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Scientific Uses of Automatic Differentiation

By Michael P. Brenner and Ella M. King

Recent progress in machine learning (ML) technology has been nothing short of spectacular. The last two years alone have seen remarkable technological advances, including models that can win art competitions by generating images from text and chatbots with near human-level proficiency. At the heart of these advances is the ability to obtain high-quality solutions to non-convex optimization problems for functions with billions—or even hundreds of billions—of parameters. Many deep and surprising mathematical questions have emerged as part of this work. Among other topics, these queries pertain to the success of overparameterized models, the relative importance of local minima in the loss landscape, and the underlying theoretical basis for empirically determined optimizers. A fundamental theory is still missing, so we will no doubt be grappling with these questions for many years.

Nevertheless, the technological developments that have enabled ML advances also present an incredible opportunity for progress in *classical* applied mathematics problems. In particular, the increased proficiency for systematically handling large, non-convex optimization scenarios may help solve some classical problems that have long been a challenge. We now have the chance to make substantial headway on questions that have not yet been formulated or studied because we lacked the tools to solve them. To be clear, we do not wish to oversell the state of the art; algorithms that identify the global optimum for non-convex optimization problems do not yet exist. The ML community has instead developed efficient software tools that find *candidate* solutions, created benchmarks to measure solution quality, and cultivated a culture of competition against these benchmarks.

Adoption of this methodology may transform exciting novel insights into important classical problems. Here, we illustrate several new opportunities that exist because of the widespread, open-source deployment of effective software tools for automatic differentiation. While the mathematical framework for automatic differentiation was established long ago [4]—dating back at least to the evolution of adjoint-based optimization in optimal control [2, 6]—ML researchers have recently designed efficient software frameworks that natively run on hardware accelerators. These frameworks have served as a core technology for the ML revolution over the last decade and inspired high-quality software libraries such

See **Automatic Differentiation** *on page 3*

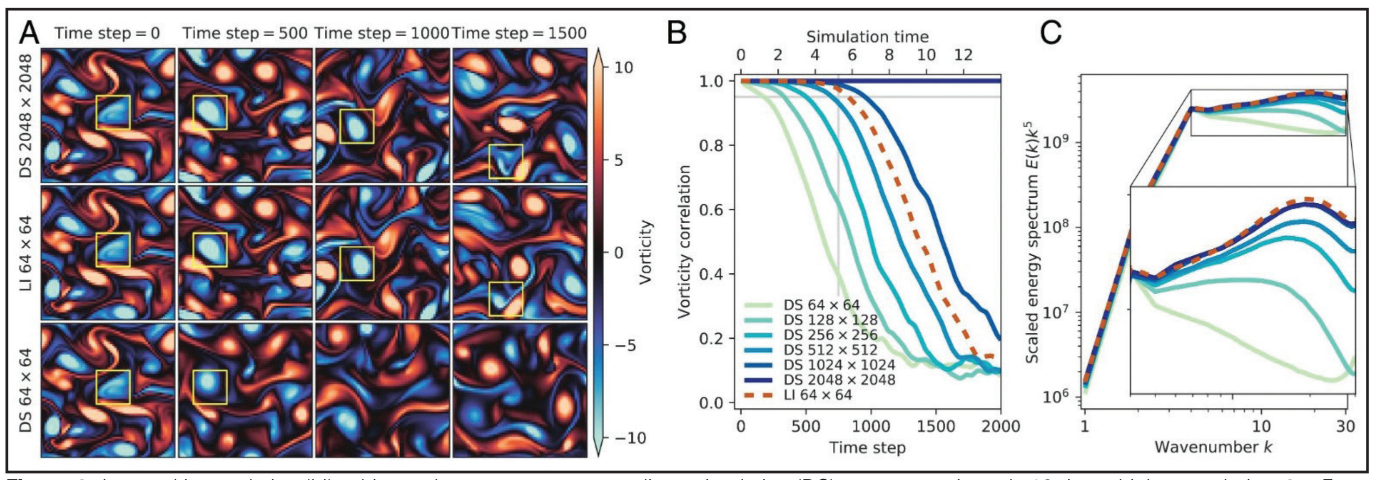

Figure 1. *Learned interpolation (LI) achieves the same accuracy as direct simulation (DS) at an approximately 10 times higher resolution.* **1a.** *From top to bottom row: Evolution of predicted vorticity fields for reference (DS 2,048 × 2,048), learned (LI 64 × 64), and baseline (DS 64 × 64) solvers that start from the same initial velocities. The yellow box in each square traces the evolution of a single vortex.* **1b.** *Comparison of the vorticity correlation between predicted flows, the reference solution for our model, and direct numerical simulation solvers.* **1c.** *Energy spectrum scaled by k^5 and averaged between time steps 10,000 and 20,000, at which point all solutions have decorrelated with the reference solution. Figure courtesy of [5].*

The Argument for Mandatory Vaccinations: A Game Theory Approach to Mpox

By Lakshmi Chandrasekaran

As the world began to cautiously emerge from the ravages of COVID-19 in early 2022, a new global outbreak arose: monkeypox/mpox,[1] a viral infectious zoonotic disease. According to the World Health Organization (WHO),[2] the virus has spread to 110 countries thus far. WHO also reported[3] that smallpox vaccines are roughly 85 percent effective in preventing mpox. Nevertheless, public health experts still debate a central question: Should public policy mandate vaccinations to prevent the spread of mpox, or should the decision to vaccinate be left to the individual? A group of undergraduate researchers at Virginia Commonwealth University—led by Jan Rychtář and Dewey Taylor—explored this question with mathematical modeling and game theory [1].

Endemic to Central and West Africa, mpox is classified as one of the neglected tropical diseases[4] that primarily impact impoverished communities. The virus, which can have especially serious consequences for expectant mothers, may cause physical impairments and limit productivity. "While these diseases don't have high death tolls, they are neglected in the true meaning of the word," Rychtář said. He contrasted mpox with the fact that scientists developed the first mathematical model of malaria more than 100 years ago; nowadays, hundreds of models for malaria exist. "Our 2020 paper on monkeypox prevention [3] was one of the first mathematical studies of that disease," Rychtář continued. "Only due to the current threat of spread in Europe and the U.S. is there now an uptick in monkeypox modeling efforts."

Rychtář and his colleagues approached this problem with an unconventional tactic; they utilized a game theoretical perspective to understand vaccination strategies in the context of human behavior. This method begins with the susceptible-vaccinated-exposed-infected-recovered (SVEIR) compartmental model of mpox [6], given by

$$\frac{dS}{dt}=\Lambda-\left(\psi+\mu+\beta\frac{I}{N}\right)S, \tag{1}$$

$$\frac{dV}{dt}=\psi S-\left(\mu+(1-e)\beta\frac{I}{N}\right)V, \tag{2}$$

$$\frac{dE}{dt}=\left(\beta\frac{S}{N}+(1-e)\beta\frac{V}{N}\right)I-(\mu+\sigma)E, \tag{3}$$

$$\frac{dI}{dt}=\sigma E-(\mu+\gamma)I, \tag{4}$$

$$\frac{dR}{dt}=\gamma I-\mu R. \tag{5}$$

Here, Λ is the natural birth rate and μ is the rate of death due to natural causes. Without vaccination, a susceptible individual becomes exposed after contact with an infectious person at rate $\beta\frac{I}{N}$, where β is the transmission rate and $N=\Lambda/\mu$ is the population size. Susceptible individuals are vaccinated at rate ψ with a vaccine efficacy of e. Equations (3) and (4) capture the dynamics of exposed and infected states, and the infectious and incubation periods in equation (5) are respectively given by $\frac{1}{\gamma}$ and $\frac{1}{\sigma}$.

The disease-free equilibrium is represented by $\varepsilon^0=(S^0,V^0,E^0,I^0,R^0)$, where

$$S^0=N\frac{\mu}{\mu+\psi} \quad \text{and} \quad V^0=N\frac{\psi}{\mu+\psi}.$$

The basic reproduction number (R_0) is the number of secondary infections that stem from a single infected individual in an otherwise healthy, unvaccinated population:

$$R_0=\frac{\sigma\beta}{(\sigma+\mu)(\gamma+\mu)}. \tag{6}$$

The researchers extended this SVEIR model by applying a game theoretical framework for a *vaccination game*, wherein

See **Mpox** *on page 4*

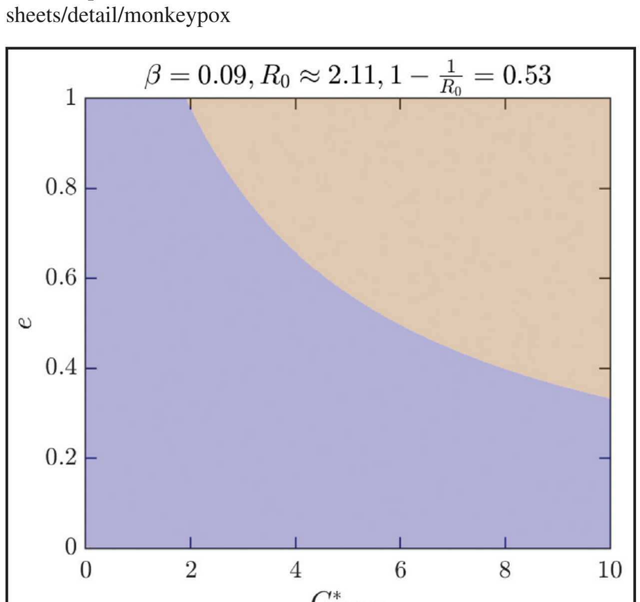

Figure 1. *Nash equilibria (NEs) as e and C^*_{MPX} vary. In the blue region, 0 is the only NE and it is a convergent stable NE (CSNE). In the brown region, positive ψ_{NE} is the only NE and is also a CSNE. Figure courtesy of [1].*

[1] https://www.who.int/news/item/28-11-2022-who-recommends-new-name-for-monkeypox-disease
[2] https://worldhealthorg.shinyapps.io/mpx_global
[3] https://www.who.int/news-room/fact-sheets/detail/monkeypox
[4] https://www.who.int/health-topics/neglected-tropical-diseases

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Introducing the New SIAM Activity Group on Equity, Diversity, and Inclusion

By Tamara Kolda

The SIAM Council and Board of Trustees recently approved the formation of the SIAM Activity Group on Equity, Diversity, and Inclusion[1] (SIAG/EDI). This new SIAG has two complementary objectives:

1. Advocacy and support for EDI in the field of applied mathematics
2. Discussion and dissemination of best practices that will create and sustain equitable, diverse, and inclusive environments in applied mathematics.

SIAG/EDI has taken shape over the course of several years due to the efforts of many supporters, including more than 200 individuals in the SIAM community who pledged to become founding members. The group is open to all members of SIAM, and we do not expect participants to have extensive experience or expertise with EDI issues. Rather, SIAG/EDI is a forum and space for SIAM members to learn about and become familiar with this important topic.

We note that the term "applied mathematics" in the SIAG's objectives is intended to broadly encompass the full range of topics and research areas that SIAM promotes, including industrial, scientific, and medical applications as well as cross-disciplinary intersections with computer science, statistics, engineering, the life sciences, data science, financial mathematics, and so forth.

Complementary Themes of SIAG/EDI

Our first objective of *advocacy and support for EDI* includes the organization of activities that endorse the research and careers of historically underrepresented groups within the broad applied mathematics community. We hope to continue to provide an umbrella for the multiple relevant activities that SIAM already maintains. We also aim to incorporate additional activities—such as EDI-focused panel discussions[2] and special programming like the Hidden Figures events[3] at the 2017 and 2018 SIAM Annual Meetings—and interface with the Association for Women in Mathematics, Society for the Advancement of Chicanos/Hispanics and Native Americans in Science, National Association of Mathematicians, and other similar organizations.

Our second objective—*discussion and dissemination of best practices*—involves the development and sharing of resources that will help the community understand barriers to participation in the field, create and sustain diversity and inclusivity in research groups, and foster best hiring practices. These pragmatic tools will target various career stages and include resources to help applicants prepare the EDI statements that are required for some academic positions. SIAG/EDI will focus on career development issues that are increasingly important in the field and assist the broader membership with the cultivation of equitable, diverse, and inclusive environments.

Group Activities

SIAG/EDI activities will be driven by members of the expansive SIAM community, ranging from senior leaders (who are seeking to find and share information on efforts to actively foster EDI within institutions) to newly minted principal investigators (who are building their research groups). Membership will comprise students who are just beginning their journeys in the field and are searching for supportive environments for their career development, as well as more senior persons who can provide such support. We welcome SIAM members at every career stage to join SIAG/EDI.

The SIAG will host gatherings either at the SIAM Annual Meeting or as virtual events, including the SIAG/EDI Business Meeting. SIAG/EDI also looks forward to working with the Diversity Advisory Committee[4] (DAC) on activities such as the long-running Workshop Celebrating Diversity (WCD), which is funded by the National Science Foundation. Furthermore, we plan to implement and host many more activities in the context of SIAG/EDI themes. The following list presents some proposed examples of these ventures:

- Sponsoring special panels and minisymposium sessions at SIAM conferences
- Interfacing with and supporting the EDI activities of other SIAGs
- Hosting online seminars that support the goals of SIAG/EDI
- Generating a website with useful resources for members
- Building cohorts around EDI best practices in various contexts (e.g., job seeking, recruiting, and hiring; leading a research group; writing a diversity statement; and furthering international perspectives)
- Developing mentoring programs, including peer-to-peer programs
- Sponsoring book clubs
- *You tell us!*

We will soon be sending a poll to SIAG/EDI members to solicit ideas for activities.

Relationship to SIAM Leadership and Committees

The DAC and Vice President for Equity, Diversity, and Inclusion (VP for EDI) are appointed positions that directly advise SIAM leadership on EDI matters. In the 1990s, SIAM established the DAC to help address policy issues that arise in relation to underrepresented groups. The committee has three main responsibilities: (i) Overseeing the organization of the WCD; (ii) informing the SIAM Council of opportunities to promote diversity within the SIAM community; and (iii) consulting on diversity issues that come to SIAM's attention through its membership or sponsored activities, such as the collection or management of data that pertains to questions of diversity. The DAC consists of the chair and up to 12 members, including the VP for EDI. Like most SIAM committees, DAC members are appointed by the SIAM President in consultation with the SIAM Secretary and the Committee on Committees and Appointments.[5]

In 2021, SIAM welcomed Ron Buckmire as its first VP for EDI.[6] The VP is an appointed voting member of the SIAM Council who is involved in the development of SIAM programs and policies that promote EDI, both inside SIAM and within the larger mathematics community.

While the DAC and VP for EDI are appointed positions with important advisory roles, SIAG/EDI is open to everyone in the SIAM community and its leadership is elected by the SIAG members themselves. The group will not directly advise SIAM or any institution *per se*; instead, it will develop its own member-driven activities that support EDI and the needs of the applied mathematics field. SIAG/EDI will also coordinate closely with the DAC and VP for EDI on events such as the annual WCD and other future programs.

The initial slate of officers for SIAG/EDI is as follows:

- Chair: Tamara Kolda (MathSci.ai)
- Vice Chair: Juan M. Restrepo (Oak Ridge National Laboratory)
- Program Director: Suzanne Sindi (University of California, Merced)
- Secretary: Carola-Bibiane Schönlieb (University of Cambridge).

Get Involved with SIAG/EDI

SIAM members with a passion for EDI are invited to join SIAG/EDI! Interested persons can register for the group when renewing their SIAM membership this fall, or at any time by going to **my.siam.org**. Learn more about SIAG/EDI by visiting the website.[7]

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Tamara Kolda is a consultant under the auspices of her California-based company, MathSci.ai. She previously worked at Sandia National Laboratories. Kolda specializes in mathematical algorithms and computational methods for data science, especially tensor decompositions and randomized algorithms. She is a SIAM Fellow, a Fellow of the Association for Computing Machinery, and a member of the National Academy of Engineering. She co-founded and is editor-in-chief of the SIAM Journal on Mathematics of Data Science and is active within SIAM, having previously served three terms on the SIAM Board of Trustees and as an officer for both the SIAM Activity Group (SIAG) on Computational Science and Engineering and the SIAG on Linear Algebra.

[1] https://www.siam.org/membership/activity-groups/detail/equity-diversity-and-inclusion

[2] See page 9 of this issue for an article that recaps the recent "Diversity Retention and Mentoring" panel at the 2023 SIAM Conference on Computational Science and Engineering.

[3] https://sinews.siam.org/Details-Page/unhidden-figures

[4] https://www.siam.org/about-siam/committees/diversity-advisory-committee

[5] https://www.siam.org/about-siam/committees/committee-on-committees-and-appointments-cca

[6] https://sinews.siam.org/Details-Page/a-conversation-with-ron-buckmire-siams-first-vice-president-for-equity-diversity-and-inclusion

[7] https://www.siam.org/membership/activity-groups/detail/equity-diversity-and-inclusion

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Automatic Differentiation

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as JAX,[1] PyTorch,[2] and TensorFlow.[3] The technology's key feature is the fact that the computational cost of computing derivatives of a target loss function is independent of the number of parameters; this trait makes it possible for users to implement gradient-based optimization algorithms for functions with staggering numbers of parameters.

We outline two example problems in classical applied mathematics that are inspired by these new tools: (i) The development of numerical algorithms for the solution of nonlinear partial differential equations (PDEs) and (ii) the design of materials with novel functionality. In each of these problems, we begin with a dynamical system

$$dx/dt = f_\theta(x), \qquad (1)$$

where $x \in R^n$, parameterized by $\theta \in R^m$. Both n and m are typically large, reflecting a high-dimensional optimization problem in a high-dimensional dynamical system. We then attempt to solve the optimization problem, which is characterized by a loss function $L = L(x|\theta)$. The structure of this mathematical problem bears a strong resemblance to the neural network (NN)-based optimization problems in modern ML. Yet while it is sometimes natural to parameterize arbitrary functions in (1) with NNs, θ can parameterize any aspect of the system — from interaction potentials to interpolation weights in a numerical scheme.

Nonlinear Partial Differential Equations

Our first set of examples involves algorithms for the solution of nonlinear PDEs. Researchers usually derive such algorithms analytically; we typically adopt an appropriate spatial basis (e.g., polynomial, spectral, or Chebyshev) that yields a discretization of the equations in space, then further discretize the equations in time. Doing so gives rise to an update rule for the solution at the new time step. However, these algorithms are plagued with inaccuracy or instability if the spatial grid is too coarse; as a result, one must often resolve the solution's finest features with many grid points (which increases the computational cost).

An alternative method for the derivation of update rules involves generating high-resolution data for the solutions of a *particular* nonlinear PDE, then algorithmically deriving the update rule as an optimization problem. This update rule differs from the classical algorithms in that it is *equation specific*; moreover, it can yield accurate results in a regime that is inaccessible to classical numerical solvers. For example, Figure 1 (on page 1) provides solutions from a solver that is trained on two-dimensional turbulence in the Navier-Stokes equations. We use an update rule that learns equation-specific interpolants to more accurately estimate unresolved quantities instead of directly averaging them. These interpolants are parameterized via NNs with initially unknown weights. We train the weights to match the solver's accuracy on a 10 times coarser grid and time step than the baseline classical method, with an approximate 100-fold savings in computational cost.

This scenario is just one example of an algorithm that we can derive with a differentiable solver. Other possibilities include the parameterization of unknown physical effects or discrete algorithms that implement turbulence models [5] or dynamic boundary layers [1]. And algorithm development only scratches the surface of the realm of possibility. For instance, a recent study used a differentiable solver to find periodic orbits in a turbulent flow that were an order of magnitude more unstable than previously known [7]; this discovery provides the first compelling evidence that one can construct the statistics of a fully developed turbulent flow with a set of unstable periodic orbits.

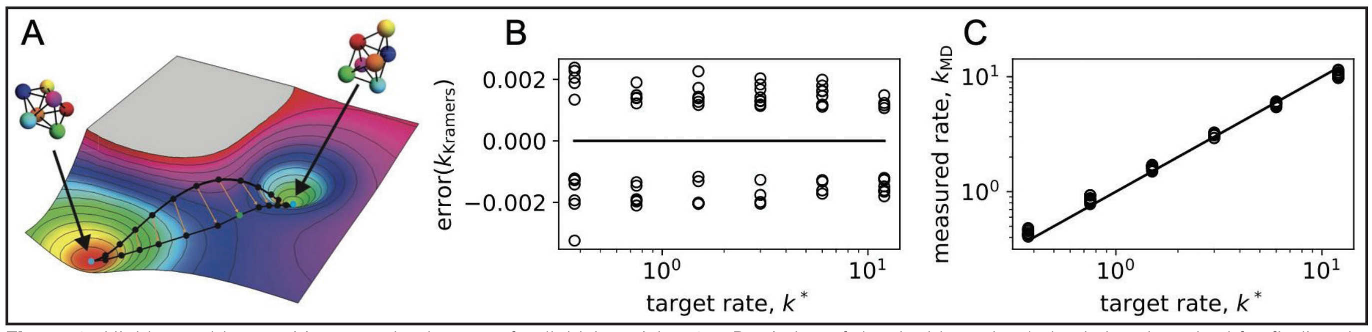

Figure 2. *Highly tunable transition rates in clusters of colloidal particles.* **2a.** *Depiction of the doubly nudged elastic band method for finding the transition state between two local energy minima. Here we consider the transition between two seven-particle clusters.* **2b.** *Absolute error as a function of target rate. Optimization achieves an error rate of 0.2 percent of the target rate.* **2c.** *Target rates versus rates from the molecular dynamics (MD) simulation. The solid line indicates perfect agreement. Figure adapted from [3].*

Molecular Dynamics

The resourceful design of functional materials has much potential for the creation of novel technologies that range from maximum efficiency solar cells to self-repairing materials. A key challenge within this process is *inverse design*, i.e., finding the parameter settings for the materials as a solution to a non-convex optimization problem with an exponentially large parameter space. Molecular dynamics (MD) is a common tool for dynamic materials modeling, which simulates the collective motion of particles under classical mechanical forces. By simulating materials with MD, scientists have uncovered mechanisms for viral assembly and elucidated frictional forces in nanocrystals. However, designing and optimizing materials to have desired functionalities requires more than just simulation of these systems — researchers must also optimize over these simulations to find input parameters that reliably yield functional outputs. Efficient automatic differentiation algorithms have enabled the development of fully differentiable MD simulators like JAX MD,[4] which allow users to directly differentiate through entire dynamical trajectories. We can explore a much broader design space of functional materials as a result.

An illustrative set of examples arises from the field of *self-assembly*, which involves the design of interactions among particles so that they will spontaneously form complex structures if randomly thrown together. This property is critical to biological function, from organelles in the cell to embryonic development. Equilibrium self-assembly, which designs interactions to achieve desired equilibrium targets, has experienced significant progress. But biological systems do not rely solely on controlling the structure; they also depend on *kinetics*. Although kinetic features of self-assembly were long considered too complex for direct design, the ability to directly differentiate with MD simulations provides immediate access to the relationship between kinetics and tunable system properties. Such access makes it possible for us to create both structural features of self-assembly and kinetic pathways. For instance, we previously established quantitative control over the rate of bulk crystal formation and the transition rate between small clusters of particles [3].

Figure 2 demonstrates quantitative control over the transition rate between clusters of seven unique particles that are interacting via the Morse potential. Figure 2a depicts the energy landscape of the clusters, from which we extract an approximate transition pathway (shown in black) with the doubly nudged elastic band method. We then estimate the transition rate between the two states from this approximate pathway. Since the transition rate calculation is fully differentiable, we can optimize the parameters of the interaction potential to directly tune the transition rates. Figure 2b charts the difference between the target and achieved rates in the optimization results, and Figure 2c displays the target rates versus the measured rates that stem from full MD simulations. The ability to tune transition rates provides a gateway into an entirely new materials design space; automatic differentiation in the context of dynamical systems has already changed the scope of the material properties that we can generate.

Discussion

The ML community has developed efficient software tools to search for minima in non-convex landscapes, as well as benchmarks to measure solution quality. Both of these advances represent significant opportunities in applied mathematics. Though we have focused on the use of automatic differentiation within dynamical systems, an equally important lesson from the ML revolution pertains to the construction of benchmarks and community efforts to improve them. An appropriately designed suite of benchmarks could precipitate immense progress in the computational design of materials and algorithms.

We have only explored the tip of the iceberg in the realm of automatic differentiation for dynamical systems. Current projects within our own research groups include the design of fluid microstructures to achieve target rheologies; chaotic mixers; swimmers in complex environments; catalysts that cause self-assembled materials to disassemble on cue; and models for tissue development wherein individual cells control their division and apoptosis rate through measurements of chemical and mechanical fields in their local environments. We hope that the coming years will match recent improvements in ML models with just as much progress in applied non-convex optimization problems for the sciences.

References

[1] Alieva, A., Hoyer, S., Brenner, M.P., Iaccarino, G., & Noorgard, P. (2023). Towards accelerated data-driven Rayleigh Benard convection simulations. *Eur. Phys. J. E.* Under review.

[2] Bryson Jr., A.E., & Ho, Y.-C. (1969). *Applied optimal control: Optimization, estimation, and control*. Waltham, Mass: Ginn and Company.

[3] Goodrich, C.P., King, E.M., Schoenholz, S.S., Cubuk, E.D., & Brenner, M.P. (2021). Designing self-assembling kinetics with differentiable statistical physics models. *Proc. Natl. Acad. Sci.*, *118*(10), e2024083118.

[4] Griewank, A., & Walther, A. (2008). *Evaluating derivatives: Principles and techniques of algorithmic differentiation* (2nd ed.). Philadelphia, PA: Society for Industrial and Applied Mathematics.

[5] Kochkov, D., Smith, J.A., Alieva, A., Wang, Q., Brenner, M.P., & Hoyer, S. (2021). Machine learning-accelerated computational fluid dynamics. *Proc. Natl. Acad. Sci.*, *118*(21), e2101784118.

[6] LeCun, Y. (1988). A theoretical framework for back-propagation. In D. Touresky, G. Hinton, & T. Sejnowski (Eds.), *Proceedings of the 1988 connectionist models summer school* (pp. 21-28). Pittsburgh, PA: Carnegie Mellon University.

[7] Page, J., Norgaard, P., Brenner, M.P., & Kerswell, R.R. (2022). Recurrent flow patterns as a basis for turbulence: Predicting statistics from structures. Preprint, *arXiv:2212.11886*.

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[1] https://jax.readthedocs.io/en/latest/index.html
[2] https://pytorch.org
[3] https://www.tensorflow.org
[4] https://jax-md.readthedocs.io/en/main

Mpox

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individuals decide whether or not to vaccinate themselves. "Game theory models are useful for studying complex epidemiological scenarios in which self-interested individuals take actions based on the decisions of the rest of the population," Rychtář said. He explained that vaccination games are akin to the tragedy of the commons — a well-studied model that pits the interests of a group against those of the individuals that comprise it [7]. For instance, one set of individuals may decide to pay taxes and contribute to the common good, while another set opts not to pay taxes but still reaps the benefits from those who do. Similarly, vaccination could be prone to "free riders" who avoid the costs of getting vaccinated themselves while benefiting from the immunity that vaccines confer on others. People tend to balance the perceived costs of vaccination against a vaccine's effectiveness, and individuals' actions generally maximize their own self-interest rather than the interests of the group.

Previous studies have utilized the extended model of disease transmission with game theory in the context of COVID-19 [5], as well as measles, smallpox, and other childhood illnesses [4]. The present model assumes that the vaccination game consists of susceptible and presumably rational individuals who act in their own self-interest.

The expected cost of mpox infection relative to the cost of vaccination is $C^*_{MPX} = \frac{C_{MPX}}{C_V}$. Rychtář, Taylor, and their collaborators noted that there are many types of vaccination costs, including the actual price of the vaccine as well as indirect factors such as time away from work, travel expenses, and potential side effects. These costs may negatively affect the probability of achieving complete vaccination. On the other hand, mpox infection generally does not seem to impose a significant cost to individuals, apart from mild symptoms and time off of work (although some mpox cases can be severe). As a result, the researchers' model assumes that the value of C^*_{MPX} will range from 1 to 10. In a real-world scenario, this value will likely differ for each individual.

With a population vaccination rate of ψ, the incentive function $h(\psi)$ for an individual to receive a vaccination is given by the difference between the expected costs of vaccination versus non-vaccination (including the potential cost of contracting mpox):

$$h(\psi) = C^*_{MPX}\left(\frac{\sigma}{\sigma+\mu}\right)(\pi_{NV} - \pi_V) - 1. \quad (7)$$

Here, $\left(\frac{\sigma}{\sigma+\mu}\right)$ is the probability that an exposed individual becomes infected. The probability that an unvaccinated individual is exposed to mpox is then

$$\pi_{NV} = \frac{\beta\frac{I^*}{N}}{\beta\frac{I^*}{N}+\mu}, \quad (8)$$

where $\beta\frac{I^*}{N}+\mu$ signifies the rate at which individuals who have no intention to vaccinate leave the "susceptible" compartment. The model assumes that the epidemic has reached a steady state with I^* infected individuals [8].

The probability that a vaccinated individual becomes exposed to mpox is

$$\pi_V = \frac{(1-e)\beta\frac{I^*}{N}}{(1-e)\beta\frac{I^*}{N}+\mu}. \quad (9)$$

The Nash equilibrium (NE)—the solution to the vaccination game—is the population vaccination rate ψ_{NE}, which ensures that individuals do not have an incentive to deviate from the population strategy. "The existence of multiple optimal strategies was truly unique but not unexpected," Rychtář said. "This was the consequence of an imperfect vaccine against mpox." A perfect vaccine would imply that the efficacy $e = 1$, which is usually the assumption in vaccination games. But in the more general imperfect vaccine scenario of the current work, $e < 1$; consequently, there can be multiple NEs and roots of h.

Figure 1 (on page 1) depicts the efficacy e versus the expected cost of infection C^*_{MPX}, with $R_0 \approx 2.11$ and $\beta = 0.09$. The blue region indicates that when C^*_{MPX} is low, people have minimal incentive to vaccinate. The only NE is $\psi = 0$, which is a stable solution that holds true even when C^*_{MPX} is high (and the disease is more dangerous) but e is low (between 0.2 and 0.4). Under these conditions, not vaccinating is an optimal strategy from an individual's perspective. Yet as C^*_{MPX} and e increase, the vaccination rate becomes positive ψ_{NE} — the only NE and stable. The brown region in Figure 1 indicates this optimal strategy, wherein individuals choose to vaccinate. For a low value of β, the model predicts these scenarios as the only two optimal strategies.

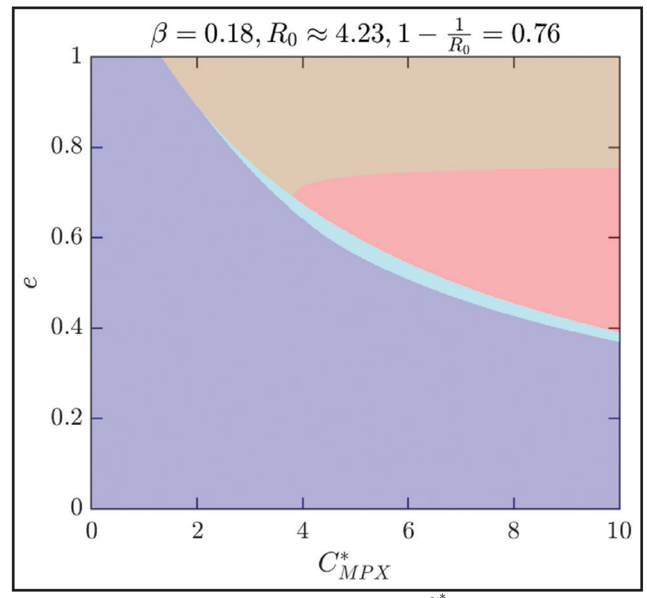

Figure 2. *Nash equilibria (NEs) as e and C^*_{MPX} vary for a higher transmission rate, $\beta = 0.18$. In the blue region, 0 is the only NE and it is a convergent stable NE (CSNE). In the brown region, positive $\psi_{NE} < \psi_{\max}$ is the only NE and it is a CSNE. In the light blue region, there are three NEs; 0 and the larger NE are CSNEs. In the red region, the maximal feasible vaccination rate is the only CSNE. Figure courtesy of [1].*

But how do higher transmission rates of mpox impact the vaccination game? In Figure 2, β has increased to 0.18 and $R_0 \approx 4.23$. There are now four patterns of NEs, which are marked by four different colored regions. In the bottommost blue region at low values of C^*_{MPX} (between 0 and 2) or e (between 0 and 0.4), the cost of mpox is too low for individuals to get vaccinated. Here, 0 is the only NE and it is stable.

"The brown region on the top is where we want to be or should be," Rychtář said. In this area, C^*_{MPX} is high (the disease is more dangerous) but e is also high. The brown region signifies where people tend to vaccinate the most, and a positive ψ_{NE} is the only NE and is stable. The red region to the right is an unfortunate case, as the high C^*_{MPX} and low e indicate that mpox would not be eradicated even if people vaccinated as much as possible.

Finally, the light blue region in the middle of Figure 2 is particularly interesting because it has multiple NEs. Individuals in this region have two potentially optimal strategies that are stable NEs: to vaccinate at a higher rate or refrain from vaccination entirely. There is also a third, unstable NE wherein some people do vaccinate, but the voluntary vaccination rate may not be sufficient enough to substantially decrease the number of mpox cases. Vaccinating a larger group of individuals is therefore necessary to avoid the unstable region. Based on these predictions, Rychtář, Taylor, and their collaborators recommended a minimal mandated vaccination rate from a public health standpoint; otherwise, the overall population vaccination rate could decline to 0.

"Without game theory, our model would be largely like the model from previous work in [6]," Rychtář said. "It would calculate R_0 and specify what vaccination coverage is needed to achieve herd immunity, i.e., what kind of vaccination effort the government must implement to protect its citizens. [A game theory perspective has] highlighted human behavior and the actions of individuals, as well as what they need to do to protect themselves from infection."

The researchers mentioned that their current work includes many simplifying assumptions, such as a homogenous and well-mixed population — i.e., that everyone has the same amount of contact with infected individuals and that the risk of infection is homogenous. Additionally, if the perceived cost of mpox is smaller than the cost of vaccination in the current model, people will decide not to vaccinate. But in a real-world heterogenous population, some nonnegligible proportion of the group may still choose to receive the vaccination.

Nevertheless, scientists frequently incorporate human behavior into disease modeling to enhance a model's realism. "The significance of this paper is that it shows the existence of multiple equilibria, a phenomenon that has not been previously studied in many details," Hyunju Oh, an associate professor at the University of Guam who is not affiliated with the study, said. She also noted similar results for other infectious diseases [2], including COVID-19 [5].

"A game theory approach can even be applied to novel infectious diseases, especially because people may be hesitant to get new vaccines due to concerns about side effects," Eunha Shim, a professor at Soongsil University who was also not associated with the study, said. Future research could better guide public health officials to make strategic vaccination decisions and help limit the spread of fatal infectious diseases.

References

[1] Augsburger, I.B., Galanthay, G.K., Tarosky, J.H., Rychtář, J., & Taylor, D. (2022). Voluntary vaccination may not stop monkeypox outbreak: A game-theoretic model. *PLOS Negl. Trop. Dis.*, *16*(12), e0010970.

[2] Augsburger, I.B., Galanthay, G.K., Tarosky, J.H., Rychtář, J., & Taylor, D. (2023). Imperfect vaccine can yield multiple Nash equilibria in vaccination games. *Math. Biosci.*, *356*, 108967.

[3] Bankuru, S.V., Kossol, S., Hou, W., Mahmoudi, P., Rychtář, J., & Taylor, D. (2020). A game-theoretic model of monkeypox to assess vaccination strategies. *PeerJ*, *8*, e9272.

[4] Bauch, C.T., & Earn, D.J.D. (2004). Vaccination and the theory of games. *Proc. Natl. Acad. Sci.*, *101*(36), 13391-13394.

[5] Choi, W., & Shim, E. (2021). Optimal strategies for social distancing and testing to control COVID-19. *J. Theor. Biol.*, *512*, 110568.

[6] Grant, R., Nguyen, L.-B.L., & Breban, R. (2020). Modelling human-to-human transmission of monkeypox. *Bull. World Health Organ.*, *98*(9), 638-640.

[7] Hintze, A., Staudacher, J., Gelhar, K., Pothmann, A., Rasch, J., & Wildegger, D. (2020). Inclusive groups can avoid the tragedy of commons. *Sci. Rep.*, *10*, 22392.

[8] Usman, S., & Adamu, I.I. (2017). Modeling the transmission dynamics of the monkeypox virus infection with treatment and vaccination interventions. *J. Appl. Math. Phys.*, *5*(12), 2335-2353.

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SIAM Convenes Researchers to Envision a Sustainable and Resilient Future

By Katherine Evans, Lea Jenkins, and Suzanne Weekes

"World Removes More Carbon Than It Produces for the First Time!"

"Net Negative: Significant Reduction in Greenhouse Gases Through Math!"

"First Truly Carbon Neutral Transatlantic Commercial Flight!"

"The Missing Link Filled — Battery Technology Breakthrough Allows 100 Percent Renewable National Grid!"

These eye-catching predictions are examples of the bold, future-looking news headlines that participants generated at the SIAM Convening on Climate Science, Sustainability, and Clean Energy.[1] The three-day workshop—which took place in Tyson's Corner, Va., in October 2022—was SIAM's response to the U.S. National Science Foundation's (NSF) call to action on *Critical Aspects of Sustainability: Innovative Solutions to Climate Change*,[2] which encouraged "science and engineering communities to develop forward-thinking research that will demonstrably aid in the Nation's goal of reaching net-zero greenhouse gas emissions and developing approaches for adapting to the change that is already occurring." The SIAM workshop was funded by NSF Division of Mathematical Sciences (DMS) grant 2227218.

In 2021, the SIAM Climate Task Force—an offshoot of SIAM's Committee on Science Policy[3]—produced a report titled "Research and Education Priorities to Address Climate Change, Boost Environmental Resilience, and Advance Clean Energy"[4] [1]. That report came from the SIAM viewpoint, but there was also a need to engage an even broader group of researchers and stakeholders. For the convening, SIAM therefore recruited participants from outside of SIAM membership — and even some who were unfamiliar with the Society.

Suzanne Weekes, SIAM's Executive Director, assembled a multidisciplinary steering committee that worked closely with Annemarie Boss of KnowInnovation[5] (KI) and Annie Imperatrice, Senior Assistant to the Executive Director at SIAM, to plan the workshop. KI is an organization that facilitates discussion and idea generation to guide and accelerate academic, scientific, and interdisciplinary innovation. Ultimately, more than 55 researchers from academia, industry, nonprofit organizations, and government research laboratories came together to articulate challenges, recognize problems, and identify foundational long-term research and workforce needs that would benefit from federal investment. These researchers included social and economic scientists, atmospheric scientists and geoscientists, physical scientists, and mathematical scientists and engineers. The consequent deliverable of the convening—with additional work by a subset of attendees after the event—was a comprehensive

See **Resilient Future** *on page 6*

[1] https://www.siam.org/publications/reports/siam-convening-on-climate-science-sustainability-and-clean-energy

[2] https://www.nsf.gov/pubs/2021/nsf21124/nsf21124.jsp

[3] https://www.siam.org/about-siam/committees/committee-on-science-policy-csp

[4] https://www.siam.org/Portals/0/Publications/Reports/SIAM_Climate_Task_Force_Report_with_Appendix.pdf

[5] https://knowinnovation.com

At the SIAM Convening on Climate Science, Sustainability, and Clean Energy—which took place in Tyson's Corner, Va., in October 2022—scientists from academia, industry, nonprofit organizations, and government research laboratories worked together to define climate- and sustainability-based challenges and identify large-scale recommendations for proposed future research directions. Photo courtesy of Annie Imperatrice.

Some Shallow Observations

MATHEMATICAL CURIOSITIES

By Mark Levi

Water in a clear pool is deeper than it looks. What seems like five feet when looking straight down is actually seven feet — an unpleasant surprise for a non-swimmer. And this disparity between the true and apparent depths is quite striking for objects that are viewed at an angle. For example, when I direct my gaze 30 degrees below the horizontal, the true depth is more than five times greater than what I see!

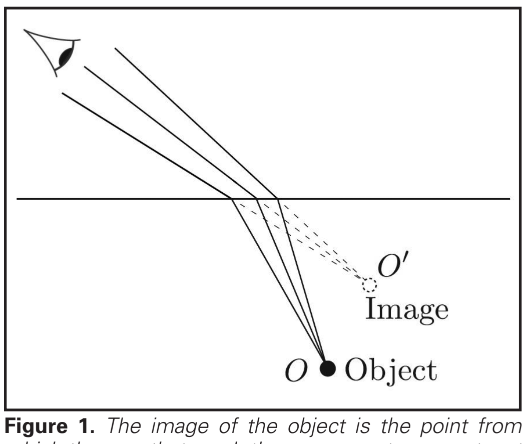

Figure 1. *The image of the object is the point from which the rays that reach the eye seem to emanate, at least to the leading order of accuracy. In reality, each dotted line is tangent to a caustic (see Figure 4) and it only looks like they come out of one point.*

Location of the Image

The image O' of the object O in Figure 1 is the apparent source of rays, i.e., the point from which the rays that reach the eye *seem* to emanate. To find the location of O' given O, let us advance the crossing point C in Figure 2 by a small distance dx, causing small changes in α and β. To the leading order of approximation, the length of the thick segment in Figure 2b can be expressed in two ways:

$$L\,d\beta = dx\cos\beta.$$

In a similar way, $L'd\alpha = dx\cos\alpha$ and thus

$$\frac{L'}{L} = \frac{\cos\alpha}{\cos\beta}\cdot\frac{d\beta}{d\alpha}. \qquad (1)$$

To find $d\beta/d\alpha$, we differentiate Snell's law $\sin\alpha/c_{\text{air}} = \sin\beta/c_{\text{water}}$ to obtain

$$\frac{d\beta}{d\alpha} = c\frac{\cos\alpha}{\cos\beta},$$

where

$$c = c_{\text{water}}/c_{\text{air}} \approx 0.7,$$

the reciprocal of the refraction index. Substituting this into (1) results in the nice expression

$$\frac{L'}{L} = c\frac{\cos^2\alpha}{\cos^2\beta} \qquad (2)$$

for the ratio of the apparent length to the true length. *This is the factor by which the underwater part of a tilted stick seems to shorten.*[1] Note that this shortening becomes drastic at oblique angles; for $\alpha\uparrow\pi/2$, we have $L'/L\to 0$.

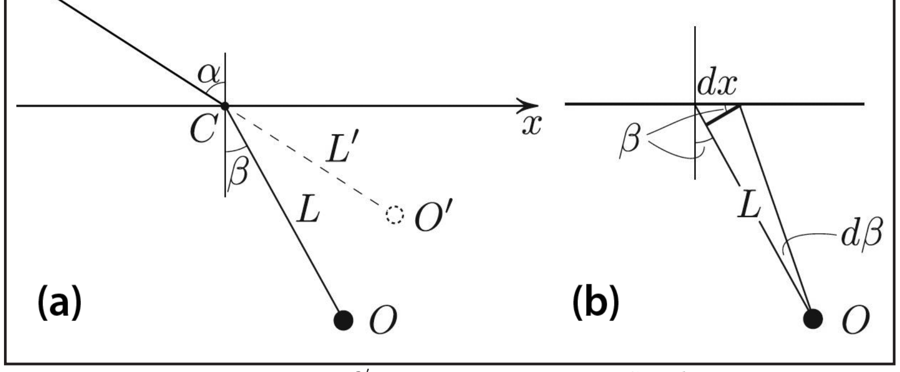

Figure 2. *Computing the location of O'—an infinitesimal move of C by dx—results in infinitesimal changes to α and β.*

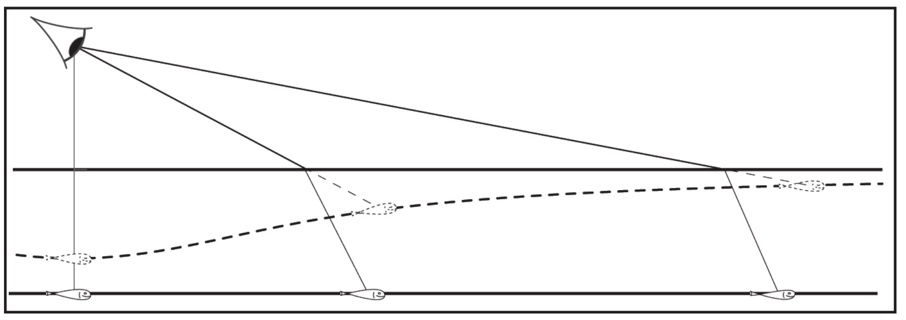

Figure 3. *The image (dotted) of a straight log on the bottom of the lake is an inverted bell-shaped curve whose asymptote is the surface of the water.*

Apparent Depth Versus True Depth

This ratio is given by an elegant expression that we obtain by dividing the apparent depth $L'\cos\alpha$ by the true depth $L\cos\beta$ and using (2):

$$\frac{\text{apparent depth}}{\text{true depth}} = c\frac{\cos^3\alpha}{\cos^3\beta},$$

where c is as before. For example, the above ratio for $\alpha=\pi/3$ is $<1/5$, a surprisingly small number; the water is more than five times deeper than it seems at that angle.

Distorted Images

Straight lines underwater do not look straight to the above observer (see Figure 3). A "dual" problem that may interest some students is to find the shape of the bottom whose image is straight (for the position of the eye fixed).

The Path of the Image

When the object O is fixed, all of its possible images for all viewers form a cusp (see Figure 4). As an observer swings around—as shown in the figure—the image travels along the caustic. The cusp's shape varies homothetically with the depth of O.

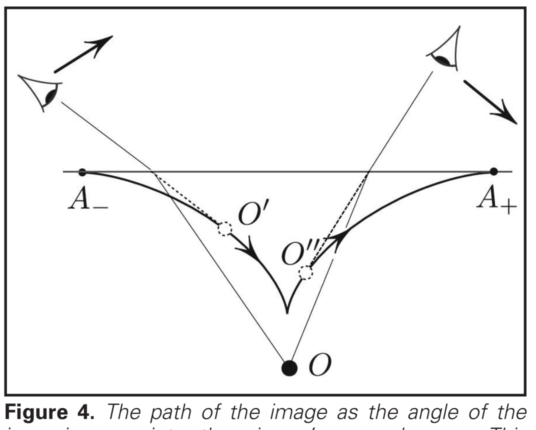

Figure 4. *The path of the image as the angle of the incoming ray into the viewer's eye changes. This cusped path is the envelope of the family of the above-water rays that originate at O. As the eye swings from left to right, the image travels from A_- to A_+.*

[1] Although it should be noted that the image of a straight stick isn't quite straight, albeit not noticeably so.

More Questions

With the eye's position fixed, the map $\varphi := O\mapsto O'$ of the lower half plane onto itself is well defined. It would be interesting to describe precisely how this map distorts small objects. That is, can we say something nice about the Jacobian of φ? What is its polar decomposition, for example? For my purposes here, however, that is going too deep.

The figures in this article were provided by the author.

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Resilient Future

Continued from page 5

report[6] that describes major challenges, themes, and recommendations. It is helpful for decision makers to hear directly from researchers and important that they have recommendations in hand when determining investment directions.

On the first day of the meeting, DMS Division Director David Manderscheid and DMS Deputy Division Director Junping Wang addressed the participants. Jody Reimer, an assistant professor in the Department of Mathematics and School of Biological Sciences at the University of Utah, then delivered a call to action on behalf of the convening's steering committee. Reimer displayed some impactful images and shared current news headlines that answered the question, "Why are we here at this workshop?" She challenged attendees to consider *how society might take ambitious interdisciplinary leaps towards net-zero emissions, sustainability, climate change mitigation and adaptation, food security, and climate equity and justice*. In addition, Reimer framed the convening as an opportunity to (i) expand the range of actionable scientific research, (ii) broaden the participation of scientists, policymakers, and communities, (iii) quickly and strategically identify solutions to pressing problems, and (iv) contribute to an exciting future of human flourishing. She explained that at present, scientific communities often pursue small, incremental steps at too slow a pace; remain siloed within their disciplines; and fail to tackle complex problems holistically.

KI facilitators kept attendees' brains and bodies active with engaging and energizing activities. Participants moved beyond their research comfort zones; effectively collaborated with members of distinct fields; and quickly became accustomed to the acronym "WIBGI" (pronounced wib-ghee), which stands for "Wouldn't It Be Great If [aspiration] by doing [approach]." Throughout the workshop, attendees posted WIBGIs on the wall and organized them into "Mild," "Medium," and "Spicy" categories. The "Spicy" WIBGIs eventually yielded nine recommendations[7] for federal research and development agencies. More information about these recommendations is available in the final report, and short presentations that explore each topic are accessible via SIAM's YouTube Channel.[8]

Recommendations: The Big Ideas

The nine recommendations aim to advance scientific knowledge, anticipate future conditions, accelerate clean energy innovations and sustainable practices, and increase resilience in the face of climate change. Here, we briefly explore the key points of each recommendation.

As climate systems continue to change more rapidly than scientists had originally anticipated, we must develop a multi-fidelity, open-source, scalable platform that serves as a **digital twin for planet Earth**.[9] By ingesting new data and updating model information in real time, this twin would provide characterization and forecasting in the presence of uncertainty — ultimately leading to new scientific insights and informing policy decisions.

Water crises in multiple regions of the U.S.—and indeed across the entire globe—highlight the difficulty of ensuring access to this vital resource. Existing systems are becoming defunct, and climate change has impacted both the availability and overabundance of water. The creation of a **nationwide smart water grid**[10] could distribute water more efficiently and improve the resilience of our country's water infrastructure. Engineering solutions must be coupled with water access models and economic analyses to guarantee the equitable sharing of this basic human need.

Extreme weather events are increasingly making headlines around the world and leaving devastation in their wakes. Such disasters, which are visible effects of a changing climate, necessitate the development of **new learning tools that accurately model, characterize, and predict extreme events**.[11] Classification of the various types of extreme weather requires more data collection and additional input from meteorological subject matter experts. Data analysis demands novel algorithms to better quantify the likelihood of these events—which occur in the tails of frequency distributions—in the presence of nonstationary behavior.

[6] https://www.siam.org/Portals/0/Programs/climate_convening/Report_SIAMClimateConvening.pdf
[7] https://www.siam.org/Portals/0/Programs/climate_convening/Recommendations_SIAMClimateConvening.pdf

[8] https://go.siam.org/klBWuK
[9] https://sinews.siam.org/Details-Page/a-paradigm-for-digital-twins-to-safeguard-the-planet
[10] https://sinews.siam.org/Details-Page/sustainable-smart-water-systems-aka-sustainable-water-grid
[11] https://sinews.siam.org/Details-Page/extreme-learning

Participants brainstorm "WIBGIs" (Wouldn't It Be Great If...) during the SIAM Convening on Climate Science, Sustainability, and Clean Energy, which was held in Tyson's Corner, Va., in October 2022. This engaging activity eventually led to the creation of nine recommendations for federal research and development agencies that pertain to future directions of climate research and sustainability. Photo courtesy of Annie Imperatrice.

Scientists often view climate events as cascading consequences of the **dynamics of Arctic systems**.[12] The loss of sea ice and thawing of Arctic permafrost are signature indicators of planetary warming; however, we do not fully understand the ways in which small-scale effects control the large-scale mechanisms in this region of the Earth. The difficulty and expense that are associated with experimental data collection further exacerbate these challenges and prevent significant progress. Researchers could use mathematical constructs to fill these knowledge gaps.

Local and community-based efforts can ensure sustainability as a priority area. It is therefore important to connect research teams with community stakeholders to **identify vulnerabilities and increase resiliency**[13] in human and ecological systems. Decision makers and local stakeholders could employ high-resolution models of climate, social, ecological, and economic systems to enact policies that allow communities to adapt to and mitigate climate change vulnerabilities. Connecting multiple layers of the decision process ensures that the most effective strategies are identified and targeted.

Another option for community stakeholder involvement is the introduction of **new data analysis approaches that empower local decision making**[14] on climate mitigation. The development and application of metrics for data streams—as well as the formation of networks that connect data to decisions—would provide decision confidence and reduce dependence on anecdotal evidence or misused facts. Local decision makers and community leaders could use mathematically sound metrics (designed for public understanding) to quantify and prioritize solutions and incentivize behaviors that enhance sustainability initiatives. Such programs would require the integrated involvement of mathematical, computational, social, behavioral, and political scientists at research centers throughout the U.S.

Discussions about sustainability initiatives also focused on the creation of **a circular economy**.[15] Novel carbon-free production methods and materials must ultimately replace petroleum-reliant and/or petroleum-derived manufacturing and output, and allow for the increased production of novel products. These solutions should span the entire production cycle: reuse, recycle, repurpose, and replace. Research investments in the development and improvement of lifecycle and planning models, optimization and minimization algorithms, consumer behavior data, and community engagement would expedite the eventual shift to a circular economy.

There is also a significant need for accelerated efforts to **decarbonize the planet**.[16] Larger and broader support from multiple collaborating agencies could build on initial governmental investments and deliver results with urgency. The shift away from fossil fuels will require a functioning green infrastructure that allows for the reduction of energy demands and the transition from fuel-based systems to electricity and renewables. Such an infrastructure would yield numerous benefits, including more green jobs, energy independence, and a cleaner environment.

Connecting all of these ideas is an urgent need to **develop the next-generation workforce**.[17] Students must be able to place their coursework in a broader context and synthesize concepts to attack complex problems. Instructors should design collaborative approaches to curricula, classes, and pedagogy that cross boundaries among STEM, social science, and other disciplines and graduate *thinkers* who can contribute to solutions for society's grand challenges.

Consistent across all nine of these themes is the necessary development of mandatory infrastructure—including both human and capital resources—to enable significant progress. A dedicated effort to bring more voices and experts into all relevant fields is therefore integral, as is funding from multiple agencies that can collectively tackle these interdisciplinary challenges.

Our community is invested in building a sustainable future. The dynamism of the group at the SIAM Convening on Climate Science, Sustainability, and Clean Energy reflected a strong motivation and passion within the diverse STEM community to tackle these difficult problems, and the discussions coalesced into multiple invigorating ideas. The interdisciplinary aspect of the event generated fresh viewpoints, unique collaborations, and transformative initiatives that we hope will germinate and blossom throughout the entire scientific community.

References

[1] Aceves, A., Kaper, H., & Leyffer, S. (2021, October 1). Addressing climate change, boosting environmental resilience, and advancing clean energy: Reflections of the SIAM Climate Task Force. *SIAM News*, *54*(8), p. 12.

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[12] https://sinews.siam.org/Details-Page/what-happens-in-the-arctic-does-not-stay-in-the-arctic
[13] https://sinews.siam.org/Details-Page/unraveling-the-climate-vulnerability-web-integration-of-physical-biological-social-and-economic-models-in-time-and-space
[14] https://sinews.siam.org/Details-Page/change-the-conversation-at-the-local-level
[15] https://sinews.siam.org/Details-Page/aced-accelerated-circular-economy-development

[16] https://sinews.siam.org/Details-Page/the-end-of-fossil-fuels
[17] https://sinews.siam.org/Details-Page/transforming-education-to-address-complex-futures

Medical Mathematics Outside of Math Departments

By Helen Moore

I had not expected to find myself in a cancer biology lab on campus, looking at a micrograph image of an immune T cell attacking a cancer cell. The image showed a partial circular shape (the T cell) adjoined to a larger circular shape (the cancer cell). "Doesn't this look like the soap bubble problem you told me about?" asked a postdoc I had recently met. "Yes," I answered. "Are you interested in modeling their shapes?" "No," said the postdoc's advisor, "but we'd like to talk to you about some other types of modeling." Thus began my transition from differential geometry to systems medicine. I switched from studying surfaces that minimize area under constraints to studying drug regimens that maximize efficacy and minimize toxicity under constraints.

Years later, I was discussing my work on disease modeling and regimen optimization with someone else, who mentioned that their company really needed this type of expertise. I quickly received an interview and then a job offer from Genentech.[1] Leaving academia was a difficult decision, but I took the leap and embarked on a 15-year career as a math modeler in the biotechnology/pharmaceutical (biopharma) industry. I returned to academia in 2021 and joined a group of mathematicians in the Laboratory for Systems Medicine[2] in the College of Medicine at the University of Florida.

Here, I will share advice for early-career mathematicians who are considering working in the biopharma industry. I will describe some of the math modeling used in biopharma as well as skills that employers look for in job candidates. I will then address future modeling directions in industry, the process of returning to academia from industry, alternatives to industry, and the differences between academic and industrial careers. More information is available in [1].

CAREERS IN MATHEMATICAL SCIENCES

Mechanistic Modeling in Biopharma

Although empirical modeling of drug concentrations has been used in biopharma since at least the 1970s, a type of mechanistic modeling called quantitative systems pharmacology (QSP) modeling is increasingly used today. A QSP model is a mathematical, mechanistic model — typically a system of ordinary differential equations (ODEs). However, it could instead consist of a system of partial differential equations or stochastic differential equations, an agent-based model, or other types of mathematical models that can mechanistically represent diseases and therapies in individuals. Many mathematical biologists in academic math departments use ODE systems to model susceptible-infected-recovered (SIR) individuals in a population. Unlike SIR-type models that track the spread of disease at the population level, QSP models are in-host models of disease dynamics within an individual, hypothetical patient. Such models focus on disease mechanisms, identifying potential therapeutic targets, and testing hypothetical or actual therapies. With adequate data for calibration, QSP models can also serve as medical digital twins [6].

QSP modeling contributed to Pfizer's successful development of the antiviral therapy Paxlovid for patients with COVID-19. Modelers created a QSP model to simulate patient outcomes under various dosing scenarios and determined that patients should begin the drug within five days of symptom onset for best results [5, 8].

Skills Needed for QSP Modeling in Biopharma

Here are some of the capabilities and experiences that will make you a good candidate for QSP modeling positions in biopharma. I have listed them starting with the most important, based on my personal involvement with the interviewing and hiring processes:

1. Experience in building and working with ODE models in relevant settings
2. Familiarity with MATLAB or similar software (e.g., Python and R)
3. Use of appropriate sensitivity analysis methods to assess model dependencies
4. Ability to collaborate with scientists who are not modelers
5. Strong presentation and writing skills
6. Professionalism, including prioritizing and meeting timelines.

When interviewing for a job, applicants should discuss examples that demonstrate these specific capabilities or experiences.

The SIAM Job Board[3] sometimes has job listings for QSP modelers, and the International Society of Pharmacometrics[4] typically lists dozens of QSP opportunities. You can also check the career pages at top biopharma companies, or search sites like Indeed and LinkedIn for keywords such as "QSP," "systems pharmacology," or "math

See **Medical Mathematics** *on page 8*

[1] https://www.gene.com
[2] https://systemsmedicine.pulmonary.medicine.ufl.edu
[3] https://jobs.siam.org
[4] https://go-isop.careerwebsite.com

Helen Moore (center, at the whiteboard) and her colleagues within the Laboratory for Systems Medicine at the University of Florida's College of Medicine recap and discuss a recent talk that they attended. Photo courtesy of Helen Moore.

On the Recent Growth and Future Paths of the Colombia Section of SIAM

By Andrés Rivera

For more than 12 years, the Colombia Section of SIAM[1] (CoSIAM) has been promoting the application of mathematics within different branches of science and industry in Colombia. The section aims to facilitate the exchange of basic research and novel mathematical methods between applied mathematicians and other scientific and technical personnel.

CoSIAM[2] hosts multiple events for its members throughout the year, such as an Annual Meeting,[3] Math Modelling Challenge,[4] Workshop and International Seminar on Complexity Sciences,[5] and School of Applied and Industrial Mathematics.[6] These and other activities bring together hundreds of students, academics, and industry professionals to improve their knowledge of mathematical theories and techniques in order to solve current industrial and social problems. Recent application areas include the implementation of artificial intelligence to develop a search facility for social networks that protects social leaders in Colombia, as well as sustainable and green supply chain management in the Colombian industrial energy and transport sectors.

The most recent Workshop and International Seminar on Complexity Sciences,[7] which took place in December 2022, focused on *Social Transitions* — a field of research with exciting emerging applications in the circular economy and sustainability theory. CoSIAM's Board of Directors and Advisory Committee selected this topic based on members' research activities and knowledge of mathematical studies in the academic and private spheres within Colombia and around the world. During the seminar—which addressed climate change, governance, sustainable development, food security, new energy, and resilience—researchers from across the nation spoke about their respective projects, discussed the scope and limitations of their approaches, and emphasized the necessity of collaboration for successful implementation.

One strategic tool that increases CoSIAM's visibility amongst academics and professionals within Colombia and abroad is its YouTube channel.[8] We created the CoSIAM YouTube channel in 2020 in response to COVID-19 pandemic restrictions that prevented in-person meetings; though it began modestly, with just three online training courses and one massive open online course (MOOC), the number of subscribers steadily increased. More than 90 videos with over 14,000 total views now populate the channel, which is slowly becoming one of the more popular channels devoted to mathematics on YouTube in Colombia (see Figure 1). Some of our most-viewed lessons include introductions to mathematical modeling, systems dynamics, blockchains, machine learning, data science, optimization theory, and population dynamics. CoSIAM's Board of Directors has used the channel's analytics to better understand mathematical trends in Colombia and more precisely and effectively propose CoSIAM courses, mathematical challenges, and MOOCs each year.

The YouTube channel also provides an avenue through which we can imagine a future for CoSIAM beyond Colombia. For example, CoSIAM training courses receive hundreds of views in Latin American countries like Chile, Mexico, Bolivia, Peru, and Ecuador. When we discovered that just 10 percent of viewers are women, we implemented a policy that requires at least one of the training course speakers in the School of Applied and Industrial Mathematics to be female. This policy went into effect two years ago, with excellent results for course quality and audience reception.

Additionally, CoSIAM is actively working to increase and strengthen its connections to other SIAM sections. For instance, several CoSIAM members participated in the Annual Meeting of the Mexico Section of SIAM[9] by creating a program of presentations on recent advances in celestial mechanics and optimization theory. Utilizing this platform enables Colombian mathematicians and private sector professionals to showcase their research to SIAM members in other countries. This strategy is naturally reciprocal in nature, and we expect to share a complete event with other SIAM sections in the coming years.

CoSIAM's next goal is to increase the number of members and subscribers to its YouTube channel by adding content from the aforementioned series of four main annual events, as well as short videos of experts (mathematicians, physicists, engineers, economists, and general scientists and professionals) who explain unique mathematical techniques and their applications in the industrial sector. The Board of Directors invites you to join us on this new venture and reach out with ideas for future events and materials.

Figure 1. *Example playlists from the Colombia Section of SIAM's (CoSIAM) YouTube Channel.*

Andrés Rivera is an associate professor in the Department of Natural Sciences and Mathematics at Pontificia Universidad Javeriana, Cali. He earned his Ph.D. in mathematical sciences from Universidad de Granada in 2012, and his research interests pertain to the qualitative theory of differential equations; celestial mechanics; and nonlinear dynamics of physical, economic, and biological models. Rivera is the current president of the Colombia Section of SIAM.

[1] https://www.siam.org/membership/sections/detail/colombia-section-of-siam-cosiam
[2] https://www.cosiam.net
[3] https://www.cosiam.net/annual-meeting-cosiam2022
[4] https://www.cosiam.net/mmc2022
[5] https://www.cosiam.net/wiscs-cosiam
[6] https://www.cosiam.net/emai-cosiammain
[7] https://www.cosiam.net/wiscs-cosiam-2022
[8] https://www.youtube.com/@cosiam2397
[9] https://mexsiam.org

Medical Mathematics

Continued from page 7

modeling." Additionally, the Life Sciences and Dynamical Systems community forums on SIAM Engage[5] can be good places to network with like-minded individuals.

The Future of Modeling in Biopharma

For mechanistic math modelers, the future in industry is bright! Due to the success of the methods, many companies are currently looking for qualified QSP modeling applicants. Regulatory agencies are driving an emphasis on model verification, validation, and uncertainty quantification, so modelers with the depth and rigor that comes from graduate math Ph.D. training are in high demand. There is an increase in the use of methods like sensitivity analysis (especially global methods such as the Morris method, active subspaces, partial rank correlation coefficients, extended Fourier amplitude sensitivity testing, Sobol indices, extended Sobol indices, and Shapley values); identifiability analysis (both structural and practical); uncertainty quantification; and data-based validation (including k-fold cross validation and external data) [4].

Once we have a reliable model, we can use it for various predictions. For example, we can apply optimal control to determine optimal combination drug regimens [7]. We can also simulate virtual patients and predict how a different dose regimen would impact a hypothetical patient population.

The size and complexity of QSP models make the simulation of virtual patients (one virtual patient = one feasible parameter set) a lengthy process. But such simulations are necessary for testing distinct scenarios (e.g., different dosing regimens, renally-impaired populations, or effects in children). The judicious selection of virtual patients to reduce the required computational time is an active area of research [2, 9]. Model reduction techniques and surrogate modeling can help speed up the simulation of virtual patients and more thoroughly explore the parameter space, thus providing greater confidence in outcomes of simulated patient cohorts.

The use of artificial intelligence (AI) is popular in many fields these days. Methods that employ AI may help estimate model parameters, but will they ever be able to develop reliable QSP models by combining data with knowledge from the literature? The jury is still out on this use of AI. Other empirical modeling methods are used in biopharma, many of which involve regression fitting of a specified curve to a data set. Peter Bonate's book provides a mathematically-focused overview of such empirical modeling methods in drug development [3].

Returning to Academia

How easy is it to move from industry to academia? In my experience, most schools generally ignore the valuable knowledge that candidates could bring from their industry backgrounds and instead evaluate you as if you were an academic. This means that you need peer-reviewed research manuscripts. My industry groups generally did not allow me to publish anything related to my work projects. But thanks to the time I put in during weekends and evenings, I generated a small but steady stream of publications during my 15 years in industry. I had received a National Science Foundation grant and two teaching awards while in academia, and I spent a few of my industry years teaching biopharma modeling methods and software. I also had a long track record of mentoring and working to increase diversity in multiple settings. So when applying to return to academia, I was able to write the three statements that are required for many academic positions—research, teaching, and diversity—but still had to explain gaps in my research and teaching.

Due to these particular criteria, it can be challenging to transition to academia if you have been in industry for a long time. If you want to keep such a transition as an option, you should look for jobs with groups that are enthusiastic about publishing their work. Additionally, you can give guest lectures to students and ask them to complete evaluation forms. It may also be beneficial to make a decision about returning to academia early in your career, since a gap of a few years is not as much of an issue as 15 years.

Alternatives to Industry

What if you want an academic career but would prefer to focus on research rather than teaching? You're in luck! There are now multiple groups of mathematicians outside of math departments that primarily focus on research. I am part of the Laboratory for Systems Medicine[6] in the College of Medicine at the University of Florida, which is one such group. We currently have openings for faculty, with a responsibility breakdown of roughly 90 percent research and 10 percent teaching.

Several other university groups in the U.S.—including the Computational Medicine Program[7] at the University of North Carolina at Chapel Hill and the Center for Computational Oncology[8] at the University of Texas at Austin—have a similar focus on research and often have postdoctoral or faculty openings. Groups within medical centers include the Integrated Mathematical Oncology Department[9] at Moffitt Cancer Center and the Mathematics in Medicine Program[10] at Houston Methodist Hospital.

Table 1 compares typical characteristics for settings in which a mechanistic, in-host disease modeler might be employed.

Conclusions

I have presented my own experiences and views of mathematical modeling in the biopharma industry. If you are considering a job in industry, I encourage you to talk to individuals who have worked (or are currently working) in an industry setting. You can do this by attending meetings that attract industry modelers, or career panels at SIAM conferences. You might even want to invite some of these modelers to speak in a department seminar. The SIAM Visiting Lecturer Program[11] provides profile and contact information for applied mathematicians who work in a variety of industries.

This article shares some overlap with another article by Helen Moore, entitled "Modeling Jobs in the Biopharma Industry," which published concurrently in the "Early Career Section" of the May issue of Notices of the American Mathematical Society.

Point of Comparison	Academic Math Department	Academic Medical Department	Biopharma Industry
Job security	Tenure is possible	Tenure is possible, but you still need to obtain grant funding (typically 25 percent or 50 percent of your salary)	The potential for layoffs exists
Who decides what you work on?	You, when you aren't teaching	You, but you need funding agencies to agree on some projects	Your manager or someone more senior, possibly with input from you
Type of impact	Foundational/basic science	Foundational/clinical	Drug development
Compensation	Academic math	Higher than academic math	Higher than academic medical, and many companies offer stocks and annual bonuses
Teaching	Typically one to three courses per semester; some schools allow buyout with grants	Usually only a few lectures, but you must spend time applying for grants	Usually no required teaching or grant writing, as you spend all of your time working on projects
Mentoring	Can have grad students and postdocs	Can have grad students and postdocs	Sometimes
Is publishing allowed?	Yes	Yes	Sometimes yes, but not in all projects/groups/companies
Can you attend conferences?	Yes, with a grant or school funds that you apply for	Yes, with startup funds or grant money	Yes, companies usually pay for at least one conference and/or training course per year (more when there is impactful work to present)
Which conferences do you attend?	SIAM Conference on the Life Sciences (held biannually) and Society for Mathematical Biology (SMB) Annual Meeting	SIAM Conference on the Life Sciences, SMB Annual Meeting, and therapeutic area conferences	SIAM Conference on the Life Sciences, SMB Annual Meeting, and the annual American Conference on Pharmacometrics
Can you present?	Yes, often you submit a talk	Yes, often you submit a poster abstract	Yes, often you submit a poster abstract
Moving positions	Many people stay at the schools where they started their careers	Many people stay at the schools where they started their careers	Many people move jobs more than once in their careers; some people work remotely, but those who do not can easily change jobs without moving homes if they live near a biopharma modeling hub like Boston or San Francisco

Table 1. *Comparison of academic and industry settings in which a mechanistic, in-host disease modeler might find employment.*

References

[1] Allen, R., & Moore, H. (2019). Perspectives on the role of mathematics in drug discovery and development. *Bull. Math. Biol., 81*(9), 3425-3435.

[2] Allen, R.J., Rieger, T.R., & Musante, C.J. (2016). Efficient generation and selection of virtual populations in quantitative systems pharmacology models. *CPT Pharmacometrics Syst. Pharmacol., 5*(3), 140-146.

[3] Bonate, P.L. (2011). *Pharmacokinetic-pharmacodynamic modeling and simulation* (2nd ed). New York, NY: Springer.

[4] Braakman, S., Pathmanathan, P., & Moore, H. (2022). Evaluation framework for systems models. *CPT Pharmacometrics Syst. Pharmacol., 11*(3), 264-289.

[5] Dai, W., Rao, R., Sher, A., Tania, N., Musante, C.J., & Allen, R. (2021). A prototype QSP model of the immune response to SARS-CoV-2 for community development. *CPT Pharmacometrics Syst. Pharmacol., 10*(1), 18-29.

[6] Laubenbacher, R., Niarakis, A., Helikar, T., An, G., Shapiro, B., Malik-Sheriff, R.S., … Glazier, J.A. (2022). Building digital twins of the human immune system: Toward a roadmap. *NPJ Digit. Med., 5*, 64.

[7] Moore, H. (2018). How to mathematically optimize drug regimens using optimal control. *J. Pharmacokinet. Pharmacodyn., 45*(1), 127-137.

[8] Rao, R., Musante, C.J., & Allen, R. (2021). A quantitative systems pharmacology model of the pathophysiology and treatment of COVID-19 predicts optimal timing of pharmacological interventions. *NPJ Syst. Biol. Appl., 9*, 13.

[9] Rieger, T.R., Allen, R.J., Bystricky, L., Chen, Y., Colopy, G.W., Banks, H.T., … Musante, C.J. (2018). Improving the generation and selection of virtual populations in quantitative systems pharmacology models. *Prog. Biophys. Mol. Biol., 139*, 15-22.

Helen Moore is an associate professor of systems medicine in the College of Medicine at the University of Florida. She is on the Board of Trustees of the International Society of Pharmacometrics and is Vice Chair of the SIAM Activity Group on Life Sciences.

[5] https://engage.siam.org/home

[6] https://systemsmedicine.pulmonary.medicine.ufl.edu

[7] https://www.med.unc.edu/compmed

[8] https://cco.oden.utexas.edu

[9] https://moffitt.org/research-science/divisions-and-departments/quantitative-science/integrated-mathematical-oncology

[10] https://www.houstonmethodist.org/math-in-medicine

[11] https://www.siam.org/students-education/programs-initiatives/siam-visiting-lecturer-program

Diversity and Retention in the Workforce Take Center Stage at CSE23

By Lina Sorg

As universities and other research institutions take active steps to increase diversity and representation amongst their staff, the retention of minority populations remains a significant challenge at numerous organizations. Despite ongoing strategic recruitment efforts, many groups remain underrepresented in the applied mathematics and computational science workforce. During the 2023 SIAM Conference on Computational Science and Engineering,[1] which took place earlier this year in Amsterdam, the Netherlands, a panel session addressed diversity retention and mentoring in the workplace. Panelists Malena Español (Arizona State University), Juan Restrepo (Oak Ridge National Laboratory), and Damian Rouson (Lawrence Berkeley National Laboratory) shared personal insights based on their own experiences, endorsed the value of mentorship, and offered strategies to support employees from minority groups. Maria Vlasiou (Eindhoven University of Technology) moderated the constructive conversation.

Español opened the discussion by affirming that the retention of faculty members from diverse backgrounds requires intentional decision making. "Everything starts with the hiring process," she said. "We need to have a clear vision of where we want our institutions to go and hire accordingly, and that will affect retention." Hiring committees must therefore consider both research experience and commitment to inclusivity when reviewing resumes and interviewing prospective employees.

Restrepo explained that hiring and retention are two separate challenges, noting that the retention pipeline in the U.S. appears to be broken between postdoctoral appointments and full-time employment. In response, he urged employers to protect and support members of underrepresented communities on their staff. "Most come in very excited and energetic, and I don't want them to become tokens for the organization," Restrepo said. For example, people of color should not automatically be tasked with greeting visitors from historically Black colleges or universities; instead, these employees should have the same opportunities as their coworkers to focus on their careers. Restrepo also suggested a change to the way in which society views members of marginalized populations — e.g., as "professional mathematicians who happen to be women" rather than "women who happen to be professional mathematicians."

Rouson, who has worked at three different government laboratories, explained that lab recruitment is often driven by narrow project needs. Hiring groups search for individuals with specific technical backgrounds, which often makes it difficult to attract a large and diverse candidate pool. Because people frequently hire through their own networks, Rouson urged scientists to actively expand their connections. "Part of what we have to do is get out to a different set of places than where we've been going," he said. In addition, he highlighted the Sustainable Horizons Institute's Sustainable Research Pathways initiative:[2] a workforce development program that connects faculty and students from underrepresented groups with scientists at the U.S. Department of Energy National Laboratories.

Reaching a "critical mass" of employee diversity is another important component of retention. "When you're the only one, it can be a very lonely experience," Rouson continued. "We have affinity to people who are like us, that's just a natural thing. If you're in a group that's the majority, you're more likely to benefit from the natural circles that arise." Employee resource groups and workplace affinity groups combat this phenomenon by uniting underrepresented minorities within larger settings and creating a sense of community to reduce feelings of isolation.

Positive mentor-mentee relationships can achieve a similar effect, especially when the mentor listens to both the professional and personal needs of the mentee. "Mentoring is helping someone navigate not just work, but also life," Español said. A certain level of overlap usually exists between an individual's professional and personal situations, so she advised mentors to view their mentees holistically. Moreover, Español reminded junior researchers to seek out multiple types of mentors, each of whom serves a specific purpose for career advancement. The newly established SIAM Postdoctoral Support Program,[3] which is currently accepting applications, provides up to $15,000 in financial support for postdoctoral researchers to work with mentors at different institutions. The goal is to foster research collaboration and professional development; up to four postdoc/mentor pairs will be selected annually beginning in the summer of 2023.

Rouson spoke fondly of his graduate advisor at Stanford University. "The most impactful mentoring that I experienced was my Ph.D. advisor," he said. "Mentoring plays a huge role in retention, and I wouldn't have made it through that program without him." He recalled a bike ride with his Ph.D. group that involved a steep uphill climb. One of the students was struggling, so Rouson's advisor rode alongside her and alternately pushed and pulled her up the hill. Rouson used this story as a metaphor for an effective mentoring style; his advisor employed a hands-on approach when necessary and actively helped Rouson select courses and design his schedule when he was floundering.

[1] https://www.siam.org/conferences/cm/conference/cse23

[2] https://shinstitute.org/sustainable-research-pathways-2022

[3] https://www.siam.org/students-education/programs-initiatives/siam-postdoctoral-support-program

From left to right: Malena Español (Arizona State University), Juan Restrepo (Oak Ridge National Laboratory), and Damian Rouson (Lawrence Berkeley National Laboratory) discuss their personal observations and experiences with mentoring and retention in the context of diversity during a panel session at the 2023 SIAM Conference on Computational Science and Engineering, which took place in Amsterdam, the Netherlands, earlier this year. SIAM photo.

Español observed that numerous networking, funding, and research opportunities are severely underutilized, and encouraged educators—including faculty, advisors, and other mentors—to promote such opportunities amongst their students as much as possible. Even simply emailing relevant postings and application portals to entire classes can be helpful, as many students are perfectly qualified but unaware of the prospects that are available to them. This type of clear communication is particularly valuable for first-generation college students, who may not have the same knowledge of academic stipulations as their peers.

When it comes to mentorship, Restrepo believes in quality over quantity. He remarked that mentors and mentees should sometimes connect across different groups or departments within an organization in order to establish broader relationships. The postdoctoral researchers that Restrepo employs at Oak Ridge—where he is head of the Mathematics in Computation Section—write individual development plans for themselves, then work with their mentors to craft private documents that outline the expectations of both parties. These documents address objectives like the number of conference talks to present and papers to submit within a certain timeframe. Restrepo then meets with the postdocs once a year to check in and hear about their experiences.

As group lead of the Computer Languages and Systems Software Group at Lawrence Berkeley, Rouson intentionally arranges mentor-mentee relationships and actively introduces pairs when there is the prospect of mutual gain. If a staff member will soon be mentoring junior faculty due to an upcoming promotion, for example, Rouson prepares them for this responsibility by connecting them with students or other individuals who could benefit from additional guidance. "By being intentional about developing mentored relationships, you will also in some ways have a more powerful impact on those who are in the minority," he said.

Conversation then turned to the importance of new ideas and novel recruitment and retention methods. "Diversity is an issue of social justice, but it's also an issue of innovation," Restrepo said. "If your dean or president doesn't understand the very notion of innovation and you don't have a system that allows for taking chances—in a tenure situation, for example—you'll have trouble getting the idea of retention through." He pointed out that some faculty who were first-generation college students, while just as technically competent as their colleagues, might require additional support or flexibility when applying for tenure. "There is no reason to have tenure clocks be so rigid that they don't allow for certain circumstances in life," Restrepo continued.

Next, Vlasiou directed the discussion towards gender diversity. In a policy context, analysts typically use a glass-ceiling index to measure the role and influence of women in the workforce as they pursue managerial and executive-level positions. Rouson encouraged attendees to consider the glass-ceiling index and other assessments of diversity with the same type of analytical thinking that they apply to their mathematical research. "We as scientists need to get more quantitative, rigorous, and analytical about these questions — just as we are with the science itself," he said. In some cases, a passion for equal representation in the workforce can even inspire new mathematical analyses.

Departments that are working to increase retention often solicit input from their early-career members. However, Restrepo reminded directors to also consult more established employees who have lengthy firsthand experience with the metaphorical glass ceiling. "A lot of my female colleagues say that they don't have job satisfaction because they don't feel appreciated," he said. "These folks did the battle, they feel like they worked really hard and achieved quite a bit scientifically. But when they're not consulted on issues of diversity and so forth, they feel like they're being left out."

As the panel drew to a close, Español commented that both policy *and* workforce culture must change in order to improve retention in the long term. She acknowledged the value of established rules of conduct, which are becoming more common in classroom settings and at conferences and other gatherings. Nevertheless, a great deal of necessary progress remains to be made. Español recommended that scientists continue to have difficult, intentional conversations about preexisting procedures and policies, especially with the upcoming generation of researchers. "Sometimes we hit bumps, but I think society is moving in the right direction," she said.

During the 2023 SIAM Conference on Computational Science and Engineering—which took place earlier this year in Amsterdam, the Netherlands—an engaging panel session explored strategies for the recruitment and retention of individuals from underrepresented minorities in order to diversify the workforce. From left to right: the panel was moderated by Maria Vlasiou (Eindhoven University of Technology) and included Malena Español (Arizona State University), Juan Restrepo (Oak Ridge National Laboratory), and Damian Rouson (Lawrence Berkeley National Laboratory). SIAM photo.

Further Reading

Hofstra, B., Kulkarni, V.V., Munoz-Najar Galvez, S., He, B., Jurafsky, D., & McFarland, D.A. (2020). The diversity-innovation paradox in science. *Proc. Natl. Acad. Sci., 117*(17), 9284-9291.

Lina Sorg is the managing editor of SIAM News.

SIAM Fellows 2023

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

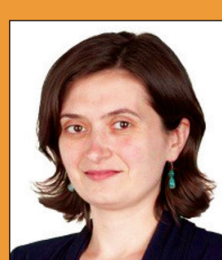
Rodrigo Bañuelos
Purdue University

George Biros
The University of Texas at Austin

Ron Buckmire
Occidental College

Fioralba Cakoni
Rutgers, The State University of New Jersey

Daniela Calvetti
Case Western Reserve University



Coralia Cartis
University of Oxford

Alina Chertock
North Carolina State University

Lenore Jennifer Cowen
Tufts University

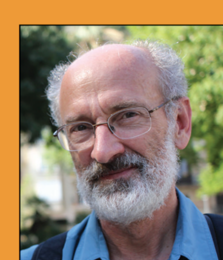
Petros Drineas
Purdue University

Aric Hagberg
Los Alamos National Laboratory

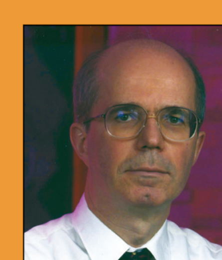
Chandrika Kamath
Lawrence Livermore National Laboratory

Angela Kunoth
University of Cologne

siam Fellow

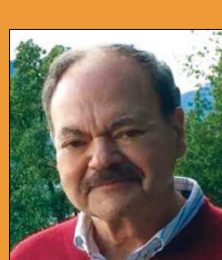


James Donald Meiss
University of Colorado Boulder



Andrew M. Odlyzko
University of Minnesota

Ali Pinar
Sandia National Laboratories



Edward B. Saff
Vanderbilt University

David James Silvester
The University of Manchester

Barry Simon
California Institute of Technology

Catherine Sulem
University of Toronto

Sivan Toledo
Tel Aviv University

Konstantina Trivisa
University of Maryland, College Park

Caroline Uhler
Massachusetts Institute of Technology and Broad Institute

John S. Wettlaufer
Yale University and Nordic Institute for Theoretical Physics

Dongbin Xiu
The Ohio State University

Laurent Younes
Johns Hopkins University

Yongjie Jessica Zhang
Carnegie Mellon University

Learn more about these esteemed individuals and nominate a colleague by October 18, 2023 for the 2024 Class of SIAM Fellows:
siam.org/Prizes-Recognition/Fellows-Program

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CSE23 Panel Reflects on Key Aspects of Mid-career Development

By Lina Sorg

As applied mathematicians, computational scientists, and data scientists move beyond the early-career stage and become more situated in their professions, they encounter a myriad of new challenges and opportunities. During the 2023 SIAM Conference on Computational Science and Engineering,[1] which took place earlier this year in Amsterdam, the Netherlands, a panel of established researchers described their mid-career experiences in academia and the national laboratories. The speakers overviewed general expectations, discussed possible leadership directions, and offered advice on managing a busier workload and supporting junior scientists. The panel—which was moderated by Carol Woodward (Lawrence Livermore National Laboratory)—comprised Jörn Behrens (University of Hamburg), Donna Calhoun (Boise State University), and Anshu Dubey (Argonne National Laboratory).

To kickstart the discussion, the panelists summarized their respective career trajectories thus far. Dubey explained that a zigzagging path in the early stages of her professional journey eventually brought her to the national labs. When she accepted a mid-career position at Lawrence Berkeley National Laboratory, she was completely unfamiliar with the laboratory system. "If you are changing from one kind of research environment to a completely different kind of environment, be prepared," she said. "Figuring out what questions I needed to ask was the hard part. It required observing, going to meetings, and volunteering to participate in community activities in the lab much more frequently than I otherwise would have." Though Dubey felt more confident when she transitioned to Argonne nearly three years later, she still faces periodic knowledge gaps in laboratory culture.

Calhoun also followed a somewhat irregular career path; after switching her undergraduate major from chemistry to math, she discovered an aptitude for programming and eventually pursued computational mathematics because it combined her programming skills and ability to solve equations. After obtaining her Ph.D. in applied mathematics and completing two postdoctoral appointments, Calhoun spent five years as a research engineer at a national laboratory in France before accepting an associate professor position at Boise State University in 2011. She has since earned tenure and is currently up for promotion to full professor. "I try to keep myself as engaged as possible in what makes this whole enterprise fun," Calhoun said.

Behrens informed the audience that his overarching career motto is to "go with the flow but keep control." Upon earning his Ph.D. and completing a habilitation in Munich, Behrens became a group leader at a laboratory that was conducting tsunami research in response to the 2004 tsunami in the Indian Ocean. He eventually returned to academia as a tenure-track faculty member at the University of Hamburg and acquired tenure in 2014. "Now I feel myself as being senior because I already see my retirement on the horizon," he quipped.

CAREERS IN MATHEMATICAL SCIENCES

Behrens stressed the importance of high-quality research, especially since the nature of one's work changes with upward career mobility. Unlike postdoctoral scholars who are attempting to gain visibility in their fields, mid-career researchers need to *maintain* visibility while also experimenting with new and creative ideas in order to advance. "The teaching and giving aspects are more important in the mid-career, as is sustainability," Behrens said. He noted that the "publish or perish" mindset commonly persists in this period but becomes more intentional. "I started thinking on more of a long-term perspective," Behrens continued, adding that he views papers as connective building blocks for his research that also serve to broaden his network of colleagues.

Another important aspect of career advancement is learning to construct, uphold, and lead groups of younger mentees. When evaluating prospective members for her own research group, Dubey keeps an open mind. "More than any technical expertise, I look for intellectual curiosity," she said. "If the person is interested in learning, they can always be taught." Behrens mentioned that established researchers should diversify their networks and connect with a wide range of professionals and faculty members while still preserving their own unique selling points. They must also begin to view themselves as leaders; broaden their research scope; focus on larger, aspirational projects and goals that can sustain their working groups; and apply for grants accordingly. "Nobody waits for you," Behrens said. "At this point in the mid-career, we are the ones who need to take responsibility for developing curricula and actually lead new research projects."

Dubey expanded upon Behrens' comments about leadership by noting that early-career researchers generally rely on principal investigators to instigate effective connections across disciplines. But as these individuals begin to lead their own projects, they are suddenly responsible for instituting such channels of communication themselves. "In my experience, that has been really hard," she said. "But it's also taught me to be more introspective about my work and interactions with other people, and not assume that I know it all. This is a lesson that has not just been useful in science, but in my life as a whole."

Calhoun remarked that group leaders must have a clear vision of their projects' future directions and regulate their own time appropriately. "In mathematics, we tend to work on a very individual basis," she said. "But that doesn't scale well when you have multiple students. I'm at a point now where I need to figure out how to manage this whole group and have some structure to it." Otherwise, leaders risk spending half of their time in one-on-one meetings with students.

Woodward then directed the conversation to the utility of long-term goals. Behrens stated that long-term objectives are helpful but should always leave room for flexibility. He encouraged attendees to focus on the work environments that best suit their own lives and make decisions appropriately. "That helped me judge whether a step would be helpful in reaching my overall vision," Behrens said. When unexpected prospects emerged, he used this frame of reference to determine their viability.

Dubey admitted that while she does maintain a vision for her career, she often ends up doing the opposite of what she had initially planned. "I've always gone along with whatever life has thrown at me," she said. "You can't be scared of facing an opportunity and making the most of it." In most cases, Dubey's major career decisions have involved actively choosing to leave a scenario that was not working (rather than deciding between two potential pathways).

Next, a session attendee inquired as to whether software publications hold weight

See **Mid-career Development** *on page 12*

[1] https://www.siam.org/conferences/cm/conference/cse23

During the 2023 SIAM Conference on Computational Science and Engineering—which took place earlier this year in Amsterdam, the Netherlands—a panel session addressed the many challenges and opportunities that arise during the mid-career stage of one's professional journey. Carol Woodward (Lawrence Livermore National Laboratory) facilitated the discussion between Jörn Behrens (University of Hamburg), Donna Calhoun (Boise State University), and Anshu Dubey (Argonne National Laboratory), all of whom offered insights into career advancement and group leadership. Here, Behrens speaks about his personal experiences with building and managing research groups. SIAM photo.

Luis Caffarelli Receives the 2023 Abel Prize

Longtime SIAM member Luis A. Caffarelli of the University of Texas at Austin is the sole recipient of the 2023 Abel Prize,[1] one of the most prestigious awards in mathematics. He is honored "for his seminal contributions to regularity theory for nonlinear partial differential equations, including free-boundary problems and the Monge-Ampère equation." Caffarelli's work focuses on equations that help describe physical phenomena, such as melting ice and fluid flow.

The Abel Prize is awarded annually to recognize pioneering scientific achievements in the field of mathematics; Caffarelli will be formally recognized during a ceremony in Oslo, Norway, on May 23. Congratulations on this incredible honor!

[1] https://abelprize.no/abel-prize-laureates/2023

Jaypee University of Information Technology SIAM Student Chapter Celebrates Successful Establishment

By Achyut Tiwari, Vivek Kumar Sehgal, and Suveer Sharma

The Jaypee University of Information Technology (JUIT) SIAM Student Chapter[1]—one of the most recent SIAM student chapters to be established in India—has already had an impactful tenure since its founding in October 2022. In fact, the chapter grew from seven founding members to 70 members—ranging from undergraduate students to Ph.D. candidates—in its first six months. All members are actively involved in chapter activities, which are led by elected officers and faculty advisor Vivek Kumar Sehgal. The chapter is engaged with other universities and has already formed solid connections with its sister chapters in India to develop plans for future collaborations.

The JUIT SIAM Student Chapter has organized two flagship events thus far: the ongoing Distinguished Speaker Seminar Series and an "Introduction to Project Euler" workshop. The chapter launched its Distinguished Speaker Seminar Series in November 2022 by inviting eminent individuals within both the academic and industrial worlds to share their wisdom and experience with attendees. The presenters are all part of the SIAM Visiting Lecturer Program,[2] which provides a roster of experienced applied mathematicians and computational scientists who can speak on a variety of topics that are relevant to junior researchers. Chapter leadership has organized at least one seminar per month and intends to sustain this effort as the chapter continues to grow. Thus far, the following prominent speakers from various domains have delivered virtual talks on their respective areas of expertise:

- Mark Squillante (IBM Research) discussed decision-making under uncertainty[3]
- Bonita Saunders (National Institute of Standards and Technology) spoke about ongoing computational and applied mathematics research at her institution[4]
- Allen Butler (Daniel H. Wagner Associates) explored possible math careers in business, industry, and government.[5]

In February 2023, the JUIT SIAM Student Chapter organized a two-day, in-person event called "Introduction to Project Euler." Named after famous mathematician Leonhard Euler, Project Euler[6] is a collection of challenging mathematical and computational problems that are meant to encourage and develop problem-solving skills in mathematics, computer science, and related disciplines. The problems in Project Euler—which was established in 2001 by Colin Hughes—vary in difficulty and cover a wide range of topics, including number theory, combinatorics, algebra, geometry, and computer science. Researchers can use programming languages to solve these problems and share their solutions on the Project Euler website.

The first day of the chapter's Project Euler event consisted of presentations and brainstorming sessions that collectively served as a crash course on the underlying mathematical logic of several Project Euler problems. During the second day, attendees took part in a hackathon and attempted to solve problems from the Project Euler collection; the winners received cash prizes.

Looking ahead, the chapter is planning to organize a workshop about ancient Vedic mathematics in the coming months. This workshop will allow participants the unique opportunity to explore mathematical concepts and techniques that are rooted in Indian history and culture. With its commitment to coordinating diverse and engaging events, the JUIT SIAM Student Chapter is a valuable resource for students who are interested in careers in applied mathematics and computational science.

Achyut Tiwari is the founding president of the Jaypee University of Information Technology (JUIT) SIAM Student Chapter. His research combines machine learning and dynamical systems to apply computational methodologies in bioinformatics. Tiwari is a member of SIAM and the Association for Computing Machinery (ACM). Vivek Kumar Sehgal is a professor and head of the Department of Computer Science & Engineering and Information Technology at JUIT, where he also serves as faculty advisor to the JUIT SIAM Student Chapter. He is a fellow of the Institution of Engineers and a senior member of ACM and the Institute of Electrical and Electronics Engineers. Suveer Sharma is the founding secretary of the JUIT SIAM Student Chapter and a member of SIAM. His research focuses on deep learning for image processing and blockchain technologies.

[1] https://siam-juit.github.io/website

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

[3] https://youtu.be/AZ6T1Sf4ESg

[4] https://youtu.be/d4wOazHixmM

[5] https://youtu.be/d8j48kADKz8

[6] https://projecteuler.net

On the second day of the Jaypee University of Information Technology (JUIT) SIAM Student Chapter's "Introduction to Project Euler" event, attendees participated in a hackathon and used programming techniques to solve mathematical and computational problems from Project Euler. Photo courtesy of the JUIT SIAM Student Chapter.

Members of the Jaypee University of Information Technology (JUIT) SIAM Student Chapter gather for a chapter meeting in January 2023. Photo courtesy of the JUIT SIAM Student Chapter.

Mid-career Development

Continued from page 11

in the "publish or perish" landscape. Behrens observed that software can be an asset if one is pursuing an applied position but is less valued in pure mathematics settings. Nevertheless, its clout continues to grow. "As more people realize that software is an outcome of many cases, it's becoming a research product in its own right," Dubey said. She promoted *SoftwareX*[2]—a peer-reviewed, open-access journal that is dedicated to scientific software—and urged interested parties to learn more about the burgeoning research software engineering initiative[3] in the U.S. Dubey also mentioned Better Scientific Software[4] and the Software Sustainability Institute[5] as groups wherein software proponents can interact with like-minded individuals, become advocates at their own institutions, and increase the credibility of software as a valuable project outcome.

Calhoun agreed that numerous institutions are beginning to recognize software as a significant contribution to the field. "You need to demonstrate that it's being used by more than just yourself," she said. "But it's definitely worth pursuing, especially if you feel like it's a way that you can really say something." Dubey added that the best way to maintain software—and thus make it a relevant component of a portfolio—is to invest in its design from the start and avoid any corner-cutting procedures in the early stages of development. If other users will be employing the software, the creator should transition it to a community-based development setup with established gatekeepers so that the software can continue "living" in its own right.

In response to another audience member's query, the panelists subsequently addressed time management. Calhoun noted that mid-career academics are typically accountable for three distinct areas: research, teaching, and service. She recommended that individuals focus their energy on two of those categories while making sure to still perform adequately in the third. "I don't think it's necessary to take on things that you won't enjoy," she said. "Time is the scarcest resource in this business. Pick what you like and try to say 'no' to the other things."

When Dubey was asked to lead a research group for the first time, she agreed under the condition that she would assess her satisfaction level in six months and step down if it was not working for her. She soon found herself to be an effective leader but discovered that the addition of another activity to her already full schedule was unfeasible. So, she gave up teaching because it was the area that she enjoyed the least. "You really need to think through your own priorities," Dubey said. "Just say 'no' to whatever you cannot do. It's part of human nature to carve out time for what you like and start to resent what you don't. You can juggle many things more effectively as long as you care about all of them."

Behrens noted that individuals who commit to a project must deliver their promised contributions in a timely manner. But because the number of obligations grows exponentially at the mid-career level, not everything can be perfect. "You need to be selective about when it has to be 100 percent and when it is enough to deliver 80 percent," Behrens said. "This is something that you learn by experience, but it's important to keep in mind." In some cases, "good enough" is satisfactory.

As the session concluded, the speakers all agreed that the mid-career is an exciting time in one's professional journey. With newfound responsibilities come additional freedoms, continued growth, expanded networking settings, and opportunities for unique collaborations. "Every day I still learn," Behrens said. "And that is a privilege."

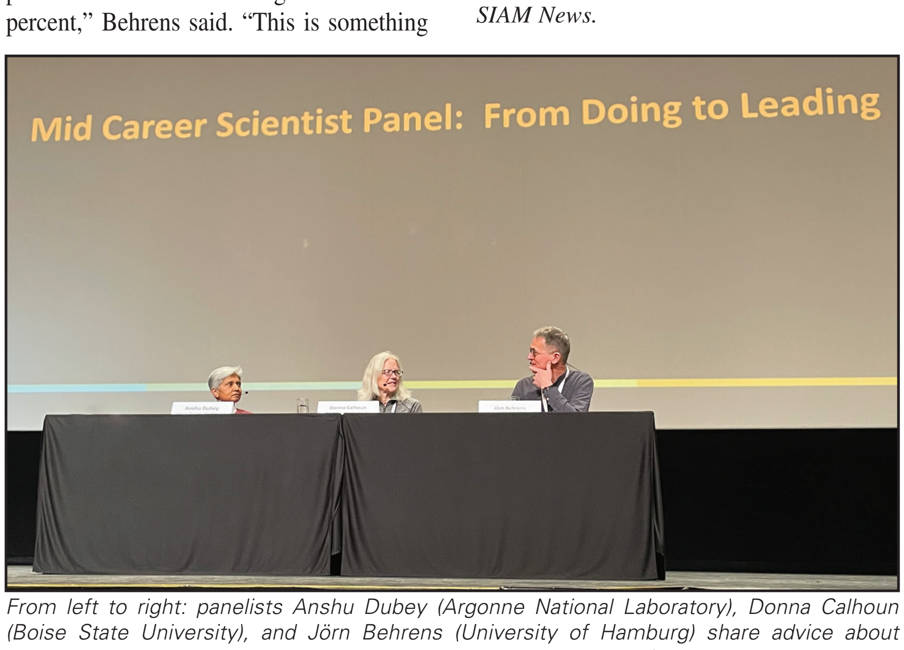
Lina Sorg is the managing editor of SIAM News.

[2] https://www.sciencedirect.com/journal/softwarex

[3] https://us-rse.org

[4] https://bssw.io

[5] https://www.software.ac.uk



From left to right: panelists Anshu Dubey (Argonne National Laboratory), Donna Calhoun (Boise State University), and Jörn Behrens (University of Hamburg) share advice about managing the expectations, responsibilities, and opportunities of the mid-career stage at the 2023 SIAM Conference on Computational Science and Engineering, which took place in Amsterdam, the Netherlands, earlier this year. SIAM photo.