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

siam news

Volume 55/ Issue 9
November 2022

Learning for Dynamical Systems When Data Are Scarce

By Ufuk Topcu and Frederick Leve

Learning-based techniques promise the possibility of modeling unknown dynamical systems and thus facilitating predictions of values of interest, synthesizing control strategies, and verifying the safety of closed-loop systems. Many such algorithms assume the availability of data that span all types of relevant behaviors for training purposes. However, employment of the existing, purely data-driven techniques for dynamical systems with a physical embodiment can result in poor data efficiency, fail to generalize beyond the training domain, and even violate the underlying laws of physics. Such deficiencies are particularly apparent when the training dataset is relatively small, as is the case with practically all dynamical systems applications with a physical embodiment — especially those in dynamic and possibly contested environments.

Physics can and should inform learning for dynamical systems. We seldom need to learn merely from data because useful *a priori* system knowledge is often available, even when the exact dynamics are unknown. Such knowledge may stem from a variety of sources, such as basic physical principles, geometry constraints that arise from the system's design, structural properties of the vector field (e.g., decoupling between the states), monotonicity of or bounds on the vector field, algebraic constraints on the states, and/or empirically-validated invariant sets in the state space. This knowledge may present itself in various representations, including parametric and functional forms.

The effective inclusion of *a priori* knowledge when learning for dynamical systems can ensure that the learned model respects physical principles; it also significantly improves data efficiency and model generalization to previously unseen regions of the state space. Data and knowledge can collectively enable the rapid deployment of learning-based control strategies for systems with physical embodiments, in addition to reliable operation in the face of unexpected changes.

Here we exemplify the effectiveness of the joint use of data and physics-based knowledge in two settings with severe data scarcity. The first involves learning after an abrupt change in a system's dynamics during its operation, when learning is limited to data that essentially come from a single trajectory (see Figure 1). And the second scenario entails training deep neural networks for dynamical systems modeling to match or exceed the accuracy of conventional, data-driven deep learning methods while also relying on a number of trajectories that is multiple orders of magnitude fewer. Although the suitable learning artifacts and expectations from learning differ between these two settings, the types, representations, and means of incorporating physics-based knowledge into learning are based on similar principles.

See **Dynamical Systems** *on page 3*

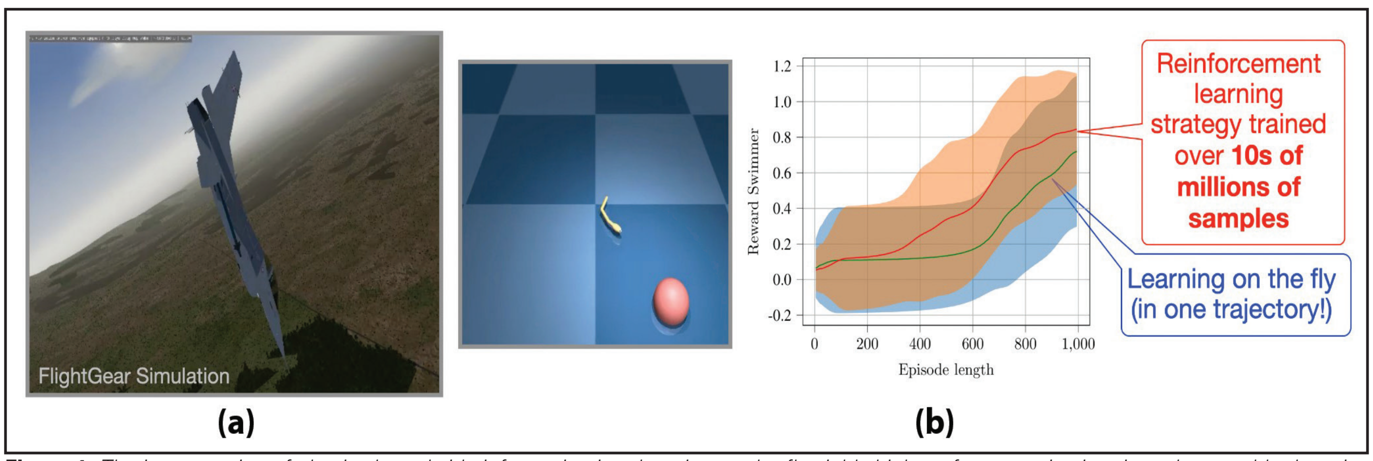


Figure 1. *The incorporation of physics-based side information into learning on the fly yields high performance in situations that would otherwise be challenging—if not impossible—for merely data-driven learning approaches.* **1a.** *Recovery of an F-16 aircraft with a priori unknown dynamics from a low-altitude, nose-down configuration.* **1b.** *A comparison between state-of-the-art reinforcement learning algorithms and pre-training via extensive data. Figure courtesy of Ufuk Topcu and concepts courtesy of [1].*

Computational Imaging Sheds Light on the Black Hole in Our Galactic Center

By Aviad Levis

Black holes, which were once considered a mathematical peculiarity of Einstein's theory of general relativity, are nowadays one of the most exciting research topics in astronomy and astrophysics. Though these bodies are not directly visible, they may leave a fingerprint in the form of a dark central region (or shadow) amid the surrounding bright gas. In May 2022, the Event Horizon Telescope[1] (EHT) collaboration debuted the first image of the supermassive black hole at the center of our galaxy: Sagittarius A* (Sgr A*, pronounced "sadge-ay-star") [3]. This result provided direct visual evidence of a black hole, depicting the tell-tale sign of a ring-like structure (see Figure 1).

The image of Sgr A* was not captured like a regular photograph; it is a computational image that was reconstructed from measurements by synchronized telescopes around the globe (see Figure 2, on page 4). When joined together with an imaging technique called very large baseline interferometry, these separate telescopes form a virtual instrument that is sensitive enough to resolve an image of a donut on the moon. During this powerful approach, each telescope pair probes a single frequency in the image's Fourier transform. The probed frequency is proportional to the *projected* baseline between the two telescopes. Simply put, nearby telescopes are sensitive to low spatial frequencies (broad, diffuse features in the image) and distant telescopes are sensitive to high spatial frequencies (sharp edges and details).

Analyzing the EHT observations of Sgr A* was not an easy feat. In fact, it took more than 300 scientists from over 80 institutions almost five years to interpret and reveal the first images. One of the key computational challenges stems from the rapid evolution of Sgr A* during the EHT acquisition; scientists believe that this apparent evolution occurs because of the hot gas that swirls around Sgr A*. Taking an image of the rapidly changing gas is somewhat analogous to trying to photograph a fast-moving sprinter.

Our first imaging attempts sought to capture the average structure of the black hole by treating the evolution as a form of noise (see Figure 1). While this "static" image certainly offers interesting insights, we also wanted to uncover the dynamic evolution of Sgr A*. To that end, we developed algorithms that can recover a video sequence from the same telescope measurements [1]. We spent years analyzing the data with these video reconstruction methods, but the results were ultimately inconclusive (see Figure 3, on page 4).

Recovering the dynamic evolution is difficult because we only have access to a sparse set of measurements at any given time; this is similar to only seeing a few pixels of the sprinter over time. Adding additional telescopes could provide more information for the recovery of a movie. The Next Generation EHT[2] collaboration is focused on expanding the EHT network with further telescope sites to image the dynamic evolution of supermassive black holes [2]. With the help of computational algorithms, we recently discovered that this supercharged EHT array might allow us to go beyond a two-dimensional (2D) image or movie and recover the three-dimensional (3D) structure of gas swirling around Sgr A*.

We therefore seek to answer the following questions: Can we use EHT observations to recover more than a 2D image or movie? For example, can we recover the 3D distribution of light around a black hole over time? To achieve this goal, we are currently developing new computational algorithms that fuse physics models with

See **Black Hole** *on page 4*

[1] https://eventhorizontelescope.org

[2] https://www.ngeht.org

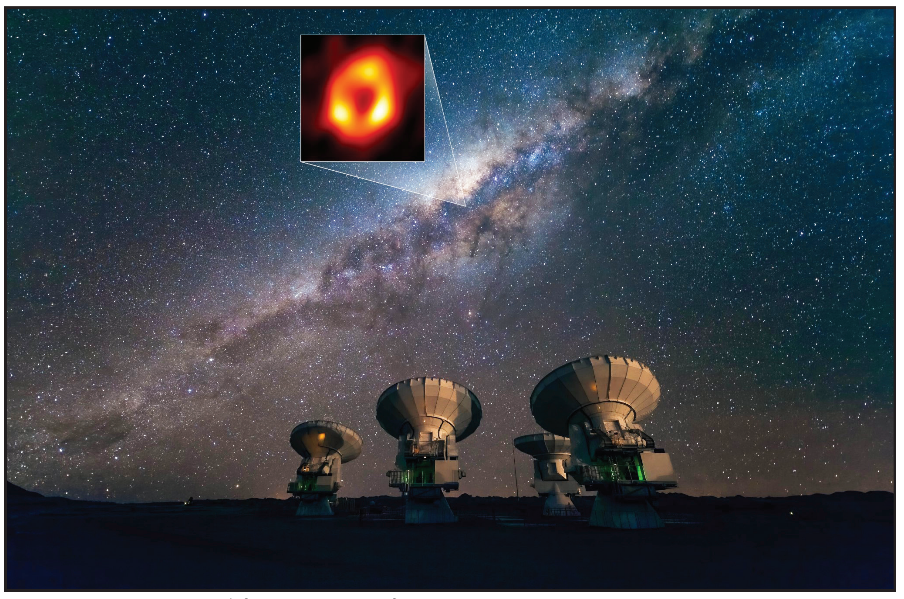


Figure 1. *The image of Sagittarius A* (Sgr A*) inset above radio telescopes at the Atacama Large Millimeter/submillimeter Array (ALMA) Observatory in Chile. ALMA is the most sensitive of the eight Event Horizon Telescopes (EHTs) that observed Sgr A* in 2017. Figure courtesy of the EHT Collaboration.*

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

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

siam news
Volume 55/ Issue 9/ November 2022

ICIAM Announces 2023 Prize Recipients

The International Council for Industrial and Applied Mathematics[1] (ICIAM) has announced the winners of the six 2023 ICIAM prizes.[2] ICIAM is a worldwide organization for professional applied mathematics societies and other associations with a significant interest in industrial or applied mathematics. It seeks to advance mathematical applications around the globe.

The associated ICIAM congresses[3] are held every four years under the auspices of the Council. The 2023 prizes will be awarded during the Opening Ceremony of the 10th International Congress on Industrial and Applied Mathematics[4] (ICIAM 2023), which will take place at Waseda University in Tokyo, Japan, from August 20-25, 2023. ICIAM President Ya-xiang Yuan (Chinese Academy of Sciences) chaired the Prize Committee, which also comprised the following individuals:

- Kim-Chuan Toh (National University of Singapore), chair of the Collatz Prize Subcommittee
- Leah Edelstein-Keshet (University of British Columbia), chair of the Lagrange Prize Subcommittee
- Gang Bao (Zhejiang University), chair of the Maxwell Prize Subcommittee
- Alfredo Bermudez (University of Santiago de Compostela), chair of the Pioneer Prize Subcommittee
- Lois Curfman McInnes (Argonne National Laboratory), chair of the Su Buchin Prize Subcommittee
- Nira Chamberlain (SNC-Lavalin Group), chair of the Industry Prize Subcommittee.

[1] https://iciam.org
[2] https://iciam.org/2023-iciam-prizes-recipients-and-committees
[3] https://iciam.org/iciam-congresses
[4] https://iciam2023.org

Collatz Prize

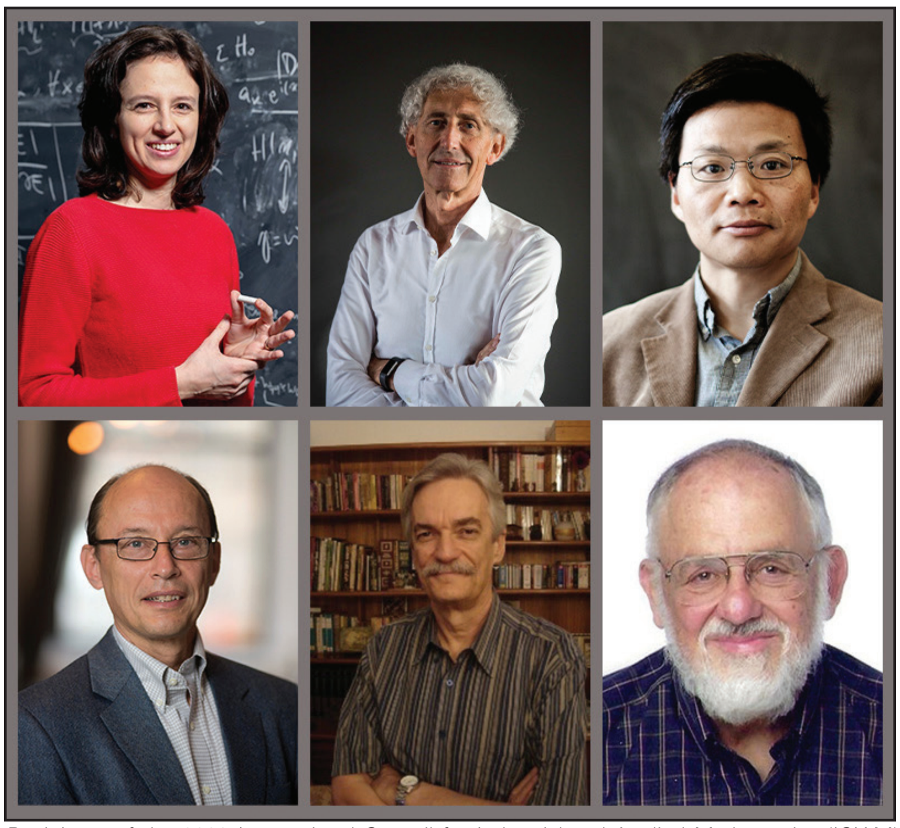
The Collatz Prize was established to provide international recognition to individual scientists under 42 years of age who have conducted outstanding work in industrial and applied mathematics. It was created by an initiative of the Gesellschaft für Angewandte Mathematik und Mechanik (GAMM) and first awarded in 1999. The Collatz Prize is currently funded by GAMM and carries a cash award of USD 5,000.

The 2023 Collatz Prize is awarded to Maria Colombo (École polytechnique fédérale de Lausanne) for her fundamental contributions to regularity theory and the analysis of singularities in elliptic partial differential equations, geometric variational problems, transport equations, and incompressible fluid dynamics.

Lagrange Prize

The Lagrange Prize was established to provide international recognition to individual mathematicians who have made exceptional contributions to applied mathematics throughout their careers. It was created through an initiative of the Sociedad Española de Matemática Aplicada (SEMA), Società Italiana di Matematica Applicata e Industriale (SIMAI), and Société de Mathématiques Appliquées et Industrielles (SMAI). The Lagrange Prize, which was first awarded in 1999, is presently funded by four of ICIAM's member societies: SEMA, SIMAI, SMAI, and Sociedade Brasileira de Matemática Aplicada e Computacional. It carries a cash award of USD 5,000.

The 2023 Lagrange Prize is awarded to Alfio Quarteroni (Politecnico di Milano) for his groundbreaking work in finite-element and spectral methods, domain decomposition methods, discontinuous Galerkin methods, numerical solutions of incompressible Navier-Stokes equations, and multiphysics and multiscale modeling. Quarteroni's work finds applications in fluid dynamics, geophysics, the human heart and circulatory system, the COVID-19 pandemic, and improved performance in the America's Cup sailing competition.



Recipients of the 2023 International Council for Industrial and Applied Mathematics (ICIAM) prizes. Top row, left to right: Maria Colombo (École polytechnique fédérale de Lausanne), winner of the Collatz Prize; Alfio Quarteroni (Politecnico di Milano), winner of the Lagrange Prize; and Weinan E (Peking University and Princeton University), winner of the Maxwell Prize. Bottom row, left to right: Leslie Greengard (New York University's Courant Institute of Mathematical Sciences and the Simons Foundation's Flatiron Institute), winner of the Pioneer Prize; José Mario Martinez Perez (University of Campinas), winner of the Su Buchin Prize; and Cleve B. Moler (MathWorks), winner of the Industry Prize. Photos courtesy of ICIAM.

Maxwell Prize

The Maxwell Prize was established to provide international recognition to mathematicians who have demonstrated originality in applied mathematics. It was founded by an initiative of the Institute of Mathematics and its Applications (IMA) with support from the James Clerk Maxwell Foundation. The Maxwell Prize, which was first awarded in 1999, is currently funded by the IMA and James Clerk Maxwell Foundation and carries a cash award of USD 5,000.

The 2023 Maxwell Prize is awarded to Weinan E (Peking University and Princeton University) for his seminal contributions to applied mathematics, particularly the analysis and application of machine learning algorithms, multiscale modeling, modeling of rare events, and stochastic partial differential equations.

Pioneer Prize

The Pioneer Prize was established to acknowledge pioneering work that introduces applied mathematical methods and scientific computing techniques to an industrial problem area or a new scientific field of application. It was created on the initiative of SIAM and first awarded in 1999. The Pioneer Prize is presently funded by SIAM and carries a cash award of USD 5,000.

The 2023 Pioneer Prize is awarded to Leslie Greengard (New York University's Courant Institute of Mathematical Sciences and the Simons Foundation's Flatiron Institute) for his pioneering work on fast algorithms, including the fast multipole method (one of the top 10 algorithms of the 20th century), fast Gauss transform, and fast direct solvers. Greengard is also honored for the development of innovative high-order, automatically adaptive algorithms for differential and integral equations.

Su Buchin Prize

The Su Buchin Prize was established to internationally recognize individuals' outstanding contributions in the application of mathematics to emerging economies and human development, particularly at the economic and cultural level in developing countries. Such contributions include efforts to improve mathematical research and teaching in these countries. The prize was created as an initiative of the China Society for Industrial and Applied Mathematics (CSIAM) and first awarded in 2007; it is currently funded by CSIAM and carries a cash award of USD 5,000.

The 2023 Su Buchin Prize is awarded to José Mario Martinez Perez (University of Campinas) for outstanding achievements in research—a combination of theory, practice, software, and applications for the solution of large-scale optimization problems—and for fostering the development of the optimization and applied mathematics communities in Latin America.

See **Prize Recipients** *on page 3*

siam news

ISSN 1557–9573.

Dynamical Systems

Continued from page 1

Control-oriented Learning on the Fly

Consider an extreme yet realistic scenario wherein an aerial vehicle suffers from an abrupt change in its dynamics—e.g., due to severe structural damage or loss of an engine—and attempts to retain control. This circumstance necessitates that researchers learn the dynamics via data from only a single (and ongoing) trajectory. Under such severe data limitations, one can only perform learning efficiently by incorporating existing side information about properties of the underlying *unknown* dynamics. It is worth emphasizing that the availability of side information does not imply that the dynamics—or even an *a priori* parametrization of them—are known.

Figure 2 depicts the workflow of a recently proposed method. Using existing data from the ongoing run as well as side information, this method computes an overapproximation of the set of states that the system may reach (see steps 2 and 3 in Figure 2). Data-driven differential inclusions that contain the unknown vector field offer control-oriented representations of these overapproximations. The method computes such differential inclusions using an interval Taylor-based technique that can enforce constraints from side information to reduce the width of the overapproximations as more data become available. It then incorporates an overapproximation into a constrained short-horizon optimal control problem (see steps 4 and 5 in Figure 2) and solves this problem *on the fly* by resorting to convex relaxations that are optimistic or pessimistic. One can provide a theoretical bound (which is also practically relevant) on the number of primitive operations that are necessary to compute the control values, thus ensuring real-time implementability.

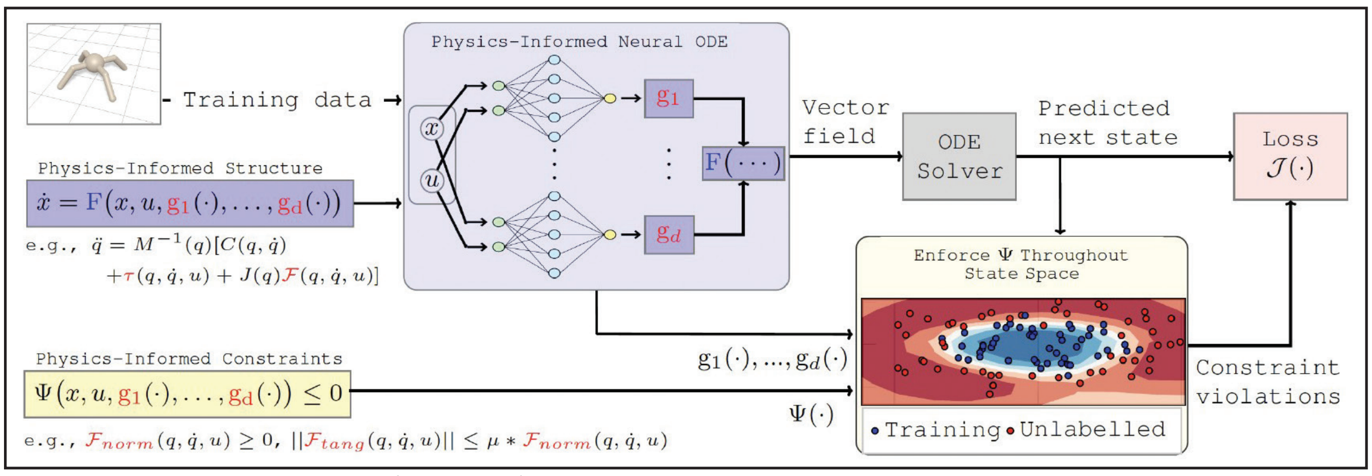


Figure 3. *A structured representation of the vector field (in blue) captures a priori physics-based knowledge, while neural networks (in red) represent unknown components. Physics-based constraints are enforced on the outputs, not only on the labeled training data points but also on any unlabeled points within the state space where the constraints are known to hold (in yellow). Figure adapted from [2].*

Dynamical Systems Models Using Neural Networks with Physics-informed Architecture and Constraints

While the first method focuses on learning over a single trajectory (and is hence only concerned with discovering knowledge that will influence the evolution along that trajectory), our second method focuses on learning complex relationships—encoded as neural networks—that model unknown dynamical systems.

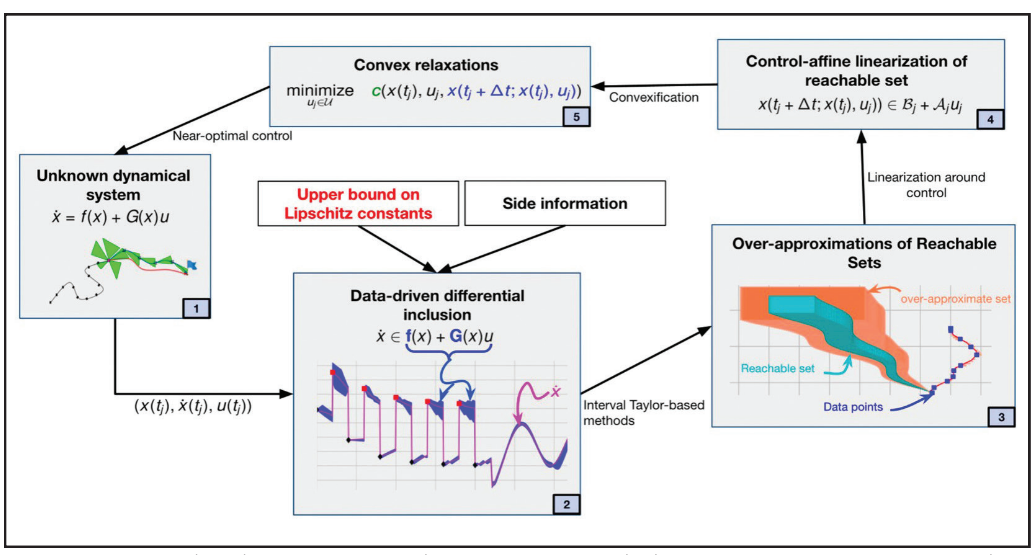


Figure 2. *The workflow for learning on the fly. Figure courtesy of Ufuk Topcu and concepts courtesy of [1].*

This method uses neural networks to parametrize the dynamical system's vector field and numerical integration schemes to predict future states, rather than parametrizing a model that predicts the next state directly (see Figure 3). Two distinct mechanisms help incorporate physics-based knowledge as inductive bias. The first mechanism informs the choice of architecture for the vector field as a composition of unknown terms that are parametrized as neural networks and known terms that are derived from *a priori* knowledge:

$$\dot{x} = h(x,u) = F(x, u, g_1(\cdot), \dots, g_d(\cdot)).$$

Here, F is a known differentiable function that encodes available prior knowledge and the functions $g_1, \dots, g_d$ encode the unknown terms. For example, Figure 4 illustrates a robotics environment whose equations of motion are only partially known; although the robot's mass matrix is available, the remaining terms in its equations of motion (i.e., its actuation and contact forces) must be learned. One can then compose neural networks that represent the unknown terms with the known mass matrix to obtain a model of the system's vector field.

The second mechanism enforces physics-based constraints on the values of the model's outputs and internal states. Consider a particular physics-informed model $F(x, u, G_\Theta)$ of the vector field with unknown terms that are parametrized by the collection of neural networks G_Θ. The objective is to solve for a set of parameter values that minimize the loss $J(\Theta)$ over the training dataset while also satisfying all of the known physics-based constraints:

$$\min_{\Theta} \mathcal{J}(\Theta) \quad \text{s.t.}$$

$$\Phi(x, u, G_\Theta) = 0, \ \forall (x,u) \in \mathcal{C}_\Phi \quad \text{and}$$

$$\Psi(x, u, G_\Theta) \leq 0, \ \forall (x,u) \in \mathcal{C}_\Psi.$$

Here, $\Phi(x, u, G_\Theta)$ and $\Psi(x, u, G_\Theta)$ are differentiable functions that respectively capture the physics-informed equality and inequality constraints (of which there may be a multitude).

While only a limited number of data points might be available for supervised learning, constraints that are derived from *a priori* knowledge will hold over large subsets of the state space — and potentially over the entire state space. Ensuring that the learned model satisfies the relevant constraints throughout the space—while also fitting the available trajectory data—yields a semi-supervised learning scheme that generalizes the available training data to the unlabeled portions of the state space.

Outlook

The potential of learning with insights from diverse sources of data and existing knowledge extends far beyond the two examples that we discuss here and has attracted considerable attention as of late. Existing approaches include physics-informed neural networks, neurosymbolic reinforcement learning, and learning with statistical invariants. We argue that such hybrid approaches will be key during the establishment of appropriate provable guarantees of safety, robustness, and generalizability within the data, as well as computational and perceptual limitations of dynamical systems with a physical embodiment.

Acknowledgments: Ufuk Topcu is supported by the Air Force Office of Scientific Research's Multidisciplinary Research Program of the University Research Initiative on "Verifiable, Control-oriented Learning on the Fly."

References

[1] Djeumou, F., & Topcu, U. (2022). Learning to reach, swim, walk and fly in one trial: Data-driven control with scarce data and side information. In *Proceedings of the learning for dynamics and control conference 2022* (pp. 453-466). Stanford, CA.

[2] Djeumou, F., Neary, C., Goubault, E., Putot, S., & Topcu, U. (2022). Neural networks with physics-informed architectures and constraints for dynamical systems modeling. In *Proceedings of the learning for dynamics and control conference 2022* (pp. 263-277). Stanford, CA.

[3] Freeman, C.D., Frey, E., Raichuk, A., Girgin, S., Mordatch, I., & Bachem, O. (2021). Brax — a differentiable physics engine for large scale rigid body simulation. Preprint, *arXiv:2106.13281*.

Ufuk Topcu is an associate professor at the University of Texas at Austin. His research focuses on the design and verification of autonomous systems at the intersection of controls, formal methods, and learning. Frederick Leve is the program officer for the Dynamical Systems and Control Theory Program within the U.S. Air Force Office of Scientific Research.

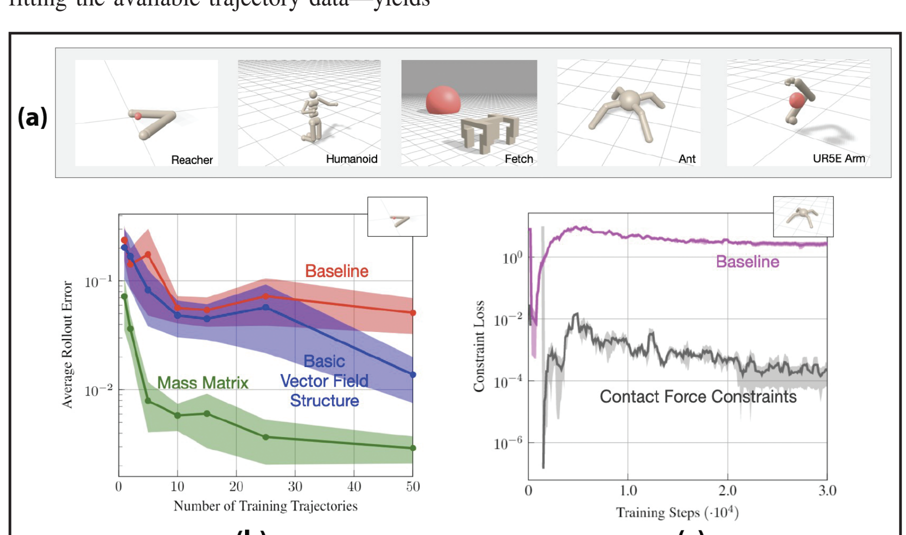


Figure 4. *Representative results that utilize a suite of robotics benchmarks [3].* **4a.** *A suite of simulated robotic systems for demonstration.* **4b – 4c.** *Selected results demonstrate the utility of incorporating different types of physics-based side knowledge, including* **(4b)** *improvement in test performance and* **(4c)** *compliance with the underlying laws of physics — even in parts of the environment with no training data. Figure adapted from [2].*

Prize Recipients

Continued from page 2

Industry Prize

The Industry Prize was established to provide international recognition to scientists who have made outstanding contributions to innovative mathematical techniques with a demonstrated impact in industry. It was created in 2020 and will be presented for the first time in 2023. The Industry Prize is presently funded by the Japan Society for Industrial and Applied Mathematics and carries a cash award of USD 5,000.

The 2023 Industry Prize is awarded to Cleve B. Moler (MathWorks) for his outstanding contributions to the development of mathematical and computational tools and methods for the solution of science and engineering problems. Moler is acknowledged for his invention of MATLAB, which allows industrial users to harness efficient and reliable numerical methods to execute numerical simulations in ever-expanding domains of science and engineering.

As a founding member of ICIAM, SIAM is proud to support the ICIAM congresses. SIAM's Annual Meeting is not held during ICIAM years, and SIAM members are instead encouraged to consider presenting their research at the 2023 ICIAM Congress in Tokyo. Submissions for minisymposia and contributed talks[5] are being accepted through **December 23, 2022**.

As with previous ICIAM congresses, SIAM will maintain and publish a list of accepted ICIAM minisymposia that were organized by members of SIAM Activity Groups (SIAGs). If you wish to have your accepted ICIAM submission identified as sponsored by a specific SIAG, please email Richard Moore, SIAM's Director of Programs and Services, at **moore@siam.org** with the minisymposium title, the speakers and individual titles if available, and the SIAG. Please do not send this information until ICIAM has confirmed acceptance of your minisymposium.

SIAM will also offer a limited number of travel awards to the 2023 ICIAM Congress, with priority given to students and early-career researchers. More information will be posted on SIAM's ICIAM 2023 webpage[6] as it becomes available.

We look forward to seeing many of you in Tokyo next year!

[5] https://iciam2023.org/1225
[6] https://www.siam.org/conferences/cm/conference/iciam23

Black Hole

Continued from page 1

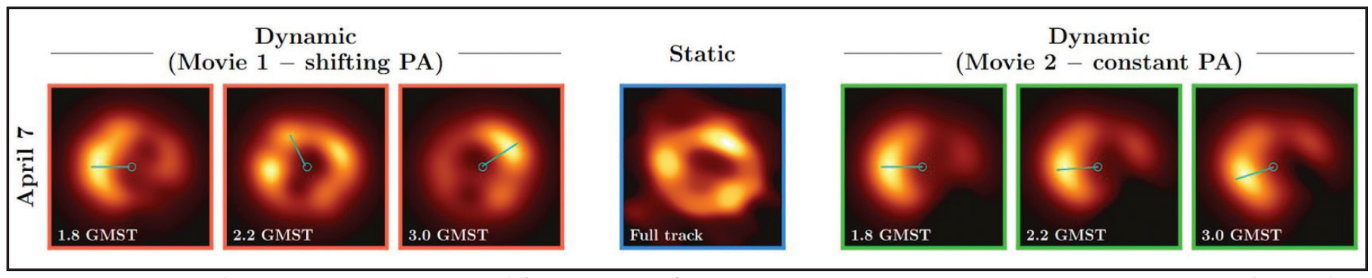


Figure 3. *Recovery of an entire video sequence of Sagittarius A* (Sgr A*) yielded inconclusive results. Here we show three frames from two recovered videos (Movie 1 and Movie 2), as well as the static image for comparison. The position angle (PA), which is loosely defined as the angle of mean brightness, is highlighted in each frame. Every recovered video was derived from the same observations using the same algorithm with different input parameters. Depending on input parameters that control the temporal smoothness of the reconstructed video, we recovered different trends (different PAs over time) in the dynamic evolution of Sgr A*. Figure courtesy of [3].*

machine learning tools to extract as much data as possible from future observations.

Recovery of the 3D volume of Sgr A* will require a form of tomography. Computed tomography (CT) is a computational inverse problem that aims to recover densities of a medium from lower-dimensional projections. For example, X-ray CT is a well-established medical imaging technology for non-intrusive diagnosis.

Unlike medical CT, *black hole tomography* faces some unique computational challenges in the form of *gravitational lensing* and the limits that are imposed by having a *single viewpoint*. The former occurs because the strong gravitational field of a black hole bends the trajectory of light as it travels nearby (see Figure 4a). This phenomenon is called gravitational lensing because the mass acts as a sort of lens. It necessitates a change from typical CT or 3D reconstruction, wherein light is assumed to move along straight paths. Utilizing the physics of gravitational lensing to model this unique image projection is a crucial component of the solution to the black hole tomography problem.

Figure 2. *Synchronized telescopes across the globe form a virtual telescope called the Event Horizon Telescope that can achieve an unprecedented resolution. Figure courtesy of Kristy Johnson.*

Additionally, while tomography typically relies on multiple viewpoints, Sgr A*'s distance from Earth means that we only have access to a single view. To overcome this limitation, we incorporated a model for orbital dynamics that effectively replaces multiple views with multiple frames over time. Doing so is akin to having access to a single X-ray view but asking the patient to rotate in order to obtain a full CT volume recovery. While gas does not rigidly rotate like a person might, its orbit around a supermassive black hole is *predictable* (to some degree).

We have taken the first steps towards 3D recovery by revealing a new imaging possibility for the future of EHT observations. While we are still far from determining the 3D structure of gas around Sgr A*, our initial simulations have shown promising results on simplified test cases [4]. We are now in the process of expanding these ideas to more realistic simulated data.

Recently, astronomers have found exciting evidence—via measurements from the Atacama Large Millimeter/submillimeter Array (ALMA) Observatory—of a hot gas bubble orbiting Sgr A* [5] (see Figure 1, on page 1). However, the evidence is thus far inconclusive; being able to resolve a 3D image of an orbiting gas bubble would therefore have immense scientific implications. Through simulations, we have shown that only 40 minutes of (future) EHT observations might sufficiently reveal such a bubble as it orbits close to the event horizon of Sgr A* (see Figure 4b). Nevertheless, we still have a ways to go before we can use this technique on real data with sufficient measurement coverage. In the meantime, we are working on extending the applicability of our approach to realistic data and its associated complexities. We hope that by utilizing the entire EHT array, including ALMA, we might be able to reveal the 3D structure and evolution of these gas bubbles.

All of the aforementioned imaging approaches—including recovery of a static image, a movie, and the 3D evolution around Sgr A*—are complimentary. We need every one of them (and more) to reveal different aspects of Sgr A*. One could say that these methods lie on a spectrum of model assumptions. Static images and videos of Sgr A*—for which we avoid biasing our algorithms towards the existence of a ring, in order to encourage flexibility and allow for scientific discovery—fall on one end of the spectrum. Because of our modest model assumptions, these procedures are limited in the types of information that they can extract from the data. On the other end of the spectrum, 3D imaging relies on a black hole model to characterize light propagation and orbital dynamics. With some reasonable model assumptions, we might be able to recover the 3D structure around Sgr A*. However, these assumptions mean that such an approach would be blind to any model inaccuracies and the possibility that Sgr A* is not a black hole.

Ultimately, the goal of this type of imaging is slightly different. Instead of establishing the existence of a black hole, we ask the following question: If Sgr A* is a black hole, can we study the 3D structure of gas around it? We hope that these new imaging methods will shed light on the complex plasma processes in our galactic center in the not-so-distant future. Through EHT tomography, we may even catch a glimpse of the very nature of space-time itself around the most extreme environment in our galaxy.

Acknowledgments: The author would like to acknowledge Katherine Bouman (California Institute of Technology) for her help with and review of this article.

References

[1] Bouman, K.L., Johnson, M.D., Dalca, A.V., Chael, A.A., Roelofs, F., Doeleman, S.S., & Freeman, W.T. (2018). Reconstructing video of time-varying sources from radio interferometric measurements. *IEEE Trans. Comput. Imag.*, *4*(4), 512-527.

[2] Doeleman, S., Blackburn, L., Dexter, J., Gomez, J.L., Johnson, M.D., Palumbo, D.C., … Zhao, G. (2019). Studying black holes on horizon scales with VLBI ground arrays. In *Astro2020: Decadal survey on astronomy and astrophysics* (APC white papers). *Bull. Amer. Astronom. Soc.*, *51*(7), 256.

[3] Event Horizon Telescope Collaboration. (2022). First Sagittarius A* Event Horizon Telescope results. III. Imaging of the Galactic Center supermassive black hole. *Astrophys. J. Lett.*, *930*(1), L14.

[4] Levis, A., Srinivasan, P.P., Chael, A.A., Ng, R., & Bouman, K.L. (2022). Gravitationally lensed black hole emission tomography. In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition* (pp. 19841-19850). New Orleans, LA: Computer Vision Foundation and IEEE Computer Society.

[5] Wielgus, M., Moscibrodzka, M., Vos, J., Gelles, Z., Marti-Vidal, I., Farah, J., … Messias, H. (2022). Orbital motion near Sagittarius A*: Constraints from polarimetric ALMA observations. *Astron. Astrophys.*, *665*, L6.

Aviad Levis is a postdoctoral scholar in the Computing and Mathematical Sciences Department at the California Institute of Technology.

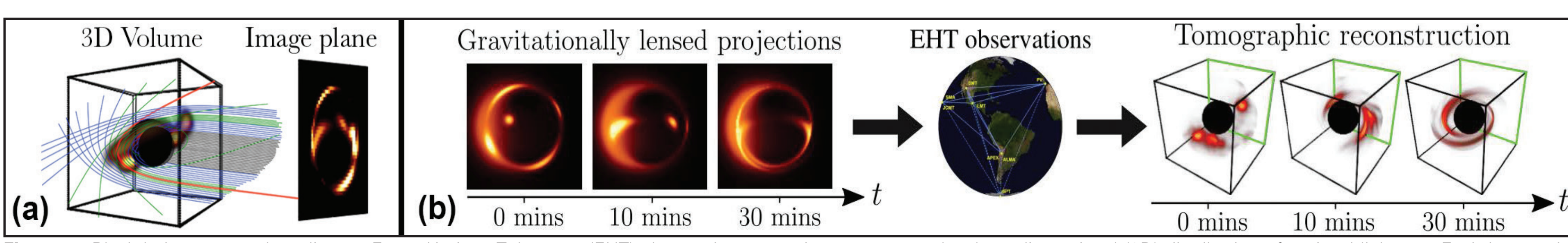


Figure 4. *Black hole tomography relies on Event Horizon Telescope (EHT) observations over time to recover the three-dimensional (3D) distribution of emitted light.* **4a.** *Each image pixel "collects" light along a path. This path is bent by the strong gravitational field — a phenomenon known as gravitational lensing. By leveraging a model for the distorted projection of the 3D volume, we seek to computationally "step out of the two-dimensional image plane."* **4b.** *During simulations, viewing the glowing gas as it orbits over a period of 40 minutes enabled a 3D reconstruction of emission. By using synthetic observations from the extended Next Generation EHT telescope array, we were able to recover the structure of bright gas bubbles that are suspected to orbit Sagittarius A* [5]. Figure courtesy of Aviad Levis.*

Panel Discussion at MDS22 Prepares Students and Early-Career Researchers for the Workforce

By Lina Sorg

CAREERS IN MATHEMATICAL SCIENCES

As they prepare to enter the workforce, all students and early-career individuals—regardless of area of expertise—likely view the possible career paths, environments, and application areas that lie ahead with a mixture of trepidation and excitement. For instance, applied mathematics and computational science students might wonder how to establish and maintain mentored relationships; whether to pursue employment in academia or business, industry, and government; and how to ready themselves for job interviews. During a panel discussion at the 2022 SIAM Conference on Mathematics of Data Science[1]—which took place in San Diego, Calif., in September—Marco Cuturi (Apple, Inc.), Tamara Kolda (MathSci.ai), and Suzanne Weekes (executive director of SIAM) shared their insights and experiences with a rapt audience of students and junior researchers. Noemi Petra (University of California, Merced) moderated the session, which was followed by a lunch that allowed attendees to network directly with the panelists and each other.

The panelists began by discussing their respective educational trajectories and career decisions. While working towards her Ph.D. in applied mathematics at the University of Maryland, College Park, Kolda conducted research on both optimization and latent semantic indexing (an early form of data science). Data science was not well known or even clearly defined at that point in time, so she initially focused much of her energy on optimization. The optimization portion of her thesis was significantly more complicated, but the data science aspects generated greater levels of enthusiasm among readers and collaborators. "It was intriguing to me that people were more excited about data science," Kolda said. "I realized that it was not about how hard the math was, but more about whether it could solve cool problems."

After earning her Ph.D., Kolda spent several years as a postdoctoral fellow at Oak Ridge National Laboratory. She then began a 20-year stint at Sandia National Laboratories before becoming an independent researcher and founding MathSci.ai,[2] her consulting company, in 2021.

Cuturi obtained his Ph.D. from École des Mines de Paris in France. When he was in graduate school, his contemporaries seemed to either pursue Ph.D.s with the intention to enter academia, or seek direct employment in industry without earning a higher degree. "The landscape was much more binary than it is today," Cuturi said, noting that researchers rarely moved between the two areas. Nowadays, however, a Ph.D. usually proves valuable regardless of one's intended career path.

Cuturi bounced back and forth between academic and industry-based settings, pursuing opportunistic projects and research areas that appealed to him. "It was a bit of a risk back then, but it ended up being a good decision," he said. "It's very important to keep reinventing yourself and look for other topics." He currently works in the Machine Learning Research Group at Apple[3] but also retains a position at the Institut Polytechnique de Paris, where he teaches a reduced course load and supervises several Ph.D. students.

Prior to serving as SIAM's executive director, Weekes spent two decades as a faculty member at Worcester Polytechnic Institute (WPI). She traced her interest in mathematics to her childhood in Trinidad and recounted the moment when her father brought home a computer, after which she learned to program. "I always enjoyed mathematics," Weekes said. "Then I fell in love with logic and computing." After graduating with a B.S. in mathematics and a minor in computer science from Indiana University Bloomington, she earned a Ph.D. in mathematics and scientific computing from the University of Michigan. As a professor at WPI, Weekes was particularly interested in bridging the gap between academia and industry. "That was my passion, so I'm glad to be in a job that connects the two," she said.

Petra then asked the panelists about the various ways in which institutions measure success — a topic that is especially pertinent for faculty seeking tenure or industry employees working towards a promotion. Though factors like tenure, teaching, funding, customer impact, and personal relations all typically serve as assessments of success, Kolda cautioned that they are not necessarily the best quantifications of accomplishment. "You can look at those metrics, but I don't think that you should be *driven* by those metrics," she said. "You have to play the game, but you also need to remember that it's a game. Do what you're going to do, have your heart and soul in it, and the rest will work itself out."

Conversation next turned to the challenge of determining what types of research projects to undertake, specifically in academia. Weekes suggested conversing with a range of people about their experiences, as the standard at one institution might not be the same at another. "If you're going into academia, make something that fits for you, not just for your faculty advisor," she said. "Don't do something that people have been laboring over for decades. Do something interesting. You're here at a data science conference and the world is yours."

The same logic applies in industry, where different-sized companies have distinct cultures and protocols. "The best environment is one where you can be exposed to a lot of ideas," Cuturi said, adding that the people within an environment are what truly makes it successful. Before joining Apple, Cuturi spent several years working for the Google Brain team; while there, he encountered impressive levels of computing power that completely changed his perspective on industry problems.

Next, an audience member inquired about the panelists' experiences with mentorship. Kolda noted that mentors have been a large part of her journey but acknowledged that finding people to fulfill those roles becomes more difficult as one's career progresses. She encouraged listeners to interact with colleagues beyond their advisor and

See **Early-Career Researchers** *on page 7*

[1] https://www.siam.org/conferences/cm/conference/mds22

[2] https://www.mathsci.ai

[3] https://machinelearning.apple.com

During the 2022 SIAM Conference on Mathematics of Data Science, which took place in San Diego, Calif., in September, a panel discussion offered valuable insights to students and early-career researchers who are contemplating future employment. From left to right: moderator Noemi Petra (University of California, Merced) and panelists Marco Cuturi (Apple, Inc.), Suzanne Weekes (executive director of SIAM), and Tamara Kolda (MathSci.ai). SIAM photo.

John Venn, the Man Behind the Diagrams

John Venn: A Life in Logic. *By Lukas M. Verburgt. University of Chicago Press, Chicago, IL, April 2022. 448 pages, $45.00.*

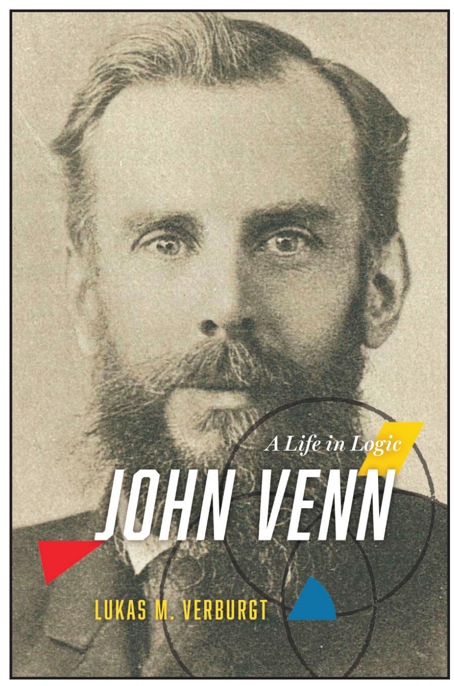
BOOK REVIEW
By Ernest Davis

Venn diagrams are everywhere: in scientific papers and corporate presentations, *The New Yorker* cartoons and social media memes. But who was the Venn who inspired these well-known graphics?

John Venn (1834-1923) was an English mathematician and philosopher who studied logic and probability theory. He is best known for his development and exposition of Venn diagrams, along with his advocacy for the frequentist interpretation of probability theory. He wrote three major books: *The Logic of Chance* in 1876, *Symbolic Logic* in 1881, and *The Principles of Empirical or Inductive Logic* in 1889; the first two were used as textbooks at the University of Cambridge and elsewhere until the 1920s. Venn taught at Cambridge—where he was involved in curriculum reform—from 1862 until his retirement in 1903. He also advocated for women's suffrage and higher education for women. During his retirement, Venn documented histories of his family and of Cambridge, particularly for *Alumni Cantabrigienses*: a register of Cambridge alumni.

Lukas Verburgt's new biography, *John Venn: A Life in Logic*, thoroughly explores Venn's life, works, thought, and faith in the context of the times. Verburgt is a philosopher at the Netherlands Institute for Advanced Study in the Humanities and Social Sciences and the editor of *John Venn: Unpublished Writings and Selected Correspondence*, published in 2022.

The simplest and most familiar form of Venn diagrams—with two or three intersecting circles—was actually already in use when Venn was born. Leonhard Euler frequently employed this style of visual, and such schematics are sometimes known as "Euler diagrams." However, Venn extended the idea in an 1880 article titled "On the Employment of Geometrical Diagrams for the Sensible Representation of Logical Propositions." He showed that it is possible to construct a diagram that illustrates all intersections of four sets via either four ellipses or three circles and a horseshoe shape, as well as a diagram that can depict all intersections of five sets using four ellipses and an annulus (see Figure 1, on page 7). He also demonstrated the use of shading and labeling to carry out more complex inferences.



John Venn: A Life in Logic. By Lukas Verburgt. Courtesy of University of Chicago Press.

Venn's second major claim to fame was his formulation and advocacy of the frequentist interpretation of probability theory, which maintains that the probability of an event's outcome is its frequency in a long series of trials. This concept was controversial in Venn's own time and remains bitterly so to this day, 150 years later. John Stuart Mill and Charles Sanders Peirce both admired Venn's work on probability. John Maynard Keynes dedicated his 1921 book, *A Treatise on Probability*, to Venn and warmly praised his efforts. In his 1956 book on *Statistical Methods and Scientific Inference*, Ronald Fisher credited Venn with "developing the concept of probability as an objective fact." Yet Venn certainly had critics as well. Francis Herbert Bradley and Francis Edgeworth sharply criticized his theory. And in Aubrey Clayton's 2021 Bayesian polemic entitled *Bernoulli's Fallacy*, Venn plays the role of a minor villain who sets the stage for archfiends Fisher and Karl Pearson.

Venn's *Symbolic Logic* became a standard textbook in mathematical logic and was still in use when Willard Van Orman Quine began to study the topic at Oberlin College in the late 1920s. The text is mostly an exposition of and commentary on George Boole's theory of logic. Venn's own view of logic never advanced much beyond that of Boole; he tended to regard other approaches as either notational variants or misdirected ventures. For instance, Venn reviewed Gottlob Frege's groundbreaking 1879 *Begriffsschrift* for the philosophical journal *Mind*, but he entirely failed to appreciate its importance.

Venn was also an expert on the history of logic and an avid book collector; by 1889, he had assembled a library of 1,100 books on the subject, many of which were very rare. By way of comparison, the New York University library system has roughly 3,600 books on logic — of which only 80 hardcover and 200 online-access titles predate 1889.

Logicians such as Frege, Alfred North Whitehead, Bertrand Russell, and other contemporaries and successors were extraordinarily successful at using a combination of Fregean logic and Cantorian set theory to develop a mathematical account of logic that completely characterizes mathematical proof. This achievement has overshadowed alternative approaches to logic, which are now almost forgotten. However, the unification of mathematics and logic did, to some extent, require a change in definition for the scope of both terms. Logicians of the 1880s might well have questioned whether mathematical logic (as it is now called) should be classified as mathematics at all; they would have likely felt that it omits issues that they considered central to logic, such as induction. Modern mathematical logic does not solve all of the problems that engaged 19th-century logicians. Instead, it excludes them as not being part of "logic."

Verburgt's biography devotes considerable space to the evolution of Venn's religious faith. Eight generations of his patrilineal ancestors were clergymen, and Venn's father and grandfather had belonged to the Clapham Sect of the Protestant church's Evangelical branch. The Clapham Sect was dedicated to reform, service to the poor, and abolitionism at the social level and earnest religiosity and moral self-improvement at the personal level (abolitionist William Wilberforce was a member of the sect). Venn thus grew up in an intensely religious atmosphere. While at Cambridge, the master and other students of his college were almost all likewise

See **John Venn** *on page 7*

John Venn

Continued from page 6

Evangelicals. After graduating, Venn even worked as a curate for several years. Gradually, however, his readings in science and philosophy—especially Mill's 1859 *On Liberty*—led him to a more relaxed view. He resigned his holy orders in 1883 because he felt that he could no longer subscribe to all the tenets of the Church of England. Nevertheless, Venn continued to be a believing Christian, and his do-gooder, rather Puritanical mindset persisted in many ways. All his life, he read mostly French novels rather than English ones; he could justify the reading of French novels as study of the language, whereas English novels were pure self-indulgence.

Yet Venn did allow himself to enjoy a number of pleasant hobbies. He was an avid hiker and mountain climber in Wales and the Alps, as well as an accomplished gardener and an amateur expert in the botany of the local wild flora. Around 1907, he and his son built and patented a machine for bowling cricket balls.

Any reader who harbors nostalgic illusions about "the good old days" at Cambridge in the first half of the 19th century will be somewhat shocked by Verburgt's account of Venn's years as a student, which were both physically miserable and intellectually narrow. The focus of Venn's studies remained exclusively on classic literature, theology, and mathematics (elementary algebra, geometry, trigonometry, and calculus), and students had to pass the Mathematical Tripos in order to graduate. In fact, Venn found cramming for the Tripos so unpleasant that he abandoned mathematics for decades and had to relearn many things when he returned to the field.

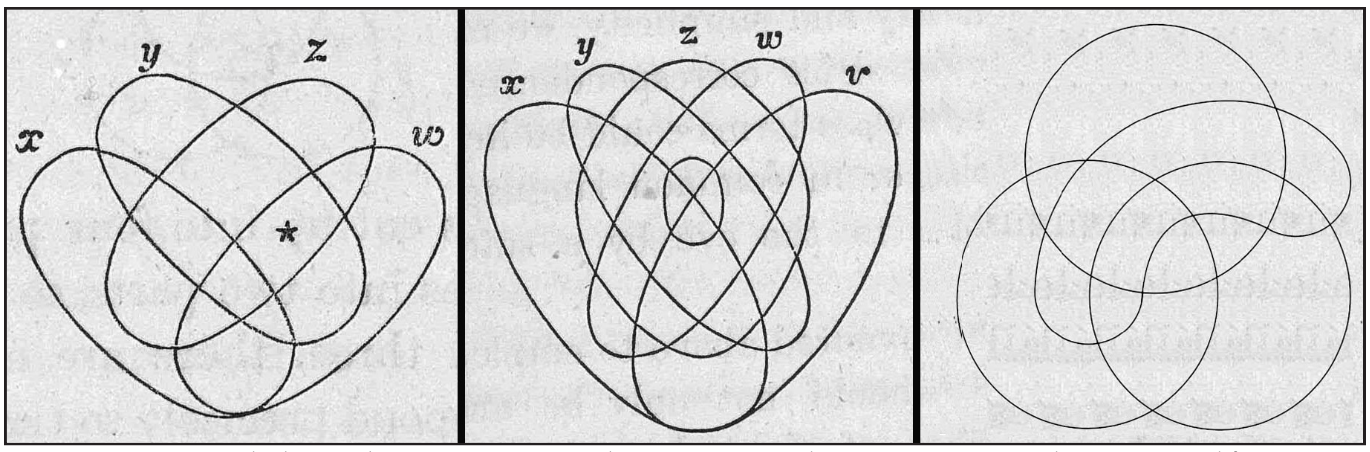


Figure 1. *Venn diagrams for four and five sets. Figure adapted from John Venn: A Life in Logic and courtesy of the University of Chicago Press.*

While teaching at Cambridge, Venn was heavily involved in the creation of a curriculum of "moral sciences" — a concept that included moral philosophy, history, political economy, and law. He also helped to establish a series of university-level lectures and examinations for female students, which were associated with Cambridge but not part of it.

Verburgt's writing often assumes that the reader is quite knowledgeable—at least, more knowledgeable than myself—on subjects like the debates among 19th-century logicians, the organization of the University of Cambridge, and the tenets of the Clapham Sect. Consequently, the discussion can at times become hard to follow. Chapter 11, which addresses "Empirical Logic," discusses Venn's own book on the subject; but I must admit that when I finished the chapter, I had no clearer idea than when I started of the intent of the field of "empirical logic," the beliefs of the various people who worked in it, or its relation to more recent and familiar forms of the philosophy of science.

All in all, Venn comes across as a significant and admirable figure, though not quite a *great* one. His intellect was capable, but neither particularly original nor sharply penetrating. Nonetheless, Verburgt's book is well worth reading. It sheds new light on one side of intellectual life in Victorian England. And if nothing else, the exploration of this comparatively unfruitful view of logic inspires a renewed appreciation for the approach that ultimately prevailed by reminding readers that, 150 years ago, it was not even clear what questions logic should address — let alone how it could answer them.

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

Early-Career Researchers

Continued from page 5

immediate circle in order to gain a wider outlook. Kolda also mentioned that talking to someone who is just slightly more senior than oneself can be valuable; e.g., a graduate student might want to glean advice from a postdoctoral researcher who has already undergone the job search. "More senior people can give perspective, but people who are just a few years ahead can give a lot of direct and useful career advice," she said.

Kolda elaborated on this concept by dividing mentorship into two categories: mentors who offer advice and mentors who serve as sponsors/advocates. Those in the latter category write letters of recommendation, nominate mentees for prizes, and promote them in social and research circles. These types of relationships often originate from casual conversations at conferences or workshops. "It really helps to build a strong network, so I'd advocate for that," Kolda said. "Don't be afraid to go and talk to people."

Because Cuturi frequently moved between France, Japan, and the U.S., he admitted that it was difficult for him to maintain solid relationships with mentors over the years. Nevertheless, he now thoroughly enjoys embracing his mentorship role as a thesis advisor to several students. "It's a really great experience when you get to the middle stage of your career and are exposed to younger researchers," Cuturi said. "They have the energy and the drive, and it's very nice to see that."

When asked for tips on how undergraduates can best prepare their resumes for an interview, Weekes emphasized the importance of internships[4] and/or summer research. Long-term research projects or related work experiences throughout the school year are similarly valuable on a resume and provide effective talking points. Kolda echoed Weekes' comments, explaining that her yearly summer internships as a student exposed her to a variety of environments and cultivated her interest in high-performance computing.

In addition, Kolda advised students to pursue leadership opportunities in college and specifically mention them to prospective employers. For example, holding an officer position within a SIAM student chapter, campus math group, or other organization exhibits both initiative and a willingness to engage with contemporaries. "These experiences make you more than just someone producing papers," Kolda said. "They make you a colleague."

Weekes reminded interviewees to discuss the technical and communication skills on their resumes, provide clear-cut examples, and store their codes and projects in a GitHub repository for easy access. Students and junior researchers might even want to perfect their interview skills through online programs or a university career center, and those seeking employment in industry should practice explaining their work to someone outside of their field. Weekes added that professional societies like SIAM—as well as organizations like the Big Math Network[5]—have ample resources that are dedicated to career preparation. She suggested that attendees visit SIAM's online Career Center[6] or consider hosting a speaker from the Visiting Lecturer Program[7] at their institution.

Ultimately, all of the panelists encouraged students and junior researchers to pursue opportunities that help them grow both personally and professionally. They also urged the audience not to be afraid to ask for assistance along the way. "Surround yourself with people who can help you," Weekes said. "This is not a solo endeavor; you're not doing it on your own."

Lina Sorg is the managing editor of SIAM News.

[4] https://sinews.siam.org/Details-Page/the-value-of-applied-mathematics-internships-in-business-industry-and-government

[5] https://bigmathnetwork.org
[6] https://jobs.siam.org
[7] https://www.siam.org/students-education/programs-initiatives/siam-visiting-lecturer-program

From left to right: Suzanne Weekes (executive director of SIAM), Marco Cuturi (Apple, Inc.), and Tamara Kolda (MathSci.ai) talk about their respective career experiences and share useful advice and personal anecdotes with junior applied mathematicians and computational scientists during a panel discussion at the 2022 SIAM Conference on Mathematics of Data Science, which took place in San Diego, Calif., this September. SIAM photo.

SIAM Establishes the Renata Babuška Prize

SIAM is excited to announce that through the generosity and dedication of longtime SIAM member Dr. Ivo M. Babuška, the Renata Babuška Prize has been established. The prize is named in memory of Dr. Babuška's late wife, Renata, who passed away in 2020. SIAM is incredibly grateful for this generous gift and looks forward to celebrating the important work of our community through this award for many years to come.

The prize of $10,000 will be awarded every two years in recognition of high-quality interdisciplinary work that targets any aspect of modeling and numerical solution of a specific engineering or scientific application, including mathematical modeling, numerical analysis, algorithms, and validation. The prize may go to an individual or group of researchers and will be first awarded in 2025. Read more about it online.[1]

Dr. Babuška was born in Prague, Czechoslovakia, in 1926. He earned his Ph.D. in civil engineering from the Technical University of Prague and his D.Sc. in mathematics from the Czechoslovakia Academy of Sciences. He met his wife, Renata, in 1953 at Charles University, where she earned a degree in mathematical statistics. They married in 1957 and immigrated with their two children to College Park, Md., in 1968. Dr. Babuška was hired as a professor in the Department of Mathematics at the University of Maryland, College Park, and Renata worked as a data and computing management consultant for several government agencies in Washington, D.C. In 1994, the couple moved to Austin, Texas, where Dr. Babuška began his tenure at the Texas Institute for Computational and Applied Mathematics (now the Oden Institute).

From left to right: Renata and Ivo M. Babuška.

Dr. Babuška has made pioneering contributions to mathematics, applied mathematics, numerical methods, finite element methods (FEMs), and computational mechanics. He is known for his studies of the FEM and the Babuška-Lax-Milgram theorem in partial differential equations. One celebrated result of FEM is the Babuška-Brezzi condition, which provides sufficient conditions for a stable mixed formulation for solutions that are related to various physical and engineering problems. He has published more than 350 papers and numerous books, and has over 65,000 citations.

Dr. Babuška has been a SIAM member for 36 years and is a 2009 SIAM Fellow. He is a professor emeritus at the University of Texas at Austin. He was also a professor of aerospace engineering and engineering mechanics, a professor of mathematics, and a senior research scientist at the University of Texas' Oden Institute, as well as a member of the Oden Institute Multiscale Modeling Group.

Thank you to Dr. Babuška for making this prize possible!

[1] https://go.siam.org/YS3w8c

Photos from the 2022 SIAM Conference on Mathematics of Data Science

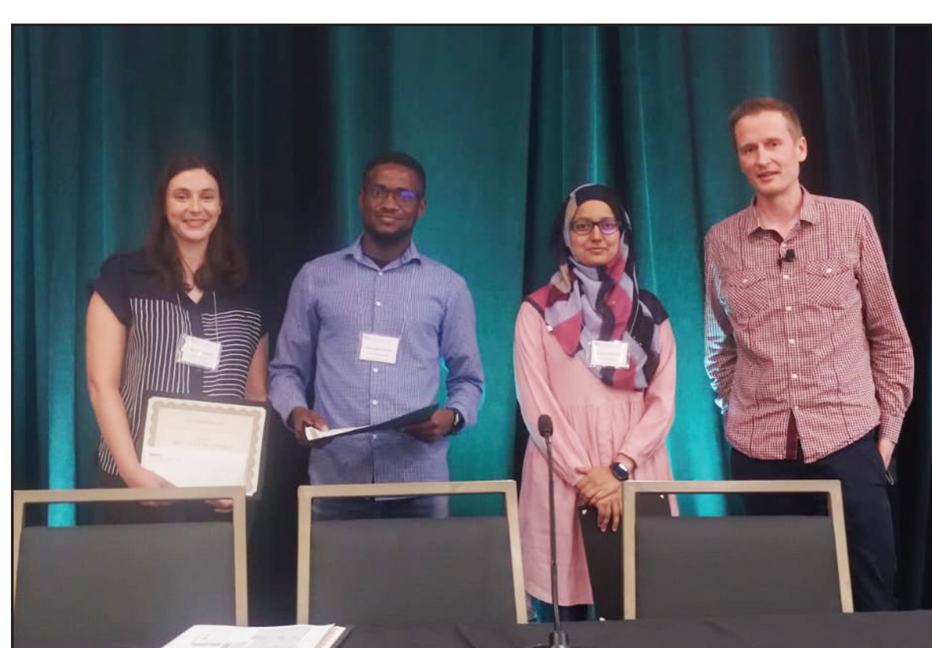
At the 2022 SIAM Conference on Mathematics of Data Science, which took place in San Diego, Calif., this September, an hour-long funding panel informed attendees of funding priorities and programmatic opportunities in the realm of data science. From left to right: panelists William Spotz (Department of Energy), Yulia Gel (National Science Foundation and University of Texas at Dallas), and Fariba Fahroo (Air Force Office of Scientific Research) pose with moderator Boris Kramer (University of California, San Diego). SIAM photo.

SIAM hosted an in-person Career Fair at the 2022 SIAM Conference on Mathematics of Data Science, which took place in San Diego, Calif., this September. During the morning and afternoon sessions, attendees had the opportunity to network and connect with representatives from a variety of organizations, including The Aerospace Corporation, Amgen, Argonne National Laboratory, Chevron, ExxonMobil, MathWorks, Oak Ridge National Laboratory, Sandia National Laboratories, and Southern Methodist University. SIAM photo.

Student attendees of the 2022 SIAM Conference on Mathematics of Data Science, which was held in San Diego, Calif., this September, work together to answer SIAM trivia questions during the Student Orientation. The orientation, which commenced prior to the Welcome Reception, allowed students to network, get to know each other through icebreaker activities, and become comfortable in a conference setting. Winners of the trivia game received free SIAM t-shirts. SIAM photo.

Weijie Su (University of Pennsylvania) received the 2022 SIAM Activity Group on Data Science Early Career Prize, which is awarded biennially to an early-career researcher who has made distinguished contributions to the field of data science. Su presented a corresponding prize talk—entitled "When Will You Become the Best Reviewer of Your Own Papers? A Mechanism-design-based Approach to Estimation"—at the 2022 SIAM Conference on Mathematics of Data Science, which was held in San Diego, Calif., this September. SIAM photo.

From left to right: Adrian De La Rocha Galan (University of Texas at El Paso) and Rebekah White (Sandia National Laboratories) received two of the six Best Poster Awards at the 2022 SIAM Conference on Mathematics of Data Science, which took place in San Diego, Calif., in September. They were recognized for their impressive displays, which they presented during the conference's Poster Session and Reception. De La Rocha Galan's poster was entitled "Detailed Description of Phase Transitions of Non-magnetic Body-centered Cubic Iron at High Pressure Through a Marginalized Graph Kernel," while White's poster addressed "Risk-aware Bayesian Goal-oriented Optimal Experimental Design." SIAM photo.



Three of the six recipients of Best Poster Awards at the 2022 SIAM Conference on Mathematics of Data Science (MDS22)—which was held in San Diego, Calif., in September—were honored during the conference's closing remarks. From left to right: Paz Fink Shustin (Tel Aviv University), Abdoulaye Koroko (IFP Energies Nouvelles), and Sufia Khatoon (Indian Institute of Technology) stand with MDS22 Organizing Committee co-chair Lars Ruthotto (Emory University). Shustin's poster addressed "Gauss-Legendre Features for Gaussian Process Regression," Koroko's work focused on "Efficient Approximations of the Fisher Matrix in Neural Networks Using Kronecker Product Singular Value Decomposition," and Khatoon's display was entitled "A Stochastic Inverse Solution to Thermo-fluid Problems." Neophytos Charalambides (University of Michigan) also received a Best Poster Award for his poster on "Approximate Matrix Multiplication and Laplacian Sparsifiers," though he presented his work virtually and was not present in San Diego. Photo courtesy of Lior Horesh.

View more photos from the 2022 SIAM Conference on Mathematics of Data Science (MDS22) at https://go.siam.org/D7VzWk.

For articles about the MDS22 student/early-career panel and industry panel, including photos from each event, see pages 5 and 9 of this issue.

MDS22 Panel Addresses the Complex Interplay Between Academia and Industry

By Lina Sorg

When considering future career paths, junior scientists may view academia and industry as completely separate spaces with their own independent interests, purposes, and goals. While this mindset was widely accepted in the past, the current workforce certainly benefits from a closer relationship between the two settings — each of which can support the other in valuable ways. During a panel session at the 2022 SIAM Conference on Mathematics of Data Science[1] (MDS22)—which took place in San Diego, Calif., in September—three industrial researchers shared their experiences at their respective companies, addressed industry's interplay with academia, and offered advice to attendees who intend to pursue careers in industry. Eldad Haber (University of British Columbia) moderated the hour-long panel, which comprised Dawn Woodard (LinkedIn[2]), Wotao Yin (Alibaba Group[3]/Academy for Discovery, Adventure, Momentum and Outlook[4]), and Shashanka Ubaru (IBM Research[5]).

CAREERS IN MATHEMATICAL SCIENCES

The panelists opened the session with a conversation about the differences between academia and industry, as well as the advantages of an ongoing dialogue between the two. "Academia goes deep, and industry makes things skatable in a business sense," Yin said, adding that assignments in industry move at a much quicker pace. Woodard agreed and commented that academic researchers tend to explore one problem very thoroughly over a long period of time, whereas industrial researchers typically address multiple problems simultaneously and on much shorter timescales. This pattern means that the breadth of problems in industry is larger than academia, though the depth is not as great. When Woodard first transitioned to industry from a faculty position at Cornell University, the interconnectivity of the problems was an unexpected change. "It's exciting that you can spit out the solution in one or two months," she said. "This was mind-blowing for me coming from academia, where it took years just to get data."

Yet because industry projects generally focus on applications of a specific product, answering fundamental research questions is not a priority. In some cases, scientists simply tweak existing techniques rather than develop novel ones. "Someone in academia has to be working on fundamental, basic questions," Ubaru said. "A good collaboration would really help that." He conceptualized a relationship wherein industry researchers pose questions that academics could subsequently spend substantial time exploring. Woodard concurred. "Figuring out how to share the data would be incredibly powerful," she said.

Haber then asked the panelists to envision future projects that would pique their interests. Woodard, who spent seven years with Uber before joining LinkedIn in May 2022, wants to see a reinforcement learning solution for routing in road networks. Meanwhile, Yin would like to create optimization solvers for data science experts and Ubaru—who is a member of the Mathematics of AI group[6] at IBM—hopes to explore the potential use of quantum on a practical research basis. When Haber inquired as to whether companies are willing to put in the necessary overhead that would allow industry-academia collaborations to pursue such projects, panelists agreed that interest would depend on the size of both the prospective company and university. "The appetite for this at small and medium-sized companies is much lower," Woodard said. "The idea of funding a university for research is a lot harder to sell."

Nevertheless, Woodard noted that certain initiatives at LinkedIn currently fund projects in the Department of Computer Science at Cornell University. Ubaru referenced IBM's fellowship programs, which provide clearly defined funding and objectives for professors to work on specific topics of interest at IBM for a year, as well as several joint programs with New York University and fellowships that allow Ph.D. students to gain industry experience. And Yin remarked that Alibaba—which is an e-commerce platform—houses a specific department that focuses on public affairs and cooperation, allocates a budget to every lab, and supports potential collaborators. The company has also sponsored visiting professorships and scholarships.

Discussion then turned to the nuances of intellectual property (IP) in the context of collaboration. Yin stated that some IP officers suggest avoiding joint IPs in favor of solo IPs or open-source licenses, though Woodard revealed that Uber does hold IP agreements with other institutions. "If you're working on a problem that's very closely related to something that we really need, that's the obvious use case," she said. "Pick something that is close to the fold for them, and you'll immediately generate interest." Conversations with colleagues in a variety of focus areas can provide researchers with a sense of relevant problems, which heightens their chances of developing collaborations with different companies. In some cases, there may be numerous options for partnerships regarding a particular idea; in the context of ridesharing, for example, a project that does not appeal to Uber might intrigue Lyft or another similar service.

Next, the panelists offered advice for job applicants who wish to effectively market themselves for industry positions. Woodard affirmed the value of a broad set of practical data-related skills, solid code,

See **Academia and Industry** *on page 10*

[1] https://www.siam.org/conferences/cm/conference/mds22

[2] https://www.linkedin.com
[3] https://www.alibabagroup.com/en-US
[4] https://damo.alibaba.com
[5] https://research.ibm.com

[6] https://researcher.watson.ibm.com/researcher/view_group.php?id=9860

Academia and Industry

Continued from page 9

a demonstrated interest in data, and a willingness to "get your hands dirty." She also warned attendees not to overcomplicate problems, as companies emphasize practical and efficient solutions. More personal qualities—including motivation, enthusiasm about the organization, and a demonstrated passion for building a successful product—are equally important.

Ubaru added that IBM seeks highly motivated people with robust programming and data science skills, the ability to deploy artificial intelligence (AI) technology on a large scale, experience with deployment on large data sets, and strong publication records. Woodard clarified that publication records are particularly important for research-heavy roles. If someone has just completed their Ph.D., employers will likely look for physical evidence of their productivity. "Since you've been working really hard for five years on one project, I want to see that you've made progress on it in a really tangible way," she said.

When an attendee asked the panelists to describe a sample project and timeline from their current positions, Woodard explained that some tasks focus on incremental improvements while others tackle long-term goals and future technologies. For instance, she recently spent a month rethinking LinkedIn's knowledge graph and laying out the company's vision for the next several years.

As with LinkedIn, the nature of IBM's activities varies widely depending on the objective. Ubaru outlined four different types of projects at IBM. Client projects have clear deadlines and fixed timelines, while exploratory science research can continue for several years without previously defined end goals or objectives. Work towards specific AI products occurs in the form of year- to year-and-a-half-long challenges with multiple stages and quarterly progress reports. Finally, grant-based efforts generally demand more rigid allocation and logging of employee work hours.

Another audience member inquired about data sharing between industry and the public sector — a topic that relates to issues of privacy and sensitivity as well as the data's worth to the company in question. "There's a value associated with data," Woodard said. "So if you release all of the data to the public, you lose that value. But there's a willingness to share data for something that's not core proprietary technology, like traffic data at Uber." Doing so ultimately allows researchers to develop better systems. Yet because many companies gain a competitive advantage from their proprietary data, they are often more willing to share example data sets at smaller volumes.

Ubaru noted that most of IBM's data comes from its clients and is therefore confidential. Since much of it is sensitive—like banking information, for instance—IBM does not really possess proprietary data. For companies that do, however, Ubaru's thoughts echoed those of Woodard. "Companies feel a sense of requirement that they need to share data, as long as it doesn't affect their bottom line," he said.

As the session wound down, one attendee wondered whether the panelists had observed a lack of certain types of skills or experiences among job applicants. "Academic curricula tend to default to being more theoretical and don't include some of the aspects around data analysis, machine learning models, and the quality of data that go into the models," Woodard said. She thus encouraged professors to include techniques like instrumentation, logging, and data collection in their lesson plans so that students learn how to identify and analyze high-quality data.

To support this recommendation, Woodard presented a sample scenario from her employment with Uber. If ridership is low and prices are high, analysts must determine the problem within the system. "Breaking down the problem using data and figuring out the root cause is a practical thing that's really important," Woodard said. Though Woodard and her colleagues usually train junior hires on these skills when they arrive, she acknowledged that it would be beneficial if early-career researchers practiced some of those techniques as students.

Yin pointed out that some of the best textbooks in academia contain outdated algorithms. As such, he would like to see a future collaboration between industry and academia to produce a linear programming textbook that suits everyone's needs. He also mentioned that the U.S. has very few mixed-integer experts, despite the numerous real-world problems that require this particular skillset.

The panel ended with several remarks about the value and utility of mathematics in the industry sector. "Many [MDS22] minisymposia are applicable to things we do at IBM," Ubaru said. "Math goes without saying; it's the first thing we need." Yin supported this sentiment and added that roughly 30 percent of the Alibaba Group's recent hires hold Ph.D.s in either mathematics or applied mathematics.

Since Woodard uses techniques that span multiple different fields—including statistics and economics—she emphasized that researchers must understand all of the probabilistic foundations of their applications, especially when extending a method or creating a reusable platform. A well-rounded education allows one to do so. "That's the beauty of SIAM," Haber said as he concluded the session. "It brings together skills from lots of areas, so you don't have to say that techniques belong only to one field."

Lina Sorg is the managing editor of SIAM News.

A panel of industry researchers at the 2022 SIAM Conference on Mathematics of Data Science, which took place in San Diego, Calif., this September, addressed the complex yet mutually beneficial relationship between academia and industry. From left to right: moderator Eldad Haber (University of British Columbia) engages panelists Wotao Yin (Alibaba Group/Academy for Discovery, Adventure, Momentum and Outlook), Shashanka Ubaru (IBM Research), and Dawn Woodard (LinkedIn) in conversation. SIAM photo.

The Ethics of Artificial Intelligence-Generated Art

By Matthew R. Francis

In recent months, many people have begun to explore a new pastime: generating their own images using several widely-distributed programs such as DALL-E,[1] Midjourney,[2] and Stable Diffusion.[3] These programs offer a straightforward interface wherein nontechnical users can input a descriptive phrase and receive corresponding pictures, or at least amusingly bad approximations of the results they intended. For most users, such artificial intelligence[4] (AI)-generated art is harmless fun that requires no computer graphics skills to produce and is suitable for social media posts (see Figure 1, on page 12).

However, AI algorithms combine aspects of existing data to generate their outputs. DALL-E, Stable Diffusion, and other popular programs pull images directly from the internet to train their algorithms. Though these images might be easily obtainable—from the huge Google Images database, for example—the creators have not always licensed their art for reuse or use in the production of derivative works. In other words, while publications like *SIAM News* obtain permission before disseminating restricted-license images, popular AI algorithms do not distinguish between pictures that are freely usable and those that are not.

ETHICS IN MATHEMATICS

For this and other reasons, the problems associated with AI art generally fall into three basic categories: (i) Ethical questions of data sourcing, (ii) legal questions involving copyright and licensing, and (iii) technical questions that surround the algorithms and their frequent reinforcement of biases. "This is a new realm for an extant conversation that's happening with algorithmic training data in other realms," Damien Williams, a professor of philosophy and data science at the University of North Carolina at Charlotte, said. "Do the people training these systems have anything like meaningfully informed consent? These are questions in other areas of algorithmic ethics, but they're being brought over into a very visible conversation about visual art and illustration. And I think that's a good thing."

To complicate matters, the ethics of AI-generated art may not translate directly into legal arguments. "From a machine learning perspective, you want the biggest possible dataset, copyright be damned," Meredith Rose, a senior policy counsel at Public Knowledge,[5] said. Public Knowledge is a 501(c)(3) organization that, according to its mission statement, "promotes freedom of expression, an open internet, and access to affordable communications tools and creative works."

At the same time, Rose noted that the sheer amount of training data for DALL-E and its ilk makes it nearly impossible to prove that a particular copyright-protected piece of art was part of a specific dataset that was utilized to generate the AI art item in question. Unless a user specifically asks for output in the style of a specific artist—as happened recently when beloved comics artist Kim Jung Gi died[6] and multiple people used his art as training data for algorithmic homages, to the horror of his friends and colleagues—individual creators would have trouble arguing misuse of their art in a court of law.

"From a strictly copyright perspective, I don't know that there's a clear answer to this," Rose said. "To the extent that any answer looks more probable, my opinion is that the fair-use case is pretty strong." In other words, the same laws that allow for parodies and (at least some) hip-hop samples might apply, but the courts generally have not yet caught up with the specific details of AI art.

The Training Wheels Come Off

While individuals have been making art with computers for more than 50 years, AI-based art is just now coming into its own. Nevertheless, many of its associated ethical and legal issues are not new. From Dadaist "readymades" to hip-hop sampling and parody news magazines, nearly every creative discipline has explored the limits of incorporating other people's material into new art. In fact, visual artists often learn by imitating the "masters" of the field — sometimes even directly copying their works.

These historical points relate to the technical side of AI art, which in many respects is the simplest of the three aforementioned issues. Some algorithms already restrict content for both input and output; for instance, DALL-E forbids sexual and broadly-defined "obscene" content. Through her own experimentation efforts, Rose has also found that DALL-E does not produce images of certain licensed properties, like those owned by the notoriously litigious Walt Disney Corporation.

Williams argued that these existing limitations show that developers can write algorithms to only use data that belongs to creators who have explicitly granted reuse and remixing permissions. "We have a wide array of available imagery and information that we can make use of without impinging on the rights of someone else," he said, stressing that ethical considerations are involved in the use of a creator's material even when that material is licensed for open distribution. "There are a lot of people who believe in some version of open-source information but don't necessarily want their imagery or their data being used to train a Google system. Ideologically, those things are not necessarily at odds."

Beyond licensing issues, training data for AI art can end up selecting subsets of available data in biased ways. DALL-E's restriction on sexual content means that its

See **Ethics** *on page 12*

[1] https://openai.com/dall-e-2
[2] https://www.midjourney.com
[3] https://huggingface.co/spaces/stabilityai/stable-diffusion
[4] For the sake of simplicity, I use the term "artificial intelligence" to encompass machine learning and algorithmically generated content, in accordance with colloquial practice.
[5] https://publicknowledge.org
[6] https://www.cnn.com/style/article/kim-jung-gi-death-cec

Reflecting on the First SIAG/ACDA Workshop

By Alex Conway, Henning Meyerhenke, and Bora Uçar

The SIAM Activity Group on Applied and Computational Discrete Algorithms[1] (SIAG/ACDA), which was founded in 2019, held its first workshop[2] in Aussois among the beautiful French Alps from September 5-9, 2022. This workshop followed last year's successful SIAM Conference on Applied and Computational Discrete Algorithms,[3] which took place virtually in July 2021; for most of the 60 participants, it was one of their first international in-person meetings since the start of the COVID-19 pandemic.

The SIAG/ACDA workshop featured 32 high-quality research presentations from academia, national laboratories, and industry, all of which reflected ACDA's broad scope and focus on cross-community interactions. The sessions highlighted theoretical results in the context of algorithms and data structures, as well as more applied algorithm engineering aspects and a wide range of real-world scenarios that require combinatorial solution methods. Such applications include scientific computing, machine learning, optimization/mathematical programming, data centers and storage systems, accountability in distributed systems, bioinformatics, and even wildlife tracking.

As with other SIAM events, coffee breaks and mealtimes provided ample opportunities for participants to connect and network with one another. Several hikes throughout the week served the same purpose, leading one participant to suggest a new "workshop performance measure" of "miles hiked per talk." Late-night work and socialization continued at the bar and patio, which overlooked breathtaking mountain peaks.

The organizing committee comprised Michael A. Bender, Aydin Buluç, and Bora Uçar, with help from current and former SIAG/ACDA officers, including Henning Meyerhenke, Uwe Naumann, Cynthia Philips, Alex Pothen, and Blair Sullivan. Le Centre national de la recherche scientifique (CNRS), Institut national de recherche en sciences et technologies du numérique (Inria), and École normale supérieure (ENS) de Lyon all supported the workshop.

SIAG/ACDA fosters activity and collaboration surrounding the computational solution of combinatorial problems that arise in real-world applications. The SIAG seeks to promote the formulation of computational problems in terms of combinatorial models; design, analysis, and implementation of algorithms on these models; and deployment of the algorithms in software. It therefore strives to unite mathematicians; computer scientists; statisticians; scientists; and engineers from academia, the national research laboratories, and industry. SIAG/ACDA is a growing community and will hold its next conference[4] from May 31-June 2, 2023, in Seattle, Wash. The meeting will be co-located with the 2023 SIAM Conference on Optimization.[5] We invite all interested SIAM members to join the group, attend the conference, and get involved in the exciting field of applied and computational discrete algorithms.

[1] https://www.siam.org/membership/activity-groups/detail/applied-and-computational-discrete-algorithms
[2] http://perso.ens-lyon.fr/bora.ucar/AcdaInAussois
[3] https://www.siam.org/conferences/cm/conference/acda21

A group of workshop participants pause before hiking to the Pointe de l'Observatoire, which offers views of the valleys of Aussois. Photo courtesy of Blair Sullivan.

Attendees of the SIAM Activity Group on Applied and Computational Discrete Algorithms' first workshop gather on the terrace of the Paul Langevin Center. Photo courtesy of Cédric Chevalier.

[4] https://www.siam.org/conferences/cm/conference/acda23
[5] https://www.siam.org/conferences/cm/conference/op23

Alex Conway is a researcher at VMware Research Group whose research interests include storage systems and external memory data structures. He is a co-creator and research lead of SplinterDB. Henning Meyerhenke is a professor of computer science at Humboldt-Universität zu Berlin; he previously held positions at the University of Cologne and Karlsruhe Institute of Technology. His main research interests concern scalable algorithms for large and complex networked systems, particularly for algorithmic network analysis and combinatorial scientific computing. Bora Uçar is a senior research scientist at the French National Centre for Scientific Research who works in the Laboratoire de l'Informatique du Parallélisme at the École normale supérieure de Lyon. His research interests include combinatorial scientific computing and high-performance computing.

Ethics

Continued from page 11

pool of images excludes many innocuous pictures of women due to a strict interpretation of the definition of "sexual." As a result, DALL-E's training data and output feature more images of men than women.

This technical issue is both well known and well studied, even if the people who build algorithms have not yet solved it. Meanwhile, scholars and advocates across a wide variety of disciplines have also examined other types of algorithmically-generated content whose developers obtained training data from public sources—such as social media—without the owners' permission.

"Think of Google returning and ranking search results, Google translation, and all of the algorithms that are figuring out what ads to serve us," Janelle Shane, an optics researcher and author of the book *You Look Like a Thing and I Love You*[7] (about the pitfalls of machine learning), said [1]. "A lot of those algorithms are based on writers' data, bloggers' data, or emailers' data — a bunch of people who did not agree to have their data as part of these datasets."

Shane's work in this area has frequently focused on the weird and unexpected results that stem from AI systems, including DALL-E. She noted that most of the output from these algorithms is not usable as-is—except perhaps humorously—which means that human artists must post-process the results via image manipulation programs like Photoshop. While this situation will probably change as algorithms improve, much of what is currently displayed as "AI art" is not purely computer generated.

[7] https://sinews.siam.org/Details-Page/the-threat-of-ai-comes-from-inside-the-house

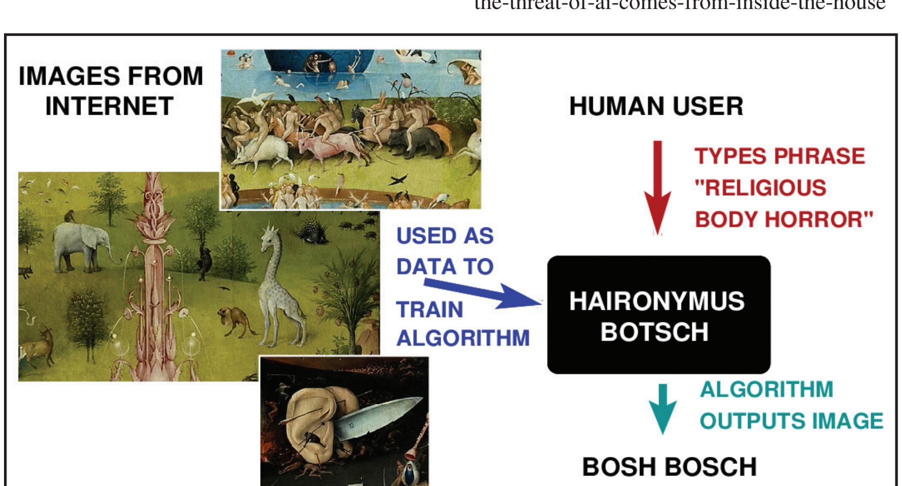


Figure 1. *A broad example of how artificial intelligence (AI) art works. Consider a user who requests that a computer generate religious art in the style of painter Hieronymus Bosch (1450-1516) via the algorithm hAIronymus BOTsch. The training data are paintings by Bosch, and the bosh Bosch output is based on features that are taken from those paintings. Bosch's work is in the public domain, but training data used by AI art algorithms are often copyrighted and not licensed for that purpose. Figure courtesy of Matthew Francis.*

The Laws and the Profits

In sharing their different perspectives, Rose, Shane, and Williams all highlighted the need to examine training data for AI art through an ethical lens — allowing ethics to guide both the technical and legal aspects of the situation. This logic applies even more so in the context of photographs, especially since DALL-E 2 just permitted their use as training data in September 2022. This decision spurred worries about the creation of *deepfake photos*, wherein a person's face or body is digitally included in unrelated images for the purposes of defamation.

"If you're using someone's photographs without their permission or knowledge, then you shouldn't be using those photographs," Williams said. He referenced the case of Clearview AI,[8] the company that collected photos from the internet—without permission from photographers or subjects—to train its facial recognition algorithms, then sold its databases to law enforcement and military agencies.

Both Williams and Shane emphasized the responsibilities of the algorithm programmers, who decide what training data to incorporate and how the AIs will use it. Williams suggested that algorithms should be required to catalog the provenance of all of their training data in some capacity, much like how museum catalogs track the history of the art that they display. Ideally, such a stipulation would also allow artists to determine whether their work has been utilized without their permission. "The responsibility lies primarily with the individuals, the teams, and the corporations building these algorithms," Williams said.

[8] https://www.clearview.ai

Shane added that current AI art programs draw indiscriminately on huge datasets, which does not have to be the case. "Probably the solution is [to say] 'Hey, we should build our algorithms with less, so we don't have to scrape everything we can get our hands on,'" she said. "We can train with a cleaner, more controlled, more consented dataset. That also has the advantage of starting to address some of the biases inherent in a dataset that you scrape from all of the art propagated on the internet, on museum websites, and so forth."

Copyright law is not currently designed to treat large training datasets that contain protected works. But other types of law might be relevant, such as those that prohibit "revenge porn." Many art-hosting websites have already begun to ban AI-generated art,[9] partly because users can flood their servers and prevent non-algorithmic artists from getting any visibility. As the appearance of AI art continues to improve—as it inevitably will—human creators, users, and lawmakers must think of ways to enhance the ethics of AI art before the harm overwhelms the fun.

Further Reading

[1] Shane, J. (2019). *You look like a thing and I love you: How artificial intelligence works and why it's making the world a weirder place*. New York, NY: Voracious/Little, Brown and Company.

Matthew R. Francis is a physicist, science writer, public speaker, educator, and frequent wearer of jaunty hats. His website is BowlerHatScience.org.

[9] https://arstechnica.com/information-technology/2022/09/flooded-with-ai-generated-images-some-art-communities-ban-them-completely