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Dynamics-based Machine Learning for Nonlinearizable Phenomena

Data-driven Reduced Models on Spectral Submanifolds

By George Haller, Shobhit Jain, and Mattia Cenedese

Machine learning (ML) has been an inspiring development for all areas of applied science, with numerous success stories in static learning environments like image, pattern, and speech recognition. Yet effective modeling of dynamical phenomena—such as nonlinear vibrations of solids and transitions in fluids—remains a challenge for ML, which tends to produce overly complex and uninterpretable dynamic models that are not reliable outside of their training range. A recent approach, however, integrates advanced dynamical systems concepts into elementary ML, ultimately yielding fast and accurate reduced-order models for nonlinear dynamics.

The idea—which we call *dynamics-based machine learning* (DBML)—is to learn models directly from phase space structures that are inferred from data. Systems with very different physics often display the same key invariant sets in their phase spaces; instead of fitting models to individual trajectories (which are sensitive to perturbations and parameter changes anyway), robust reduced-order modeling should therefore target structurally stable invariant sets. DBML focuses specifically on identifying the dynamics of ubiquitous, low-dimensional attracting invariant manifolds, which were first noted in the nonlinear vibrations literature [6]. Subsequent work in dynamical systems theory independently established the existence and properties of these manifolds, even for infinite-dimensional systems [1]. The forthcoming formulation, a higher-dimensional computational algorithm, and a data-driven implementation of these results have only appeared very recently [2-4].

DBML assumes the existence of at least one stationary state $\mathcal{M}_0$ for a dynamical system, which we take here to be finite dimensional for simplicity. To further simplify the situation, we only consider the case wherein $\mathcal{M}_0$ is an attracting fixed point; similar results hold for repelling fixed points, periodic orbits, and quasiperiodic steady states. The linearized dynamical system at $\mathcal{M}_0$ will admit eigenspaces E_j that are spanned by generalized eigenvectors of its jth distinct eigenvalue λ_j. We can order these eigenspaces by their increasing real parts, so that $\mathrm{Re}\lambda_j < \mathrm{Re}\lambda_{j+1}$. As a consequence, solutions of the linearized system within E_j decay to the fixed point $\mathcal{M}_0$ increasingly quickly as the index j grows.

By grouping some of the E_j eigenspaces together if necessary, we can build a hierarchy $E^1 \subset E^2 \subset \ldots$ of *spectral subspaces* (see Figure 1a). We construct these spectral subspaces from eigenspaces in a manner that ensures that all E^j are non-resonant. In particular, no positive-integer linear combination of the eigenvalues in E^j should equal any eigenvalue that falls outside of E^j.

See **Machine Learning** *on page 4*

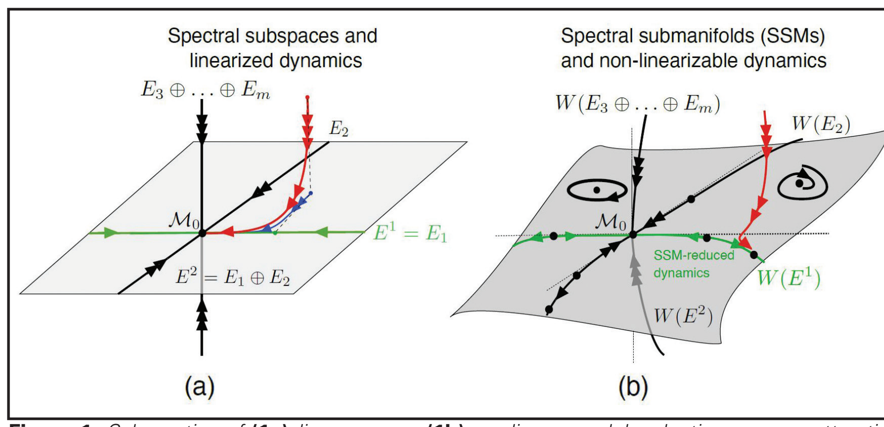

Figure 1. *Schematics of* **(1a)** *linear versus* **(1b)** *nonlinear model reduction near an attracting fixed point* $\mathcal{M}_0$*. Figure adapted from [2].*

How to Boost Your Creativity

By Nicholas J. Higham and Dennis Sherwood

As a *SIAM News* reader, you are a creative person — you would not have gotten where you are today without being creative. However, you may not understand exactly how your creativity works or how to "turn it on" when you need it. You also might not know how to train others to be creative.

In this article, we describe the basic idea behind a six-step process for creativity that Dennis Sherwood developed over the last 20 years. We have used this process together in creativity workshops during the last decade, working with groups ranging from the numerical analysis group at the University of Manchester to the SIAM leadership.

Our approach is based on the insight that creativity is not so much about creating something totally new as about identifying something *different*. The search for something different is much easier than the search for something new, for "different" means "different from now" and "now" is visible all around us. So if we observe "now" very carefully, we might notice some feature of "now" that might be different and ideally better too, and from this feature an idea might spring. Creativity therefore does not necessarily require an act of genius, or a lightning strike out of the blue. Rather, good ideas can be discovered as the result of detailed observation coupled with curiosity, and can follow a systematic process that can be applied in any circumstance.

Two of the key steps in our procedure are to write down every feature of the focus of attention (which could be a mathematical problem or something else entirely), and then ask "How might this be different?" for each one. Here we provide a glimpse into the process with an old and familiar example: iterative refinement for improving an approximate solution to a linear system $Ax=b$, where A is a square, nonsingular matrix. The basic algorithm in its original form is as follows, and we assume that it is carried out in double-precision floating-point arithmetic:

1. Solve $Ax=b$.
2. Compute $r=b-Ax$ in quadruple precision.
3. Solve $Ad=r$.
4. Update $x \leftarrow x+d$.

Repeat from step 2 if necessary.

James H. Wilkinson programmed iterative refinement in 1948 using LU factorization with partial pivoting for the solves in steps 1 and 3. For step 2, he took advantage of the ability of his computer—the Pilot Automatic Computing Engine at the National Physical Laboratory—to accumulate inner products in quadruple precision at no extra cost.

Iterative refinement became popular and was implemented in this way for the next 25 years or so. Several textbooks from the 1960s and 1970s made statements such as "It is absolutely essential that the residuals be computed in extra precision," and the method seemed to be set in stone. However, every aspect of iterative refinement is amenable to the question "How might this be different?", and the answers to this question have yielded a panoply of different versions of the method.

Here is a thumbnail sketch of some iterative refinement variants, each of which is identified by the feature that distinguishes it from the aforementioned version. Specific references for these and other developments are given in [1, 2].

Precision of the Residual

The residual r does not need to be computed with extra precision, at least not if the aim is to improve the backward stability rather than the accuracy. This was realized in the 1970s, by which time most computers could no longer accumulate inner products in quadruple precision for free. This finding opened up the possibility of using a somewhat unstable solver.

Precision of the Factorization

The algorithm still works if step 1 uses an LU factorization that is computed in single precision, as long as A is not nearly singular to single precision. This observation was made in the 2000s and was important because processors were appearing on which single precision arithmetic was much faster than double precision arithmetic.

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Participant at a creativity workshop adds ideas to a flip chart. Photo courtesy of Dennis Sherwood.

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Can Science Speak Truth to Power?

By Matthew R. Francis

Since the onset of COVID-19, government messaging has been scattershot at best. In the meantime, epidemiologists, public health experts, and other members of the scientific community have struggled to communicate accurate information to the public — sometimes without adequate data (see Figure 1). To further complicate matters, many of these same scientists are paid with public money in the form of grants or beholden to corporate funding. Additionally, the priorities of civil leaders do not always align with those of public health efforts, and scientists themselves are not apolitical machines and thus have their own biases.

These conflicts and confusions are particularly problematic during a global pandemic, but it doesn't take a virus to reveal the presence of fissures in a world where people perform both science and public policy. Climate change, nuclear weapons, space exploration, deep-sea mining, endangered species protections, and garbage disposal are only a small sample of areas in which scientific issues overlap—or conflict—with governmental priorities.

"More scientists these days acknowledge that we are not those who are elected by the public," Jim Al-Khalili of the University of Surrey said. "We understand that the policy decisions that politicians and governments make depend on more than just the scientific evidence that we present."

At the 2022 American Association for the Advancement of Science Annual Meeting,[1] which took place virtually in February, Al-Khalili—who is a physicist, broadcaster, and author—participated in a panel discussion that addressed the question "Can scientists successfully speak truth to power?" This question is clearly far too weighty to answer in a single conference session or article, but defining the breadth of its implications can help researchers determine how to best address it. What does it mean to "speak truth to power" when scientists aren't really in the business of "truth," and the "power" in question often controls their funding?

"It's not 'truth,'" Al-Khalili said. "It's speaking what we currently understand about a particular issue; it almost certainly is not the entire truth. All we can do when we speak truth to power is say, 'This is the evidence as far as we understand it today.' Of course, the other aspect—which in a sense probably even has to be done beforehand—is to communicate how science works."

Kendra Pierre-Louis, a journalist and climate reporter for a Gimlet/Spotify podcast called "How to Save a Planet,"[2] offered additional thoughts. "The phrase 'truth to power' is about institutions, whether it's a university or our government that is behaving in ways that are oppressive or antidemocratic," she said.

Yes, But

Many problems that are associated with the communication of science to governments or corporations come down to a conflict of cultures. The practice of science is iterative and tentative by nature, requiring new experiments or data sources to continually refine conclusions. Power, whether in the form of a state or capital, typically prefers immediately actionable results.

"Power ultimately isn't about facts," Max Krummel, a pathologist at the University of California, San Francisco, said. "Power is about appealing to the emotions and minds of the people you're trying to rule. And so the powers pick the 'facts' that they want to support their emotional decisions."

This is not to say that scientists are unemotional; rather, the usual methods of scientific communication emphasize fact over emotion. "Scientists don't tend to speak as humans," Krummel continued. "[They] speak on facts, and facts can be dismissed. If scientists speak against power, they're pretty powerless against the powerful who don't use facts."

More specifically, people—scientists and non-scientists alike—primarily base their decisions on their own values. Individuals typically do not change their minds upon encountering new information that contradicts their personal belief systems, including political opinions. As a result, many politically conservative scientists reject scientific evidence of climate change because its implications about the world contradict their beliefs [1]. Similarly, many people across the political spectrum have rejected recommendations on COVID-19 mitigation measures for reasons that are independent of the facts.

Though evidence itself often does not sway people, the desire to be taken seriously sometimes can. This drive may cause scientists to soften their conclusions for particular audiences, downplay risks, or even omit certain information when speaking to hostile crowds. "If you call someone biased enough, they will become biased in your favor," Pierre-Louis said. "Criticism of prestigious institutions falls on blocked ears because they feel you should be grateful."

Who Owns You?

The problem worsens considerably when specific governments or industries have agendas that explicitly oppose science. "If you work for industry, big pharma, or a government-funded body that has ideologically-driven motives, then it's very hard to be objective," Al-Khalili said. This subjectivity in turn disrupts trust between scientists and the general public. "It's difficult for wider society to say, 'Do we trust this scientific advice?'," he added. "You hope that your leaders are principled, and you hope that scientists [are too]. But scientists are people, so they have their own biases and vested interests like anyone else."

Krummel concurred with this sentiment. "Scientists are no different than other people in almost every respect," he said. "They need a roof over their heads and heat, water, and food. So they can be absolutely can be bought. Their days are paid for by other people."

In her profession, Pierre-Louis witnesses the challenges of both science and the media attempting to speak truth to power. "As a journalist, holding truth to power would mean being able to point out the contradictions," she said. "But especially in national media, that rarely happens." This disjoint is partly because of information access, which is as much of a currency

See **Truth to Power** *on page 4*

[1] https://aaas.confex.com/aaas/2022/meetingapp.cgi

[2] https://gimletmedia.com/shows/howtosaveaplanet

Figure 1. *Inconsistent government messaging about the COVID-19 pandemic means that much of the outreach on masking and additional public health measures has been left to other sources, such as this mural in the U.K. A lack of consistency from leadership has also hindered scientists' efforts. Public domain photo courtesy of Facundo Arrizabalaga.*

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Obituary: Charles William Gear

By Yannis Kevrekidis and Linda Petzold

Charles William Gear—known as Bill Gear to all—passed away on March 15, 2022, in Princeton, NJ. He was 87 years old. Bill was a larger-than-life figure whose research career spanned computer design and architecture as well as numerical analysis and scientific computation. His work on initial value problems for differential equations (particularly stiff differential equations and differential-algebraic equations solved via backward differentiation formulas) underpins much of the contemporary research in computational modeling. Bill possessed wisdom, integrity, humor, vision, a healthy dose of competitiveness, an ingrained sense of service to the profession, and a great joy for life. To the end, he was a mean programmer and he loved a good party.

In 2005, SIAM commissioned a substantial interview[1] with Bill (conducted by Thomas Haigh) that was later donated to the Computer History Museum[2] in Mountain View, Calif. It explores Bill's formative years in England with a hard-working father who expected education to provide Bill with an easier life—and never ceased to wonder that Bill kept working hard anyway, since he loved what he did—and who impressed upon him the need to treat people fairly. It also reminds us of the joy of taking apart radios and reveals a fascination with all things electrical that followed Bill throughout his career and was evident in his interest in computer graphics and the "Gear anode."

Bill studied mathematics at the University of Cambridge's Peterhouse College, where his rowing team won "Head of the River" for the first time in 108 years. After graduating from Cambridge and receiving a fellowship to study in the U.S., Bill sailed to New York on the Queen Mary and made his way to the University of Illinois at Urbana-Champaign (UIUC). He ended up staying at UIUC until he completed his Ph.D. in 1960, under the direction of Abraham Taub. The field of computer science proved to synthesize Bill's mathematical skills and instincts for building mechanical things and controlling them electrically.

"Once I started working with computers, I knew that this was what I wanted to do," Bill said in 2005. "There was no doubt about it. This combined all things that I liked: some amount of mathematical analysis, the mechanical stuff of programming, the invention, the design. I'm a cross between a scientist and an engineer." From programming the ILLIAC I (Illinois Automatic Computer) as a first-year graduate student to collaborating with Don Gillies on the ILLIAC II and eventually writing his first paper about the ILLIAC II assembler in 1964, Bill's early research was shaped by computer architecture, assembly-level programming, and creative debugging. This period of his life was also rich with interactions with numerical analysts, such as his classmate Gene Golub and UIUC visitor William "Vel" Kahan. In the meantime, Bill formed new interests in areas like ordinary differential equations as he worked on the ILLIAC II.


Charles William (Bill) Gear, 1935-2022. Photo courtesy of Princeton University.

This brings us to the Bill Gear with whom many of us on the numerical analysis/scientific computing side are familiar. He is especially remembered for his work on backward differentiation formulas, stiff differential equations, and the DIFSUB subroutine (often referred to as "Gear's method") — which eventually lead to the Livermore Solver for Ordinary Differential Equations (LSODE). Bill's visits to Argonne National Laboratory—and an analog computer programmer's challenge that "I've got the sort of problems you digital guys can't solve"—inspired his interest in problems with conservation laws and differential-algebraic equations. As a result, his paper on the "Simultaneous Numerical Solution of Differential-Algebraic Equations" appeared in 1971 [4]. During this time, Bill also started writing important books: *Computer Organization and Programming* in 1969 [1] (a sabbatical in Nice, France, provided the opportunity for a revised second edition); the now-classic *Numerical Initial Value Problems in Ordinary Differential Equations* in 1971 [3]; and the 1971 *Introduction to Computer Science* [2], which was a truly influential textbook for computer science students for more than two decades.

Bill rose through the ranks at UIUC and became head of the Department of Computer Science from 1985 to 1990. While in this position, he instituted the faculty-sponsored "Friday Extravaganza" for graduate students that continues to this day. He then left the department to pursue an exuberant dream at the NEC Research Institute in Princeton, NJ; NEC recruited him to build its Computer Science Research Division. Bill became president of the institute two years later and served in that role until his retirement in 2000. After retiring, he developed a new interest in multiscale numerics and made seminal contributions in equation-free multiscale methods with collaborators and students from Princeton. These efforts led to 20 additional years of exceptional productivity, everyday presence, and creative programming.

Bill remained dedicated to the applied and computational mathematics community throughout his entire career, and what follows is a very incomplete sampling of this allegiance. He served SIAM in various capacities over the years, including as Vice President for Publications and a member of the SIAM Council and the Committee on Programs and Conferences. Most notably, he was president of SIAM from 1987 to 1988. Bill was also involved with the Association for Computing Machinery (ACM) and the International Council for Industrial and Applied Mathematics (including a stint as president). He held multiple journal editorships, one of which was for the *SIAM Journal on Scientific Computing;*[3] was a valued invited speaker across the world; retained membership with several National Research Council boards and committees; and advised 22 Ph.D. students. Their memories recount an inquisitive and involved advisor who would return from a seminar and say "An interesting idea — let's try it ourselves and see what happens!" Bill's fascination and creativity resurge again and again in their current work.

Bill was recognized with many accolades over the course of his life, including membership in the National Academy of Engineering. He was a Fellow of SIAM, the ACM, the American Association for the Advancement of Science, the Institute of Electrical and Electronics Engineers, and the American Academy of Arts and Sciences. He also received the ACM SIGNUM George E. Forsythe Memorial Award and an Outstanding Civilian Service Award from the U.S. Department of the Army. In 1986, the "GearFest" conference in Albuquerque, NM, was held in his honor. Beyond official recognition, the testimonies to Bill's wisdom, integrity, good judgement, fairness, joy, humor, and friendship from the people whose lives he made better speak for themselves.

Bill's interests went well beyond mathematics; in his free time, he regularly attended concerts, operas, and plays. He also enjoyed sailing, tennis, *The New York Times* crossword puzzle, parties, and—above all—travel to destinations around the world.

In addition to Bill's professional community, he is survived by his wife Ann Lee Morgan, his companion of 50 years; his daughter K. Jodi Gear and son Christopher Gear (both from a previous marriage to Sharon Smith); four grandchildren; and his sister Kate Redding. We will all miss Bill: the world traveler, truly creative scientist, inspiring scholar and collaborator, and the smiling man in the photograph.

As he himself said, "It is the path that is fun — in the end, there is no *there* when you get there." Bill made many people's paths fun as a person, teacher, and friend, and he continues to make our paths fun with his contributions to science and mathematics.

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[1] http://history.siam.org/oralhistories/gear.htm
[2] https://www.computerhistory.org/collections/catalog/102746786
[3] https://www.siam.org/publications/journals/siam-journal-on-scientific-computing-sisc

Creativity

Continued from page 1

The Solver

The solver in steps 1 and 3 does not need to be LU factorization with backward and forward substitution. Iterative refinement works with an arbitrary solver, subject to some assumptions on its numerical behavior. Moreover, the solver on step 3 does not have to be the same as the one on step 1. For step 3, the generalized minimal residual method (GMRES)—preconditioned by the LU factors that were computed on step 1—increases both the accuracy and range of matrix condition numbers for which convergence is obtained.

Interplay of Precisions

This process is not limited to two precisions; we can independently choose the precisions in steps 1 through 3 and even employ more than one precision inside the solvers used on steps 1 and 3. We can determine good combinations of precisions based on the relative speed of the arithmetics and the properties of the matrix.

Hardware

We can deploy this method on more than just digital hardware. It has been used with the correction equation on step 3 solved using low-precision analog circuitry and residuals computed using higher-precision digital circuitry.

Multiprecision

Computer hardware provides floating-point arithmetic in a limited number of precisions, but arbitrary-precision arithmetic is available in software. Iterative refinement can be done with a precision that increases during the iteration until any desired accuracy is obtained.

These are just some of the ways in which iterative refinement has been modified over its more than 70 years of use on digital computers; many of the changes were motivated by the evolution of computer architectures. Any numerical analyst could have discovered these variations by observing all of the algorithm's features and asking "How might this be different?" for each one. It is essential, however, not to judge ideas too quickly after generating them, as doing so risks prematurely throwing out some of the best ones. Having noted that we can compute the residual at the working precision, we might be tempted to dismiss this idea in light of conventional wisdom. But great ideas often go against conventional wisdom!

We invite you to try the steps that we have illustrated on a topic that interests you. Write down all of its features and underlying assumptions and ask how each one might be different. Make sure not to evaluate your ideas too soon.

While our process can be applied by individuals on their own, it is most powerful when used in small groups. Different people spot different features of a focus of attention, and a group produces a wider selection of ways in which those features can be changed than any individual is likely to do.

Our creativity workshops consist of between six and 20 people who work in groups of up to eight, ideally meeting for one or two days. They can generate a large number of ideas for future evaluation. These workshops are great ways to train people in creativity and help build a team environment in which creativity flourishes.

For full details about our six-step creativity process—as well as other techniques for generating ideas—see our new SIAM book: *How to Be Creative: A Practical Guide for the Mathematical Sciences*,[1] which is available for purchase at **bookstore.siam.org**.

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[1] https://my.siam.org/Store/Product/viewproduct/?ProductId=42453396

Machine Learning

Continued from page 1

Each E^j thus contains linearized solutions that do not exchange energy via resonances with higher members of the spectral subspace hierarchy.

The subspace E^j serves as an observed attractor for typical linearized trajectories until the components of those trajectories in $E^j - E^{j-1}$ die out. At that point, E^{j-1} becomes the observed attractor (see Figure 1a, on page 1). The reduced dynamics on E^j therefore provide the best possible reduced model of the linearized dynamics if we wish to filter out transients that are associated with all stronger decay exponents $\mathrm{Re}\,\lambda_\ell$ for $\ell > j$.

The fundamental result of *spectral submanifold* (SSM) theory is that this hierarchy of observed linear attractors also persists in a smoothly deformed form within the full nonlinear dynamical system. Specifically, a nested family of SSMs $W(E^1) \subset W(E^2) \subset \ldots$ exists such that $W(E^j)$ is invariant under the full dynamics, has the same dimension as E^j, and is tangent to E^j at the steady state $\mathcal{M}_0$. These SSMs are not unique; they share their invariance, dimensionality, and tangency to E^j with infinitely many other manifolds. Under the addition of small periodic or quasiperiodic forcing, both $\mathcal{M}_0$ and its SSMs persist smoothly and inherit the time dependence of the forcing.

Therefore, SSM-reduced dynamics provide a hierarchy of mathematically exact low-dimensional models for nonlinearizable behavior — even with the addition of moderate external forcing. Such behavior includes coexisting steady states, transitions among them, and chaotic dynamics. SSM-reduced models can be computed in seconds or minutes and reveal the details of nonlinearizable, damped-forced responses in mechanical systems with tens or even hundreds of thousands of degrees of freedom. For example, the red curve in Figure 2 traces an accurate and highly accelerated prediction of forced response from a two-dimensional reduced model on $W(E^1)$ for a 267,840-dimensional finite element model of an aircraft wing. Such a numerical prediction is currently impossible for even the most advanced numerical continuation packages [4].

The SSMTool[1] computations in Figure 2 require explicit knowledge of nonlinearities in the governing equations, which is not available from commercial finite element codes. Even the evaluation of functions that implicitly define the nonlinearities is costly. The prohibitive expense for long-term simulations of individual trajectories means that model reduction is unavoidable.

One possible workaround is a fully data-driven algorithm for SSM construction [2]. This algorithm—which is implemented in an open-source MATLAB package called SSMLearn[2]—uses data to identify the dimension and spectrum of the dominant spectral subspace E^j. The procedure then utilizes regression to reconstruct the SSM in the observable space and computes a sparse normal form for the SSM-reduced dynamics.

This approach yields previously unthinkable computational speed-ups for dynamic finite element simulations. One can simply learn the unforced normal form on SSMs from a small number of decaying, unforced trajectories, then use these low-dimensional models to predict full bifurcation curves of the forced response without any simulation. The blue curve in Figure 2 is an example of this type of nonintrusive, data-driven model reduction, which yields remarkably close agreement with the exact analytic predictions from SSMTool. Here, SSMLearn was trained on a single unforced trajectory and predicted the full forced response curve in only five minutes.

SSM-based model reduction has multiple other uses as well. It is equally applicable to experimental data with arbitrary physics, such as sloshing dynamics in surface-wave experiments that are relevant in the design of tanks on cargo ships and commercial trucks (see Figure 3). Data-driven SSM reduction also provides low-dimensional reduced models for global transitions in infinite-dimensional nonlinear evolution equations. Such transitions occur, for example, in the Navier-Stokes equations for planar Couette flows, which admit multiple steady states beyond their stable, constant-shear base state (see Figure 4).

Here we have illustrated a physically diverse group of dynamical data sets from which DBML constructs accurate and predictive reduced-order models for nonlinearizable dynamics on SSMs. These dynamics display coexisting stable and unstable steady states with transitions among them, which cannot be simultaneously captured by a linear model. Promising ongoing extensions of SSM theory to more general $\mathcal{M}_0$ sets, external forcing types, and non-smooth effects will further enhance the power of DBML.

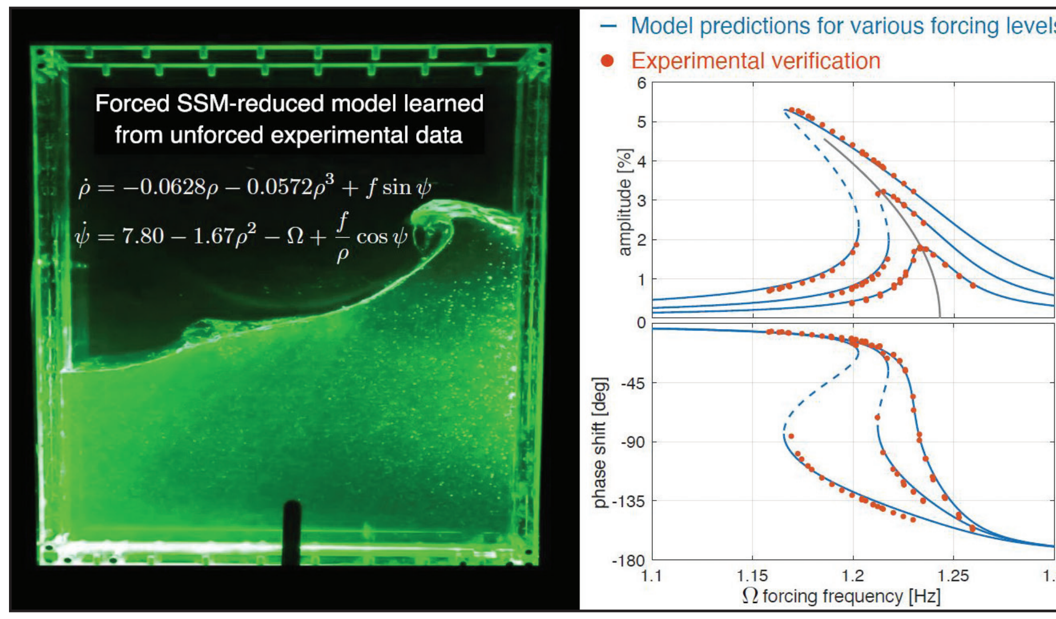

Figure 3. *Predictions for the forced horizontal oscillations of a sloshing fluid's center of mass by a model that is trained on unforced experimental data. Figure adapted from [2] and left image courtesy of Kerstin Avilla.*

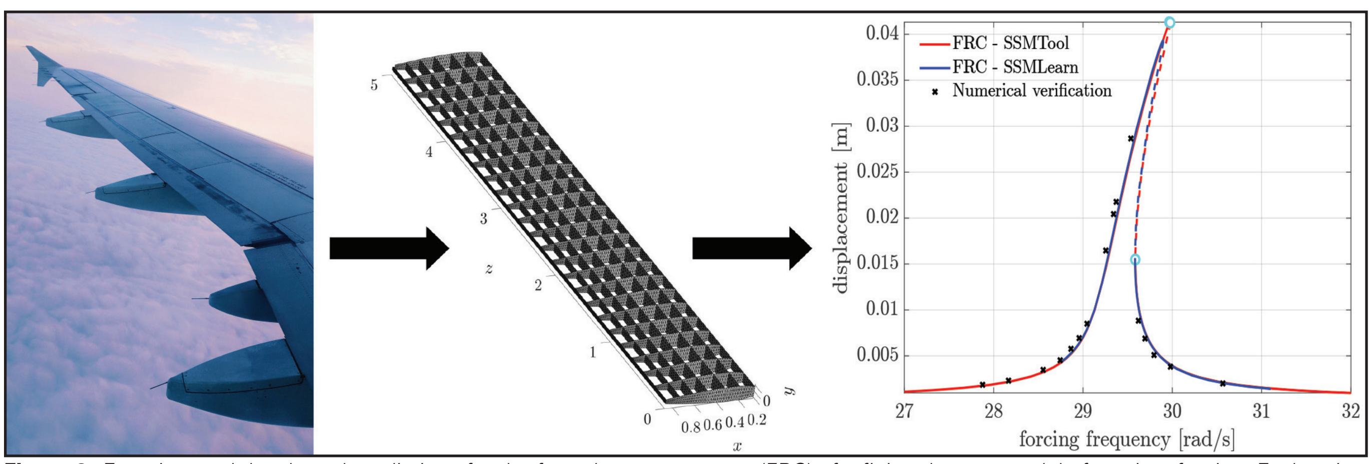

Figure 2. *Equation- and data-based predictions for the forced response curve (FRC) of a finite element model of an aircraft wing. Each trajectory integration in the forced finite element model (black cross) requires approximately four days to cover roughly 20 seconds of physical model time. In contrast, an equation-driven, spectral submanifold (SSM)-based prediction by SSMTool [4] (red curve) for the full FRC takes about 40 minutes. Finally, a purely data-driven FRC prediction by SSMLearn [2] (blue curve) that is trained on a single unforced trajectory takes about five minutes. Dashed portions of the SSM-based FRC predictions, which indicate unstable periodic response, are unavailable to direct numerical integration. Figure courtesy of the authors.*

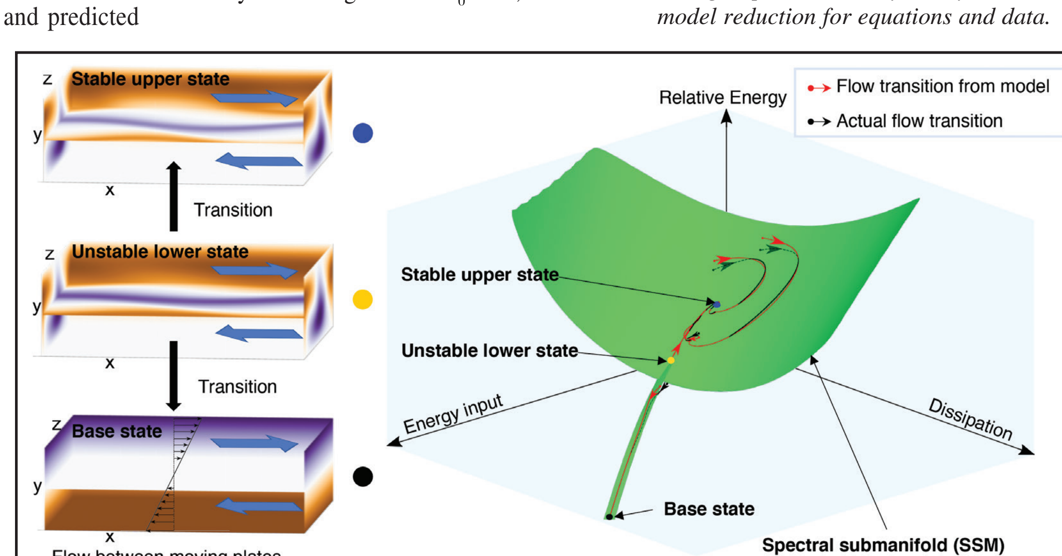

Figure 4. *Data-driven spectral submanifold (SSM)-based model and predictions for global transitions between stable and unstable states in a Couette flow. Figure adapted from [5].*

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[1] https://github.com/haller-group/SSMtool

[2] https://github.com/haller-group/SSMLearn

Truth to Power

Continued from page 2

as money in media circles. Speaking truth to power can thus have consequences, like the loss of funding or access to necessary information. Either of these outcomes can damage a career — as well as one's ability to make a living.

"Back Off, Man, I'm a Scientist"

"It's difficult when those in power are so ideologically removed from one's own principles or worldview," Al-Khalili said. "The model of just saying, 'We are the experts, you are the empty vessels to be filled with our knowledge and wisdom,' is not going to work."

Instead of the *Ghostbusters* "Back off, man, I'm a scientist!" approach, Al-Khalili argued that scientists must explain their methodologies and expose their own humanity. Krummel expanded upon this viewpoint. "[Media] has popularized the scientist as white coat-wearing, bespectacled, and very precise," he said. "And there are realities to that. But many of us love the outdoors, many of us go to church and are spiritual — all of this stuff is not part of the popular perception."

Such commonalities can help bridge the divide. Krummel added that scientists should speak from the heart, verbalize how they feel about the issues at hand, and acknowledge that audiences respond to who they are as people, not just to their facts.

In short, science can provide the necessary evidence to oppose ideologically-driven assaults on climate change, LGBTQ+ rights and healthcare, the U.S. Supreme Court's recent leaked stance on abortion, and other important issues. At the same time, the shared humanity between scientists and non-scientists may be a more effective way for science to speak truth to power.

References

[1] Oreskes, N., & Conway, E.M. (2010). *Merchants of doubt: How a handful of scientists obscured the truth on issues from tobacco smoke to global warming*. New York, NY: Bloomsbury.

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

Introducing Spectra: The Association for LGBTQ+ Mathematicians

By Alexander Hoover and Ron Buckmire

In the early morning hours of June 28, 1969, a group of LGBTQ+ individuals in New York City fought back against homophobic, transphobic, and racist police violence in what has since become known as the Stonewall Uprising. These actions—in which trans women of color played a central, if often overlooked and marginalized role—marked a crucial turning point in the LGBTQ+ rights movement in the U.S. and beyond. In honor and remembrance of the Stonewall Uprising as well as the struggles and successes of all LGBTQ+ people, June is commonly known as LGBTQ+ Pride Month in the U.S., Canada, and multiple other countries. This June, we highlight the recent work of Spectra[1]—the Association for LGBTQ+ Mathematicians—and describe ways in which SIAM members can get involved.

Spectra was founded in 2015[2] as a volunteer-run, professional society for LGBTQ+ mathematicians [2]. The society has a regular presence at the Joint Mathematics Meetings (JMM), where it organizes panels, holds board meetings with volunteers, and hosts a reception for LGBTQ+ mathematicians. Spectra has also coordinated and sponsored more than a dozen events, including the first biannual Spectra LGBTQ+ in Mathematics Conference,[3] which took place virtually through the Institute for Computational and Experimental Research in Mathematics[4] in August 2021. In addition, it launched several initiatives to increase the visibility of LGBTQ+ mathematicians and works with various mathematical societies and publishers to adopt policies that are more inclusive to mathematicians who are trans and nonbinary. Spectra has even held sessions and smaller outreach events at previous SIAM meetings, though the COVID-19 pandemic has delayed the growth of a physical presence at SIAM conferences.

Recently, Spectra has taken steps to raise its profile as an organization. By adopting a new set of bylaws, a formal board of officers, and official membership status, the association intends to better serve and support the LGBTQ+ math community. We hope that these changes will make it easier for people to become involved with and shape the future of Spectra, and allow Spectra to undertake larger and wider-reaching initiatives that will ultimately make mathematics a more inclusive space. As our new mission states, Spectra's goal is *"to support and encourage LGBTQ+ individuals in mathematics by working to create an inclusive and affirming environment that supports the well-being and professional development of LGBTQ+ mathematicians. Spectra strives for a time when LGBTQ+ mathematicians are able to bring their whole selves to the mathematical community."*

Next month, we hope to mirror Spectra's JMM presence at the 2022 SIAM Annual Meeting,[5] which will take place from July 11-15 in a hybrid format in Pittsburgh, Pa. We invite any interested parties to attend our two-part minisymposium, entitled "Presentations by LGBTQ Mathematicians."[6] In the future, we hope to offer travel grants for LGBTQ+ students, awards that help LGBTQ+ individuals with graduate school fees, funds to support transgender and nonbinary mathematicians with some of the professional costs of transitioning, research opportunities for LGBTQ+ undergraduates, and research groups for LGBTQ+ mathematicians who are seeking support and community.

In addition to these future goals, there are more timely and concrete ways for readers to get involved with Spectra:

• **Donate:** To jumpstart the aforementioned programs, we created the Queer Foundations fundraising campaign with the goal of raising $30,000 to place Spectra on solid ground for future growth. Additional information about the campaign is available online[7] (most donations are tax deductible).

• **Serve:** If you are passionate about supporting the LGBTQ+ community and interested in making mathematics more inclusive, we would love for you to volunteer your time. Committees are dedicated to a range of issues—from outreach and research to politics and equity, diversity, and inclusion—so there are many opportunities for involvement. Members of the LGBTQ+ community as well as allies are

See **Spectra** *on page 6*

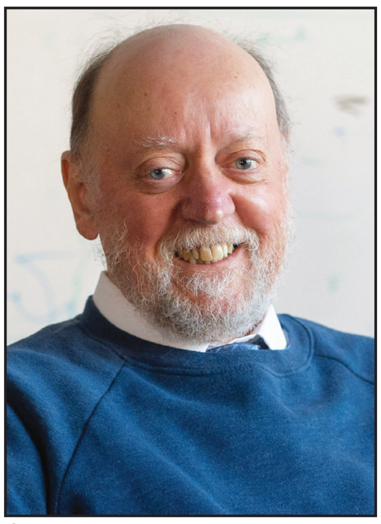
Spectra, the Association for LGBTQ+ Mathematicians, aims to support and encourage LGBTQ+ individuals in mathematics by creating an inclusive and affirming environment.

[1] http://lgbtmath.org
[2] https://www.ams.org/journals/notices/201906/rnoti-p875.pdf
[3] https://icerm.brown.edu/topical_workshops/tw-21-smc
[4] https://icerm.brown.edu
[5] https://www.siam.org/conferences/cm/conference/an22
[6] https://meetings.siam.org/sess/dsp_programsess.cfm?SESSIONCODE=74182
[7] http://lgbtmath.org

Jack Dongarra Receives the 2021 ACM A.M. Turing Award

By Jillian Kunze

SIAM Fellow Jack Dongarra received the prestigious 2021 Association for Computing Machinery (ACM) A.M. Turing Award[1] earlier this year. The award is named for Alan Turing—whose work heavily shaped the mathematical foundations of computer science—and honors individuals who have made lasting contributions to the field of computing. It carries a $1 million prize for the winner, with financial support from Google, Inc. The 2021 prize announcement[2] states that Dongarra was honored "for pioneering contributions to numerical algorithms and libraries that enabled high performance computational software to keep pace with exponential hardware improvements for over four decades."



SIAM Fellow Jack Dongarra received the 2021 Association for Computing Machinery A.M. Turing Award. Photo courtesy of Tara Kneiser.

Dongarra has a long history of extensive research on parallel computing, numerical algorithms in linear algebra, advanced computer architectures, and programming. He is a University Distinguished Professor of Computer Science in the University of Tennessee's Department of Electrical Engineering and Computer Science, a Distinguished Research Staff Member at Oak Ridge National Laboratory, and a Turing Fellow in the University of Manchester's Department of Mathematics.

"The ACM A.M. Turing Award is a tremendous and humbling recognition, and I am honored to have been chosen," Dongarra said. "I know about the past Turing Award recipients. I have learned from their books; read their papers; used their programming languages, theorems, techniques, standards, and algorithms; and even written papers with a couple of them. To be in that class of people is overwhelming."

Dongarra is a longtime member of SIAM and has been actively involved with the SIAM community for multiple decades. He served on the SIAM Council for six years and has presented many times at SIAM conferences. He was also the founding chair of the SIAM Activity Group on Supercomputing[3] (SIAG/SC) and subsequently became the first recipient of the SIAG/SC Career Prize[4] in 2010. In addition, he received the 2019 SIAM/ACM Prize in Computational Science and Engineering[5] and has written a number of successful SIAM books, including several software user guides and *Numerical Linear Algebra for High-Performance Computers*.[6]

Reflecting on the Turing Award, Dongarra expressed gratitude for the encouragement of friends and colleagues throughout his career. "An award like this couldn't have happened without the support and contributions of many people over time," he said. "I have to credit the generations of colleagues, students, and staff who have helped and influenced me over the years to obtain this recognition. It comes about by having a great group of people and mentors who push you in the right direction."

Moving forward, Dongarra seeks to honor the legacy of past Turing Award winners. "I hope I can live up to all the greatness that the Turing Award has recognized and become a role model, as many of the recipients have been, for the next generation of computer scientists," he said.

Jillian Kunze is the associate editor of SIAM News.

[1] https://amturing.acm.org
[2] https://awards.acm.org/about/2021-turing
[3] https://www.siam.org/membership/activity-groups/detail/supercomputing
[4] https://www.siam.org/prizes-recognition/activity-group-prizes/detail/siag-sc-career-prize
[5] https://sinews.siam.org/Details-Page/siam-announces-major-cse-prizes
[6] https://my.siam.org/Store/Product/viewproduct/?ProductId=1183

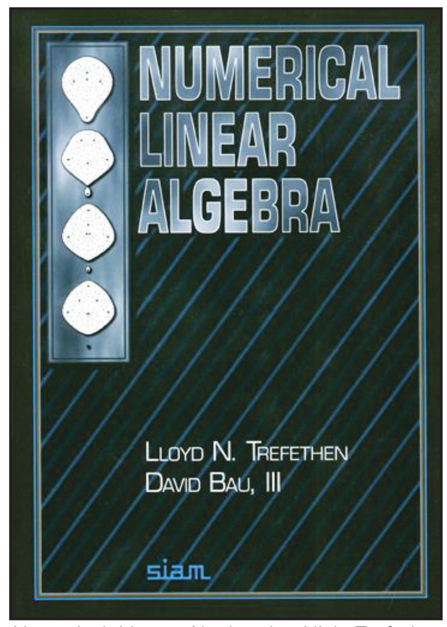
Some Recollections of Trefethen and Bau on the Occasion of Its 25th Anniversary

By Lloyd N. Trefethen

When I was a graduate student at Stanford in 1978, I remember Gene Golub telling me that Pete Stewart's *Introduction to Matrix Computations* was very good (he was right). Of course, Gene added, it's quite a few years old. But it had only been published five years before, in 1973! So it almost seems like science fiction that *Numerical Linear Algebra*[1]—which was published in 1997—is still going strong today, 25 years later.

I was not a numerical linear algebraist by training; I'd written my thesis with Joe Oliger on finite difference methods for partial differential equations. Still, I'd been exposed to the subject in courses by Golub, Jim Wilkinson, and Cleve Moler — and indeed by the whole atmosphere of Golub's numerical analysis group at Stanford. When I landed at MIT as the only numerical analyst on the faculty, naturally enough they wanted me to teach this subject. We put together a course numbered 18.335, and the masterpiece *Matrix Computations* by Golub and Van Loan had just come out. I had the perfect combination of first-rate students from a mix of departments with an outstanding reference text that provided details about everything I could possibly want to teach. MATLAB emerged around the same time and changed my outlook permanently, making me more professionally interested in linear algebra and also a believer in the importance of programming at a high conceptual level.

The Golub and Van Loan book, however, was too much. After a few years of teaching numerical linear algebra, I had developed my own views on what subset of topics should be included in a course and in which order they should appear to avoid boring the students with Gaussian elimination in lecture 1. By this point I was at Cornell and 18.335 had become Applied Math 621 (Charlie Van Loan was now my colleague, but he generously allowed me to teach his subject anyway). I found myself tempted to write a book of my own that would be shorter and more student-friendly than Golub and Van Loan, and at just the right moment, along came a Ph.D. student who liked to write and with whom I got along very well. Most readers have probably not met David Bau, but that's your loss. He's an extraordinary person and we have a lot in common, including growing up in a western suburb of Boston and attending Phillips Exeter Academy and Harvard. Now that my course had been running for a few years and such a simpatico student had arrived at Cornell, I had an idea: I could ask David to take thorough notes of my lectures and we could turn them into a book. I think the end result benefitted from his freshness as a newcomer to the subject, and indeed from my own fresh perspective as a nonexpert.



Numerical Linear Algebra by Nick Trefethen and David Bau was published by SIAM in 1997.

It all unfolded as I had hoped, and David contributed hugely to *Numerical Linear Algebra* — including the first sentence, which I like very much: "You already know the formula for matrix-vector multiplication." The figures are drawn straight in native PostScript, with no MATLAB or other intermediary. Somewhere along the way, David had become a PostScript hacker. At SIAM, Vickie Kearn and Beth Gallagher made the book attractive and free of glitches.

I have happy memories of teaching numerical linear algebra at Cornell as these lectures took shape. One year saw about 25 participants in the course, all of whom were Ph.D. students except for one undergraduate. The undergraduate turned in dazzlingly good homework assignments and got the highest mark in the class. He was called Jon Kleinberg.

I like a lot of things about Trefethen and Bau, including the short chapters — a pattern I've followed in my subsequent books. Perhaps my single favorite item is the observation that for computing the QR decomposition, Gram-Schmidt is *triangular orthogonalization* whereas Householder is *orthogonal triangularization*. I also enjoy the section "When Vectors Become Continuous Functions," which led to Chebfun[2] and a whole new way of thinking in terms of continuous analogues of all the classical structures and algorithms.

Our book came along at the perfect time. Classical ideas had been established, including Krylov subspace iterations, yet it was still an era when many mathematical scientists were barely aware of the singular value decomposition (SVD). This may have been the first textbook to put the SVD up front as a fundamental topic, not just a subordinate tool to another problem like least squares. Page 26 provides a sketch emphasizing that every $m \times n$ matrix maps the unit sphere to a hyperellipse, without exception. *Numerical Linear Algebra* seems to have been welcomed as a good foundation for all kinds of things, and Yuji Nakatsukasa's afterword for the 25th anniversary edition is an exciting review of developments in the years after its initial publication.

With each passing decade since the introduction of computers, linear algebra has become more important. This is a trend that I don't think Alan Turing and John von Neumann saw coming, yet has had something of the inexorability of Moore's Law (if not quite the same time constant). The growth is continuing in the present era of data science, as everybody in the tech world now seems to want to know more linear algebra. Back in 1997, we hoped the SVD would come to be appreciated as important; we hardly imagined it would one day even be cool.

The 25th anniversary edition of Numerical Linear Algebra will be available for purchase at the 2022 SIAM Annual Meeting,[3] which will take place in a hybrid format from July 11-15, 2022, in Pittsburgh, Pa. A book signing with Nick Trefethen will accompany its debut.

Nick Trefethen is Professor of Numerical Analysis at the University of Oxford. He was president of SIAM during 2011-2012.

1 https://my.siam.org/Store/Product/viewproduct/?ProductId=950

2 https://www.chebfun.org

3 https://www.siam.org/conferences/cm/conference/an22

Spectra

Continued from page 5

all welcome to join committees. Check out our website for more information.

• **Join:** Spectra offers both individual and institutional memberships. Visit us on the web to learn more.

As the LGBTQ+ community continues to grow and evolve, so too must our efforts to make mathematics a welcoming and inclusive space. Please join us if you are interested in helping Spectra grow as an organization that strives to create a more vibrant and prideful mathematical community. Happy Pride!

Article adapted with permission from "A Word From... Spectra" by Juliette Bruce, which will appear in the June/July 2022 edition of Notices of the American Mathematical Society [1].

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[1] Bruce, J. (2022). A word from… Spectra. *Notices Am. Math. Soc*. To appear.

[2] Bryant, R., Buckmire, R., Khadjavi, L.S., & Lind, D.W. (2019). The origins of Spectra, an organization for LGBT mathematicians. *Notices Am. Math. Soc*., *66*(6), 875-882.

Alexander Hoover is an assistant professor of mathematics at Cleveland State University and a board member of Spectra. His research areas are in mathematical biology and fluid dynamics, and he is firmly committed to increasing equity and representation within mathematics. Ron Buckmire is a professor of mathematics and Associate Dean for Curricular Affairs at Occidental College. He publishes research in numerical analysis, mathematics education, and data science. Buckmire is also the Vice President for Equity, Diversity, and Inclusion at SIAM.

Spectra hosted a joint panel with the Association for Women in Mathematics on "Queer Families and Mathematical Careers" at the 2020 Joint Mathematics Meetings, which took place in January 2020 in Denver, Colo. From left to right: Moderator Alice Mark and panelists May Mei, Chikako Mese, Dylan Thurston, Amanda Folsom, and Matt Voigt, with co-organizer Corrin Clarkson seated in the foreground. Photo courtesy of Alexander Hoover.

A Conversation with Mathematical Consultant John D. Cook

By Krešimir Josić

Many articles, resources, and personal accounts address the transition from an applied mathematics career in academia to a position in business, industry, and/or government. These types of materials typically focus on traditional jobs within companies and organizations. However, mathematical consulting is a distinct career path with its own set of unique challenges and opportunities. John D. Cook[1]—a consultant in applied mathematics, statistics, and technical computing—is a prime example of a success story within this niche field.

Cook began his career by earning his Ph.D. at the University of Texas, where he studied nonlinear partial differential equations. After completing a postdoctoral appointment at Vanderbilt University in the same topic, he left academia and worked as a software developer and project manager for several years. Cook joined the Department of Biostatistics at MD Anderson Cancer Center in 2000, where he first served as a software development manager and then as a research statistician. While at MD Anderson, his research centered on Bayesian statistics, clinical trials, and numerical algorithm development. In 2013, Cook left to start his own applied math consulting company.

Krešimir Josić of the University of Houston recently sat down with Cook to explore the nuances of founding and maintaining an independent mathematics consulting business. Here they share their conversation with *SIAM News*.

Krešimir Josić: You hold a Ph.D. in mathematics and have worked in both academia and industry for more than a decade. Why did you decide to become a consultant?

John Cook: For one thing, I love the variety that comes with consulting. I had worked for a software consultancy in the past, and there wasn't much variety of work despite the variety of clients. Now I have a variety of clients *and* a variety of work.

I also wanted more agency over my income. There's usually not much that salaried employees can do to change their income by more than a few percentage points per year, but business owners can decide how much money they want to make. Not entirely of course, but to a much greater extent than traditional employees.

Finally, I desired the security of multiple income sources. Salaried workers effectively have one client; if they lose that client, they lose 100 percent of their income all at once. As a consultant, I usually have several clients at a time.

KJ: How did you ensure that your business would succeed? Did you have any fallback plans in case it didn't grow as fast as you anticipated?

JC: Looking for consulting work is not much different from looking for employment, and I figured that the effort I was expending to identify projects would also find job leads. Once I started consulting, several of my initial clients offered to hire me as an employee; my backup plan was to pursue one of those offers.

KJ: How do you determine which projects to accept?

JC: I'd recommend taking almost any project that pays when you first start, then gradually becoming more selective. I'd also recommend increasing your minimum project size over time. All projects take up some amount of transaction cost and mental overhead, regardless of their size; as a result, smaller projects are less profitable.

By initially casting a wide net, consultants can explore the types of available work. After a while, they may start to receive referrals in a certain area and begin to concentrate more in that particular subject. It pays to not be too set on one kind of work until you learn about existing demands in the field.

Risk analyst Nassim Taleb advocates for a barbell portfolio investment strategy.[2] One end of the barbell consists of reliable income without much downside potential, which probably also means not much upside potential. The other end can be speculative or stimulating. I try to follow this strategy by maintaining a mix of reliable projects and more interesting projects. "Interesting" often means "unpredictable," and consultants risk overloading themselves if they take on too many interesting projects at once.

KJ: I imagine that managing a team of consultants is quite different than managing a team in academia or most other professions. What unique challenges do you face in your position?

JC: I work with a loose network of consultants and collaborate with different people as needed, which is less effort than managing a standing team. Also, the work is very results-oriented. There are no office politics or other distractions that consume energy in large organizations.

See **Mathematical Consultant** *on page 8*

John Cook delivers a presentation that introduces Bayesian statistics at KeenCon 2014, a software developer conference that took place in San Francisco, Calif., in September 2014. Photo courtesy of KeenCon 2014.

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

[2] https://vantagepointtrading.com/nassim-talebs-barbell-portfolio-investment-strategy

Datathons4Justice Address Social Justice Issues with Data Science

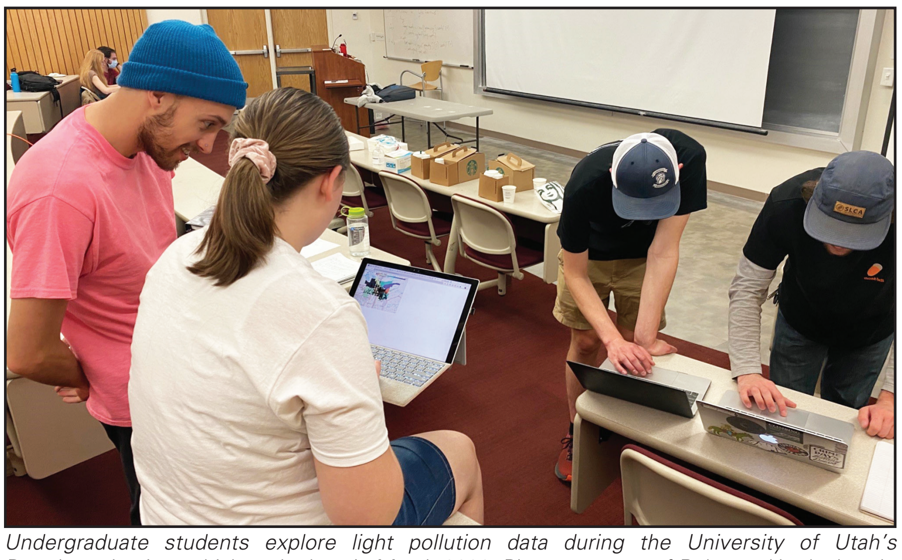
By Trent DeGiovanni, Wesley Hamilton, Rebecca Hardenbrook, Jude Higdon, Owen Koppe, Keshav Patel, and Chad M. Topaz

The world is currently facing many complex challenges. Issues such as climate change, war, and rising authoritarianism exist alongside (and are sometimes linked with) ongoing injustices based on race, gender, gender identity, sexual orientation, and other personally- and socially-constructed identities. Effective responses to many of these conflicts have thus far remained elusive.

The growing field of data science can provide the research base to identify and enact ambitious, compelling, and evidence-based solutions to global problems. Emerging and established data scientists must ask compelling and nuanced research questions; find, procure, clean, and analyze data from many sources; and draw reasoned conclusions that activists and policymakers can leverage during the decision-making process. In short, we need a well-trained generation of data scientists who apply their craft to real-world scenarios and create effective solutions.

Data science's connection to issues of criminal justice and economic equity is clear. Communities of color experience disproportionate impacts from policing practices, judicial sentencing, hiring biases, social mobility, voting restriction laws, and a host of other obstacles. Similarly, women and LGBTQIA+ individuals face less economic mobility, poor representation in the arts and media, and diminished educational pathways when compared to their male and/or heterosexual counterparts. However, the connections in other forms of activist data science may be more subtle. For example, the general public is often less aware that climate change disproportionately impacts communities of color, human trafficking targets women and children of color at overrepresented rates, healthcare is delivered to individuals of color in a vastly inferior manner, and light pollution more severely affects the quality and quantity of sleep for lower socioeconomic status groups and people of color. Data scientists must work in concert with mathematicians, physical and biological scientists, social scientists, humanities scholars, and activists to propose solutions to these types of discriminations.

To simultaneously train emerging data scientists and call attention to specific social justice issues, universities, companies, and other organizations should consider hosting a datathon — in particular, a Datathon4Justice.



Undergraduate students explore light pollution data during the University of Utah's Datathon4Justice, which took place in March 2022. Photo courtesy of Rebecca Hardenbrook.

QSIDE's Inaugural Datathon4Justice

In October 2021, the Institute for the Quantitative Study of Inclusion, Diversity, and Equity[1] (QSIDE) hosted its inaugural Datathon4Justice.[2] Over 10 research teams of students, faculty members, and activists from more than 30 institutions of higher learning and mission-driven organizations took part in the event, which commenced virtually. QSIDE's Datathon4Justice focused on two unique datasets: (i) Judicial sentencing disparities in the Minnesota court system and (ii) police data from a small town in rural, western Massachusetts with a troubling history of reported racial and gender bias. Some participating schools could support their own teams, while other teams comprised a mix of registrants from different schools and organizations. Groups worked with the provided datasets for two days before reporting their findings to everyone.

This initial Datathon4Justice inspired two research labs[3]—the Small Town Policing Accountability (SToPA) lab and JUdicial System Transparency for Fairness through Archived Inferred Records (JUSTFAIR) state research lab—to continue the projects. These labs meet weekly to study state-level judicial sentencing disparities and police accountability, and more than 50 scholars and activists regularly engage in the ongoing work. QSIDE's datathon also inspired subsequent datathons at a number of other institutions, including Tufts University[4] and the University of Utah. In addition, QSIDE partnered with the National Math Festival[5] to create a curriculum and support a High School Datathon4Justice[6] earlier this year; MathWorks Math Modeling Challenge,[7] a program of SIAM, provided additional support for this event. The datathon saw four U.S. high schools engage in introductory data science with RStudio[8] to analyze the dataset from QSIDE's existing research about diversity in major U.S. art museums.[9]

The University of Utah's Datathon4Justice

In March 2022, the University of Utah hosted its own in-person Datathon4Justice[10] that concentrated on light pollution — an environmental justice issue in Salt Lake City. Low socioeconomic communities are often located close to industrial spaces, which are typically well lit. The emitted light can impact the health of nearby residential neighborhoods in a number of ways, including poor sleep quality. Furthermore, streetlights in Salt Lake City's lower socioeconomic neighborhoods tend to have brighter and harsher bulbs; the resulting luminescence can negatively affect driving conditions and cause more vehicular accidents between cars, pedestrians, and/or bicycles. For these and other reasons, the issue of light pollution is particularly relevant to the local community in Salt Lake City and thus made for a timely topic for Datathon participants.

The Datathon4Justice consisted of three components: (i) Preparatory workshops, (ii) the datathon itself, and (iii) opportunities for teams to present their work. A month before the event, organizers from the University of Utah's Department of Mathematics and School of Medicine developed and implemented a four-session workshop series to prepare students for the

See **Datathons4Justice** *on page 9*

[1] https://qsideinstitute.org

[2] https://qsideinstitute.org/events/datathon4justice

[3] https://qsideinstitute.org/join-the-qside-research-labs

[4] https://now.tufts.edu/2022/03/01/hacking-diversity-and-representation

[5] https://www.nationalmathfestival.org

[6] https://qsideinstitute.org/high-school-datathon4justice

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

[8] https://www.rstudio.com

[9] https://sinews.siam.org/Details-Page/when-data-meets-diversity

[10] https://datascience.utah.edu/events/datathon/2022

Mathematical Consultant

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I remember having a phone call one time with someone to whom I was subcontracting work and thinking afterwards, "I suppose that was project management." It was so easy that I hadn't thought about it in those terms. We simply discussed what needed to get done.

It's a lot of fun to work with people who have clearly differentiated skillsets, which is the opposite of group projects in academia. The division of labor is obvious, and people don't step on each other's toes.

KJ: Tell us about some of your most interesting projects. Are there any that seemed routine and easy at the outset but actually turned out to be challenging? Or vice versa?

JC: Working with GSI Technology[3] and their associative processing unit (APU) has been fun. The APU is a device that computes directly in memory rather than moving data back and forth between memory and central processing units. It's like a large, three-dimensional array of bits. You can carry out thousands of computations in parallel by conducting bit-wise operations between slices of this array (see Figure 1). For the right problems, the APU can be much more efficient than conventional hardware in terms of both time and energy. The programming model is unique, meaning that familiar operations require new approaches.

[3] https://www.gsitechnology.com

One project that turned out to be much more challenging than expected was related to psychoacoustics; the client wanted to make machine noises less annoying. Doing so meant reducing the subjective perception of noise intensity, not simply reducing the noise as objectively measured in decibels. The relationship between sound pressure levels and perceived loudness is very nonlinear, and perceived loudness is not the only factor that contributes to people's irritation towards a sound. Even though psychoacoustics is obviously subjective, general consistency exists in individuals' perception of sounds.

Some projects turn out to be simpler than I anticipate. Academics are often disappointed if a solution is too simple because that means it might not be publishable, but private sector clients are delighted with simple solutions.

KJ: Which skills from your mathematical training and subsequent time in academia do you find most useful in your current work?

JC: Clients often need to have a conversation with someone who thinks like a mathematician. This means carefully defining terms and focusing on the largest ones, making implicit assumptions explicit, knowing when an approximation is or is not good enough, and so forth. But consultants can't do these things until they speak their clients' language. They must be able to comprehend their clients' needs and use metaphors that they will understand.

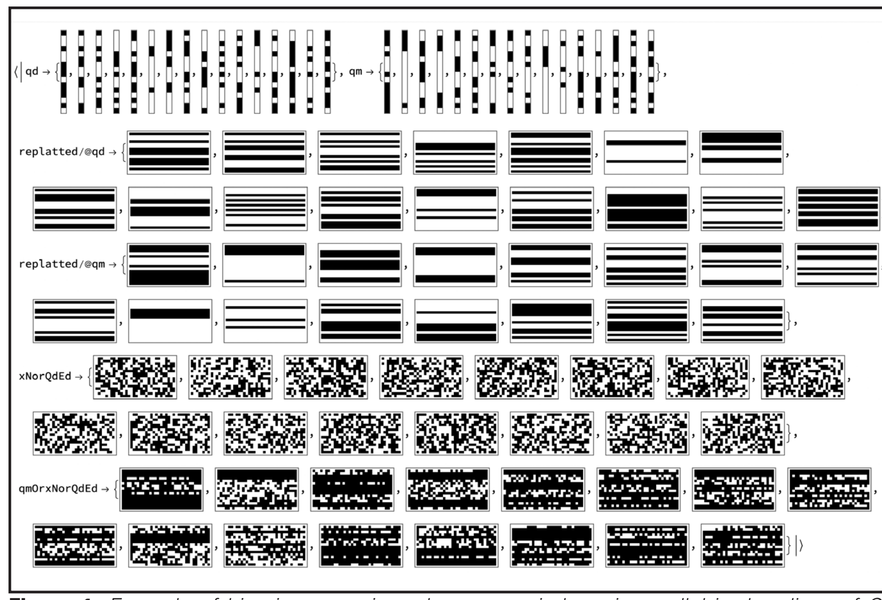

Figure 1. *Example of bit-wise operations that are carried out in parallel in the slices of GSI Technology's associative processing unit (APU). Figure courtesy of GSI Technology.*

John Tukey said that the best part of being a statistician is that you get to play in everybody else's backyard. This sentiment is also true of applied mathematics in general. As a consultant, I've had the opportunity to learn a little bit about a lot of different areas.

KJ: Do you perceive a divide between mathematics and statistics in consulting? How much of your work deals with mathematical questions and how much involves statistics?

JC: Applied statistics may be closer to epistemology than mathematics. You have to question what you know, why you think you know it, and how confident you are (or should be) in that knowledge. You must make simplifying assumptions and determine whether they are justified. Statistical modeling is hard to do *well*. It's easy to write down a model if you're not overly concerned with the accuracy of your results. As the old saying goes, fools rush in where angels fear to tread.

Sometimes I get to work on statistical problems with crisp mathematical statements, such as finding an efficient way to compute something. These projects are fun because the epistemological concerns are someone else's responsibility.

My work in applied mathematics has been more objective than my work in statistics. When you're dealing with voltages or velocities, what you're measuring (and what it means) is pretty clear. There's much less anxiety around modeling, and your level of success at the end is usually obvious. I prefer mathematical work, but there are more statistical opportunities in consulting. These days I often hand over statistical projects to someone else; I work on statistical problems about data privacy but am moving away from medical statistics.

KJ: What advice do you have for those who are considering careers in consulting?

JC: When people ask me for advice regarding consulting, I tell them several things. One is that finding the work is harder than doing the work, assuming that the person in question possesses the technical skills for consulting. Another is that consulting can require more savings than you think, as consultants may face dry spells between projects. Also, clients—particularly large clients—can be slow to pay their invoices.

Many people think that they'll start consulting on the side and leave their day jobs once the side business brings in enough income. That didn't work for me, and I doubt that it works for many individuals. It's hard to find the time or credibility to do much consulting while simultaneously holding down another job. At some point, you have to take the leap.

John is active on social media, with 18 technical Twitter accounts[4] and a blog that has more than 3,000 articles.[5]

Krešimir Josić is a John and Rebecca Moores Professor of Mathematics, Biology, and Biochemistry at the University of Houston. He is also the current chair of the SIAM Activity Group on Life Sciences.

[4] https://www.johndcook.com/blog/twitter_page
[5] https://www.johndcook.com/blog

Datathons4Justice

Continued from page 7

event. Each session was attended by 15-20 students and tailored to specific groups of participants based on their comfort levels with Python programming.

The first two sessions were meant for non-programmers; attendees primarily came from social sciences backgrounds and were interested in conceptually understanding the programming basics to better communicate with their teammates. The last two sessions targeted students with more programming experience. For example, session three discussed exploratory data analysis and examined the ways in which data science can drive meaningful change, while session four introduced two Python packages: GeoPandas[11] and Scikit-learn.[12] This final session utilized the Datathon4Justice dataset as an example and served as a data-focused introduction to the datathon; the justice-focused introduction occurred during the kickoff event. Exit survey results indicated that students felt more comfortable with data science and Python packages after the workshop and were more confident taking part in the datathon.

To obtain data for the event, organizers contacted Daniel Mendoza—a professor in the Departments of Atmospheric Sciences, Internal Medicine, and City and Metropolitan Planning at the University of Utah—to discuss potential environmental justice topics that would work well in the datathon format. Mendoza is the coordinator of Utah's Dark Sky Studies minor,[13] and he quickly suggested light pollution as a theme — particularly since he already possessed large datasets of light fixtures and crashes within Salt Lake City. He also recommended that the organizers consult with Alpha Lambert and Brenna Connely—two students in the Dark Sky Studies capstone course—when preparing potential questions for participants.

During the Datathon4Justice kickoff festivities, QSIDE co-founders Chad Topaz and Jude Higdon spoke about QSIDE's work and the impact of their initial datathon. Lambert and Connely then characterized light pollution as an environmental justice issue, particularly in Salt Lake City. Team formation and initial groupwork time followed these introductions.

The next morning, 10 teams with three to four members each regrouped to continue their assessments. Generous support from the Utah Center for Data Science[14] provided coffee, a light breakfast, and lunch. Throughout the day, experienced data scientists—both graduate students and faculty—stopped by to answer questions and engage with teams. The event concluded that afternoon with a final address by Mendoza that further described his ongoing research on light pollution's effects in the Salt Lake City area.

Datathon participants were genuinely excited to use their mathematical and computational skills to address relevant, real-world issues. Mick Wagner, a third-year applied mathematics undergraduate, reveled in the realization of career opportunities at the intersection of mathematics and social justice. "I have always assumed that to survive capitalism, I would have to keep these interests separate," Wagner said. "But after the datathon, I was excited to see people and companies working towards something I thought was just a dream career."

After the event, teams had the opportunity to present their work at the university's Undergraduate Research Symposium[15] on April 5 and QSIDE's virtual Student Quantitative Action Research for Equity, Diversity (SQuARED), and Justice Conference[16] on April 16. At the research symposium, five teams debuted polished, refined, and interpreted findings based on their initial analyses at the datathon; for some participants, this was the first research and presentation opportunity of their academic careers. The subsequent SQuARED Justice Conference, which commenced as an online poster session with undergraduate and graduate student research from 15 colleges and universities, attracted more than 100 attendees from around the world.

Datathons engage students and faculty by showing participants that they can utilize computational math and data science to address quantitative questions about social justice. The success of both QSIDE and the University of Utah's Datathons4Justice demonstrate that these types of events effectively encourage students from interdisciplinary backgrounds to explore science, technology, engineering, and applied math fields.

Mick Wagner (left) and Muskan Walia present their results from the University of Utah's Datathon4Justice at the university's Undergraduate Research Symposium, which commenced in April 2022. Photo courtesy of the University of Utah's Office of Undergraduate Research.

Acknowledgments: We would like to acknowledge the QSIDE Institute, the Utah Center for Data Science, and the University of Utah's Office of Undergraduate Research for their support in organizing Utah's Datathon4Justice.

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[11] https://geopandas.org
[12] https://scikit-learn.org
[13] http://plan.cap.utah.edu/dark-sky-studies-minor
[14] https://datascience.utah.edu
[15] https://our.utah.edu/events/undergraduate-research-symposium
[16] https://qsideinstitute.org/squared-justice-2022

Wisconsin High Schoolers Honored for First-place Mathematical Model of Telecommuting Tendencies

2022 MathWorks Math Modeling Challenge Explores the Future of Remote Work

By Lina Sorg

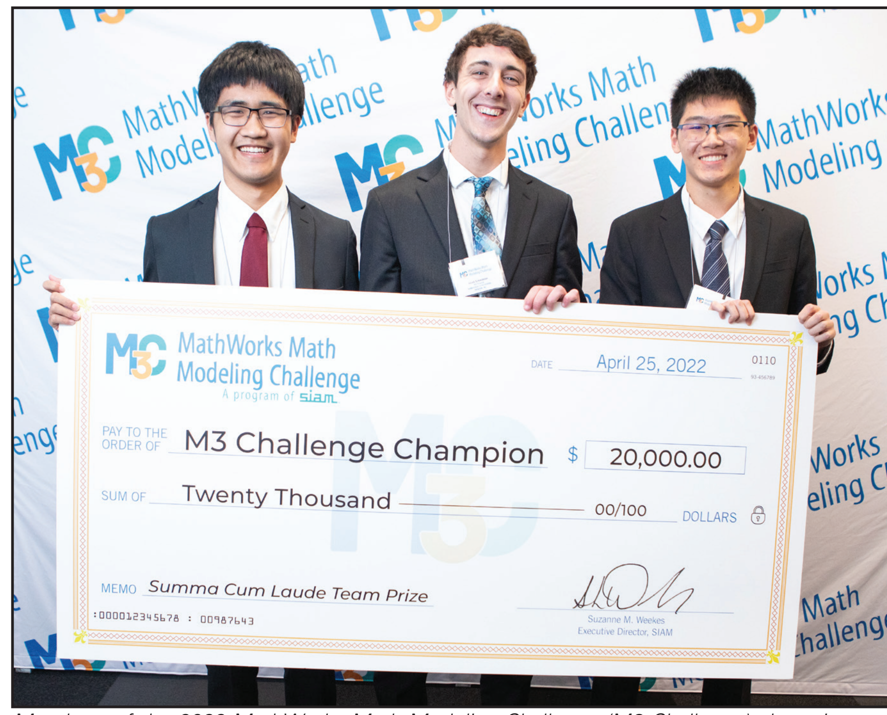
Despite previous industry predictions[1] that large numbers of employees would begin telecommuting in the 1990s and 2000s, only about 5.5 percent of Americans[2] and 4.7 percent of U.K. residents[3] routinely worked from home in 2019. However, the onset of COVID-19 in early 2020 marked a discernable shift towards remote work as offices around the world shuttered their doors and many people began telecommuting out of necessity. More than two years later, both employers and employees must make difficult decisions regarding an eventual return to the physical workplace. Some companies are offering flexible options for hybrid or remote work, while others are encouraging staff to return to the traditional office setting. Meanwhile, numerous factors—such as age, travel time, childcare obligations, and societal pressure—impact employees' willingness to commute to the office.

"We think a lot about the COVID-19 pandemic and the potential short- and long-term impacts," Chris Musco, an assistant professor of computer science and engineering at New York University, said. "Remote work stands out as a big question mark. There has clearly been a huge shift towards telecommuting, but the verdict seems out on whether this shift will stick around."

The nuanced complexity of remote work made it a pertinent topic for the MathWorks Math Modeling Challenge[4] (M3 Challenge): an annual mathematics competition that is a program of SIAM with MathWorks as its title sponsor. 2022 marked the 17th year of the student contest, during which participating high school juniors and seniors in the U.S. and sixth form students in England and Wales compete for more than $100,000 in scholarship money. Teams of three to five students work together over 14 consecutive hours during Challenge Weekend to address a complicated, real-world problem with mathematical modeling and report their findings in a 20-page solution paper; three Technical Computing Awards are also available for groups that choose to write or employ outstanding code as part of their responses. Over 125 Ph.D.-level applied mathematicians then evaluate the papers during several rounds of blind judging to determine the finalists. This year, the top teams traveled to New York City in late April and presented their solutions to a live panel of judges at the offices of Jane Street, a quantitative trading firm.

Musco—a 2008 M3 Challenge winning alumnus—was the primary author of the 2022 Challenge problem,[5] with assistance from the M3 Challenge Problem Development Committee. The problem questioned whether remote work is "fad or future," a topic that many students have experienced firsthand in their own educational endeavors over the last few years. "A number of factors make this a strong topic for the Challenge," Musco said. "The topic should have a lot of data and resources available, and both the U.S. and U.K. have government organizations that collect a ton of interesting data on workers — what jobs they do, how they work, where they work, and so forth. We also try to consider what mathematical tools might be used to solve the problem, and make sure that many interesting possible angles exist."

The Challenge problem asked students to create a model to estimate the percentage of workers in five U.S. and U.K. cities whose jobs are currently remote-ready, then calculate the percentage of remote-ready positions that will exist in 2024 and 2027. Next, they were tasked with generating a model that predicts whether an individual with the ability to telecommute will be allowed and choose to do so. Finally, participants approximated the percentage of employees in the U.S. and U.K. who will actually work remotely in 2022, 2024, and 2027, then ranked the cities in terms of magnitude of impact.



Members of the 2022 MathWorks Math Modeling Challenge (M3 Challenge) champion team from Homestead High School in Mequon, Wis., will split $20,000 in scholarship funds for their stellar model of remote work. They presented their results at the M3 Challenge Final Event in New York City on April 25. From left to right: Ethan Wang, Jacob Schmidman, and Eric Wan. Teammate Adam Garsha is not pictured. SIAM photo.

This year's first-place team hails from Homestead High School in Mequon, Wis., and comprised Adam Garsha, Jacob Schmidman, Eric Wan, and Ethan Wang; Schmidman, Wan, and Wang represented the group at the M3 Challenge Final Event in New York City. The students began by examining previous remote-readiness trends for jobs in different industries and sub-industries. They then fitted this data to a linear regression to predict future remote readiness of the workforce in Seattle, Wash.; Omaha, Neb.; Scranton, Pa.; Liverpool, England; and Barry, Wales. This approach allowed them to avoid the bias of economic booms or busts, which follow unpredictable cycles. "Linear regression is a simple model that captures the general trend of job growth without overfitting to smaller variations in data," Wan said. "Since the time frame for extrapolation was small, we thought it was acceptable to use."

The team did not find significant changes in any of the five cities from 2022 to 2027 — a result that they attributed to the difficulty of altering a city's industrial structure in the short term. Specifically, they found that the remote readiness of Seattle, Omaha, Scranton, and Barry would respectively increase from 41.50 to 41.94 percent, 41.04 to 41.51 percent, 33.84 to 33.94 percent, and 46.62 to 46.98 percent, while Liverpool's remote readiness would decrease from 28.02 to 27.22 percent.

Next, the Homestead students investigated whether a worker in a remote-ready position will indeed work from home. "We approached this problem through an economic lens," Garsha said. "We decided to quantify the decision to work from home using dollars. Working from home will occur if the combined benefit to the worker and employer is positive. Even if one party suffers a negative outcome, the other's positive gain can offset the negative during negotiations."

Garsha and his teammates consulted external data from outside sources and ran a Monte Carlo simulation over one million times. The simulation considered several factors from the perspectives of both the employer and employees. "On the employer side, we considered the change in worker productivity," Wang said. "On the worker side, we considered the benefit of no commute time and no need for childcare. In a future version of the model, more factors can be considered to increase the robustness."

The students then imagined two example workers with different personal situations and computed the likelihood that each would telecommute. They predicted that an individual who makes $30/hour with two kids, an eight-hour workday, and a 30-minute commute will work from home more than 99 percent of the time. In contrast, an individual who makes $50/hour with no children, a 10-hour workday, and a one-hour commute has about a 74 percent chance of working from home.

Finally, the Homestead team multiplied the percentage of remote-ready jobs by the percentage of employees who will actually work from home to estimate the total percentage of workers who will telecommute in 2022, 2024, and 2027 in Seattle, Omaha, Scranton, Liverpool, and Barry. To measure the effects of the shift to remote work in these cities, the students calculated an impact factor that was based on several components. "We considered the environmental benefit of reduced carbon emissions

See **Telecommuting** *on page 12*

[1] https://theconversation.com/50-years-of-bold-predictions-about-remote-work-it-isnt-all-about-technology-135034
[2] https://havenlife.com/blog/cities-with-the-most-remote-workers
[3] https://thehomeofficelife.com/blog/work-from-home-statistics
[4] https://m3challenge.siam.org
[5] https://m3challenge.siam.org/practice-problems/2022-challenge-problem-remote-work-fad-or-future

From Real Estate to High School Mathematics: An M3 Challenge Journey on the Joy of Open-ended Modeling Problems

By Kathryn Smith

Teaching mathematics was not my first career. I spent 12 years in commercial real estate development, during which I collaborated with architects, building owners, space designers, engineers, and contractors to lease and develop commercial spaces for large clients. Each client had complex logistical needs that required me to make assumptions, provide justifications, and generate predictions based on the company's expected growth. I routinely modeled scenarios to determine projected optimal solutions that—given a variety of constraints and parameters—would best suit the current and growing space demands of my commercial clients.

After more than a decade in real estate development, I decided to switch careers and become a teacher. I wanted to work with students in the Philadelphia, Pa., public school system; the schools were chronically understaffed and in specific need of math and science instructors, and I thought that I could help fill this void.

In 2006, I took a job at Julia R. Masterman Demonstration and Laboratory School[1] within the School District of Philadelphia (after having taught in the district for 10 years). Masterman is a public magnet school that offers robust and rigorous curricula for academically talented students in grades five through 12. Many of my students go on to pursue degrees in mathematics, engineering, physics, and computer science. I taught algebra, honors precalculus, and Advanced Placement calculus courses throughout my tenure at Masterman, and I founded the math club and robotics team soon after I arrived.

Despite my industrial modeling experience and the excitement of quantifying real-world scenarios with mathematics, I did not incorporate extensive, open-ended math modeling exercises into my classes until a poster for MathWorks Math Modeling Challenge[2] (M3 Challenge)—then called Moody's Mega Math Challenge—came across my desk 15 years ago. From that moment on, I became actively involved in the contest as both a coach for student teams and—upon my retirement from teaching—a judge for the competition.

The poster advertised $100,000 in prize money for successful teams, and I was certain that I could find enthusiastic and motivated students to participate. I shared the poster with a colleague, and we worked to identify a few students who might be interested in competing for the $20,000 first-place prize. Five students showed up to an introductory meeting, and our math modeling team was born. We barely made the deadline for entry that first year and only had a few days to prepare. We prepped by sorting through and thoroughly evaluating the winning papers from previous years,[3] which were available on the M3 Challenge website. Our goal was to do our very best work within the constraints of the problem.

For the next 14 years, this is exactly what my Challenge teams at Masterman did. We experimented with different types of training strategies but always took full advantage of the available resources, including math modeling handbooks,[4] judges' commentary,[5] practice problems,[6] and previous winning solutions. We usually put forth both a junior and senior team so that seasoned veterans could lead preparation efforts and bring new participants up to speed. Each year, I was in awe of the students' work, thought processes, and results.

As the contest changed over the years to allow for more sophisticated modeling and technical computing, our teams benefited from students who could write code and utilize more advanced modeling software. However, our emphasis on context and creativity remained the same. It was critical to me that my teams understood the relevance of the Challenge problem and the significance of their solutions. Students addressed the importance of their models' real-world applications in the synopsis of their papers, and this understanding formed the basis for all subsequent modeling efforts both within and beyond the classroom.

As a result, a Masterman team received an M3 Challenge honorable mention award during 13 out of my 14 years as a coach. Only about six to eight percent of all participating teams are distinguished with any type of recognition, so this was a big deal. In 2021—my final year of teaching and coaching—our team finished in the top six as a finalist, which meant that they presented their solution at the M3 Challenge Final Event[7] (which took place virtually due to the COVID-19 pandemic). This team's stellar performance had a notable impact on the popularity of our math club, and membership doubled over the following year!

After experiencing M3 Challenge's remarkable effect on my modeling teams firsthand, I realized that all of my students would significantly benefit from open-ended math modeling. The 14-hour M3 Challenge was invigorating and stimulating in ways that traditional mathematical problem solving was not. Every year, the junior team members were eager to compete again. Students enjoyed the opportunity to be creative and collaborative, and they appreciated the intellectual demands associated with producing mathematical models that provide reliable, robust insight into profound universal issues. M3-style modeling offers more advanced challenges that connect mathematical thinking to real-world applications; I had already incorporated content from the American Mathematics Competitions problem banks[8] and the Art of Problem Solving curricula[9] into my classes, and I began to introduce open-ended modeling projects as well.

For example, my precalculus students annually completed a long-term project during which they developed a retirement portfolio for a fictitious client. They had to conduct research, make assumptions and justifications, generate parameters, perform sensitivity testing, and employ the same types of modeling strategies that M3 Challenge requires. In doing so, they learned about the importance of retirement planning, the power of compounding funds over time, and the value of investment diversification to mitigate the effects of market downturns. One year, my seventh-grade algebra students generated happiness scales that used weighted averages. The students had to justify the various parameter weights in order to plausibly quantify happiness.

I retired from teaching at the end of the 2020-2021 school year. One of the things that I loved most about my time at Masterman was the chance to work with students to prepare for M3 Challenge. Former students often say that the contest was the best academic exercise they encountered in high school.

In 2022, I served as an M3 Challenge judge for the first time. This new role offered a different perspective on the competition and greater insight into the processes that I observed as a coach. Once again, I was incredibly impressed by the participants' talent and creativity. I also continued to find myself wanting to remind them not to forget why they are doing the math in the first place. Students must refrain from becoming so caught up in the procedural aspects of number crunching that they subsequently fail to thoughtfully connect their predictions to possible social, economic, or environmental impacts. The purpose of the Challenge problem should always remain at the forefront of solution development. When students prioritize the objective, they are more likely to produce a solution paper that provides critical insight into the current, real-world issue at hand.

As a long-standing competition coach and now as an M3 Challenge judge, I am absolutely certain of at least one thing: On any given day, a group of creative and motivated students can deliver extraordinary work in response to an open-ended prompt about an issue with relevancy to their everyday lives. They just need the opportunity and encouragement to do so.

M3 Challenge 2022 concluded on April 25 at Jane Street, a quantitative trading firm in New York City, during which top teams presented their solution papers to a panel of judges. A brief sizzle reel from this event is available online.[10] Registration for M3 Challenge 2023 will open in November, and the next Challenge Weekend will take place from March 3-6, 2023.

Kathryn Smith is a retired math teacher in the School District of Philadelphia, where she taught for 25 years. She currently works in real estate development.

The senior members of Julia R. Masterman Demonstration and Laboratory School's 2021 MathWorks Math Modeling Challenge (M3 Challenge) team hold a cake that commemorates their impressive performance at an end-of-year math party in Philadelphia, Pa., in May 2021. The team finished in the top six and was honored as a finalist. From left to right: Tanay Bennur, Ethan Soloway, Tobias Beidler-Shenk, and Owen Moss. Junior team member Hayden Gold is not pictured. Photo courtesy of Kathryn Smith.

[1] https://masterman.philasd.org

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

[3] https://m3challenge.siam.org/archives

[4] https://m3challenge.siam.org/resources/modeling-handbook

[5] https://m3challenge.siam.org/archives/2022/judge-commentary

[6] https://m3challenge.siam.org/resources/sample-problems

[7] https://go.siam.org/NsgSzU

[8] https://artofproblemsolving.com/wiki/index.php/AMC_Problems_and_Solutions

[9] https://artofproblemsolving.com/store/list/aops-curriculum

[10] https://go.siam.org/j3hiiB

Mines Mathematics and Computing Collaborative: Stimulating Mathematical Interest in Young Minds

By Jacqueline del Castillo, Justin Garrish, Soraya Terrab, and Jennifer Ryan

Students at the Colorado School of Mines are actively building a more diverse science, technology, engineering, and mathematics (STEM) community. In 2021, they founded the Mines Mathematics and Computing Collaborative[1] (MMCC): a student-led outreach organization that aims to close the STEM exposure gap by offering inspiring, hands-on mathematics and computing workshops for high schoolers in the Denver, Colo., metropolitan area. MMCC targets high school students who may not have much experience with the world of mathematics, or who feel pessimistic about the subject in general.

MMCC was created by graduate student members of the Diversity, Inclusion, & Access Committee[2] in the school's Department of Applied Mathematics and Statistics (AMS). Jacqueline del Castillo, Justin Garrish, and Soraya Terrab all wanted to help the community around Mines by tutoring younger students or sponsoring other outreach activities. They decided to concentrate on fostering student interest in mathematics by actively demonstrating compelling and relevant applications of math, with the ultimate goal of motivating students to excel and possibly consider STEM as an academic and/or career path.

MMCC's membership consists of both undergraduate and graduate students from AMS, the Department of Computer Science, and the Department of Chemical and Biological Engineering (though all are welcome). The organization is run entirely by the students, who both construct the workshops and perform the numerous administrative tasks that enable workshop success. MMCC members decide which subjects to develop, what mathematical tools are necessary, and how to make the content appealing. They also design computing exercises that support mathematical learning, though doing so can be challenging since not every participant knows how to code.

A successful workshop requires a lot of communication with Denver Public Schools (DPS), administrators at Mines, education leaders, community members, and event advertising personnel. By providing engaging content and activities that go beyond the typical curriculum, MMCC encourages students to appreciate the many real-world applications of mathematics, science, and computing. The organizers believe that framing mathematics in a relevant, applicable manner and targeting practical issues will strengthen attendees' existing interest in math and establish new fascinations in any young skeptics. The collaborative seeks to create a welcoming environment wherein underrepresented students can learn and flourish.

Members of the Mines Mathematics and Computing Collaborative (MMCC) at the Colorado School of Mines. From left to right: Soraya Terrab, Owen Ruggeri, Miranda Manfre, Cameron Kelly, Justin Garrish, Samuel Koller, Leah Bandy, Ethan Lewellin, Jacqueline del Castillo, Tyler Dendy, Sweta Rai, Ian Stonecypher, and Jennifer Ryan (faculty advisor). Photo courtesy of Soraya Terrab.

The workshops begin with an introduction of MMCC, followed by a panel during which faculty and graduate students with industrial experience discuss their paths towards careers in applied math. Workshop organizers then familiarize attendees with the mathematics that pertains to the content at hand, as well as simple coding exercises with open-source software that reinforce mathematical ideas. The first MMCC workshop—which took place virtually in June 2021 due to COVID-19 restrictions—had a financial math theme and focused on the compound interest model (with annual and monthly compounding) as an example of exponential growth to help students understand the benefits of saving early and frequently.

Local middle and high schoolers from Denver, Colo., partake in a financial mathematics workshop about the compound interest model. The Mines Mathematics and Computing Collaborative (MMCC), a student-led outreach organization at the Colorado School of Mines, hosted the workshop in February 2022. Photo courtesy of Soraya Terrab.

Though this initial workshop began humbly with only four student attendees, the series has experienced significant growth since then. The February 2022 workshop on the same topic hosted 75 students from 10 different middle and high schools in Denver. This second workshop commenced in person despite snow, subzero temperatures, and complications with student transportation.

Most of the participants in both workshops had taken algebra, but less than half were able to code. Session feedback has been quite positive and encouraging; the majority of students said that the workshops increased their mathematical curiosity, which was the goal. These outreach workshops are successful in part because of Greg Moldow, the Gifted and Talented Coordinator for DPS, who acts as a liaison between the school system and MMCC.

MMCC organizers are confident about the program's growth and are currently focused on content creation for the next academic year. In the future, they hope to incorporate undergraduate panels as well as information about the college application process. They also intend to host a weeklong summer workshop series to further immerse high school students from all backgrounds and experience levels in mathematical and scientific thinking.

Jacqueline del Castillo is a third-year graduate student whose research focuses on the detection of fractional singularities. Justin Garrish is a fourth-year Ph.D. student who researches mathematical and statistical models of metabolic dynamical systems. Soraya Terrab is a third-year Ph.D. student with research interests in numerical data filtering and imaging science. Jennifer Ryan is an associate professor of computational and applied mathematics and faculty advisor of the Mines Mathematics and Computing Collaborative (MMCC). All four authors are part of the Department of Applied Mathematics and Statistics at the Colorado School of Mines. They are passionate about the mission of MMCC and are members of SIAM.

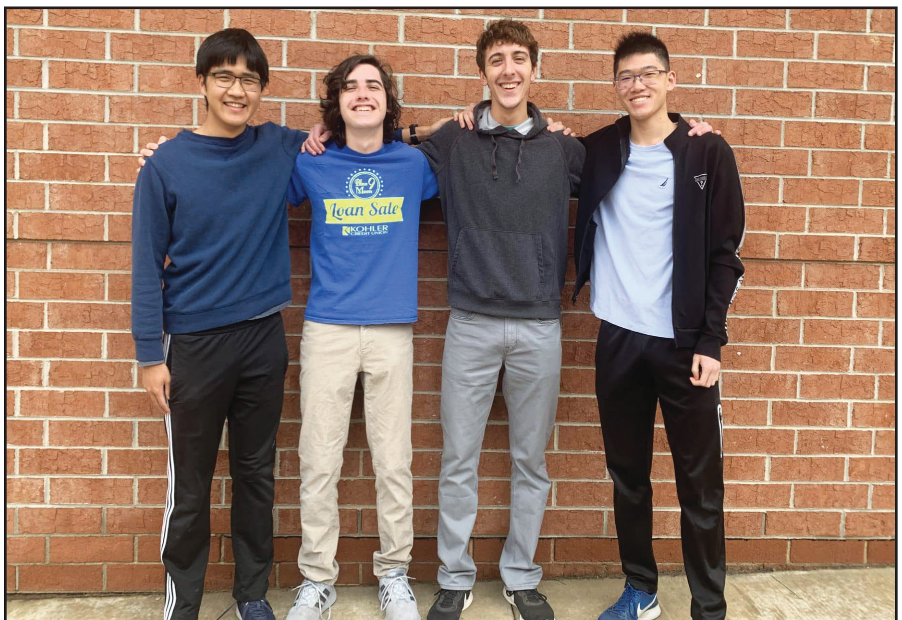
[1] https://orgs.mines.edu/mmcc
[2] https://ams.mines.edu/diversity-inclusion-access-at-ams

Telecommuting

Continued from page 10

from commuting and the economic loss of reduced property taxes paid to the city," Schmidman said. "We then combined these factors and relativized them based on each city's gross domestic product." A higher impact factor signifies a greater effect, and Schmidman and his collaborators found that Liverpool experienced the highest impact while Omaha had the lowest.

All four members of Homestead's winning team, who collectively received $20,000 in scholarship funds for their top-notch solution, are high school seniors who participated in M3 Challenge last year as well — a circumstance that better equipped them for the 2022 event. Three of the students plan to pursue careers in applied mathematics, computer science, and mechanical engineering, while the fourth hopes to attend law school. Yet regardless of their future areas of study, the participants all concurred that M3 Challenge provided valuable tools that they will take with them to college and beyond. "Participating in M3 Challenge has given me unbelievable experiences," Wang said. "Aside from the obvious benefits in math, I have had increased experience with collaboration, communication, time management, data collection, data interpretation, and so much more. All of these skills will be very beneficial."



The MathWorks Math Modeling Challenge (M3 Challenge) first-place team from Homestead High School in Mequon, Wis. From left to right: Ethan Wang, Adam Garsha, Jacob Schmidman, and Eric Wan. Photo courtesy of Elliot Nimmer.

Homestead High School—coached by Weizhong Wang, the father of team member Ethan Wang—has a long history of competing in M3 Challenge. In the last five years, the school received three honorable mentions. However, 2022 was the first year in which they were selected as a finalist and nabbed the top spot. "Our students value their experiences with M3 Challenge very highly," Coach Wang said. "That is why we keep doing it year after year. In my opinion, modeling has been and will continue to be one of the most powerful tools offered by mathematics. As our society becomes more connected and collaborative, data-driven decision-making becomes more important in our lives. And mathematical modeling is the foundation."

M3 Challenge is a unique, rigorous contest that goes well beyond the traditional high school mathematics curricula and seeks to prepare students for a data-oriented future. It allows teams to apply math modeling to real-world phenomena and conduct research, analyze data, and make supported predictions with broad societal significance. "In school, math is always about *convergent* thinking," Schmidman said. "When presented with a problem, you're looking for a single, definite answer and there's often only one way to find it. Conversely, M3 Challenge asks participants to partake in *divergent* thinking. You have to be creative, and there's potentially infinite solutions and ways to get there."

Homestead High School's winning solution paper[6] is available online, as is their final presentation.[7]

Lina Sorg is the managing editor of SIAM News.

[6] https://m3challenge.siam.org/sites/default/files/uploads/2022%20winner_15333.pdf
[7] https://www.youtube.com/watch?v=91p7C32S-FA