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

siam news

Volume 51/ Issue 8
October 2018

Information Theory in Earth and Space Science

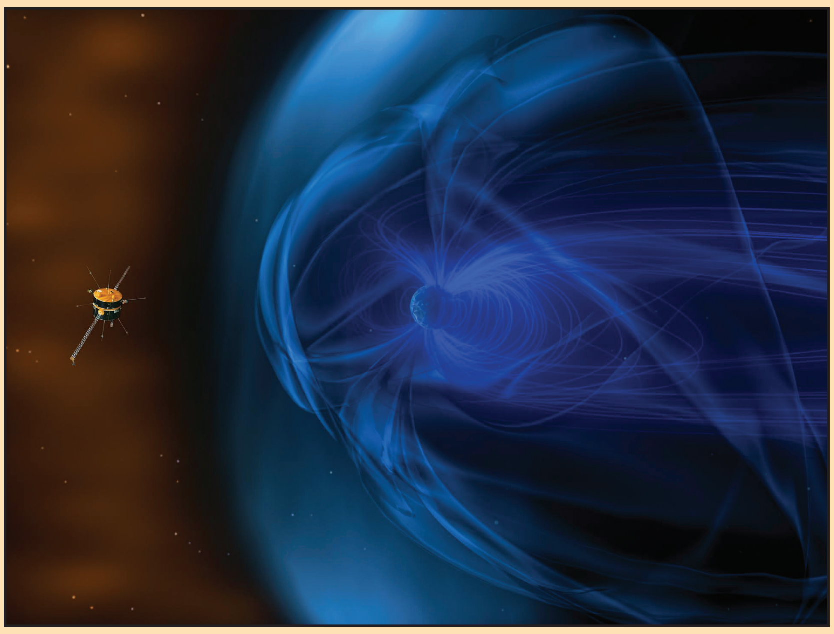

Figure 1. *The Wind spacecraft from NASA's Heliophysics System Observatory has spent nearly two decades observing particles and measuring crucial properties of the solar wind before it impacts Earth's magnetic field. Image courtesy of NASA.*

In an article on page 5, Joshua Garland and Elizabeth Bradley discuss the ways in which scientists can use information theory and relevant time-series data to address pressing questions pertaining to Earth and space science.

Wormlike Micellar Solutions, Polymers, and Mucins

By Paul Davis

Any parent rushing to organize dinner for tired children can speak knowledgably about the rheological vicissitudes of cooked spaghetti. Sitting motionless in the strainer, spaghetti forms a pile of slippery threads. But scoop up one large portion to split between dishes and the strands solidify into a single mass that slithers onto one plate or another, parental intentions notwithstanding.

At the 2018 SIAM Annual Meeting, which took place in Portland, Ore., this July, Pam Cook of the University of Delaware spoke about molecular-level modeling of materials that exhibit similarly schizoid behavior. She was simultaneously delivering the Past President's Address and the Julian Cole Lectureship. The latter's prize citation recognized Cook's "comprehensive mathematical modeling of the structure and dynamics of wormlike micellar solutions." These anomalous materials, positioned "at the boundary between solids and fluids," as Cook put it, are commonly used in drag-reducing agents in oil fields and as thickeners and surfactants in home and personal care products.

Despite their unappetizing name, wormlike micellar solutions have attracted their share of mathematical modelers. These solutions display horrendously complex rheological properties and can exhibit highly variable viscosity, shear thinning and thickening—sometimes visible as elastic recoil or extensional fracture—and even self-assembly. Their behavior varies widely over diverse time scales. Such micelles are wormlike because each has a length of about 2 microns and a radius of approximately 0.001 microns — a 2,000:1 ratio (for context, the radius of a human hair is a relatively enormous 25 microns).

Micelles typically have a hydrophilic head and a hydrophobic tail. In an aqueous solution, they become "living polymers" — "worms" that continuously break and reform; true polymers do neither. Environmental factors like temperature, solvent salinity, and the nature of the flow field influence the particular properties that micelles manifest.

The associated modeling challenges are substantial. One approach involves modeling a three-dimensional dynamic assembly of individual "worms" that randomly break

See **Micellar Solutions** *on page 4*

Untangling DNA with Knot Theory

By Matthew R. Francis

Long before there were sailors, nature learned to tie—and untie—knots. Certain DNA types, proteins, magnetic fields, fluid vortices, and other diverse phenomena can manifest in the form of loops, which sometimes end up tangled. But knots, kinks, and tangles are often undesirable for the system in which they occur; for instance, knotted DNA can kill its cell. In such cases, nature finds ways to restore order.

Mariel Vazquez of the University of California, Davis, uses topology to understand the knotting and unknotting of real-world molecules. Specifically, she and her colleagues employ topological concepts from knot theory to demonstrate that cells detangle DNA with optimal efficiency.

During her talk at the 2018 SIAM Annual Meeting, held in Portland, Ore., this July, Vazquez emphasized her work's multidisciplinary nature; although she focuses on DNA, her research has applications beyond molecular biology.

DNA, a magnetic field, or another flexible "chain" that is twisted or knotted is under tension and therefore in a higher, undesirable energy configuration. The various systems have mechanisms for "reconnection" — breaking or otherwise reorganizing the chains to relieve this tension.

For example, the sun's magnetic fields wind up over an 11-year period, like a rubber band stretched around a ball. These "field lines" repel each other, so that tension increases with greater proximity between the lines. Magnetic reconnection abruptly rearranges the lines, releasing energy into the sun's atmosphere and causing solar flares.

While DNA reconnection is less dramatic, the rearrangement does change the chains' topology, i.e., the number of loops and/or the way they cross each other. Knot theory describes these twists and links independently of the chains' length or the physical forces that govern them. Applying knot theory to reconnection helps researchers understand how real-world systems simplify their topology to minimize energy and tension.

A Knotty Problem

The starting point for knot theory is the "unknot" — a simple loop with no crossings or breaks. Think of the unknot as a rubber band; all the ways in which the band can stretch or twist without breakage are topologically equivalent. Knots within knot theory are also loops, but they have crossings that cannot be undone without cutting the band. The simplest of these is the trefoil and all of its topologically equivalent forms.

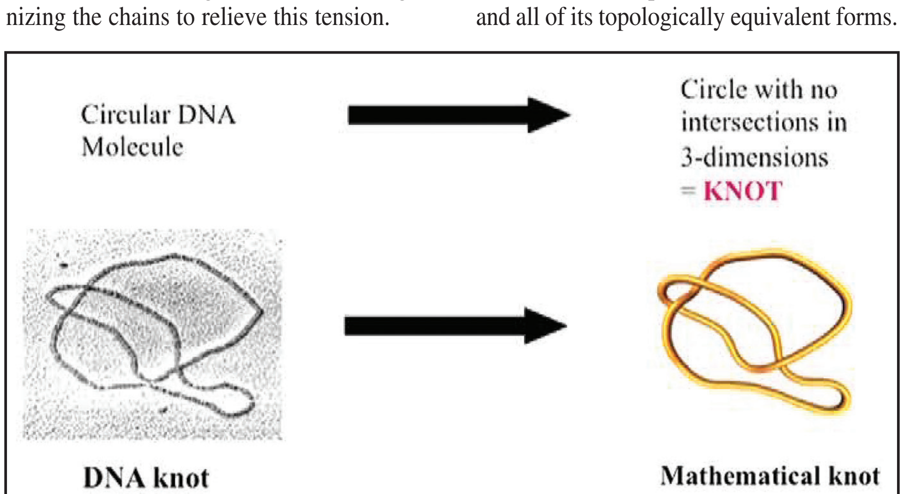

Figure 1. *One can model a circular DNA molecule as a mathematical knot. Figure courtesy of Mariel Vazquez.*

All mathematical knots require unbroken loops devoid of any loose ends. This is in contrast to everyday knots, such as those on a shoelace. One can untie ordinary knots without cutting the band, so by mathematical standards they are topologically equivalent to each other.

Knot theory also describes "links" between two or more loops. Take, for example, two strips of paper with arrows drawn along their lengths. There are two ways to create a two-link paper chain from the strips, depending on the relative directions of the arrows when one assembles the chain.

As Vazquez pointed out, real-world applications of knot theory often concern the way in which a system's topology changes. Consider the DNA of the E. coli bacterium. These microbes usually live harmlessly in our intestines, but gain national attention when they cause food poisoning. Besides DNA in the form of chromosomes, E. coli have additional circular strands known as plasmids that duplicate independently from cell division, making them easy to observe in a laboratory.

DNA is famously a "double helix" — two long polymer strands forming a shape like a twisted ladder. The "rungs" of this ladder are pairs of four types of molecules—assigned the "letters" A, C, G, and T that produce the genetic code necessary for life—linked by molecular forces. The order of the letters provides a direction for the overall DNA molecule. The "tails" of E. coli plasmids and other circular DNA chains connect back to their "heads." Knot theory can describe the way DNA molecules twine together, and connect the topology of the strands to biochemical behavior (see Figure 1). From a high-level knot theory perspective, DNA's helical nature is not important; what matters is how the double strand itself forms knots and links. However, the molecular structure of DNA resists tangling within cells, so the system's biomechanics push it towards the simplest topology: the unknot.

See **Knot Theory** *on page 3*

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siam news
Volume 51/ Issue 8/ October 2018

The Unwinding Number

Cartoon created by mathematician John de Pillis.

FROM THE SIAM PRESIDENT
By Nicholas Higham

While Fortran 66 had a complex data type, this was not true of most other early programming languages, such as Algol 60. As a result, programmers had to write their own procedures to implement complex arithmetic and transcendental functions in terms of separately stored real and imaginary parts. They quickly realized that this is not a trivial task; in the early 1960s, it took five published attempts over three years to obtain a correct implementation of the complex logarithm in Algol 60.[1]

Nowadays we take for granted the seamless availability of complex arithmetic and complex elementary functions in languages such as MATLAB, Julia, and Python. The questions that arise when computing in complex arithmetic often revolve around multivalued functions, such as the logarithm.

Certain relations that are obviously true for positive real numbers, such as $\log \mathrm{e}^x = x$ and $\log xy = \log x + \log y$, do not generally hold for complex arguments. If you consult a textbook on complex analysis, you will likely find statements such as "$\log z_1 z_2 = \log z_1 + \log z_2$ holds for all z_1 and z_2 with an appropriate choice of the branch of the logarithm in each term." This is not terribly helpful for an applied mathematician who wants to use a specific branch.

In practice, it is usually the principal logarithm—the one whose imaginary part lies on the interval $(-\pi, \pi]$—that is of interest. From this point on, let $\log$ denote the principal logarithm.

The equation $\log \mathrm{e}^z = z$ can clearly only hold if $\operatorname{Im} z \in (-\pi, \pi]$. If $\operatorname{Im} z$ is outside this range, then a discrepancy of some integer multiple of $2\pi\mathrm{i}$ exists in the equation. Would it be useful to give this discrepancy a name?

Rob Corless, David Hare, and David Jeffrey asked this question in 1996 [5, 7]. Deciding that the answer was "yes," they defined the *unwinding number* of z by

$$\mathcal{U}(z) = \frac{z - \log \mathrm{e}^z}{2\pi \mathrm{i}}$$

(the unwinding number is unrelated to the winding number of a contour in the complex plane). It is not hard to show that

$$\mathcal{U}(z) = \left\lceil \frac{\operatorname{Im} z - \pi}{2\pi} \right\rceil, \qquad (1)$$

where $\lceil \cdot \rceil$ is the ceiling function; thus, the unwinding number is an integer. Since

$$z = \log \mathrm{e}^z + 2\pi \mathrm{i}\, \mathcal{U}(z),$$

it is clear that $z = \log \mathrm{e}^z$ (that is, $\mathcal{U}(z) = 0$) if and only if $\operatorname{Im} z \in (-\pi, \pi]$.

Corless and his coauthors realized that $\mathcal{U}$ is a useful tool to analyze a wide range of complex arithmetic functions. Our original question about a product's log has a neat answer in terms of $\mathcal{U}$:

$$\log(z_1 z_2) = \log z_1 + \log z_2 \\ -2\pi \mathrm{i}\, \mathcal{U}(\log z_1 + \log z_2).$$

Furthermore,

$$(z_1 z_2)^{1/2} = z_1^{1/2} z_2^{1/2} (-1)^{\mathcal{U}(\log z_1 + \log z_2)},$$

where the square root is the principal square root (the one that lies in the right half-plane).

The unwinding number can aid thinking and simplify proofs. For example, is it true that $(1-z)^{1/2}(1+z)^{1/2} = (1-z^2)^{1/2}$? It turns out that it is, but the subtly different identity $(z-1)^{1/2}(z+1)^{1/2} = (z^2-1)^{1/2}$ is true only for $\arg z \in (-\pi/2, \pi/2)$. The unwinding number enables neat proofs of these results [3].

The unwinding number is also valuable when answering questions such as "when does $\operatorname{acos}(\cos z) = z$ hold?", which is useful to know when testing the correctness of an arc cosine function implementation [2].

The unwinding number generalizes to matrices in an obvious way: by replacing z with $A \in \mathbb{C}^{n\times n}$ in (1) [1]. In the case of a matrix, it proves extremely useful for understanding the behavior of multivalued matrix functions [2].

The unwinding number is gradually gaining recognition. It is a built-in function in Maple (called unwindK), and is starting to appear in books [4, 6]. It is a valuable addition to our toolkit for handling multivalued complex functions.

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Obituary: Gregory Kriegsmann

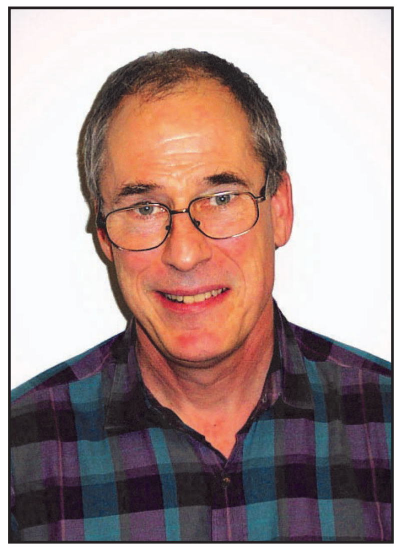
By Pam Cook, Michael Booty, and W. Edward Olmstead

It is with great sadness that we note the passing of mathematician Gregory Anthony Kriegsmann in May 2018.

Greg was born in 1946 and grew up in Chicago, Ill., as one of two sons of a sheet metal worker and a homemaker. He earned a B.S. in electrical engineering at Marquette University; an M.S. in both electrical engineering and mathematics from the University of California, Los Angeles (UCLA); and a Ph.D. in mathematics under the supervision of Charles Lange, also from UCLA. Greg traveled to Los Angeles as a Hughes Master Fellow, which allowed him to obtain his master's degrees while working part-time at Hughes Aircraft Company.

Greg had an abiding affection for the Midwest and all things related to electromagnetism, wave propagation, and applied mathematics. His early interest in electrical engineering persisted, and time away from work often involved studying or building electrical circuits and practicing his skills with amateur/ham radio. "Greg doesn't need to take vacations," his wife Barbara quipped, as work and play were the same to him. Nathaniel (Nick) Grossmann, a professor at UCLA, remembers working with Greg to solve problems—for fun—from *SIAM Review*'s "Problems" section.

Upon graduating from UCLA in 1974, Greg—along with his wife and their two sons—moved east and became an instructor at New York University's Courant Institute of Mathematical Sciences. While at Courant, he worked with Cathleen Morawetz and initiated a long-term collaboration with Edward Reiss. Greg then returned to Hughes Aircraft for one year before taking positions in the University of Nebraska-Lincoln's Department of Mathematics (1977-1980)—where he received tenure—and Northwestern University's Department of Engineering Sciences and Applied Mathematics (1980-1990). Following this, he became Foundation Chair and Distinguished Professor of Mathematics at the New Jersey Institute of Technology (NJIT), where he also served as department chair from 1992 to 1996.



Gregory Anthony Kriegsmann, 1946-2018. Photo courtesy of the New Jersey Institute of Technology.

At NJIT, Greg worked with Daljit Ahluwalia and Robert Miura to attract, employ, and support a number of new faculty hires. One cannot overstate the thought, support, and mentoring advice that he offered, especially to young faculty.

Greg's research centered primarily on wave propagation and scattering for acoustic and electromagnetic fields. The main tools of his craft were asymptotic, perturbation, and computational methods. A hallmark of Greg's work was his formulation and reduction of a complex and apparently-intractable problem to a simpler form that was more amenable to analysis but still retained the original's essence.

Greg published work both independently and with coauthors from a broad representation of fields. His publications—well over 100—have appeared in a wide variety of well-respected applied mathematics and disciplinary journals. Noteworthy among them are the *SIAM Journal on Applied Mathematics*, the *SIAM Journal on Scientific and Statistical Computing* (as it was then known), *Physics of Fluids*, the *Journal of Physical Oceanography*, *IEEE Transactions on Antennas and Propagation*, the *Journal of the Acoustical Society of America*, the *Journal of Elasticity*, *IEEE Transactions on Circuit Theory*, *Communications on Pure and Applied Mathematics*, and the *Journal of Computational Physics*.

Greg advised or co-advised a total of 18 Ph.D. students, 11 at Northwestern and seven at NJIT. He served on editorial boards of a number of journals, including the *SIAM Journal on Applied Mathematics*, the *IMA Journal of Applied Mathematics*, the *Journal of Engineering Mathematics*, the *Journal of Analysis and Applications*, the *Journal of Electromagnetic Waves and Applications*, and *Wave Motion*.

From 1998 to 2002, Greg was editor-in-chief of the *SIAM Journal on Applied Mathematics*. A stint as SIAM Vice President for Publications soon followed. He was a member of SIAM's inaugural class of fellows, as well as a fellow of the Institute for Mathematics and its Applications (U.K.), the Acoustical Society of America, and the Electromagnetics Academy.

Greg is survived by his wife Barbara, their sons Karl and James (and their families), and his brother John Kenneth. He will be sorely missed by his many friends, colleagues, collaborators, students, and mentees.

Pam Cook is Unidel Professor of Mathematics, associate dean of engineering, and professor of chemical engineering at the University of Delaware. Michael Booty is a professor in the Department of Mathematical Sciences at the New Jersey Institute of Technology. W. Edward Olmstead is professor emeritus of applied mathematics at Northwestern University.

Knot Theory

Continued from page 1

When DNA replicates, the bonds in the "rungs" of the ladder are broken and the molecule unravels into two. Duplication of circular DNA results in two linked molecules, which are often more complicated than the aforementioned two-link paper chain. The linkage means that the new molecules are not topologically *or* biologically equivalent to the original molecule. One must separate the links to complete duplication.

Additionally, the act of splitting DNA—for duplication or copying of portions for other purposes—creates tension away from the splitting point. The result is a "supercoil," a process in which the DNA twists itself into a tangle to compensate for the uncoiling needed for strand separation.

Breaking links and fixing supercoils involves reconnection, but it is more complicated than simply splitting the molecule and gluing it back together. The orientation of the molecule is important, as is rematching the split pieces to preserve genetic information carried by DNA.

The Writhe Stuff

Vazquez and her colleagues performed Monte Carlo simulations to verify their mathematical model and understand how cells execute DNA detangling. These methods tested the number of recombination steps required to unlink chains, based on the assumption that each step should either reduce or maintain the topological complexity. In other words, each alteration in the DNA tangle should remove links or twists, resulting in two unknots.

One measure of the tangle's complexity is its "projected writhe," which accounts for both the number of crossings and their chirality or "handedness." To calculate handedness, picture the system projected onto a surface, with arrows defining each molecule's orientation. Consider each link separately as a letter X, with one leg crossing over the other. If the left-to-right leg crosses over the right-to-left leg, assign a +1 to the link; otherwise, assign a -1. The projected writhe is the sum over all of these crossings.

Imagine two interlocking right-handed strands with a total of six crossings, like a Star of David (see Figure 2). In knot theory language, this is a 6_1^2 link, where 6 represents the number of crossings, 2 is the number of strands, and 1 indicates that this is the simplest combination (see Figure 3). This link's writhe is +6. There are two ways to cut and re-glue the link to simplify it, both of which reduce the writhe. However, only one also reduces the number of crossings.

Vazquez and her collaborators proved that the shortest number of steps to unlink two tangled strands of a particular class of links equals the number of crossings; thus, the six-crossing link requires six steps to unlink. To treat the problem computationally, they depicted molecules as linear segments joined at 90- or 180-degree angles, like edges on a three-dimensional lattice. This allowed the program to manipulate the molecules in a straightforward way, performing stepwise cuts and connections and computing important knot properties like the writhe straightforwardly. The Monte Carlo simulation tested all possible recombinations from a given starting point that resulted in two unknots, and found that this was true: the simplest route is also the most probable.

In a living cell, various enzymes—proteins that perform specific tasks—help duplicate DNA, cut links, and combine strands. Failure of these enzymes can trigger cell death. Vazquez suggested that actively suppressing the action of these enzymes could be useful for antibiotics or anticancer drugs, not least since plasmids in bacteria transfer antibiotic resistance between cells.

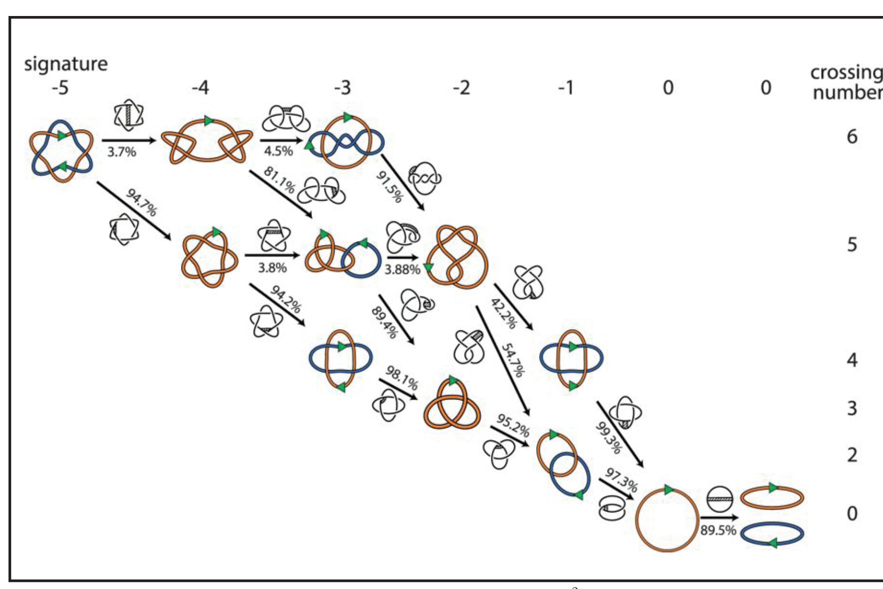


Figure 3. *All of the possible steps to unlink a link of type 6_1^2 (upper left corner), assuming that each step simplifies the link or knot. The numbers represent the probability of the corresponding steps, based on Monte Carlo simulations; this demonstrates that the shortest possible path (from the top left to bottom right) is also the most likely. Figure courtesy of [2].*

Beyond biology, the topological approach may provide a nice demonstration of reconnection's occurrence in other systems. Many processes follow a path of energy minimization to attain maximum efficiency, and the knot theory method demonstrates this preferences's ability to reduce the complexity of tangled strands.

Vazquez dedicated her talk to mathematician and Fields Medalist Maryam Mirzakhani (1977-2017) in honor of Mirzakhani's love for the beauty of mathematics.

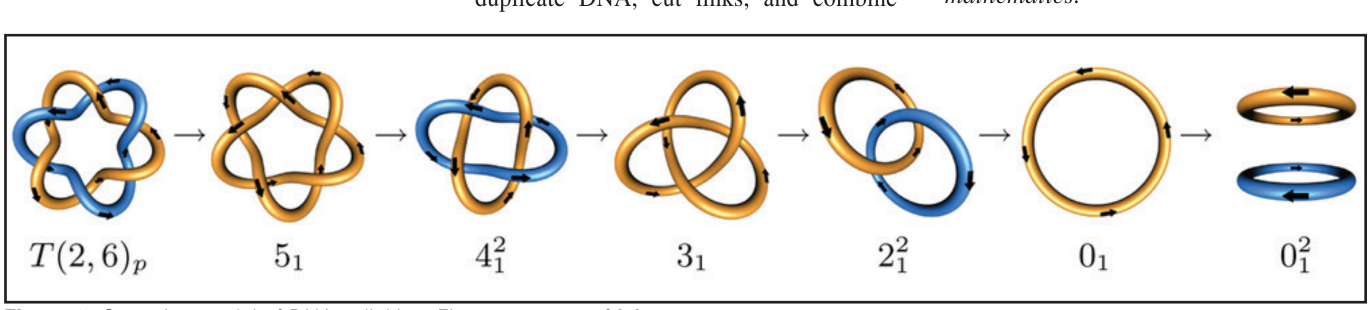


Figure 2. *Stepwise model of DNA unlinking. Figure courtesy of [1].*

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Further Reading

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

Micellar Solutions

Continued from page 1

and reform over a continuous range of lengths. Regardless of the method, such models must yield to analysis—numerical or otherwise—to fit to experiments, account for observed phenomena, and test for behavior that violates observations.

Ignoring the appeal of modeling these "worms" in their full behavioral glory, Cook and her collaborators Paula Vasquez (University of South Carolina) and Gareth McKinley (Massachusetts Institute of Technology) created a model that permits only two sizes rather than allowing a continuous distribution of worm lengths. In the Vasquez-Cook-McKinley (VCM) model, just two lengths—L and $L/2$—define the two species of worms whose interactions carry the burden of explaining a considerable range of novel rheological behavior that is evident both experimentally and in practice (see Figure 1).

The short worms are linear springs connecting two equal masses; Cook calls them "elastic dumbbells." Their longer cousins arise when two short worms connect; this reforming rate is modeled as constant. However, the rate at which one double-length worm ruptures into its two constituent halves depends upon the deformation rate and the local elongation rate. The newly-created halves can retract slightly as the solvent convects them back into the flow. The VCM model tracks the halves with a configuration distribution function that depends on time, location of the worm's center of mass, and orientation of the vector that connects the two end-point masses (Q in Figure 1).

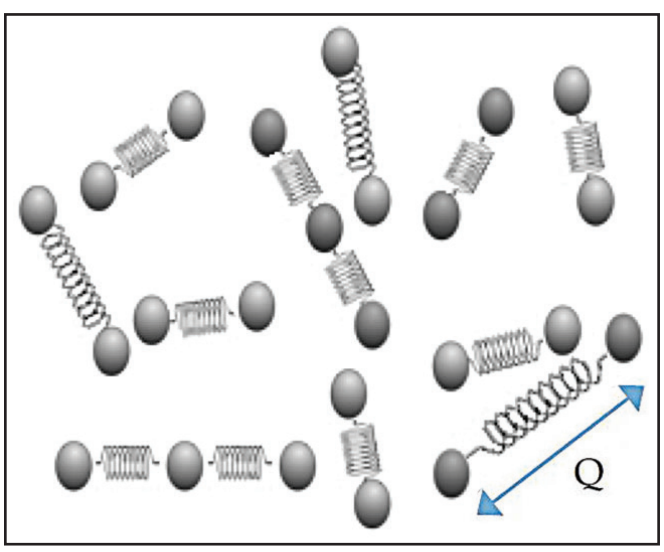

Figure 1. *The two sizes of micellar "worms" in the Vasquez-Cook-McKinley model. Two short units can combine to form one double-sized unit, as shown in the lower left. A linear spring connects the ends of the half-sized "worms." Figure courtesy of [1].*

It is perhaps surprising that the drastic simplification of permitting worms of only two lengths pays off with a theory that leads to improved understanding of micellar solutions' unusual rheology. This success seems to arise from two features of the VCM model. It accounts for the splitting and reconnecting of the worms (scission and reforming in the jargon of this branch of non-Newtonian fluid mechanics), and the corresponding reduction in the model's overall complexity facilitates its analysis. Furthermore, the model incorporates the aqueous solvent's viscosity as well as its corresponding interactions with the two length species, L and $L/2$.

Nonetheless, the simplicity of the two-species VCM model is relative. It requires 18 coupled partial differential equations, while shear flow modeling demands only half as many.

A classic rheological experiment studies viscosity variations in simple shear flow in a Couette cell; a micellar solution is confined between two concentric cylinders, the inner of which rotates while the outer remains stationary. When the inner cylinder rotates relatively slowly, the spinning fluid's velocity decreases almost linearly (curvature accounts for most of the change) from the inner rotating wall to zero at the outer stationary wall. Thus, the velocity gradient is close to constant across the gap between cylinders. At higher velocities, wormlike micellar fluids exhibit so-called shear banding; a band of high shear rate (a large velocity gradient) exists near the inner wall and quickly transitions to a band of lower shear rate (lower velocity gradient) through the bulk of the fluid to the outer wall (see Figure 2).

In work with Lin Zhou (New York City College of Technology), Cook and her collaborators show that the relative dominance of either the shorter or longer species of micellar worms explains shear banding in the VCM model. As shear rate increases, breakage of the double-length species overwhelms the ability to stretch, and scission dominates. However, most of the longer worms disappear at very large shear rates; in these cases, the shorter worms dominate.

Besides its success in illuminating shear band mechanics, the VCM model has helped explain the possibility of multiple shear bands, elastic recoil, and other rate- and time-scale-dependent phenomena. Indeed, much of the VCM model's effectiveness across a variety of flow types stems from its coupling of the two species' local number density to local stresses and velocities via the solvent. These two number densities are surrogates for a smooth distribution function in a more complex model that incorporates a continuum of worm lengths.

In framing their model for this important class of materials, Cook and her team have found and followed the narrow path that separates uninformative models from the intractable. Cook once described her late colleague Julian Cole as having had "the ability to simplify a problem down to the essential elements." He would have been pleased by the path finding she described.

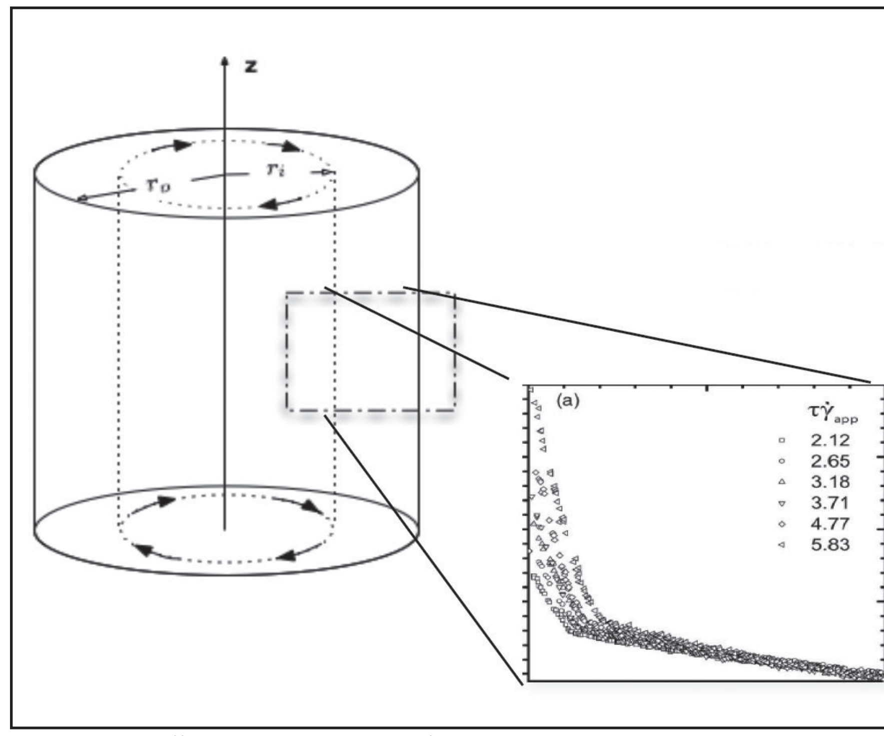

Figure 2. *At sufficiently high velocities of the inner cylinder, the micellar solution in this Couette cell exhibits shear banding, a region of steep velocity gradient near the inner cylinder, a kink, and finally a broader band of more gradual velocity reduction to the stationary outer cylinder. Figure courtesy of [2].*

Cook's presentation is available from SIAM either as slides with synchronized audio or a PDF of slides only.[1]

The Julian Cole Lectureship was established in 1999 in memory of Julian D. Cole and his work in mathematical applications to aerodynamics. The prize is awarded every four years to an individual for an outstanding contribution to the mathematical characterization and solution of a challenging problem in the physical or biological sciences or in engineering, or for the development of mathematical methods for the solution of such problems.

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Information Theory in Earth and Space Science

By Joshua Garland and Elizabeth Bradley

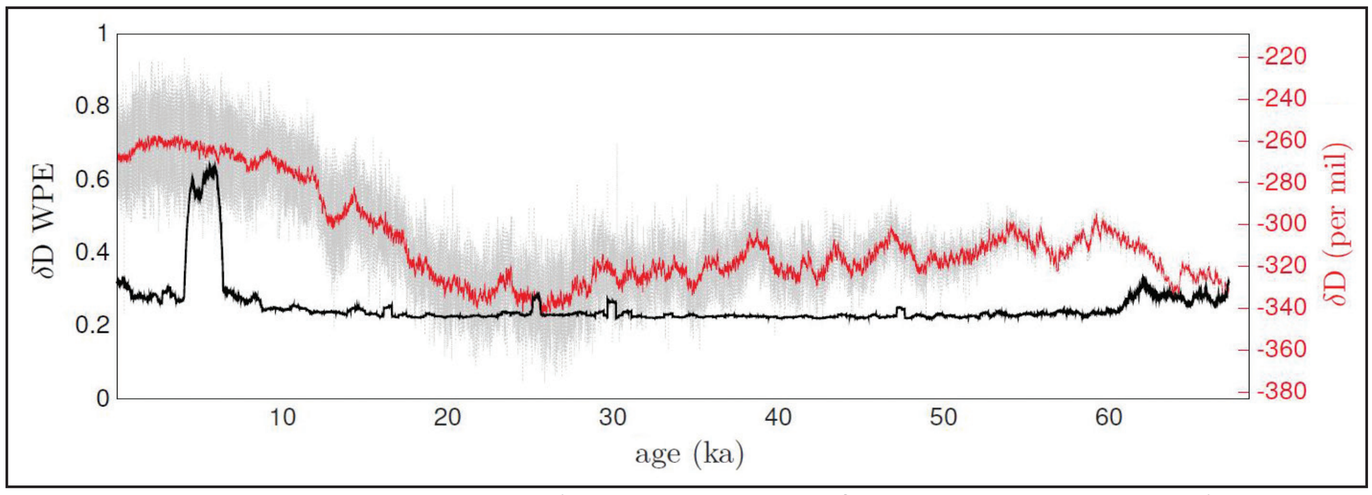


Figure 2. *The deuterium/hydrogen ratio (δD) measured from the West Antarctic Ice Sheet Divide core in kiloyears (ka) before present day. The original data is shown in grey, the smoothed data (500-year moving average) is in red, and the weighted permutation entropy (WPE) calculated from the original data is in black. WPE values run from 0 (no new information and fully predictable) to 1 (all new information and completely unpredictable). Figure courtesy of [4].*

Recent advances in information theory—coupled with vast improvements in the extent and resolution of Earth- and space-science-related time series data—can help answer some of the biggest questions facing humanity. Such developments enable our understanding of the dynamics of abrupt climate changes and allow us to assess the predictability of geomagnetic storms.

Until fairly recently, time series data sets with enough accuracy, length, and temporal resolution to support information-theoretic analysis have been hard to come by in some areas of Earth and space science. Replicability is also a major issue. Drilling a three kilometer core through an ice sheet and analyzing each centimeter in a spectrograph is an expensive proposition, as is launching a spacecraft to sample conditions on Pluto. However, recent developments in laboratory techniques have improved ice core sampling resolution by an order of magnitude, and the number of satellites observing the solar system has increased remarkably. Other long, high-resolution geoscience data sets are also available. These advances provide a host of exciting opportunities for the applied mathematics community to make meaningful contributions to the fields of Earth and space science using information theory.

For example, in 2005, Tom March, Sandra Chapman, and Richard Dendy applied mutual information—a measure of how much one random variable reveals about another—to observations made by NASA's Wind spacecraft to trace solar-wind effects at different points on Earth (see Figure 1, on page 1) [6]. Scientists have also used other members of the family of entropy measures nucleated by Claude Shannon's work in Earth and space sciences. However, some associated challenges persist. For instance, calculation of the Shannon entropy rate from a real-valued time series requires symbolization[1] of the data, a procedure that is fragile in the face of noise and susceptible to biased results. *Permutation entropy* [1] sidesteps these issues with ordinal analysis—conversion of the sequence of real values into value-ordered permutations—to symbolize the data. Researchers have used both binned Shannon entropy and permutation entropy to explore the predictability of different climate change events captured in El Niño-Southern Oscillation proxy records derived from Laguna Pallcacocha sedimentary data [8].

Permutation entropy techniques are particularly useful in the study of ice core data. For example, the 3,300-meter West Antarctic Ice Sheet (WAIS) Divide core captures climate samples from the past 68,000 years. Figure 2 shows the weighted permutation entropy (WPE)—a variant of a technique that uses a normalization to de-emphasize noise effects [3]—calculated in sliding 500-year windows across a water-isotope trace from that record. The large jump in WPE between five to eight kiloyears (ka) was initially puzzling. Lab records solved the mystery, showing that an older instrument—used to analyze that segment of the core—introduced noise into the data, an effect that was not visually apparent in the δ*D* data itself. Outliers that are all but invisible in the raw data also leave clear signatures in the WPE, in the form of square waves as wide as the calculation window (this is visible at roughly 17, 26, and 47 ka in Figure 2). In addition to detection of data problems, information-theoretic analysis can also lead to fascinating *scientific* knowledge. For instance, the patterns in WPE values reveal possible signatures of geothermal heating at the core's base and appear to correlate closely with accumulation [5]. Another observation of interest is the absence of any signature of the large, abrupt *Dansgaard-Oeschger* events—which punctuated the last glacial period—in the WPE trace [2], suggesting that these events may not represent significant changes in the climate system's information mechanics [4, 5].

Timelines from Earth and space science data sets are often irregular, and observations tend to aggregate in strange ways. For example, ice cores are sampled at evenly-spaced intervals *in depth*, but spaced nonlinearly (and unevenly) in time because the core's upper layers compress the lower layers. Indeed, multiple factors affect these timelines; thickness of ice core layers depends on annual accumulation rate,

See **Earth and Space Science** *on page 7*

[1] Conversion of numerical exam scores to letter grades using a set of bins.

Changing the Way We See Sports – with Computer Graphics

By Kai Berger

Kai Berger is a computational scientist at Genius Sports Media, a company that offers state-of-the-art, data-driven solutions in sports data technology for leagues and federations. In this issue's Career Column, he discusses his professional trajectory and current role at Genius Sports.

I work as a machine vision researcher in the areas of motion capture, image registration, and uncalibrated camera synchronization at Genius Sports Media. My role entails developing prototypes in MATLAB or deriving formulae in Mathematica to read and manipulate unsynchronized camera footage from sporting events.

However, as a young student I had envisioned a very different future. In middle and high school, I considered a career in music. But shortly before college, I realized that images and graphics can convey the same beauty as music. While assessing musical flair is an instantaneous act that requires attention to each specific note, chord, or phrase, evaluation of an image is to some extent more timeless. The eye can move back and forth over the same picture multiple times, uncovering increasingly more facets.

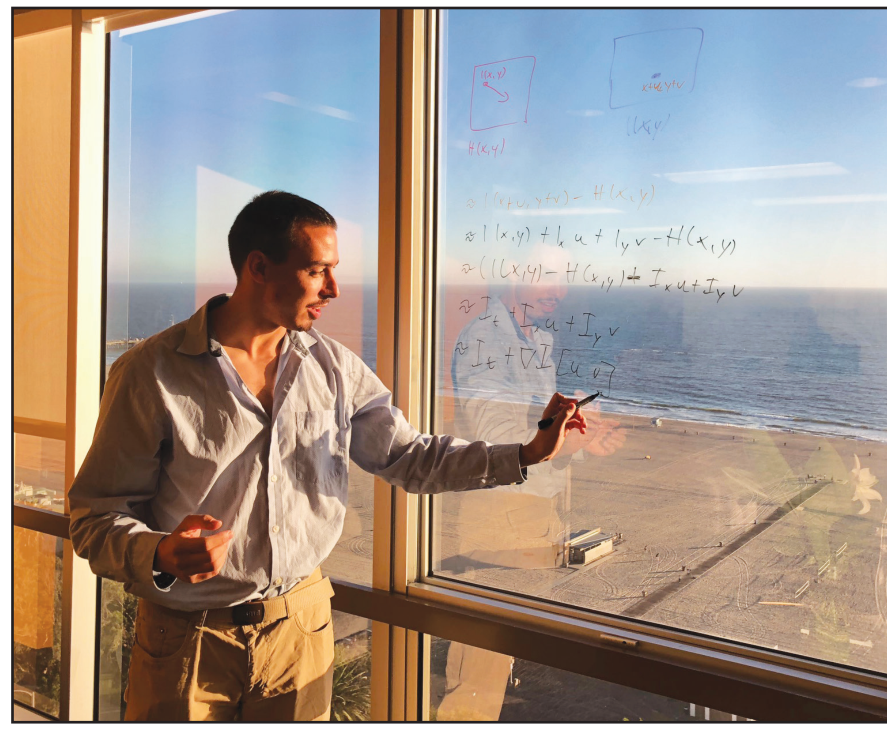
This realization motivated me to reach out to the Computer Graphics Laboratory at the Technische Universität Braunschweig in pursuit of internships for high school students. The department allowed me to work on a three-week "practicum," during which I learned some OpenGL programming. The professor teaching the course encouraged me to study computer science and revisit his department upon entering college and declaring a major.

When I returned two years later, I found that my contact had left the university and a young professor named Marcus Magnor had recently taken over the Computer Graphics Laboratory, which he was looking to grow. I stopped by one day and asked him for a job as a student assistant; he agreed, contingent upon my successful completion of the computer graphics and computer vision classes offered in his lab. I accepted and spent the next year taking classes and pursuing undergraduate studies in computer science.

During this time, TU Braunschweig elected to participate in the Defense Advanced Research Projects Agency's urban challenge with a self-driving car. Magnor decided to form undergraduate and graduate student teams to help with the vision/environmental sensing aspects of the car. I became quite involved in the project and ended up publishing a paper about my work, which was accepted at a conference in New Zealand. To secure travel funding for the conference—and due to university stipulations for such grants—I began working on my master's thesis earlier than normal on the condition that I spend a month conducting research in a laboratory in Auckland, New Zealand. I was able to present my paper, spend time collaborating with the lab, and finish my thesis on time. Magnor then offered me a Ph.D. position in his lab, and I worked on several exciting projects related to computer graphics, visualization, and computer vision. During visits to partner universities, I met other researchers in institutions like the Max Planck Institute for Informatics in Saarbrücken and the University of British Columbia in Vancouver.

CAREERS IN MATHEMATICAL SCIENCES

My first postdoctoral appointment was with the Oxford e-Research Centre, where I provided computer-vision-based solutions for large data visualizations. Together with the research team, I developed a camera-based traffic monitoring toolkit to overlay on Google Maps. I also worked on a project that visualized anomalies in cardiovascular magnetic resonance images (MRIs), which aimed to compute image analysis operations on time-varying MRI data and comprehensibly overlay it on the gray-level video.



Kai Berger explains an optical flow algorithm to his group in Genius Sports Media's Santa Monica, Calif., office. Photo credit: Pareen Kalia.

Next, I accepted an appointment with a group that focused on particle imaging velocimetry at the French Institute for Research in Computer Science and Automation (INRIA). Here I presented new solutions that incorporated Compute Unified Device Architecture/graphical processing unit computing in online visualizations of flow reconstructions on MacBooks. This reduced computation time for flow data from hours to seconds, thus increasing productivity.

Following my time at INRIA, I worked at NASA's Jet Propulsion Laboratory as a robot vision scientist. I sought solutions to help robots navigate environments that challenge their perception, such as off-road terrains, forests, and urban settings with many glass windows and reflective surfaces. I provided new means of visualizing a robot's vision, perception, and subsequent interpretation in three dimensions.

In my current position at Genius Sports, I am also tasked with simulating various situations, such as sensor placement scenarios for potential sporting venues. Simulation relies on quick-to-evaluate, highly parallelizable formulae for camera projection and scene reprojection. Furthermore, the outcome of such simulation may be a 10+ dimensional dataset of millions of data points. To envision the benefits and tradeoffs of certain placement setups, I create new visualization techniques that facilitate interactive dataset exploration. Users can choose up to three dimensions for a layered type of visualization. Scalar color coding then allows them to assess the optimality of a certain visualized subset with respect to the entire dataset's overall value range. Doing so enables us to derive optimal placements for setup capture and efficiently communicate our findings to customers in a way that is visually understandable.

To ensure that uncalibrated and unsynchronized camera sensors work together effectively, I devise new methods for proper calibration. In a pending patent, I have derived a method that allows one to use a laptop or tablet of his/her choice to display a defined series of checkerboard patterns individually into each camera. A postprocessing algorithm then permits detection of the series in the camera footage, helping to distinguish each video stream from others in temporal space. The output is a set of cameras calibrated to our sports court and synchronized to the individual frame that provides two-dimensional information about court activity. I utilize this information, along with the cameras' calibration, to reconstruct court action in three dimensions.

Many of my daily computations and algorithms involve the use of algebraic vision, linear algebra, and projective geometry. Ready-built functions like MATLAB's stereo vision toolbox help with the calibration and reconstruction process. I like to design prototypes as independent graphical user interfaces (GUIs) in MATLAB to provide colleagues and customers with maximal freedom in interacting with our datasets and defining ways to process them. As a personal maxim, my desire is that the GUIs and visualized content be as intuitive and self-explanatory as possible. Shapes and colors must optimally convey the datasets' underlying meaning and the associated applied processing. In other words, I aim for results that meet the highest level of visual appeal. Therefore, I often include recent findings from color science and statistics to increase the data plots' comprehensibility.

During the course of my career, I have continually sought understandable, intelligible, and appealing ways to visualize data. Recognizing how my algorithms interpret and compute that data is equally important. The meaningful use of shapes and colors is key to rendering a successful solution that not only works on data but also tells a coherent story.

Kai Berger is a senior machine vision scientist at Genius Sports Media (http://www.visual-data-science.org). He received his Ph.D. from the Technische Universität Braunschweig. As a member of the Institute of Electrical and Electronics Engineers and the Association for Computing Machinery, he regularly reviews for Eurographics, the Eurographics Symposium on Rendering, 3DV, and Multimedia Tools and Applications.

Earth and Space Science

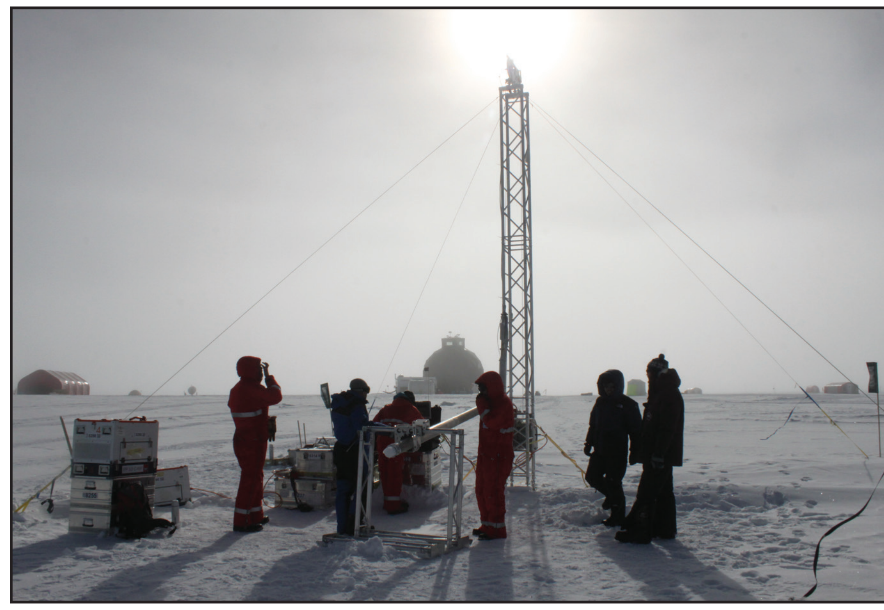
Continued from page 5

diffusion mixes isotope data through the ice over time and space, and some sections of data go missing altogether between ice sheet and laboratory. Sensor data rates vary wildly during long space missions like New Horizons due to hardware issues, power allocation choices, and cloud occlusions that impact Earth-observing satellites.

Such timeline irregularities pose a problem for *any* rate-based calculation, information-theoretic or otherwise. To work around them, even out timelines, and fill in gaps, scientists use methods ranging from linear interpolation to complex physics models. These strategies can have profound—and heretofore unexplored—effects on the signals' information content. Understanding these ramifications is an interesting mathematical problem, as they can cause spurious short-term correlations and regularities that skew outcomes. For instance, the "ramps" introduced by linear interpolation create artificial permutations that are repetitive and completely predictable, which lowers the permutation entropy. Since interpolation plays an increasingly large role as one delves deeper into an ice core, this effect is depth-dependent. Timelines in sediment cores, where material can be carried away by currents and bioturbated by marine organisms, may also be problematic. Interpolation is used routinely in these situations as well, generally without consideration of its repercussions on the data. The mathematics necessary to understand this kind of data preprocessing's impact on information content is still under development, although researchers have made some recent progress in the general area of irregularly-sampled data [7, 9].

The scientifically critical problem of significance testing is also an issue when working with data sets like the water isotope record from the WAIS Divide or the solar-wind temperature on Pluto, which are expensive to gather and all but impossible to replicate. Significance testing or uncertainty quantification with only a single data set is nearly impossible. But this is also changing; the new South Pole Ice Core[2] provides replicate data in a few segments, a number of new ice core drilling projects are underway around the world, and recent technological advances can vastly improve time series data pertaining to Earth and the solar system.

[2] http://spicecore.org/



Climate researchers on the site of the Eastern Greenland Ice-core Project use a drill to collect ice core samples. Public domain image.

A key question about any event is whether it is an expected, natural part of the associated system—e.g., changes in seasonal solar insolation at a point on Earth—or unexpected and random, like the impact of a large asteroid or a coronal mass ejection. Information theory has the power to answer these and other important Earth and space science questions, and the resolution and extent of time series data are improving to the point of supporting these analyses. These developments are inspiring heightened interest in this area from both the geoscience and applied mathematics communities.

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Joshua Garland received an M.S. in applied mathematics and a Ph.D. in computer science from the University of Colorado Boulder. He is currently an Omidyar Postdoctoral Fellow at the Santa Fe Institute. Elizabeth Bradley holds an S.B., S.M., and Ph.D. from the Massachusetts Institute of Technology and has been a member of the University of Colorado's Department of Computer Science since 1993. Her research interests include nonlinear dynamics, time series analysis, and artificial intelligence.

Reproducible BLAS: Make Addition Associative Again!

By James Demmel, Jason Riedy, and Peter Ahrens

A few years ago, a commercial finite element software developer expressed interest in a reproducible parallel sparse linear equation solver [5], i.e., one that can yield bitwise identical results from multiple runs. Some customers and civil engineers had requested this type of solver at the behest of lawyers, who required that civil engineers' earthquake safety analysis code (and approval) of building designs remain consistent during multiple runs.

This motivated me to email 100 or so faculty members at the University of California, Berkeley affiliated with the school's Computational and Data Science and Engineering Program to ask whether they knew that one could no longer expect reproducibility from run to run. The majority of responses were similar. "How will I debug my code if I can't reproduce errors?" many people asked. But there were some unique replies as well. "I know better, I do error analysis to trust my results," one colleague said; of course, these skills (for which that colleague won a Turing Award) are not so common. Another coworker articulated a different concern. "I do fracture analysis with large-scale simulations to look for rare events, and then need to reproduce these rare events exactly to conduct further analysis of why they occurred," he said. "How will I do my science if I can't reproduce them?" A third colleague—whose software is used by the United Nations to detect illegal underground nuclear testing—expressed a further dilemma. "What if my software says 'They did it,' and then 'They didn't do it'?" he said. "That will be a political mess!"

Since then, attendees at numerous supercomputing conferences have discussed the need for reproducibility and proposed ways to achieve it [7]. A number of hardware and software vendors, as well as two standards committees, have begun addressing this challenge.

Of course, there are many reasons why a code may be nonreproducible. The user could link in a different math library, change compiler optimization flags, or write parallel code with race conditions or even "`random_number_seed = get_time_of_day()`." Here we address the more mathematically challenging issue of floating-point addition's nonassociativity due to roundoff, i.e., adding numbers in different orders yields *slightly* different answers, such as $(1+10^{20})-10^{20}=0\neq 1=1+(10^{20}-10^{20})$.

On a parallel machine with a variable (e.g., dynamically allocated) number of processors, a dynamic execution schedule, or even a sequential machine where diverse data alignments may cause a different use of single instruction, multiple data instructions, the order of summation can easily vary between runs or subroutine calls in the same run. This nonreproducibility appears wherever one has computed a parallel sum, from simple cases such as the OpenMP "`reduction(+, ...)`" clause to widely-used libraries like the `Basic Linear Algebra Subprograms` (`BLAS`). Nonreproducibility in the `BLAS` affects higher-level applications and the libraries that use them, including most linear algebra packages.

A number of vendors (including Intel and NVIDIA) have responded to this challenge with versions of their libraries that provide reproducibility under limited circumstances using the same summation order, while others (like ARM) offered new hardware instructions to support reproducible summation. Some have suggested correctly-rounded (and thus reproducible) summation techniques [2, 3], which require very large accumulators to exactly represent the entire floating-point sum. Our approach uses just six floating-point numbers to represent a "reproducible accumulator" and produces the same reproducible result when used in any reduction tree over summands in any order. To our knowledge, our method is the first to satisfy all of the following design goals:

1. Achieve reproducible summation independent of summation order using only standard floating-point operations
2. Provide tunable accuracy at least as good as "standard" summation
3. Perform one read-only pass over the summands and one reduction operation in parallel
4. Reproducibly handle overflow, underflow, and other exceptions
5. Enable tiling optimizations common in the `BLAS` and higher-level libraries like `LAPACK` and its parallel extensions using as little memory as possible
6. Provide primitives so parallel runtimes and higher-level environments can implement reproducible linear algebra operations.

SOFTWARE AND PROGRAMMING

Our technique attains these goals and costs $7n$ standard floating-point additions to sum n numbers into a reproducible accumulator consisting of six floating-point values (plus n `max()` and n `abs()` operations). We can extend our work on communication lower bounds and communication-avoiding algorithms to show that linear algebra's communication costs increase proportionally to the square root of the reproducible accumulator's size; thus, smaller is better [4].

One can easily describe the algorithm at a high level, although the details and proofs are more complicated [4]; we divide the range of all floating-point exponents into "bins" of a certain fixed width W ($W=40$ bits for double precision numbers). At execution time, we divide the mantissa bits of each summand into their respective bins and separately sum all the bits within each bin. Since the bits in one bin roughly share a common exponent, summation within a bin behaves like fixed point arithmetic and is exact and reproducible. Furthermore, we only retain the few (typically three) bins corresponding to the highest exponents of any summands seen so far, and discard or omit computation of the rest; this limits both the work and size of the reproducible accumulator and introduces an error with a much smaller bound than is standard. At the end of summation, we can convert the reproducible accumulator back to a standard floating-point number using a few more operations.

An initial implementation of the `Reproducible BLAS (ReproBLAS)` using this algorithm is freely available.[1] This implementation is sequential but vectorized for many Intel architectures. `ReproBLAS` provides primitives for parallel runtimes with an example summation operation for message passing interface (MPI) reductions. Use of these operations in `MPI_Reduce` delivers reproducible reductions like dot product regardless of the reduction tree's shape. The reductions remain reproducible even if computed redundantly (in possibly different orders) to remove a final, global broadcast.

See **Reproducible BLAS** *on page 12*

[1] https://bebop.cs.berkeley.edu/reproblas/

Ingrid Daubechies receives William Benter Prize in Applied Mathematics

Ingrid Daubechies

City University of Hong Kong (CityU) has awarded the William Benter Prize in Applied Mathematics 2018 to Ingrid Daubechies, James B. Duke Professor of Mathematics and Electrical and Computer Engineering at Duke University, for her exceptional contributions and pioneering work in a wide spectrum of scientific and mathematical subjects.

Daubechies is the first female recipient of the William Benter prize. Her work in functional analysis, particularly related to wavelets in image-compression technology, has had a profound impact in mathematics, science and engineering. The results of her work are evident in many aspects of our daily life, including digital communication systems, medical image compression, audio and videos coders, and even tools for art history and art authentication. The impact of her work is symbolic of our era.

The William Benter Prize in Applied Mathematics was set up in 2010 by the Liu Bie Ju Centre for Mathematical Sciences at CityU in honour of Mr William Benter, the donor of the prize, for his dedication and generous support for the enhancement of the University's strength in mathematics. The Prize recognises outstanding mathematical contributions that have had a direct and fundamental impact on scientific, business, finance and engineering applications. It includes a cash prize of US$100,000 and is given once every two years.

The Prize was presented to Ingrid Daubechies at the opening ceremony of the International Conference on Applied Mathematics, organised by the Liu Bie Ju Centre for Mathematical Sciences at CityU, on 4 June 2018.

Biographical Sketch

Ingrid Daubechies was born in Houthalen, Belgium. She obtained her Bachelor's degree in physics in 1975 and her PhD in 1980 from Vrije Universteit Brussel. After teaching for 12 years at her alma mater, she joined AT&T Bell Laboratories in 1987. She was a Professor of Mathematics at Rutgers University from 1991 to 1993 and moved to Princeton University in 1994. Daubechies was the first-ever female professor of mathematics at Princeton and was the William R. Kenan Jr. Professor of Mathematics from 2004 to 2010. She joined Duke University in January 2011 and is currently the James B. Duke Professor of Mathematics and Electrical and Computer Engineering.

Daubechies has received many awards and honours for her achievements and contributions over the years. She is a member of the US National Academy of Sciences, a member of the US National Academy of Engineering, and a foreign member of the French Academy of Sciences. Daubechies received two AMS Steel Prizes: one for Exposition (1994) and one for her seminal contribution to research (2011). Her monograph *Ten Lectures on Wavelets* has been cited more than 20,000 times. She was a plenary speaker at the International Congress of Mathematics in 1994 and gave the SIAM John von Neuman lecture in 2011. She received the National Academy of Sciences Award in Mathematics in 2000 and the Nemmers Prize in 2012. Daubechies was also the first female president of the International Mathematical Union from 2011 to 2014.

Citation

Over the past 20 years, digital signal processing has exploded in significance. The mobile smartphone revolution has completely changed the face of commerce, education and ultimately human culture. At the core of this revolution is the transformation of digital data from one format to another for transmission in compact forms…. Daubechies' work on wavelet transforms figures prominently in the literature of compression and noise removal. Her work is truly symbolic of the technology that has enabled the massive digital media content revolution.

Daubechies' work spans an amazing breadth of scientific disciplines, with deep impacts in signal and image processing, numerical computation and data analysis.

She has made numerous other contributions to scientific and mathematical problems in a wide spectrum of subjects, ranging from computer graphics, analysis of internet traffic, machine learning and randomized algorithms to mathematical biology and functional MRI, and even mathematical tools for art history and art authentication. She is unique in her ability to penetrate a completely new subject and contribute to it in a novel and fundamental way.

– City University of Hong Kong

Changes Coming to CBMS Regional Conferences

By David Bressoud

Next year marks the 50th anniversary of the National Science Foundation-Conference Board of the Mathematical Sciences (NSF-CBMS) Regional Research Conferences in the Mathematical Sciences.[1] These conferences and the publication of the resulting monographs are conducted in cooperation with SIAM, the American Mathematical Society, the Institute of Mathematical Statistics, and the American Statistical Association. This is an opportune moment to reflect on the series' contributions thus far and update its requirements to better meet future needs.

The Regional Research Conference series began in 1969 with three distinctive features:

• Conferences are awarded across a diverse set of geographic locations and institution types

• Conferences run for five days and are organized around a single "principal lecturer" who delivers 10 lectures, offering insight into an exciting area of current research

• The lecturer produces a monograph based on his/her talks, enabling dissemination of conference information to a much wider audience.

The NSF currently funds up to ten conferences per year. A description of past conferences, links to the monograph series, and information on proposal preparation are available online.[2]

Beginning with conference proposals for 2020, several significant changes will occur. These include loosening the restriction that there be only one principal lecturer. The rationale behind this original stipulation—to provide a well-connected, focused flow that progresses from a basic introduction to detailed current research—is still important. Moving forward, the CBMS will allow up to three people to deliver the 10 lectures, provided that one "principal lecturer" coordinates the progression of these presentations.

While continuing to require the production of a monograph based on the 10 lectures, we will also require the submission of information for the CBMS website:

• Principal lecturers will be responsible for preliminary materials that include historical context, a reading list, basic definitions, relevant results, and an outline of the 10 forthcoming talks

• Principal lecturers will use prepared slides (e.g., PDF, PowerPoint, or Beamer) that they will submit to the CBMS by the end of the conference

• Conference organizers will record video of at least the 10 principal lectures, which the CBMS will make available on Vimeo or a comparable site

• Principal lecturers will be responsible for an expanded account of the 10 talks within 45 days of the conference's conclusion.

The most effective conferences allocate large chunks of time for new researchers to interact with other attendees regarding questions and methods. With this in mind, conference organizers will now be required to describe the facilitation of this networking, whether through problem sessions, hands-on experiences with software, small group Q&A discussions, or other means.

It its earliest incarnation, the CBMS was solely responsible for deciding which conferences received funding; it still had a role in these decisions through 2017. The NSF has now completely taken over this task, which gives the CBMS a much more active role in identifying candidates for principal lecturer, matching them with institutions that might not normally host major research conferences and helping these institutions write competitive proposals. The CBMS has created an advisory board to assist in the identification of potential speakers and sites. Initial members include Susmita Datta (University of Florida), David Donoho (Stanford University), Bengt Fornberg (University of Colorado Boulder), Ken Ono (Emory University), and Mary Lou Zeeman (Bowdoin College). The board is intentionally weighted toward applied mathematics and statistics.

The NSF-CBMS Regional Research Conference series has a proud history. 231 monographs have been produced thus far, with another dozen in the pipeline. SIAM's *CBMS-NSF Regional Conference Series in*

See **CBMS Conferences** *on page 12*

[1] Support from NSF #1804259

[2] http://www.cbmsweb.org/regional-conferences/

New NSF Supplemental Funding Opportunity

Non-Academic Research Internships for Graduate Students (INTERN)

The nation's global competitiveness depends critically on the readiness of its science, technology, engineering, and mathematics (STEM) workforce, and the National Science Foundation (NSF) seeks to continue its investment in programs that directly advance this workforce. As part of this effort, a supplemental funding opportunity is available in fiscal years 2019 and 2020 to provide support for non-academic research internships for graduate students and ultimately bolster career opportunities in all sectors of the U.S. economy.

The NSF's Science and Engineering Indicators 2018 report[1] reveals that 79 percent of master's level STEM graduates and 57 percent of doctoral degree holders work in industry or government. It is therefore important that graduate students supported by NSF grants have opportunities to develop skills that prepare them for success in a broad range of academic and non-academic career paths. In addition to deep and broad preparation in their technical areas of expertise, skills and knowledge regarding communication, innovation and entrepreneurship, leadership and management, and policy and outreach are becoming increasingly valuable in any sector of the workforce.

The principal investigator of an active NSF award may request supplemental funding for one or more graduate students to gain knowledge, skills, and experiences through an internship in a non-academic setting that will augment their preparation for a successful long-term career. For eligibility, graduate students must have completed at least one academic year in their graduate programs and be satisfactorily progressing towards completion of their degrees. More details are available online.[2]

Due dates for available funds:
For FY 2019 funds: May 1, 2019
For FY 2020 funds: May 1, 2020

[1] https://www.nsf.gov/statistics/2018/nsb20181/report

[2] https://www.nsf.gov/pubs/2018/nsf18102/nsf18102.jsp

The Moon Sine

MATHEMATICAL CURIOSITIES
By Mark Levi

The Sun-Moon-Eye Angle

On a long car ride from State College to Boston in late August, my wife and I were accompanied by a waning gibbous moon — a disk low on the horizon with a bit nibbled off, as in Figure 1a. During the forced idleness of the long ride I realized how easy it is to tell the sun-moon-eye angle θ of Figure 2 from the face of the moon: namely,

$$\cos\theta = \frac{v}{r}, \tag{1}$$

where v and r are marked in Figure 1. Here, v may either be positive or negative, as stated in the caption. This sign convention gives an acute θ for the gibbous moon and an obtuse θ for the crescent moon, in agreement with common sense. Figure 3 explains the proof of (1). For the harvest moon, θ vanishes, and therefore so does sine on harvest moon.

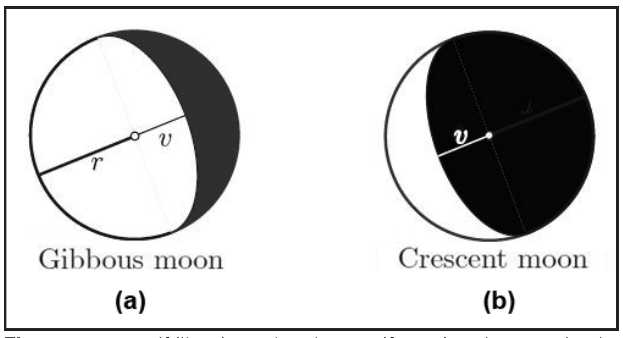

Figure 1. *$v>0$ if illuminated and $v<0$ if not. In other words, the positive direction is away from the sun.*

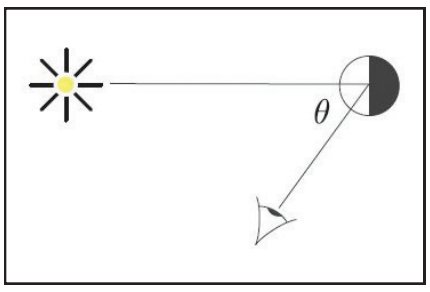

Figure 2. *The sun-moon-eye angle.*

The Terminator

The great circle on the moon that separates light from dark is called the lunar terminator. To our eye the terminator is an ellipse, since it is a parallel projection of a circle. Where are the foci of this ellipse? The answer is given by the same sun-moon-eye angle θ, as Figure 4 shows. And how do these foci move in time? It turns out that they execute harmonic motion if we neglect the eccentricities of the orbits of Earth and the moon. I leave out the proof of these claims.

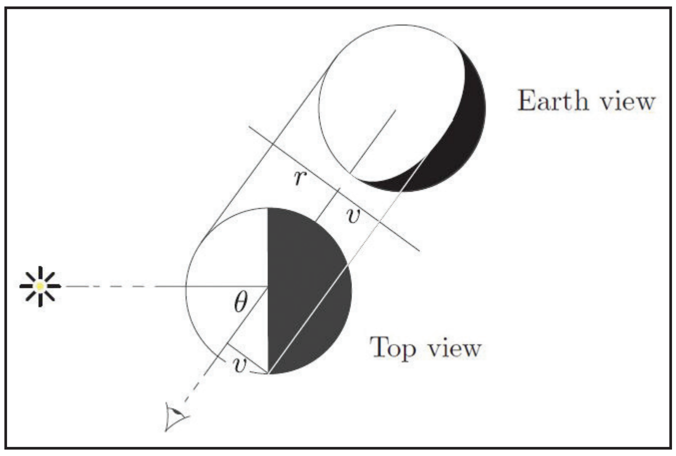

Figure 3. *The proof of (1).*

The Lunar Tilt Illusion

To conclude, I would like to mention a somewhat related Moon Tilt Illusion pointed out to me by Nick Trefethen: the tilt of the crescent seems wrong, and the moon should look fuller. Very nice discussions of this are available in [1] and [2].

The figures in this article were provided by the author.

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Mark Levi (levi@math.psu.edu) is a professor of mathematics at the Pennsylvania State University.

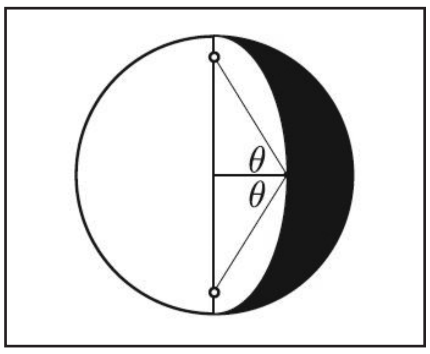

Figure 4. *The foci of the lunar terminator are given by the same θ as in Figure 2.*

ICIAM Announces 2019 Prizes

The International Council for Industrial and Applied Mathematics (ICIAM) is pleased to announce the winners of the five ICIAM prizes for 2019. ICIAM is a worldwide organization for applied mathematics societies and other associations with a significant interest in industrial or applied mathematics.

The ICIAM congresses, held every four years, are run under the auspices of the Council. The 2019 prizes will be presented at the next congress, the Ninth International Congress on Industrial and Applied Mathematics (ICIAM 2019), which will take place next year from July 15-19 in Valencia, Spain.

Collatz Prize

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

The 2019 ICIAM Collatz Prize is awarded to Siddhartha Mishra (ETH Zürich, Switzerland) for his breakthrough contributions that skillfully combine real-world modeling and rigorous mathematical analysis with the development of efficient and accurate numerical schemes and high-performance computing.

Lagrange Prize

The Lagrange Prize was established to provide international recognition to individual mathematicians who have made exceptional contributions to applied mathematics throughout their careers. It was created on the initiative of the Sociedad Española de Matemática Aplicada, the Società Italiana di Matematica Applicata e Industriale, and the Société de Mathématiques Appliquées et Industrielles, and was first awarded in 1999. The Sociedade Brasileira de Matemática Aplicada e Computacional joined the group of sponsors in 2017. All four member societies fund the Lagrange Prize, which carries a cash award of USD 5,000.

The 2019 ICIAM Lagrange Prize is awarded to George Papanicolaou (Stanford University, USA) for his brilliant use of mathematics to solve important problems in science and engineering, particularly those involving inhomogeneity, wave propagation, random media, diffusion, scattering, focusing, imaging, and finance.

Maxwell Prize

The Maxwell Prize was established to provide international recognition to mathematicians who have demonstrated originality in applied mathematics. It was created on the initiative of the Institute of Mathematics and its Applications (IMA) with support from the J.C. Maxwell Society, and first awarded in 1999. Carrying a cash award of USD 5,000, the Maxwell Prize is presently funded by the IMA.

The 2019 ICIAM Maxwell Prize is awarded to Claude Bardos (Université Paris Denis Diderot (Paris 7), France) for his seminal contributions to nonlinear partial differential equations, kinetic theory, and mathematical fluid mechanics.

Pioneer Prize

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

The 2019 ICIAM Pioneer Prize is awarded to Yvon Maday (Sorbonne University, France) for his leading role in the introduction of powerful methods for numerical simulation, such as spectral methods, reduced-order modeling, domain decomposition, models and simulation in medical sciences, fluid-structure interaction, and ab initio chemistry. Several of his works led to the launch of start-ups and are intensively used in industry.

Su Buchin Prize

The Su Buchin Prize was established to internationally recognize individuals' outstanding contributions in the application of mathematics to emerging economies and human development, particularly at the economic and cultural level in developing countries. It was created on the initiative of the China Society for Industrial and Applied Mathematics (CSIAM) and was first awarded in 2007. Carrying a cash award of USD 5,000, the Su Buchin Prize is presently funded by CSIAM.

The 2019 ICIAM Su Buchin Prize is awarded to Giulia Di Nunno (University of Oslo, Norway) for her long-lasting record of active and efficient encouragement of top-level mathematical research and education in developing African countries.

Professional Opportunities and Announcements

Send copy for classified advertisements and announcements to ***marketing@siam.org****. For rates, deadlines, and ad specifications, visit* ***www.siam.org/advertising****.*

*Students (and others) in search of information about careers in the mathematical sciences can click on "Careers and Jobs" at the SIAM website (****www.siam.org****) or proceed directly to* ***www.siam.org/careers****.*

Williams College

Department of Mathematics and Statistics

The Department of Mathematics and Statistics at Williams College invites applications for a new **tenure-track position in statistics**, beginning fall 2019, at the rank of assistant professor. A more senior appointment is also possible for a qualified candidate at a later stage in their career. The candidate should have a Ph.D. in statistics or a closely-related field by the time of appointment. We are seeking candidates who show evidence and/or promise of excellence in teaching and a strong research program that can engage undergraduate students. The candidate will become the seventh tenure-track statistician in the department, joining a vibrant and innovative group of statisticians within an established statistics major. For more information on the Department of Mathematics and Statistics, visit **http://math.williams.edu/**.

Candidates may apply via **https://apply.interfolio.com/50978** by uploading a cover letter addressed to Professor **Richard De Veaux**, a curriculum vitae, a teaching statement, a description of research plans, and three letters of recommendation on teaching and research. The department is committed to building a diverse and inclusive community. In your application materials, we also ask you to address how your teaching, scholarship, mentorship, and/or community service might support Williams' commitment to diversity and inclusion.

Expectations: The teaching load is two courses per 12-week semester and a winter term course every other January. The candidate will be expected to teach introductory statistics, core courses for the statistics major, and elective courses in their areas of interest. The successful candidate will establish an independent research program that results in scholarly publications. Williams College provides broad support for start-up funds, funding for student research assistants, faculty professional development funds, and a shared computer cluster for parallel computation.

Review of applications will begin on or after **October 1st** and will continue until the position is filled. All offers of employment are contingent upon completion of a background check. Further information is available at **https://faculty.williams.edu/prospective-faculty/background-check-policy/**.

Williams College is a coeducational liberal arts institution located in the Berkshire Hills of western Massachusetts. The college has built its reputation on outstanding teaching and scholarship, and on the academic excellence of its approximately 2,000 students. Please visit the Williams College website at **http://www.williams.edu**. Beyond fully meeting its legal obligations for nondiscrimination, Williams College is committed to building a diverse and inclusive community where members from all backgrounds can live, learn, and thrive.

California State University, Fullerton

Department of Mathematics

Applications are invited for at least one tenure-track faculty position in applied mathematics at the assistant professor level, beginning August 2019. Candidates should be applied mathematicians with a background in computation, numerical analysis, machine learning, and mathematical modeling (with preference to statistical modeling). Responsibilities include teaching undergraduate and graduate courses in applied mathematics; conducting research resulting in publications in high-quality, peer-reviewed journals; directing faculty-student collaborative research; and advising undergraduate students. Successful candidates will contribute to the mathematics community at Cal State Fullerton through teaching, research, professional activities, and service. In particular, they will be expected to solicit industrial consulting projects for students in the graduate program in applied mathematics, mentor the students in completing these projects, and participate in the transdisciplinary Center for Computational and Applied Mathematics (CCAM) within the College of Natural Sciences and Mathematics. The qualified candidate must

See **Professional Opportunities** *on page 11*

Professional Opportunities

Continued from page 10

have a Ph.D. in applied mathematics or a related field, plus at least one year of postdoctoral experience in either research, teaching, or a related industrial field. For more details, please visit us at **www.fullerton.edu/math**. Applicants must submit their materials through **www.mathjobs.org**. Application deadline is **November 4, 2018**.

California Institute of Technology

Department of Computing + Mathematical Sciences

The Computing + Mathematical Sciences (CMS) Department at the California Institute of Technology (Caltech) invites applications for a tenure-track faculty position in the fundamental mathematics and theory that underpins application domains within the CMS Department, the Division of Engineering and Applied Science (EAS), or the institute as a whole. Areas of interest include (but are not limited to) algorithms, data assimilation and inverse problems, dynamical systems and control, geometry, machine learning, mathematics of data science, networks and graphs, numerical linear algebra, optimization, partial differential equations, probability, scientific computing, statistics, stochastic modeling, and uncertainty quantification.

CMS is a unique environment where research in applied and computational mathematics, computer science, and control and dynamical systems is conducted in a collegial atmosphere; application foci include distributed systems, economics, graphics, neuroscience, quantum computing, and robotics and autonomous systems. The CMS Department is part of the broader EAS Division, comprising researchers working in—and at intersections of—the fields of aerospace, civil, electrical, mechanical, and medical engineering, as well as in environmental science and engineering plus materials science and applied physics. The institute as a whole represents the full range of research in biology, chemistry, engineering, physics, and the social sciences.

A commitment to world-class research, as well as high-quality teaching and mentoring, is expected. The initial appointment at the assistant professor level is for four years and is contingent upon the completion of a Ph.D. degree in applied mathematics, computer science, statistics, or a related field in engineering or the sciences.

Applications will be reviewed beginning **November 7, 2018**, and applicants are encouraged to have all of their application materials, including letters of recommendation, on file by this date. For a list of required documents and full instructions on how to apply online, please visit **https://applications.caltech.edu/jobs/cms**.

Questions about the application process may be directed to **search@cms.caltech.edu**.

We are an equal opportunity employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, sexual orientation, gender identity, national origin, disability status, protected veteran status, or any other characteristic protected by law.

Sandia National Laboratories

2019 John von Neumann Fellowship in Computational Science

Sandia National Laboratories is now accepting applications for the 2019 John von Neumann Fellowship in Computational Science. This is one of Sandia's most prestigious postdoctoral fellowships, funded in part by the Applied Mathematics Research Program in the U.S. Department of Energy's Office of Advanced Scientific Computing Research. The appointment is for one year, with a possible renewal for a second year, and includes a highly-competitive salary, moving expenses, and a generous professional travel allowance.

Do you dream of an opportunity to conduct creative research in computational mathematics and scientific computing on advanced computing architectures? Are you passionate about research that impacts a broad range of problems of national importance? If so, you could be the next John von Neumann Fellow at Sandia! This fellowship does not require U.S. citizenship.

Applications will be accepted through **November 26, 2018**. To apply, visit **https://www.sandia.gov/careers/** and search for job **#663469**.

Dartmouth College

Department of Mathematics

The Department of Mathematics at Dartmouth College announces two senior openings in applied mathematics at the rank of professor, with initial appointment as early as 2019-2020, as the inaugural Jack Byrne Professors of Applied Mathematics. We seek acknowledged international leaders in applied mathematics with exemplary track records in creating mathematical and statistical methodological advances and their applications, especially in relation to the social, health, or financial sciences. These positions will sit within the Department of Mathematics and extend our existing group in applied mathematics. Current applied and computational interests in the department include complex systems, computational social sciences, network analysis, statistical learning, mathematical biology, stochastic processes, numerical analysis, PDEs, imaging, and signal processing. Our strength in applied mathematics is complemented by strength in several areas of theoretical mathematics.

Together with a recent third senior position in decision sciences in Dartmouth's top-ranked Tuck School of Business, these positions will be part of the Byrne Cluster. They represent further investment in the department's continued efforts to expand its research efforts and related pedagogy in applied mathematics. We seek candidates with the potential to bridge multiple research areas both inside and outside the Department of Mathematics. The Byrne Cluster comes with programmatic funds to support those goals. In addition to research qualifications, candidates should have a keen interest and demonstrated excellence in teaching and mentorship of both undergraduates and graduate students.

Initiate application at **www.mathjobs.org**. Position ID: **JBPAM #12522**.

Society for Industrial and Applied Mathematics

Director of Development and Corporate Relations

The director of development is responsible for planning, organizing, and directing all of the Society for Industrial and Applied Mathematics' (SIAM) fundraising, including the major gifts program, annual fund, planned giving, corporate giving, special events, and capital campaigns. The director works closely with the executive director and the Board of Directors in all development and fundraising endeavors.

Responsibilities include the following: Develop fundraising strategies for the implementation of a development program for SIAM • Annually create and execute a fundraising plan with goals • Meet prospective donors and supporters on a continual basis to establish effective communication • Grow a major gifts program, including identification, cultivation, and solicitation of major donors • Oversee grant-seeking for special projects, including research, proposal writing, and reporting requirements • Build the planned giving program with a focus on deferred gifts through estates and charitable gift annuities and trusts • Direct the annual fund program, including mailings and annual fundraising drives • Develop a corporate giving program and build strategic alliances with corporate partners, including a focus on STEM education and research • Direct capital campaigns and other major fundraising drives • Coordinate fundraising special events • Oversee prospect research • Staff liaison for the Board Development Committee meeting • Oversee fundraising database and tracking systems • Oversee creation of publications to support fundraising activities • Maintain gift recognition programs • Perform other related duties as requested.

Qualifications are as follows: B.A. (required), M.A. (a plus) • Five-plus years of experience in development • Demonstrated excellence in organizational, managerial, and communication skills.

Please send a cover letter and resume to **Susan Palantino** at **palantino@siam.org**. EOE.

SIAM is an international community of 14,500+ individual members. Almost 500 academic, manufacturing, research and development, service and consulting, government, and military organizations worldwide are institutional members. SIAM was incorporated in 1952 as a nonprofit organization to convey useful mathematical knowledge to other professionals who could implement mathematical theory for practical, industrial, or scientific use. Today, SIAM continues to advance the application of mathematics and computational science to engineering, industry, science, and society. SIAM is located at 3600 Market Street, Philadelphia, PA, 19104.

Society for Industrial and Applied Mathematics

Director of Programs and Services

The Society for Industrial and Applied Mathematics (SIAM) seeks a creative, strategic director of programs and services to support the technical activities of the society. Reporting to the executive director, the director of programs is responsible for the oversight and management of programs and projects mostly concentrated on the society's membership program and conference program, including the administration of grants in those areas. This position plays a central role in assuring the continuity and reliability of SIAM activities and ensuring timely response to changing needs and new opportunities, taking a leadership role in advancing these programs with the proven ability to be innovative and original in the development and enhancement of member and conference programs and services.

The position has two direct reports. The individual selected for the position must have excellent written and verbal communication skills and be able to interface with SIAM governance, including officers, board members, and members of related committees. The position requires a knowledge of applied mathematics and/or computational science; advanced degree preferred. Please submit a cover letter and either a CV or resume to **Susan Palantino**, chief operating officer, 3600 Market Street, 6th floor, Philadelphia, PA, 19104, or via email to **palantino@siam.org**. EOE.

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Society for Industrial and Applied Mathematics

Membership Coordinator

The Society for Industrial and Applied Mathematics (SIAM) is looking for a talented and self-motivated individual to fill a role in the Membership Department.

Duties include the following: Manage the 21 topical SIAM Activity Groups, including corresponding with leadership, administering elections, scheduling, and creating materials for meetings and teleconferences • Create or update Membership Department applications, documentation, and marketing materials • Coordinate Membership Department activities surrounding conferences, including shipping materials, creating email marketing campaigns, and occasionally attending conferences to recruit members • Design and write copy for Membership Department communications in print, online, and via email • Assist the department as needed with student chapters, membership renewal, customer service, conferences, sections, committees, or other tasks.

Attributes of an ideal candidate are as follows: Excellent skills with Microsoft Office suite, including Outlook, Excel, PowerPoint, and Word • Strong written and verbal skills • A bachelor's degree or commensurate relevant experience • Ability to produce professional documents and correspondence • Some knowledge of database management • Ability to effectively handle numerous tasks and assignments • Discipline to work successfully without close supervision • Ability to quickly and effectively develop new skills to meet new tasks • Methodical, analytical, and creative problem-solving ability • Excellent listening and interpersonal skills.

Additionally, the following experience is a plus: Familiarity with the nonprofit sector, with experience in associations and international organizations being even more pertinent • Previous experience with programming and graphic design tools • Experience with marketing and publications • SQL and data analysis • Web content management systems.

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SIAM provides a competitive salary, excellent benefits, and a great location in the heart of Philadelphia's University City. Perhaps most importantly, we are a small team where each member is encouraged to participate and develop their skills to make a significant contribution to SIAM's business goals.

Interested candidates should send a resume, salary requirements, and optional writing/work samples to **Tim Fest**, SIAM, 3600 Market Street, 6th floor, Philadelphia, PA, 19104, or via email to **fest@siam.org**. EOE.

R·I·T

Department Head - School of Mathematical Sciences

4005BR
College of Science
COS School of Mathematical Sciences

Faculty Type (Tenure Status): Tenure-Track, Tenured
Faculty Discipline: Applied Mathematics, Applied Statistics, Computational Mathematics, Data Analytics
Faculty Rank: Professor
Employment Category: Fulltime
Anticipated Start Date: 01-Jul-2019

The Rochester Institute of Technology seeks a visionary and dynamic leader to serve as the Head of the School of Mathematical Sciences (SMS), an academic unit dedicated to advancing the frontiers of mathematical sciences. As the chief academic, fiscal, and administrative officer of the School, the Head provides leadership, advocacy, oversight, and management. The Head is responsible for overseeing the academic, student, faculty, and staff affairs and for leading the research and operational activities of the School. The daily operation of the School emphasizes an open and inclusive management style that inspires and supports the faculty, staff, and students in their individual and collaborative efforts.

How To Apply
Apply online at **http://apptrkr.com/1280711**

Any questions on the position should be directed to Dr. Nathan Cahill via email (nathan.cahill@rit.edu).

Review of applications will begin on November 1, 2018 and will continue until a suitable candidate is found. It is expected that the new Head will assume the position no later than July 1, 2019.

INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

The *Institute for Computational Engineering and Sciences (ICES)* at *The University of Texas at Austin* is searching for exceptional candidates with expertise in computational science and engineering to fill several Moncrief endowed faculty positions at the Associate Professor level and higher. These endowed positions will provide the resources and environment needed to tackle frontier problems in science and engineering via advanced modeling and simulation.

This initiative builds on the world-leading programs at ICES in Computational Science, Engineering, and Mathematics (CSEM), which feature 16 research centers and groups as well as a graduate degree program in CSEM. Candidates are expected to have an exceptional record in interdisciplinary research and evidence of work involving applied mathematics and computational techniques targeting meaningful problems in engineering and science. For more information and application instructions, please visit: www.ices.utexas.edu/moncrief-endowed-positions-app/.

This is a security sensitive position. The University of Texas at Austin is an Equal Employment Opportunity/Affirmative Action Employer.

THE UNIVERSITY OF TEXAS AT AUSTIN

Reproducible BLAS

Continued from page 8

Wide use of `ReproBLAS` naturally depends on performance cost. We compare `ReproBLAS` performance to routines in Intel's Math Kernel Library (MKL) on an Intel Sandy Bridge (i7-2600)-based system. For vectors that fit in the processor's top-level (L1) cache, a double-precision dot product (ddot) runs 3.3 to 4.2 times slower than the optimized MKL ddot — a worst-case scenario for ddot. The performance penalty is around $2.6\times$ for vectors that are too long for any cache. Implementing the inner loop in two hardware instructions [6] decreases the performance gap to $1.8\times$. Finally, the slowdown was just $1.2\times$ when comparing the speed of summing 1M numbers spread across 1K processors of a Cray XC30; this is because the required time for arithmetic is small compared to the reduction's network latency time. When data transfer dominates execution time, reproducibility could become the default. More performance comparisons are available in [4], including higher-level `BLAS`.

This work is influencing the possible directions of two ongoing standards committees: the IEEE 754 Standard for Floating-Point Arithmetic, which is up for renewal in 2018, and the `BLAS` standard, which is considering a variety of possible extensions — including a reproducible version of the `BLAS`. It turns out that our algorithm's inner loop uses a slight variation of a well-known operation, often called two-sum, that takes summands x and y and precisely returns both their rounded sum (call it h for "head") and the exact rounding error (call it t for "tail"), i.e., $h = \mathrm{round}(x+y)$ and $t = x+y-h$. Researchers have long used two-sum (and variants) to simulate extra-precise arithmetic, like double-double and compensated summation.

Implementing two-sum can take from three to seven standard floating-point operations, depending on prior (application-dependent) information about the relative magnitudes of x and y. Standardizing two-sum's behavior permits hardware implementations in one or two instructions. But we cannot use the conventional IEEE 754 rounding directions. In order to maintain reproducibility while supporting existing uses, new operations must break ties in a value-independent manner. Rounding to nearest but breaking ties toward zero works; this mode already exists for decimal arithmetic but not for binary works. In July 2018, the IEEE 754 committee voted to send a standard—including two-sum and related operations—to the next level of the standards process.

Implementing these operations as one or two hardware instructions reduces reproducible summation's arithmetic cost from $7n$ to $3n$ or $4n$. Removing performance as a bottleneck widens its appeal. Meanwhile, the `BLAS` standard group is working on a portable specification and names for both this and other algorithms [1].

Future work (possibly for many!) includes completion of the sequential and parallel `ReproBLAS` and exploration of its role in making higher-level linear algebra libraries and environments reproducible.

An expanded list of references is available online.[2]

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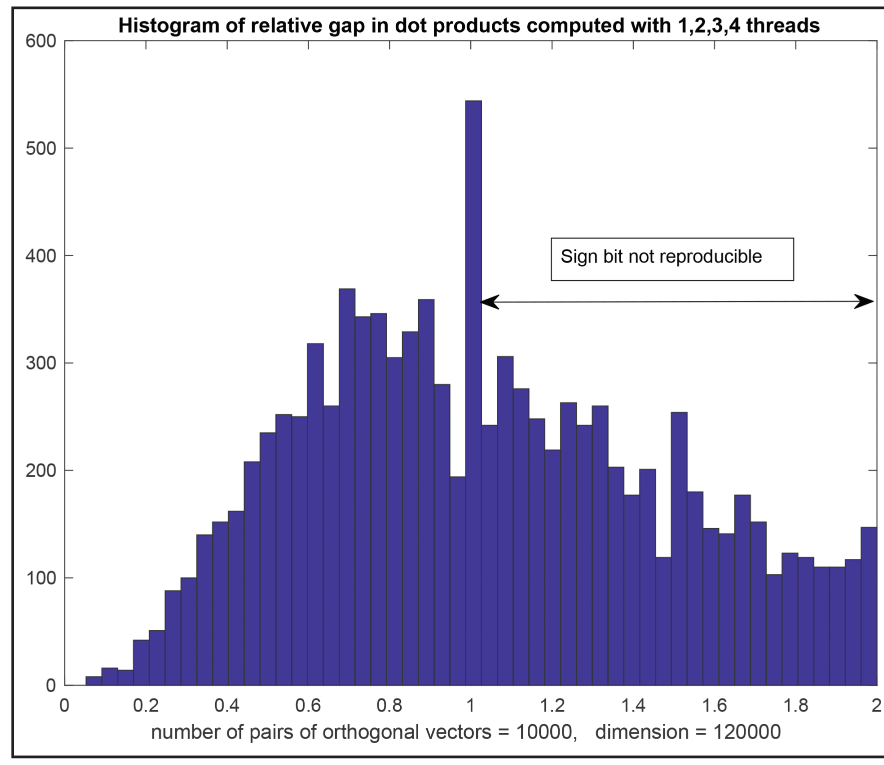
[2] https://bebop.cs.berkeley.edu/reproblas/



We illustrate how parallel summation with a different number of processors can lead to non-reproducibility. We generate many pairs of random orthogonal unit vectors and compute their dot products in MATLAB with four different summation orders, corresponding to 1, 2, 3 or 4-way parallel summation. For each set of four dot products `s(1:4)`*, which would be identical if summed reproducibly, we compute the relative gap =* `(max_i s(i) - min_i s(i))/max_i abs(s(i))`*, or 0 if all* `s(i)` *= 0. The relative gap lies in the range [0, 2] and exceeds 1 if not even the sign bit is reproducible. The histogram depicts relative gaps for 10,000 dot products of dimension 120,000. In about half of the cases, not even the sign bit is reproducible. Figure courtesy of James Demmel.*

James Demmel is a professor of electrical engineering and computer sciences (EECS) and mathematics at the University of California, Berkeley and current chair of the Department of EECS. In his spare time he avoids communication. Jason Riedy is a senior research scientist in the Georgia Institute of Technology's College of Computing. His research ranges from high-performance data analysis and novel computing architectures to urban honey bees. Peter Ahrens is a third-year computer science graduate student and Department of Energy Computational Science Graduate Fellow at the Massachusetts Institute of Technology. His research focuses on writing algorithms to automatically optimize linear algebraic operations.

CBMS Conferences

Continued from page 9

Applied Mathematics[3] has published 92 of these volumes. The first in this series was Garett Birkhoff's *The Numerical Solution of Elliptic Equations* [2], while Doug Arnold's *Finite Element Exterior Calculus* [1] is the most recent. Four volumes from the SIAM series have prompted second editions [5-7, 9], and three have sold over 10,000 copies each [3-4, 8]. Perhaps the most famous is Ingrid Daubechies' *Ten Lectures on Wavelets* [3], based on her 1990 conference at the University of Lowell (now the University of Massachusetts Lowell), which has sold 17,000 copies and been cited almost 30,000 times.

As we collected input for future adjustments, we were heartened by the outpouring of support. While not everyone agreed on the best way forward, all participants communicated the value of these conferences — both in the past and for the future. We are grateful for the legacy of the past 50 years and the opportunity to reimagine this series for coming decades.

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[3] http://bookstore.siam.org/cbms-nsf-regional-conference-series-in-applied-mathematics/

David Bressoud is DeWitt Wallace Professor of Mathematics at Macalester College. In 2017, he inherited the role of director of the Conference Board of the Mathematical Sciences from Ron Rosier, who had shepherded the organization for almost 30 years.