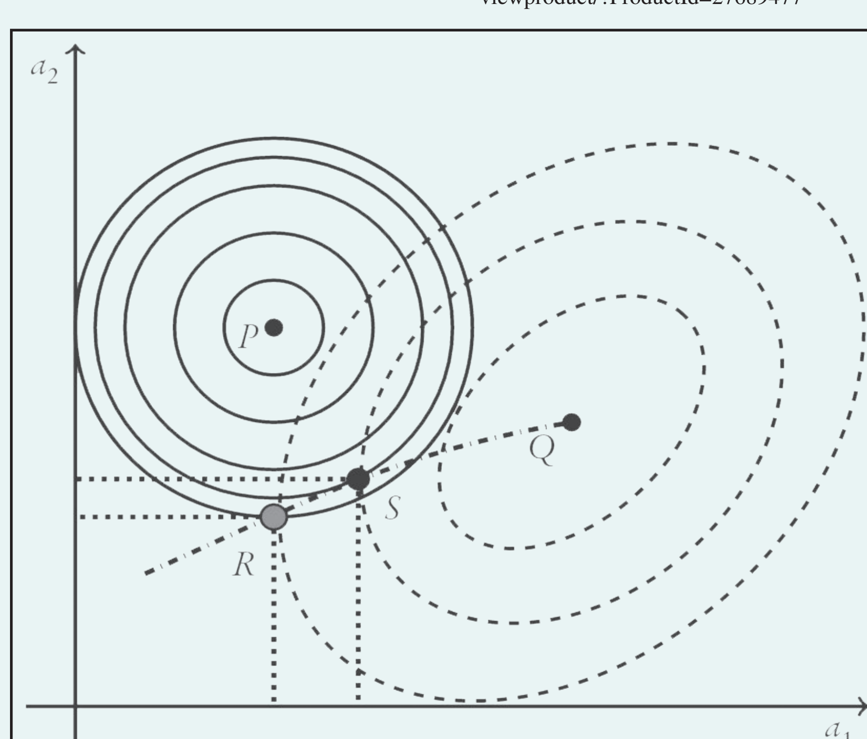


Figure 1. *Noncooperative game between two players. The horizontal axis represents the action set for player 1 and the vertical axis represents the action set for player 2. The plot illustrates the level curves for both player 1 (solid) and player 2 (dashed). The optimum for player 1 is P and the optimum for player 2 is Q. If they play simultaneously, the best outcome that they can obtain is R (the Nash equilibrium). But if player 1 is the leader and player 2 is the follower, they converge to S (the Stackelberg equilibrium). Figure courtesy of Game Theory with Engineering Applications and reprinted with permission from Springer Science+Business Media.*

1 https://my.siam.org/Store/Product/viewproduct/?ProductId=27689477

2 https://my.siam.org/Store

3 https://my.siam.org/Store/Product/viewproduct/?ProductId=27689477

Electric Biking

Continued from page 8

The Thomas Jefferson team, which was coached by mathematics and computer science teacher Quinn McFee, took home $20,000 in scholarship money for their first-place solution paper. They also received one of three Technical Computing Awards for their impressive use of coding and programming, as well as the Outstanding Communication of Results prize for their extraordinary presentation; these two additional accolades collectively earned them an extra $2,500.

2023 marks only the second time that Thomas Jefferson students have participated in M3 Challenge in the recent past; last year, the school received an Honorable Mention after Sheng—an officer of the Math Modeling Club—encouraged his fellow club members to participate. The group then spent the next year preparing for the 2023 Challenge by practicing outside of the classroom and reviewing the winning papers of previous competitors.

"While math education demonstrates many different approaches to the same solution, using math to understand an imperfect or incomplete system engages a very different kind of critical thinking," McFee said. "Students not only had to apply what they know about statistics and programming, but also account for authentic constraints such as lack of data, make predictions with incomplete information, and develop a robust but accessible argument to answer a question that can only be validated by other researchers and time. It is difficult to recreate this experience in the classroom; in that regard, the contest is a meaningful learning experience for aspiring mathematicians."

This is precisely the goal of M3 Challenge, which is now in its 18th year. The Challenge has grown significantly since its first iteration in 2006, which was only open to students in the New York City metro area. 129 teams submitted viable solutions during that initial year; in contrast, 650 teams participated in 2023. Michelle Montgomery—who helped to develop the contest—has served as the competition's leader and organizer since its onset. She is retiring from her current role as M3 Project Director and was honored during the 2023 Final Event in New York City.

"M3 Challenge is special for so many reasons, and working on this program feels more like a really fun hobby than a job sometimes," Montgomery said. "It is so gratifying to facilitate all of these transformational moving parts. The math modeling process is a fun and interesting team-based activity that can lead to amazing careers doing meaningful things. The teams intermingle and exchange contact information at the Final Event, and I often think that these are some of tomorrow's world changers — there's no doubt about it."

The 2023 MathWorks Math Modeling Challenge (M3 Challenge) champion team from Thomas Jefferson High School for Science and Technology in Alexandria, Va., presents their winning models of electric bicycle use in the U.S. to a panel of judges at the M3 Challenge Final Event, which took place in New York City on April 24. From left to right: Rishabh Prabhu, Rishabh Chhabra, Jerry Sheng, and Laura Zhang. SIAM photo.

Prabhu, who intends to pursue a career in applied mathematics, acknowledged that M3 Challenge has helped to shape his long-term plans and overall perspective of mathematical modeling. "Applied mathematics is used in almost every computational analysis that runs the modern world," he said. "It is an incredibly crucial and fundamental skill for numerous professions, but the core mathematical models that serve as the foundations for many machine learning and data science algorithms are not understood by most of their beneficiaries. I want to create and improve these fundamental models, as they can have profound impacts on various fields that use applied mathematics."

As the Thomas Jefferson students look toward the future, they expressed gratitude for M3 Challenge and encouraged future competitors to embrace creativity, experiment with new techniques, and participate in the Challenge — even if they are not familiar with mathematical modeling. "Before this year, I had no experience with modeling," Zhang said. "This was the first time that I experienced the power of math in real-world situations. My biggest takeaway from M3 Challenge is that math is everywhere and can be used to model actual phenomena. I now have a much better grasp of different mathematical models and the situations in which to use each of them."

Thomas Jefferson High School for Science and Technology's winning solution paper[8] *is available online, as is their final presentation.*[9]

Lina Sorg is the managing editor of SIAM News.

[8] https://m3challenge.siam.org/sites/default/files/uploads/CHAMPION%2BTC%20RUNNER-UP_16401.pdf

[9] https://www.youtube.com/watch?v=0krGJ259qN8

University of Strathclyde SIAM-IMA Student Chapter Celebrates International Day of Women and Girls in Science

By Sophie McLauchlan

The University of Strathclyde SIAM-IMA Student Chapter[1] recently sponsored an event to mark the International Day of Women and Girls in Science,[2] which was observed by the United Nations on February 11, 2023. The Strathclyde session took place in the Department of Mathematics and Statistics on February 15 and comprised four talks by women from the department at various stages of their careers, followed by networking time for attendees. The event was open to everyone regardless of gender or experience level, and participants ranged from undergraduates to senior academics.

The organizers sought to celebrate female mathematicians, inspire the audience, and encourage early-career researchers with success stories from the profession. The four speakers included senior academics Alison Ramage and Apala Majumdar, postdoctoral research associate Hannah-May D'Ambrosio, and Ph.D. student Noura Alshammari. These women discussed their motivations for working in science, described their respective career paths and typical days in the workforce, and introduced their research. Each talk provided a unique perspective due to the individuals' personal experiences.

Ramage opened the event by reflecting upon her younger self at various points throughout her life. She spoke about her mindset and outlook as a high school student, an undergraduate, and a Ph.D. student, and explained how various decisions and opportunities led to her current position. Next, Majumdar commented on the driving factors of her career. She expressed her longstanding appreciation for science and proudly acknowledged the thriving group of researchers that she leads and supports at the university.

Apala Majumdar discussed her career motivations and overviewed her research with liquid crystals during the University of Strathclyde SIAM-IMA Student Chapter's event to mark the International Day of Women and Girls in Science, which took place in February 2023. Photo courtesy of Sophie McLauchlan.

During the University of Strathclyde SIAM-IMA Student Chapter's event to celebrate the 2023 International Day of Women and Girls in Science on February 15, Alison Ramage reflected upon her educational pathway and spoke about the factors that led to her current position at Strathclyde. Photo courtesy of Sophie McLauchlan.

D'Ambrosio, who recently earned her Ph.D., offered a different viewpoint. First, she talked about the new responsibilities that are associated with her role as a postdoctoral researcher versus a Ph.D. student. D'Ambrosio then reassured listeners that they do not have to compromise or delay other life events as Ph.D. students or early-career researchers, and used her own trajectory as proof that it is entirely possible to get married and start a family in the initial stages of an academic career.

Alshammari rounded out the presentations by noting that a career in science or mathematics was seemingly inevitable for her, given her technological curiosity and affinity for logical thinking even as a young child. She shared aspects of the journey to her current position as a Ph.D. student, which included periods of work to save money for the next qualification. Alshammari's infectious enthusiasm and commitment to obtaining a Ph.D. in mathematics was palpable.

Listening to the candor, sincerity, and excitement of the speakers was truly a privilege. Their talks celebrated women in science and inspired audience members at all stages of their careers.

The University of Strathclyde SIAM-IMA Student Chapter is led by students Sophie McLauchlan, Ibrahim Mohammed, Tasnia Shahid, and Minhui Zhou, with support from academic mentor Jennifer Pestana.

Sophie McLauchlan is a Ph.D. student in applied mathematics at the University of Strathclyde. She is president of the University of Strathclyde SIAM-IMA Student Chapter.

[1] https://siamimastrathclydesc.wixsite.com/mysite

[2] https://www.un.org/en/observances/women-and-girls-in-science-day

George Washington University SIAM Student Chapter Hosts Conference on Applied Mathematics

By Wangbo Luo, Conglong Xu, Yaqi Wu, Yanfang Liu, and Yanxiang Zhao

The George Washington University (GW) SIAM Student Chapter[1] hosted its Spring 2023 Conference on Applied Mathematics[2] on April 8. The conference united researchers from multiple universities in the Washington, D.C., area to present their work in applied and computational mathematics.

The GW SIAM Student Chapter was founded in 2014 to promote applied math and computational science at GW. The chapter sponsors a variety of talks, conferences, and social opportunities throughout the school year. The Conference on Applied Mathematics was previously an annual event for the GW SIAM Student Chapter, with three consecutive gatherings in 2017, 2018, and 2019. Although the COVID-19 pandemic unfortunately interrupted the conference's regularity, the chapter reinstated the meeting in 2023. We hope to continue the tradition and once again restore it as a yearly event in the future.

The 2023 conference drew a diverse crowd of approximately 30 individuals, including professors, postdoctoral researchers, graduate students, and undergraduates from institutions in the greater D.C. metro area. Attendees had the chance to learn about a wide range of topics in applied mathematics and connect and network with their contemporaries in the field.

The conference featured seven invited speakers (one professor, three postdocs, and three graduate students) from four different universities. Topics ranged from geometric analysis and inverse problems to computational methods in imaging science and large deviation theory in stochastic partial differential equations. The following is a list of speakers and the titles of their respective presentations:

- Chong Wang (Washington and Lee University): "Periodic Minimizer of a Ternary Nonlocal Isoperimetric Problem"
- Yanfang Liu (GW): "Deterministic-statistical Approach for an Inverse Acoustic Source Problem Using Multiple Frequency Limited Aperture Data"
- Madhu Gupta (George Mason University): "Nonlinear Reconstruction of Optical Parameters in Photoacoustic Tomography"
- Guillaume Bonnet (University of Maryland, College Park): "Virtual Element Method for Nondivergence Form Elliptic Equations"
- Mengzi Xie (University of Maryland, College Park): "The Smoluchowski-Kramers Approximation of Nonlinear Wave Equations with Variable Friction"
- Shuo Yan (University of Maryland, College Park): "Random Perturbations of Hamiltonian Systems"
- David Sayre (George Mason University): "An Optimal Control Framework for Neuromorphic Imaging."

The engaging talks exposed attendees to cutting-edge research in a variety of areas within applied mathematics. Each talk lasted 25 minutes and was followed by a brief question-and-answer session that allowed the audience to converse with the speakers and pose additional inquiries about their work. "I was excited to have the opportunity to participate in this event and meet young researchers with diverse backgrounds," Yi Nie of GW's Department of Statistics said. "I learned a lot from the talks and will definitely attend the conference next year."

Attendees of the George Washington University (GW) SIAM Student Chapter's Spring 2023 Conference on Applied Mathematics, which took place on April 8, pose together on the GW campus. Photo courtesy of Conglong Xu.

The GW SIAM Student Chapter would like to thank SIAM and the Department of Mathematics at GW for their financial support. We look forward to hosting students from across the region again in 2024.

Wangbo Luo is a Ph.D. student in the Department of Mathematics at George Washington University (GW). He is the president of the GW SIAM Student Chapter. Conglong Xu and Yaqi Wu are Ph.D. students in the GW Department of Mathematics who serve as vice presidents of the GW SIAM Student Chapter. Yanfang Liu is a visiting assistant professor in the GW Department of Mathematics who serves as the co-faculty advisor of the GW SIAM Student Chapter. Yanxiang Zhao is an associate professor of mathematics at GW. He is the founding faculty advisor of the GW SIAM Student Chapter.

[1] https://blogs.gwu.edu/gwsiam/main-2

[2] https://blogs.gwu.edu/gwsiam