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Bayesian Search for Missing Aircraft, Ships, and People

Finding a Needle in a Haystack

By J. Van Gurley and Lawrence D. Stone

On July 23, 2013, the lobster boat *Anna Mary* was heading out from Montauk, New York, to the fishing grounds off Long Island. Around 9:00 p.m., Anthony Sosinski went below to get some sleep while his partner, John Aldridge, stayed on deck to prepare for the next day's fishing. When Sosinski awoke at 6:00 a.m., the boat was still motoring out on autopilot but Aldridge was gone – no visible sign of when or where he fell overboard [9]. Given the many uncertainties in the circumstances under which Aldridge fell overboard, the motion of the boat, and the influence of tides, currents, and winds, how does one even begin to mount an effective search? The U.S. Coast Guard faces this type of scenario daily. The problem also occasionally arises for major aviation accidents, such as the disappearance of Air France Flight 447 over the South Atlantic in 2009 and Malaysian Air Flight 370 in the Indian Ocean in 2014. Fortunately, Bayesian search theory provides a principled approach for problems of this nature.

Developed by the U.S. Navy in response to the German submarine threat in the Atlantic Ocean during World War II, Bayesian search theory is a systematic mathematical method for planning searches for lost objects. It has been used to plan successful searches for lost submarines (*USS Scorpion* [5]), aircraft (Air France Flight 447 [7]), and treasure ships (*SS Central America* [6]). Bayesian search theory is the analytic core of the U.S Coast Guard's national Search and Rescue Optimal Planning System (SAROPS), credited with helping save scores of lives, including that of John Aldridge.

Key Concepts

Complicated searches, such as those listed above, are one-time events. One cannot recreate the conditions 1,000 times and record the distribution of locations to obtain an empirical probability distribution based on the relative frequency notion of probability. Instead, the probability distribution for the likely location of the missing object (person, plane, ship) must be estimated in the presence of uncertainties and conflicting information, which often necessitates the use of subjective probabilities. Time is critical in such search and rescue operations, so one cannot wait for more data to resolve these uncertainties before taking action. Bayesian search analysis offers a principled method for handling these problems. It produces a prior probability distribution for the target (search object) location that is a synthesis of objective data and subjective information based on the analyst's best understanding of the scenario. This prior represents a fused understanding of all available information and can be used directly to plan the search and estimate the amount of effort/time required to meet a given probability of success. More importantly, the Bayesian approach provides a framework to continually update this prior, in the form of a sequence of posterior distributions, as additional information becomes available.

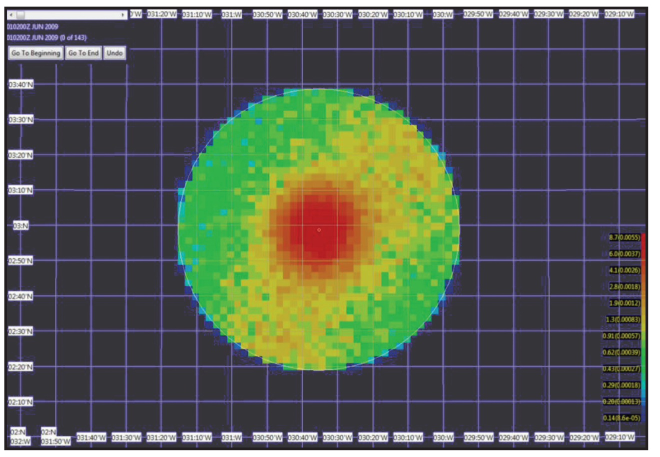

Figure 1. *Prior distribution for the Air France Flight 447 search. Red represents high probability, while blue represents low probability. Image courtesy of [7].*

The key concepts are (1) the use of objective and subjective information to produce a prior probability distribution on target location, (2) the application of Bayes' rule to update the prior as new information is obtained during the search, and (3) the use of the prior and posterior distributions to plan future search efforts in a way that maximizes the probability of success in the shortest possible time.

See **Bayesian Search** *on page 4*

A Reconstruction Algorithm is a Key Enabling Technology for a New Ultrafast CT Scanner

By Federico Giudiceandrea, Alexander Katsevich, and Enrico Ursella

A sawmill's goal is to produce as much valuable wood as possible from forest logs. Due to natural variability, every log is different, though most distinguishing characteristics are visible only after sawing. As a result, the process of deciding how to best cut a log is mainly driven by the log's external appearance, which significantly reduces the ability to exploit the raw material's true value. For this reason, knowing the real internal characteristics of a log before deciding its use has remained but a dream for sawmills.

The possible creation of an image depicting the internal details of each log during production would allow for the simulation of various production strategies from which to choose. Typically, a large number of decisions must be made about each stem that enters a sawmill: how to buck it into shorter logs, which boards to produce, and how to best rotate and position the log in front of the saws. Advanced simulation of different solutions could improve these decisions. Many trials have demonstrated that the introduction of this technology could improve the productivity of a sawmill by between 5% and 20%. If we consider a large sawmill producing wood with a value of 70 million Euro/year, the uplift of 5% in production value would mean 3.5 million Euro/year.

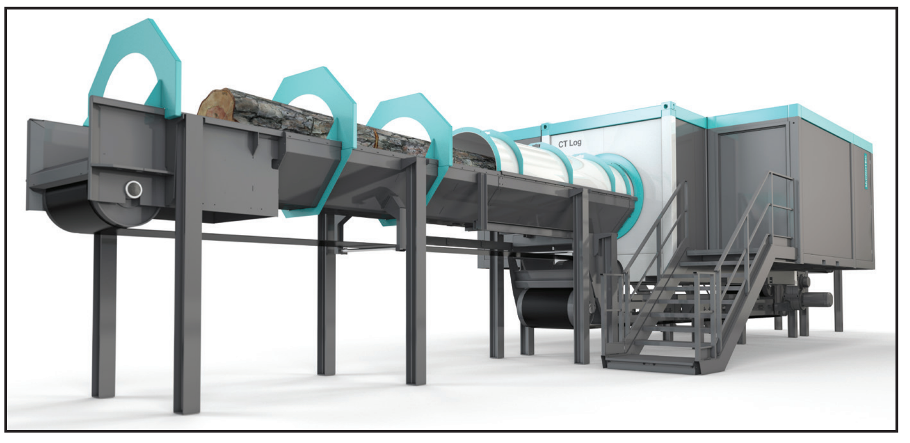

Figure 2. *Image of the CT Log scanner. © Microtec.*

In 2008, Microtec developed a first prototype of a computed tomography (CT) scanner for log imaging. It used a 180 kilovolt (kV), 10 milliamp (mA) X-ray source, rotated at 2.8 rev/sec, and implemented spiral tomography with a small cone angle of 0.5°. An approximate algorithm by Feldkamp, Davis, and Kress (also known as the FDK algorithm, see [3]) was implemented for the tomographic inversion, but the maximal scan speed was 5 m/min, much less than desired. Reaching the necessary speed with the same cone angle would have required an impossible gantry rotation speed. While wide cone angle scanning would allow one to reach the desired speed, there were no algorithms that would reconstruct efficiently and accurately from such data. On the one hand, approximate algorithms, like the FDK algorithm, are efficient, but produce artifacts at large cone angles. An accurate wide cone angle reconstruction with iterative algorithms, on the other hand, is prohibitively computationally expensive. However, the theoretically exact and efficient Katsevich inversion algorithm [6-8], the first enabling solution for implementing wide cone angle scanning developed in 2001, provides the key step to demonstrating the feasibility of a CT scanner for wood [4].

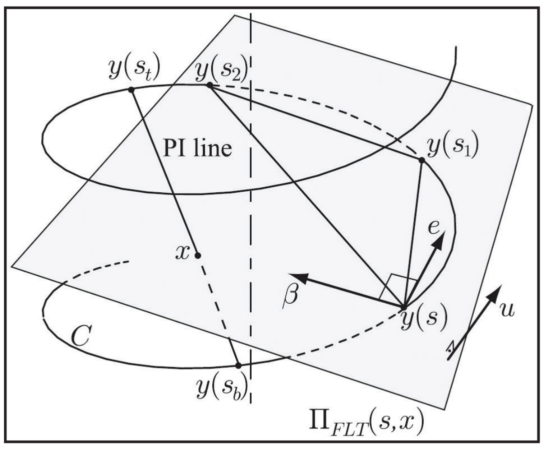

Figure 1. *Plane $\Pi_{FLT}(s,x)$ through $x, y(s)$, $y(s_1)$, and $y(s_2)$ contains vectors $\beta(s,x)$, $e(s,x)$ and is perpendicular to $u(s,x)$. Image credit: Alexander Katsevich.*

The Katsevich algorithm is theoretically exact and provides accurate reconstruction at any cone angle. It also has a very efficient filtered back projection (FBP) structure; it is easily parallelizable and can be implemented on a graphics processing unit (GPU). Every cone beam projection is used only once, an advantage implying that an image slice can be sent to the user as soon as all projection data for that slice has been collected and processed, without having to wait for collection of all projection data for a log. This property is very useful for a scanner, which operates in a continuous fashion. The original version of the algorithm, which was developed for an ideal constant pitch helix, was later generalized to include variable pitch helices and even more general curves [5, 9-10]. The resulting algorithm is still theoretically exact and maintains the FBP structure. Accounting

See **Reconstruction Algorithm** *on page 3*

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Measuring Gender Representation on Editorial Boards in the Mathematical Sciences

By Andrew J. Bernoff and Ursula Whitcher

Big data and underrepresentation of women in the mathematical sciences are two hot topics in the applied mathematics community. Chad Topaz and Shilad Sen, enterprising researchers at Macalester College, are using cutting-edge data collection and analysis techniques to study the shortage of women in mathematics, specifically on the editorial boards of mathematics journals [4]. Mathematical journal editors are an interesting cross between mentors and gatekeepers of academic success; a strong publication record is necessary to flourish in most faculty settings, and a supportive editor can be the difference between an article publishing speedily in a top-notch journal or never appearing in a public venue.

Topaz and Sen argue that women are underrepresented on mathematical editorial boards relative to the proportion of women ladder faculty at research universities. They also find that the editorial boards of SIAM journals have significantly more women editors than their counterparts, perhaps even more than might be expected from unbiased choice among the available academics.

To understand what this means, one must explore the so-called "leaky pipeline" of academia. This idiom is meant to capture the slow loss of women along the academic ladder, from entering college to obtaining a tenure track faculty position, followed by achieving some of the hallmarks of success in that position, such as being asked to edit an academic journal in one's specialty area. We live in an era where 58% of all bachelor's degrees awarded in the United States are conferred on women [5]. Specifically, women receive 41% of U.S. bachelor's degrees [5] and 31% of new Ph.D.s in the mathematical sciences [2]. They hold 31% of the full-time positions in mathematics and statistics, but constitute only 16% of ladder faculty at doctoral-granting institutions [1]. SIAM membership appears to be comparable to that of ladder faculty; merely 15% of the non-student members who report their gender are female [3].

Topaz and Sen estimate that 8.9% of editorships at mathematics journals are held by women. Editors, they write, "act as stewards who ensure the quality of research being reported and whose editorial decisions even influence the broad course of research within the community," and note that "women excluded from editorial board membership do not have access" to the associated "opportunities for intellectual growth" and professional networks [4]. They suggest this poses potential harm not only to individual women who are overlooked, but to the vibrancy of the field as a whole.

The study samples 13,067 editorships (since some people are editors of multiple journals, the number of distinct individuals serving on mathematical editorial boards will be smaller). How does one identify the gender of a mathematical editor? After all, journals do not usually publish the demographics of their editorial boards.

Topaz and Sen used an innovative hybrid approach to obtain this information. For approximately half the editorships in their database, they were able to assign a gender of male or female with high confidence using the genderize.io database.[1] The other half required further research. However, instead of making educated guesses on their own, Topaz and Sen crowdsourced their investigation through Amazon's Mechanical Turk platform. For each editorship, five different Mechanical Turk contractors (known as Turkers) independently researched the person and reported both a gender (male, female, non-binary, or unable to determine) and a degree of confidence in the gender assessment.

Mechanical Turk allows many people to contribute small amounts of labor to a project. This work isn't free, and the eventual price tag for identifying editors and assessing gender came to roughly $15,000. Topaz and Sen obtained a seed grant of $4,950 from Macalester College to prototype their project, but struggled to find further funding. "Most agencies didn't answer" or could not quickly fund this type of project, Sen recalls. Finally, the pair decided to turn to crowdfunding, through the website experiment.com.[2] They were "shocked" by the mathematics community's enthusiastic response, Topaz says. "It took a week to meet our initial funding goal. Clearly we struck a nerve. Our colleagues in the scientific community apparently care deeply about this issue."

After collecting the data, Topaz and Sen looked for factors associated with a rate of women's editorships higher or lower than the "background rate" of 8.9%. They found that applied mathematics in general, and SIAM publishing in particular, were both associated with greater representation of women. "Within the pool of editorships on journals classified as applied, representation of women is 10.3%," they write [4]. Women editorships made up 7.2% of pure mathematics journals, while journals classified as publishing both pure and applied mathematics were at 7.4%. With 19.9% women editorships, SIAM was "the only publisher that is [statistically] significantly higher than the background level" (see Figure 1). Another professional society, the American Mathematical Society, came in second at 16.3% [4].

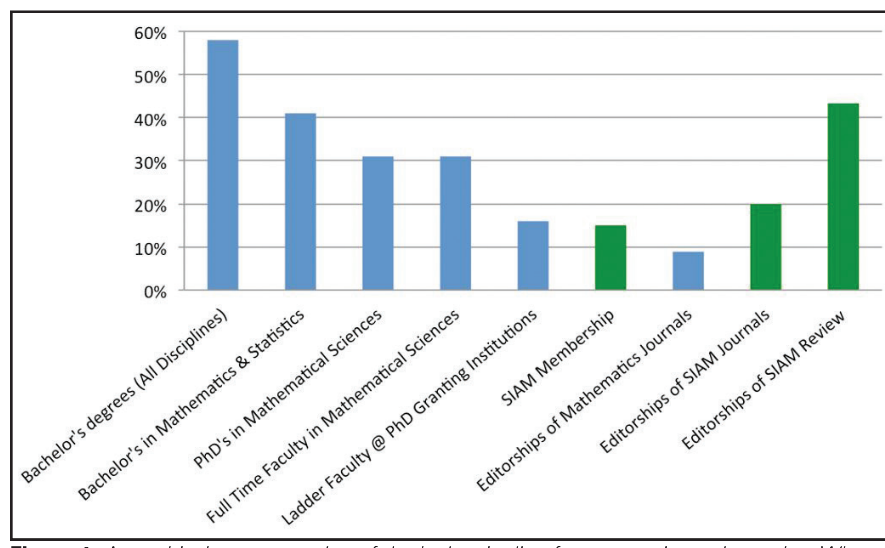

Figure 1. *A graphical representation of the leaky pipeline for women in mathematics. Whereas women receive 58% of bachelor's degrees awarded in the U.S., the percentage of bachelor's in the mathematical sciences declines to 41% and the percentage of Ph.D.s to 31%. While women represent 31% of full-time faculty in the mathematical sciences, they make up only 16% of the ladder faculty at doctoral-granting institutions, which is comparable to the percentage of female non-student members at SIAM (15%). While Topaz & Sen estimate that mathematics journals in general have only about 9% of editorships held by women, SIAM journals have a significantly higher percentage of women editorships (nearly 20%). SIAM Review is particularly impressive; 43% of its editors are women. Image credit: Andrew Bernoff.*

What makes SIAM publications stand out? One possibility is that women are more highly-represented in applied mathematics than pure mathematics. "My guess is that the applied mathematics business has greater gender diversity as a community than other parts of science and engineering," says C.T. Kelley, a professor at North Carolina State University, editor of multiple SIAM journals, and chair of the SIAM Board of Trustees. Statistics do support this hypothesis at the Ph.D. level. The AMS *Report on the 2014-2015 New Doctoral Recipients* (the most recent data currently available) shows that 33.9% of new Ph.D. recipients in applied mathematics, 41.4% in statistics and biostatistics, 56.2% in mathematics education, and 23.4% in the remaining "pure" mathematics categories are women [2]. But we have already observed that the demographics of ladder faculty in Ph.D.-granting departments are different from the demographics of new Ph.D.s; we do not know whether the greater proportion of women in applied mathematics as compared to pure mathematics at the Ph.D. level extends to the pool of likely editorships.

Another possibility is that professional societies are more committed to diversity than commercial publishers. When we asked editors of SIAM journals about gender on their editorial boards, many commented that gender was one of multiple factors (including race, geographic distribution, seniority, subfield, and industrial versus academic employment) they considered when striving for a diverse editorial board. "There are

See **Gender Representation** *on page 5*

[1] https://genderize.io/
[2] https://experiment.com/projects/gender-representation-on-mathematical-sciences-journal-editorial-boards

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Reconstruction Algorithm

Continued from page 1

for a variable pitch is important in saw mills because the belt speed can change quite frequently.

Let us briefly describe the dynamic pitch algorithm of [9]. Let

$$C := \{y \in \mathbb{R}^3 : y_1 = R\cos(s), \\ y_2 = R\sin(s), y_3 = \psi(s), s \in \mathbb{R}\} \quad (1)$$

denote a dynamic pitch helix. Here $\psi(s)$ is a three times continuously-differentiable function that maps the parameter s to the y_3 (or z) position of the X-ray source on the helix. In particular, for a traditional, constant pitch helix, we have $\psi(s) = sh/(2\pi)$, where h is the distance advanced by the source along the y_3 axis in one rotation. Here we assume that ψ satisfies the condition $\psi'(s) + \psi'''(s) > 0$.

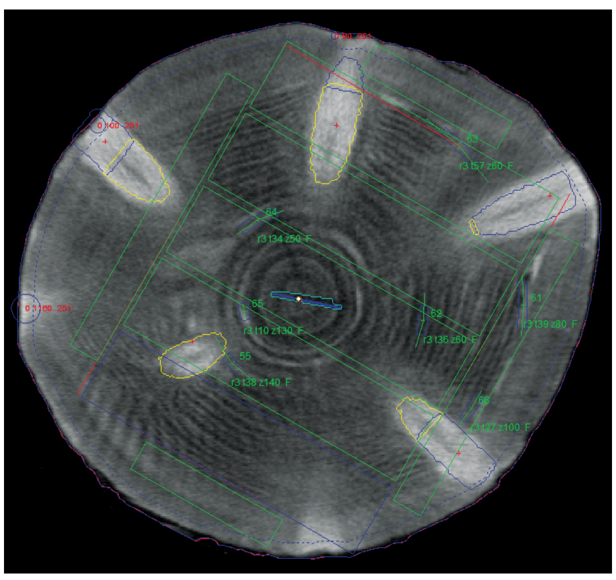

Figure 3. *Reconstructed cross-section of a log showing identified defects and a virtual cut. © Microtec.*

Let U be an open set strictly inside the helix:

$$\bar{U} \subset \{x \in \mathbb{R}^3 : x_1^2 + x_2^2 < R^2\}. \quad (2)$$

The cone beam transform of a function f supported on U is $D_f(y,\Theta) := \int_0^\infty f(y + \Theta t)\mathrm{d}t$, where $\Theta \in S^2$ and S^2 is the unit sphere in $\mathbb{R}^3$. Furthermore, let $\beta(s,x)$ denote the unit vector that "points" to x from the source $y(s)$, i.e., $\beta(s,x) = \dfrac{x - y(s)}{|x - y(s)|}$ for $x \in U$ and $y(s) \in C$. *PI lines* are an important concept in the constant pitch case. A PI line is a line segment connecting two points on the helix that are separated by less than 2π [1]. As in the constant pitch case [2], [9] shows that for any $x \in U$ there exists a unique PI line of a dynamic pitch helix containing the point *x*. We let $s = s_b(x)$ and $s = s_t(x)$ denote the two source positions that define the PI line containing *x*, and $I_{PI}(x) := [s_b(x), s_t(x)]$ is the corresponding PI parametric interval (see Figure 1, on page 1).

Consider filtering planes $\Pi_{FLT}(s, s_2)$ defined by three points along the helical trajectory $s < s_1 < s_2$ or $s_2 < s_1 < s$, with normal vector

$$u(s,s_2) = \\ \frac{(y(s_1) - y(s)) \times (y(s_2) - y(s))}{|(y(s_1) - y(s)) \times (y(s_2) - y(s))|} \quad (3) \\ \times \operatorname{sgn}(s_2 - s), 0 < |s_2 - s| < 2\pi.$$

Here we assume that $s_1 = (s + s_2)/2$. For each x and $s \in I_{PI}(x)$, find s_2 such that $x \in \Pi_{FLT}(s, s_2)$ (see Figure 1, on page 1). The dynamic pitch reconstruction formula for $f \in C_0^\infty(U)$ is

$$f(x) = -\frac{1}{2\pi^2}\int_{I_{PI}(x)} \frac{1}{|x - y(s)|} \\ \int_0^{2\pi} \frac{\partial}{\partial q} D_f(y(q), \Theta(s,x,\gamma))\,|_{q=s} \quad (4) \\ \times \frac{\mathrm{d}\gamma}{\sin\gamma}\mathrm{d}s,$$

where

$$\Theta(s,x,\gamma) := \cos\gamma\beta(s,x) \\ + \sin\gamma e(s,x), \quad (5) \\ e(s,x) := \beta(s,x) \times u(s,x).$$

The condition $\psi' + \psi''' > 0$ does not always hold in practical situations, and a suitably-adapted approximate version is used when that condition is violated.

On the hardware side, a wide X-ray detector with a surface of 1.25 m^2 enables a wide cone angle scanner, which is capable of reconstructing at 180 m/min with a rotational speed of 4 rev/sec. This implies a helical pitch of 66 cm and a cone angle of about 30°. The resolution required for the reconstructed images is pretty low relative to other CT applications: 1 × 1 mm in the plane orthogonal to the axis of the helix and 10 mm along the axis. For this reason, Microtec has developed custom X-ray sensors with a sensitive area of 7 × 2 mm, assembled in an array of 47 × 758 pixels. The sensors were read at 1,500 frames per second (fps), to be back-projected in a volume of 900 × 900 × 60 voxels. As long as the back-projection of each voxel requires 20 floating point operations, the required computational power is 1.5 teraflops, with 1.2 terabytes/sec of memory access. The implementation of the algorithm in CUDA [11] using three GPUs GTX690 in parallel delivered the first computational solution to produce a system capable of generating a continuous stream of 900 × 900-pixel slice images: one slice per 1 cm of log, equivalent to a slice every 3.3 msec.

Figure 2 (on page 1) is an image of a CT Log scanner, Figure 3 (above) shows a typical reconstructed cross-section of a log with identified defects and a superimposed virtual cut, and Figure 4 provides an example of an optimal virtual cut based on the CT image.

A number of challenges regarding mechanical constraints, data transfer, safety regulations, image processing, and optimization algorithms have been addressed. Easily installable in any sawmill, the CT Log helps loggers get the most out of each sawn tree. Currently five sawmills in Europe and the Americas have a CT Log able to scan and optimize the processing of all logs at each mill.

Alexander Katsevich and Federico Giudiceandrea received the 2016 Marcus Wallenberg Prize for their development of a CT scanner for whole tree logs. They received their diploma from His Majesty the King of Sweden at a ceremony in Stockholm, Sweden this past October. The Marcus Wallenberg Prize recognizes path-breaking scientific achievements, which contribute significantly to broadening knowledge and to technical development within the fields that benefit forestry and forest industries.

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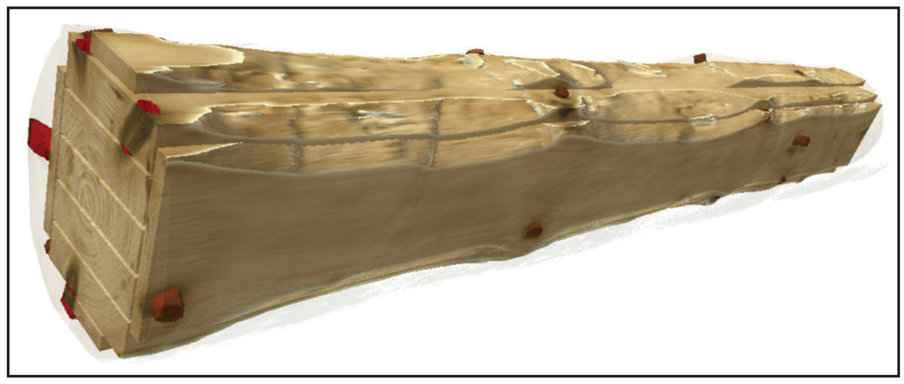

Figure 4. *Example of an optimized virtual cut obtained from CT reconstruction of a log. © Microtec.*

Federico Giudiceandrea co-founded the company Microtec in 1980. Since then, he has been President, CEO, and Director of Research and Development at Microtec, leading the development of a number of products applying computer vision and X-rays to wood and fruit processing. He has received many awards, including the Schweighofer Prize in 2013. Alexander Katsevich joined the Department of Mathematics at the University of Central Florida (UCF) in 1996, and has been a full professor there since 2008. Since 2011 he has also served as Chief Technology Officer of iTomography Corporation, a spin-off from UCF that he co-founded to develop and commercialize new and existing CT technologies. Enrico Ursella co-founded SeeLab, a spin-off applying computer vision to wood scanning, in 1994. He has been with the Microtec group since 1997, where he has worked mainly in computer vision industrial applications. He led the team developing the CT Log tomographic scanner.

The Thin Lens Formula and Springs

MATHEMATICAL CURIOSITIES

By Mark Levi

The thin lens formula relates the locations of an object and the image created by a thin lens (see Figure 1):

$$\frac{1}{d_1}+\frac{1}{d_2}=\frac{1}{f}. \qquad (1)$$

The meanings of d_1, d_2, and f are explained in the figure. The following mechanical interpretation of this formula hopefully makes the formula more transparent (apologies for the pun).

If the rays emanating at *A* focus at *B*, as in Figure 1, then all these rays have the same optical length, i.e., they all take the same time to travel. According to Pierre de Fermat, each ray takes the path of least time; if the minimizers of a functional form a continuous family, as our rays do, then the functional is constant on this family. Now the travel time as the function of the deflection s in Figure 2 is given by

$$T(s)=L_1+L_2+c+\frac{1}{2}ks^2, \qquad (2)$$

where $c+\frac{1}{2}ks^2$ is the time it takes the light to travel through the lens; $k<0$ for the magnifying lens, since the thickness decreases with s. To summarize, the rays focus at *B* if $T(s)=$const.

To explain the thin lens formula (1), let us interpret $T(s)$ as the potential energy of a mechanical system sketched in Figure 2. *AS* and *SB* are constant tension springs of tension $=1$, and *OS* is a Hookean spring with Hooke's constant k (for $k<0$, the spring tries to expand with the force proportional to its length s). The potential energy of this system is precisely the time (2). The focusing condition $T(s)=$const. thus also says that the potential energy of our system is constant, or equivalently, that our system is in equilibrium for any s or that the forces upon *S* (see Figure 2) cancel out:

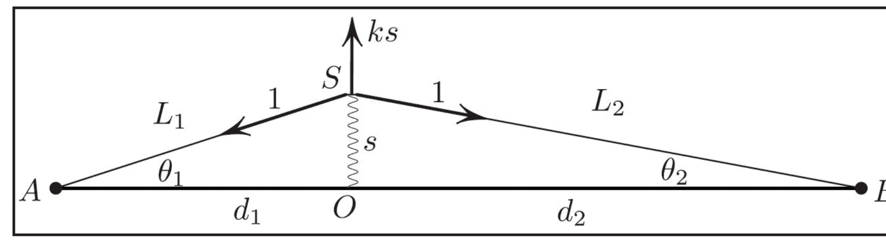

Figure 2. *The mechanical analog of the optical system in Figure 1. The point S is constrained to the vertical line through O. Image credit: Mark Levi.*

$$\sin\theta_1+\sin\theta_2+ks=0. \qquad (3)$$

Substituting $\sin\theta_i=s\,/\,d_i+o(s^2)$, $i=1,2$ into (3) and dividing by s yields

$$\frac{1}{d_1}+\frac{1}{d_2}+k=0,$$

which reproduces the lens formula (1), where $f=-k$.

To summarize, the thin lens formula amounts to an equilibrium condition of a simple mechanical system. Both sides of the formula acquire a direct physical interpretation: $f=-1/k$ is the negative reciprocal of Hooke's constant, and

$$\frac{1}{d_1}+\frac{1}{d_2}$$

is the Hooke's constant of vertical displacement of the two combined springs *AS* and *SB*.

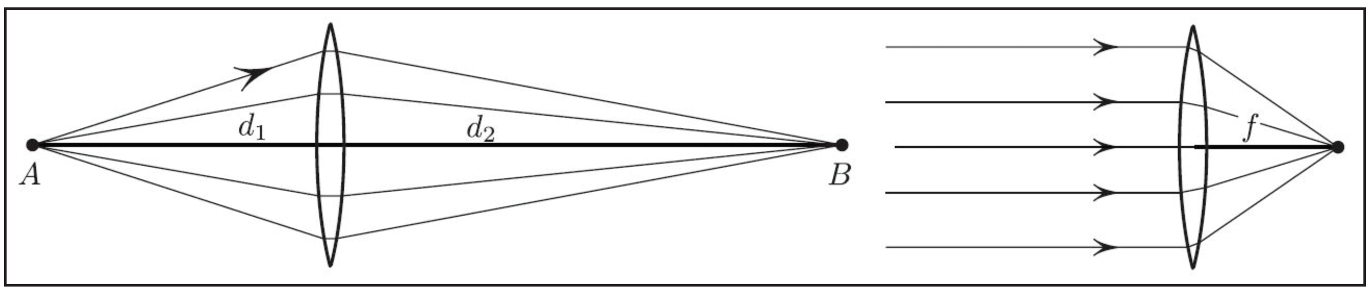

Figure 1. *Illustration of the lens formula. The lens is meant to be of near-zero thickness (this would require, for a fixed f, that the index of refraction of the glass be near-infinite). Image credit: Mark Levi.*

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

Bayesian Search

Continued from page 1

Bayesian Search Planning Process

Collect Information. In order to initialize the problem, one must collect all the information about the last known location of the missing object, quantifying uncertainties as probability distributions [1]. Often the use of subjective information is crucial in this phase. During the search for John Aldridge, Sosinski provided critical subjective information that Coast Guard search planners used to build a probability distribution on when and where Aldridge likely fell overboard. Even though large uncertainties remained, this information allowed a reduction in the search area and concentration of search assists in the correct region.

Compute Prior Distribution. Searchers often face several competing but plausible scenarios. In this case, one can individually simulate the distribution of the target location under each scenario and combine the resultant distributions according to subjective weights, representing the credibility of the scenarios, into a single probability distribution for the location of the target. Usually one divides the search area into *J* cells and computes the prior probability $p(j)$ that the target is in cell j for $j=1,\ldots,J$, where $\sum_{j=1}^{J}p(j)=1$. Figure 1 (on page 1) is the prior distribution map that Metron developed for the Air France Flight 447 search team, combining multiple scenarios (each representing a separate loss of flight control mode) and independent data sources (e.g., the aircraft's last known position and the pattern of debris found on the ocean surface).

Using models of the search sensor(s), one estimates $b_j(z)$, the probability of detecting the target given it is in cell j with z effort for $z\geq 0$. If $Z=(z_1,\ldots,z_J)$ is an allocation of search effort, then $P(Z)$, the probability of detection using that allocation, is given by

$$P(Z)=\sum_{j=1}^{J}b_j(z_j)p(j).$$

Allocate Search Effort. Suppose one has *K* effort available for the first increment of search. Then one can find the allocation Z^* that maximizes $P(Z)$, subject to $C(Z)=\sum_{j=1}^{J}z_j\leq K$. There are well-developed methods for doing this (see [8]).

Compute the Posterior Distribution Using Bayes' Rule. If the target is not found during this first increment of search, Bayes' rule computes the posterior target location distribution as follows:

$$\tilde{p}(j)=\Pr\left\{\textbf{tgt in cell } j \mid \textbf{failure to detect}\right\}=\frac{p(j)\left(1-b_j(z_j^*)\right)}{\sum_{j'=1}^{J}p(j')\left(1-b_{j'}(z_{j'}^*)\right)},$$

$$\text{for } j=1,\ldots,J.$$

Figure 2 illustrates the posterior distribution map for the Air France Flight 447 search, updated with the results of the first three unsuccessful search expeditions during 2009 and 2010.

Iterate. The posterior distribution, now incorporating both information from the prior and results of all previous unsuccessful searches, is used to determine the optimal allocation of effort for the next increment of searching. This cycle of updating and reallocating continues until the target is found or the search has exhausted all or most of the information in the prior distribution. Such exhaustion may be determined by calculating the prior probability that the cumulative effort from all the search increments would have detected the target. When this reaches a threshold, say 95%, it is reasonable to stop the search.

Incorporating Other Information. One can integrate other information obtained during the search into the posterior distribution. For example, [3] demonstrates how to incorporate the knowledge that debris from a wreck is found sometime later. The method for doing this involves computing the likelihood of finding a piece of debris at the reported location and time given the target is in cell j for $j=1,\ldots,J$, and applying that likelihood function to compute a new posterior distribution.

Operational Application. These methods have been successfully applied to a large number of real-world search operations. While Bayesian search theory provides an optimal plan for directing search operations in the face of high degrees of uncertainty, it is no guarantee of success. Sometimes the scope of the effort may dwarf available search assets, or uncertainties may be too large. In these circumstances, Bayesian search theory offers guidance on how to "stack the odds" in one's favor. It also presents a way to determine when one reaches the point where additional search effort is unlikely to significantly improve the chance of success.

For example, the team directing the international effort to find Malaysian Air Flight 370 used this Bayesian approach to calculate the prior distribution of the aircraft location by fusing information from flight dynamic modeling and the Inmarsat signals from the aircraft [2]. That analysis generated the set of high-probability ocean bottom regions that have been methodically searched over the last two years. Given the lack of positive results, the governments involved have announced that the operation will most likely be suspended in the near future, awaiting new evidence [4]. As was the case in the Air France Flight 447 search, such a pause allows for independent reanalysis of the data that formed the prior, the calculation of a posterior that incorporates information embedded in the last two years of search operations, and the potential addition of new evidence, like the pieces of aircraft debris that have been found off eastern Africa over the last year. Together, these factors might yield new insights that could lead to the discovery of the aircraft's location.

Bayesian search theory provides a principled, methodical, and effective method of planning searches for lost objects. It serves as a methodology that maximizes the probability of success, estimates the effort required to find the missing object, and gives guidance on when to call off a search. Though simply stated, it is a powerful analytic approach that has been used successfully in many complicated and difficult situations.

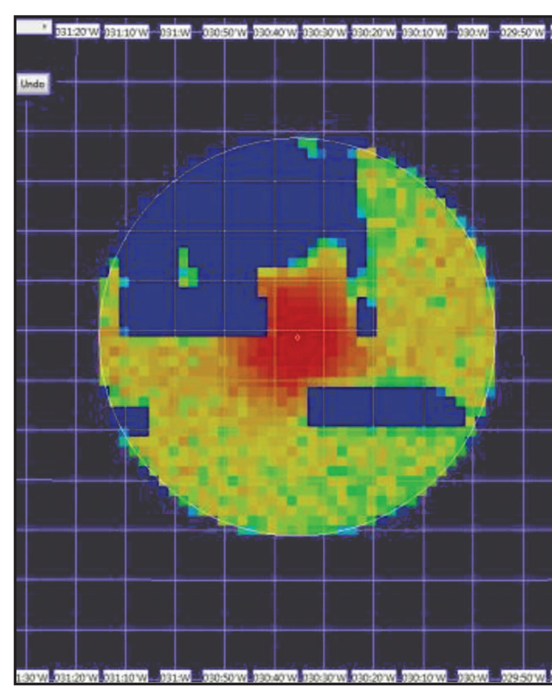

Figure 2. *Posterior distribution for the Air France Flight 447 search used to plan the fourth expedition in 2011. The aircraft wreckage was found on the ocean bottom in the grid cell just above the center point. Image courtesy of [7].*

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SIAM's Key Role in Transforming Post-Secondary Mathematics Education

By Karen Saxe

One of the themes of the 2016 SIAM Annual Meeting, held in Boston this July, was "Education, Communication, and Policy," and I was humbled to give an invited presentation on education. I outlined the role of mathematics in American higher education throughout the country's history, discussed current challenges and opportunities for those involved with undergraduate education, and offered suggestions as to how one might get involved—in small or big ways—to help improve post-secondary education in the mathematical sciences.

Part of the talk focused on my work with the Transforming Post-Secondary Education in Mathematics[1] (TPSE Math) initiative. This initiative, sponsored by Carnegie Corporation of New York and the Alfred P. Sloan Foundation, aims to implement constructive change in mathematics education at community colleges, four-year colleges, and research universities. Where are we now, and why is it so important that we fully engage the expertise of and join forces with SIAM members as TPSE Math moves forward? How can we do so?

SIAM is no stranger to work focused on improving education. Over the past 15 years, its activities in undergraduate education have grown rapidly, both within the SIAM community and in partnership with other professional associations.

In 1987, then-president Bill Gear elevated post-secondary education as a priority within SIAM by proposing the creation of a "Vice President for Campus Activities." The SIAM Education Committee[2] supports the Vice President for Education in SIAM activities related to both undergraduate and graduate-level education. The SIAM Activity Group on Applied Mathematics Education (SIAG/ED) was launched in 2015. Various reports, including SIAM's first and second *Modeling Across the Curriculum* reports,[3,4] published in 2012 and 2014, have offered important ideas that the larger mathematics community has embraced. The *Undergraduate Degree Programs in Applied Mathematics*[5] report also published in 2014. And the first SIAM Conference on Applied Mathematics Education (ED16)[6] was held in Philadelphia from September 30-October 2, 2016.

Why is this a good time to renew the conversation on improving education in the mathematical sciences? One compelling reason is that we have—via interest from the White House, as documented in the 2012 *Engage to Excel*[7] report, published by the President's Council of Advisors on Science and Technology (PCAST)—the opportunity to engage both government officials and the general public in what goes on in math classrooms and departments across the country. David M. Bressoud, Eric M. Friedlander, and C. David Levermore call us all to action in their response[8] to the PCAST report, imperatively stating that "mathematics education needs **immediate attention**" (their emphasis).

Shortly after the PCAST report came out, the National Research Council (NRC) published *The Mathematical Sciences in 2025*[9] report. This account is much more positive about the work mathematicians do with students and provides a "springboard for initiatives in mathematics education that more closely intertwine the learning of mathematics with the appreciation of its applications."

TPSE Math was launched, in part, to address challenges and galvanize the mathematical sciences community to capitalize on opportunities articulated in the PCAST and NRC reports.

In February 2013, Carnegie Corporation of New York assembled a group of higher education leaders in the mathematical sciences to take stock of the field and envision its possible transformation from a service discipline to an essential partner in post-secondary education. As a result of this meeting, Phillip Griffiths founded TPSE Math.

TPSE Math has listened to and will continue to work with the mathematical sciences community to determine how best to achieve systemic change. It is beginning to forge alliances with state and federal agencies, the policy community, university administrators, higher education associations, and professional organizations to secure the financial and structural support necessary to achieve these goals. In May 2016, TPSE Math was incorporated as an educational program affiliated with the University System of Maryland Foundation.

Through surveys, interactions at several regional meetings, and the help of strategy consultants from Parthenon-EY, TPSE has identified multiple action priorities. The following three are particularly relevant for the SIAM community:

- **Create multiple curriculum pathways:** TPSE will function as an advisory partner of the Association of Public and Land-grant Universities (APLU), the American Association of State Colleges and Universities (AASCU), and the Charles A. Dana Center (the University of Texas at Austin) in developing multiple pathways in lower-division mathematics to increase completion rates and better align coursework with students' programs of study.
- **Create enhanced alternative pathways:** TPSE will promote reform of upper-division curricula in response to evolving career opportunities and demand for mathematics courses from other subjects.
- **Broaden training for graduate students:** TPSE will encourage preparation of the next generation of faculty as both teachers and career development advisors for undergraduate students.

Systemic change in all three areas will help narrow the gap between how math is experienced in the workplace and how it is experienced in our classrooms.

The observation of this need is not new. In the early 1990s, as stated in *Looking Back, Looking Ahead: A SIAM History*,[10] "SIAM began its *Mathematics in Industry Project*, intending to ultimately formulate educational recommendations that would improve the ability of students to obtain employment in industry." One of the project's products, the *1996 SIAM Report on Mathematics in Industry*,[11] recommends broadening the graduate curriculum to improve its compatibility with the needs of industry. Ph.D. students seeking employment outside of academia will obviously benefit from such improvement. Also, new faculty members familiar with industry could be more effective classroom teachers and advisors to undergraduates, as most baccalaureate-holders work in industry and do not continue in graduate school.

Participants engaging in a breakout session at the recent TPSE Chairs + 1 Conference, held in October 2016 in Washington, D.C. Photo credit: Arlen Hastings.

Eliminating the disconnect between math in the classroom and in the workplace will undoubtedly involve hard work with our STEM partners to ultimately develop more relevant curricula, differentiated by student need according to their chosen discipline of study. SIAM is at the forefront already, with its efforts to institute a first-year modeling course that precedes and motivates the study of calculus and other fundamental mathematics for STEM majors. The *Guidelines for Assessment and Instruction in Mathematical Modeling Education (GAIMME)* report[12] articulates the case for SIAM's role in supporting the integration of mathematical modeling into K-16 education.

As TPSE Math begins its implementation phase, mathematics departments around the country develop curricula in response to demand from other departments and make changes to narrow the gap between mathematics in the workplace and in classrooms. At this time, SIAM members are particularly well-positioned to support (theoretical) math faculty and graduate students, serve as resources for a breadth of applications, and establish richer connections to colleagues in other departments on campus and in industry.

Acknowledgments: The author's private communications with James Crowley, executive director of SIAM, and Peter Turner, chair of the SIAM Activity Group on Applied Mathematics Education, contributed to the content of this article.

Further Reading

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Gender Representation

Continued from page 2

different types of diversity, and while the single most important diversity is being able to cover all the research topics in applied math, SIAM makes it very clear in the guidelines that non-mathematical diversity is also important," says Evelyn Sander, a professor at George Mason University who serves as section editor of *SIAM Review* and associate editor of the *SIAM Journal on Applied Dynamical Systems*.

Looking forward, this study and our interviews suggest some best practices for constructing and maintaining editorial boards. Assembling a large list of potential editors (generated with broad input from the target readership) facilitates the selection of a diverse editorial board. Additionally, Topaz and Sen's work serves as a compelling argument for documenting how editors (and more broadly, mathematicians) self-identify in terms of gender, race, and ethnicity.

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Extensibility in PETSc

By Matthew G. Knepley, Dave A. May, Jed Brown, and Barry Smith

It's important that modern computational science and engineering software not only handle multiphysics and multiscale simulation [3], but also support higher-level analysis, including risk-aware and optimal design, uncertainty analysis, and stochastic simulations. In addition to deeper software stacks and interdisciplinary teams, this requirement necessitates specialization in each application area (e.g., boundary conditions, geometry, subgrid closures, analysis techniques, data sources, and inherent uncertainty/bias), or *extensibility* (and customization) in the terminology of software engineering [1]. Original authors can no longer foresee all use cases for their software. Below are examples from the Portable Extensible Toolkit for Scientific computation (PETSc) library[12] for scalable solutions of partial differential equations (PDEs), illustrating the leverage gained by developing simple, composable pieces instead of monolithic software frameworks.

Dynamic Implementation Registration

At the highest level, PETSc facilitates extensibility by providing a mechanism to dynamically register implementations of class objects associated with vectors (`Vec`), matrices (`Mat`), Krylov methods (`KSP`), preconditioners (`PC`), nonlinear solvers (`SNES`), time integrators (`TS`), and mesh management objects (`DM`). This registration mechanism is used for all implementations provided by PETSc. Moreover, the end user has access to the registration API for plugins, enabling seamless use of custom implementations defined within the user's software stack (e.g., a highly-optimized, matrix-free matrix-vector product implementation) in a fashion identical to any native PETSc implementation.

Efficient Solvers through Composition

Determining the optimal solver for a given set of equations and boundary conditions appears impossible [2, 4], as its configuration also depends on the initial guess, machine architecture, required accuracy, and even problem evolution. Therefore, the most sensible software design allows for dynamically (runtime) configurable solvers. In PETSc, the user creates a solver (linear, nonlinear, timestepping, optimization), provides data defining the problem (system matrix and right-hand side, residual and Jacobian callbacks, cost function, etc.), and in some cases offers details of the data layout (topology, geometry, grid hierarchy). The solver itself is then assembled via command line options. This process allows trial of all appropriate solver combinations without repeated editing and compiling of the user's code. Shell scripts are often used to test hundreds of solvers and solver options.

SOFTWARE AND PROGRAMMING

Our strategy is to assemble complex, tailored solvers from simple, generic parts using command line options. For example, we can divide a system into parts by field or by subdomain, and combine solvers additively, multiplicatively, or with a Schur complement. We can apply these analysis and synthesis actions hierarchically to successive divisions, and similarly introduce hierarchy through coarsening or refinement. The following example demonstrates the flexibility of PETSc solvers on a problem of scientific interest and reinforces the aforementioned ideas.

Magma dynamics describes the flow of molten rock (melt) through a deformable porous host rock, which can be modeled by the two-phase formulation [6]

$$\begin{aligned} \nabla p - \nabla\left(\zeta(\phi)\nabla\cdot\vec{v}_s\right) \\ -\nabla\cdot\left(2\eta(\phi)\,\dot{\boldsymbol{\epsilon}}_S\right) &= \vec{f}, \\ \nabla\cdot\left(-\frac{K(\phi)}{\mu}\nabla p + \vec{v}_s\right) &= g, \\ \frac{\partial\phi}{\partial t} - \nabla\cdot(1-\phi)\vec{v}_s &= 0, \end{aligned} \tag{1}$$

where the equations correspond to the conservation of momentum, mass, and evolution of rock porosity (ϕ). In (1), $\vec{v}_s$ is the solid velocity, $\dot{\boldsymbol{\epsilon}}_S$ is the deviatoric strain-rate tensor, and p is the fluid pressure. The rock permeability K, shear viscosity η, and bulk viscosity ζ are all nonlinear functions of ϕ. A typical method for solving this differential algebraic equation (DAE) involves an explicit timestep for the advection of ϕ, then a nonlinear solver for $\vec{v}_s$ and p. Researchers in [5] propose to solve the nonlinear system using Newton's method with a block preconditioner for the linearized system

$$\begin{pmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}+\mathbf{L} \end{pmatrix},$$

where $\mathbf{A}$ is the divergence of the deviatoric stress and compaction from the first equation, $\mathbf{M}$ is the pressure mass matrix, and $\mathbf{L}$ is the pressure Laplacian. We can easily implement this solver using algebraic multigrid (AMG) to solve $\mathbf{A}$ and the additive Schwarz method (ASM) to solve $\mathbf{M}+\mathbf{L}$, with the following command line arguments:

```
-snes_type newtonls -snes_mf_operator
-pc_type fieldsplit -pc_fieldsplit_0_fields 0 -pc_fieldsplit_1_fields 1
-pc_fieldsplit_type additive
-pc_fieldsplit_diag_use_amat 0
-fieldsplit_0_pc_type gamg
-fieldsplit_1_pc_type asm
```

Here we use the matrix-free action of the Jacobian in a Krylov solver. `Fieldsplit` provides decomposition into the discrete $\vec{v}_s$ and p fields required by the 2×2 block preconditioner. We then construct a preconditioner using the diagonal blocks of a preconditioning matrix.

We can extend this formulation to solve a nonlinear system over all three fields in order to make the explicit update consistent with the conservation equations following that update, simply by including the porosity in our splitting:

```
-pc_type fieldsplit -pc_fieldsplit_0_fields 0,2 -pc_fieldsplit_1_fields 1
```

and Newton's method as a level smoother:

```
-snes_type fas -snes_fas_type full
-fas_levels_snes_type newtonls
-fas_levels_snes_max_it 2
-fas_levels_snes_mf
```

See **PETSc** *on page 8*

[1] http://www.mcs.anl.gov/petsc/

[2] http://www.mcs.anl.gov/petsc/petsc-current/docs/manual.pdf

Broadening Career Prospects for Mathematical Science Graduates

NSF's Enriched Doctoral Training Program Enhances Research Experience

By Sue Minkoff and Peter Constantin

In 2014, the National Science Foundation launched a new program within the Division of Mathematical Sciences entitled the Enriched Doctoral Training Program (EDT). In this article we highlight recent awards for EDT. All of these projects share the fundamental goal of broadening career options for Ph.D. graduates in the mathematical sciences. However, they differ in the ways in which they propose to achieve this goal and are thus intended to serve as experimental pilot projects, which other institutions may wish to emulate. As the EDT Program Solicitation[1] explains, "Although traditional doctoral training in mathematics has been aimed at an academic career path, recent American Mathematical Society survey data demonstrate that a substantial portion of doctoral recipients are taking positions outside of academia." The EDT program aims to enhance graduate research experiences for doctoral students, thus preparing them for a variety of academic and non-academic career paths. It supports efforts to engage doctoral students in research activities potentially supplementary to their dissertation research, which would help train them for a broader range of careers and inspire problem-solving in other disciplines through mathematics.

The program encourages collaborations between academic mathematical sciences departments and entities in the business, industry, government, or non-profit realms. Two projects (at the University of Texas at Dallas (UTD) and Princeton University) were funded in the first round of proposals reviewed in 2015, and three more projects (involving the State University of New York at Buffalo, the University of Minnesota, and a collaboration between the University of Wyoming and Colorado School of Mines) were awarded in 2016. In what follows we highlight the main emphasis of each of the 2015 projects; we will detail the 2016 projects in part two of this article, to appear in the December 2016 issue of *SIAM News*.

Students from the 2015-2016 and 2016-2017 EDT projects at the University of Texas at Dallas. From left to right: Conner Davis, Weihua Yang, Daniel Uribe, Samiha Rouf, John Langford, Azar Ghahari, Georgia Stuart, Jonathan Popa, and Cesar Contreras. Not pictured: Kusha Nezafati. Photo credit: Larry Ammann.

EDT: Team Training Mathematical Scientists through Industrial Collaborations[2]

The University of Texas at Dallas. Principal Investigator: Sue Minkoff. Co-Principal Investigators: Yan Cao, Yulia Gel, Felipe Pereira, and John Zweck.

The goal of this project is to transform the training of mathematical sciences doctoral students at UTD so that they gain marketable skills and experience developing mathematics and statistics to improve understanding of problems in science and engineering prior to the start of formal thesis research. The 16 doctoral students supported by the project spend two semesters of their second year working on an interdisciplinary research problem posed by one of our external partners from industry, a government lab, or a research institution. Students work in teams of two, along with one mathematics and one statistics faculty mentor at UTD and one external partner. These research projects replace the students' normal teaching assistant duties in their second year and provide exposure to the entire research cycle. In the summer, after this year-long research endeavor, the students are well positioned to continue work at the external partners' organizations as interns, thereby gaining experience that could ultimately lead to employment opportunities after graduation.

Last year, two mathematics students and two statistics students participated in the two EDT projects at UTD, one of which was about uncertainty quantification for seismic inversion. The students began by researching the background for both velocity and microseismic event estimation. In October, we held our first in-person partner meeting with the industry participant (Pioneer Natural Resources), during which both students and faculty gave formal presentations on goals and ideas for tackling the project. These presentations led to a discussion of those aspects of the problem that are most interesting to industry. Subsequent follow-up phone calls and in-person meetings occurred every month or two throughout the year at both Pioneer and UTD, during which students gave status updates, obtained input on direction, and posed questions to the application experts.

CAREERS IN MATHEMATICAL SCIENCES

All throughout the year, the statistics student learned about previously-unfamiliar topics, including numerical partial differential equations, inverse problems, geophysics, and high performance computing. The mathematics student was exposed to various statistical ideas, including multilevel Bayesian inverse theory and the geophysics application. Our local team at UTD met weekly, and by the end of the year we had simulation software to (1) solve the stochastic velocity estimation problem using a multilevel approximation to the wave equation and (2) apply this theory to real well log data from Pioneer. The students presented their work this summer at the 2016 SIAM Annual Meeting, and their refereed conference paper was accepted for the Society of Exploration Geophysicists' Annual Meeting, held in October 2016.

Last year's second EDT project focused on using social media data for infectious disease forecasting, and was in collaboration with RTI International. This project followed a similar timeline: students also gave several talks at meetings, and a refereed conference paper was accepted for the 2016 IEEE BigData Congress. The statistics student on this project ended the year with an internship at MIT's Lincoln Laboratories.

Professor Ning Lin, assistant professor of civil and environmental engineering at Princeton University, gave a talk to EDT participants titled "Analysis and Modeling of Tropical Cyclone (TC) Climatology." Photo credit: Tina Dwyer.

The projects for the 2016-2017 year involve six students (three mathematics students and three statistics students) and focus on (1) cone beam computerized tomography to acquire patient anatomy data for cancer radiotherapy treatments (external partner: Department of Radiation Oncology, Division of Medical Physics and Engineering, University of Texas Southwestern Medical Center); (2) multisensor tracking of multiple moving targets for defense applications (external partner: Johns Hopkins Applied Physics Laboratory Multisensor Integration Group, Air and Missile Defense Sector); and (3) the impact of climate change on insurance risks using modern deep machine learning algorithms (external partners: Kemper Corporation and NatCatRisk).

EDT: Mathematical Methods for Water Problems

Princeton University. Principal Investigator: Peter Constantin. Co-Principal Investigators: Ning Lin, Simon Levin, and Ignacio Rodriguez-Iturbe.

Students advised by associated faculty in the Program in Applied and Computational Mathematics at Princeton University form a diverse group, enjoying broad and rigorous graduate training. The EDT activity brings together faculty and students interested in environmental issues, and is centered on the theme of water. Specifically, the research projects range across disciplines, from soil moisture dynamics and cyclones to biogeochemistry and the socio-economics of cooperative management schemes for water-related resources.

The EDT project has multiple dimensions, and has involved collaborative activities among all participants, including EDT fellows, their advisors, and other faculty. In addition to the fundamental research at the interface between mathematics, water, and other environmental problems, students and faculty have been enjoying bimonthly lunch seminars, during which they discuss current research projects. These lunch seminars provide students with feedback, but also serve to broaden the perspectives of both students and faculty. A key element of the project involves placing students in internships at relevant international centers; students have participated in six-week internships to work with researchers at the Centre for Ecological and Evolutionary Synthesis in Oslo, the Universita Ca' Foscari Venezia and Fondazione Eni Enrico Mattei (FEEM) in Venice, and the Stockholm Resilience Centre.

The follow-up article, to appear in the subsequent issue, will describe the three EDT projects that were funded in 2016, as well as a precursor award funded in 2014.

Sue Minkoff is a professor in the Department of Mathematical Sciences and an affiliated professor in the Departments of Geosciences and Science/Mathematics Education at the University of Texas at Dallas. She began the Careers in Mathematical Sciences Column for SIAM News in 2010. The second EDT article, to appear in December (her 24th column), will mark the end of her time as column editor. Peter Constantin is the John von Neumann Professor of Mathematics and Applied and Computational Mathematics and serves as director of the Program in Applied and Computational Mathematics at Princeton University. He is an ISI Highly Cited Researcher, a Fellow of the Institute of Physics, a SIAM Fellow, a Fellow of the American Academy of Arts and Sciences, and an Inaugural Fellow of the American Mathematical Society.

1 https://www.nsf.gov/pubs/2014/nsf14589/nsf14589.htm

2 http://www.utdallas.edu/EDT/

PETSc

Continued from page 6

```
-fas_levels_pc_type fieldsplit
-fas_levels_pc_fieldsplit_0_fields 0,2
-fas_levels_pc_fieldsplit_1_fields 1
-fas_levels_pc_fieldsplit_type schur -fas_levels_pc_fieldsplit_schur_precondition all
-fas_levels_pc_fieldsplit_schur_factorization_type full
-fas_levels_fieldsplit_0_pc_type gamg -fas_levels_fieldsplit_pressure_pc_type gamg
-fas_coarse_snes_type newtonls
-fas_coarse_snes_mf_operator
-fas_coarse_pc_type fieldsplit
-fas_coarse_pc_fieldsplit_0_fields 0,2
-fas_coarse_pc_fieldsplit_1_fields 1
-fas_coarse_pc_fieldsplit_type schur -fas_coarse_pc_fieldsplit_schur_precondition all
-fas_coarse_pc_fieldsplit_schur_factorization_type full
-fas_coarse_fieldsplit_0_pc_type lu -fas_coarse_fieldsplit_pressure_pc_type lu
```

We also switched to a Schur complement factorization and pull off-diagonal blocks from the original Jacobian matrix. In simpler flow regimes, we can relax the fine grid solver to nonlinear Gauss-Seidel to improve performance:

```
-fas_levels_snes_type ngs
-fas_levels_snes_max_it 10
```

Simulation-Specific Customization

A given simulation framework will invariably require custom methods for visualizing/monitoring residuals, determining convergence of a linear/nonlinear solver, selecting a suitable time-step, and so on. Such requirements are supported by the respective PETSc object because they allow users to register custom implementations for these actions.

Scalable Customizable Communication

Any linear algebra/solver package, including PETSc, will fail to encompass the full range of parallel communication patterns that users desire. Thus, unless users intend to write low-level code, such as MPI, some sort of interface for unstructured parallel communication is necessary. In PETSc, parallel communication is abstracted in the `VecScatter` object, a mapping from a source serial or parallel vector to a target vector, perhaps with different parallel layout. The mapping is specified by identifying an index in the source vector with another index in the target.

For instance, suppose that we would like to gather all the values from a parallel vector on one process, say for visualization or output. We can do this by creating a VecScatter that maps all indices in the vector to a serial vector, as in the code shown below:

```
VecGetSize(global, &N);
N = rank ? 0 : N;
VecCreateSeq(PETSC_COMM_SELF, N, &serial);
ISCreateStride(PETSC_COMM_SELF, N, 0, 1, &is);
VecScatterCreate(global, is, serial, is, &scatter);
```

The code is available concisely in PETSc as follows:

```
VecScatterCreateToZero(global,&scatter, &serial);
```

Now we can redistribute the values into a serial vector:

```
VecScatterBegin(scatter, global, serial, INSERT_VALUES, SCATTER_FORWARD);
VecScatterEnd(scatter, global, serial, INSERT_VALUES, SCATTER_FORWARD);
```

We can reverse the mapping, sending the values in a serial vector to all processes, using `SCATTER_REVERSE`. If we wanted to send the distributed vector to all processes, we would simply remove the line that changes N to 0 for all processes but rank 0, which is encapsulated in the `VecScatterCreateToAll()` function.

We also make use of `VecScatter` internally, and scatter the appropriate values from the input vector on to each process when a parallel sparse matrix vector product is performed. Not only is this conceptually simpler, but it leverages architecture-specific optimizations unavailable with raw MPI, such as preference for `MPI_Alltoall()` over `MPI_ISend/Recv()`, or segregation of on-node and off-node communication. However, some interface limitations have been identified.

Since `VecScatter` is tied to the `Vec` class, it can only move floating point values. The `PetscSF` object, on the other hand, keeps the one-sided specification of data mapping while allowing storage of arbitrary types in raw arrays. The basic operations (broadcast and reduce) have been augmented with the ability to gather values instead of combine them, `FetchAndOp` for scan operations, and composition of two `PetscSF` maps, as well as inversion. Thus, `PetscSF` has exposed new opportunities for reuse and optimization inside PETSc.

With PETSc, designing and refactoring software using best practices for extensible library development increases scientific and engineering value most effectively. As we demonstrate above, doing so greatly enhances the usability, productivity, and capability of the software.

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Matthew G. Knepley is an assistant professor in the Department of Computational and Applied Mathematics at Rice University. He has been using and developing PETSc since 1997. Dave A. May is a senior research fellow in the Department of Earth Sciences at the University of Oxford. He has been using PETSc since 2002 to develop scalable HPC software for studying geodynamic processes. Jed Brown is an assistant professor of computer science at the University of Colorado, Boulder. He has been a PETSc user since 2003 and a developer since 2008. Barry Smith is a senior computational mathematician in the Mathematics and Computer Science Division at Argonne National Laboratory. He has been developing PETSc since 1991.

Luck Versus Skill
The Role of Chance in Economic Success

BOOK REVIEW
By James Case

Success and Luck: Good Fortune and the Myth of Meritocracy. *By Robert H. Frank. Princeton University Press, Princeton, NJ, April 2016. 208 pages, $26.95.*

Robert Frank, professor of economics at Cornell University, is nothing if not prolific. In addition to a host of peer-reviewed publications, contributions to edited volumes, survey articles, book reviews, and opinion pieces, his curriculum vitae lists no fewer than thirteen books. Two are textbooks—one co-authored with Ben Bernanke, former Chairman of the Federal Reserve, and one a treatise on the distributional effects of foreign investment—and ten are mildly iconoclastic examinations of underpublicized aspects of the free market system, intended for popular audiences. Of the latter, the one under review seems destined to become the most controversial, concerning as it does the role of luck, chance, and good fortune—call it what you will—in the attainment of worldly (if not necessarily material) success.

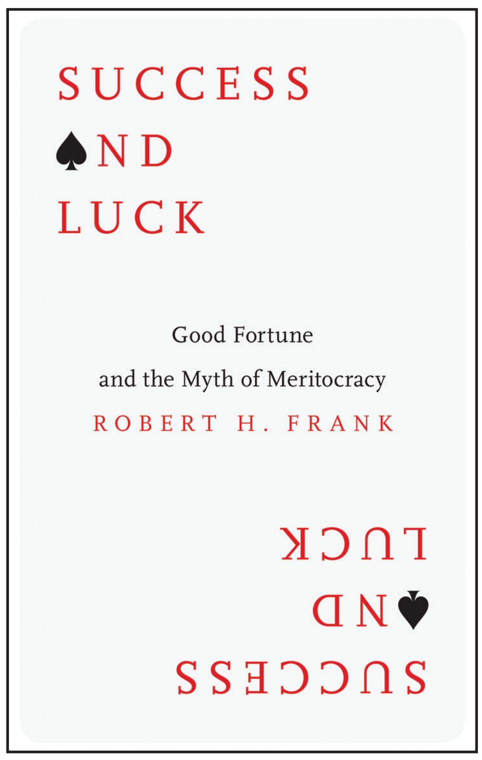
Frank assumes that his latest book will provoke controversy, because he knows from experience how bitterly successful people can resent the merest suggestion that their success could be due—even in part—to something other than their own individual talent and hard work. As E.B. White put it, "Luck is not something you can mention in the presence of self-made men." Frank learned White's lesson long ago. Having written a column exploring the influence of seemingly minor chance events on the careers of successful people, and having been surprised by the volume and negativity of the resulting letters to the editor, he had accepted an invitation to appear on *Fox Business*.[1] Rude awakening!

From the moment the segment began, the show's host was in high dudgeon, objecting to the mere suggestion that his own celebrity—and that of others like him—could be due to anything other than talent, hard work, and *willingness to bear risk*! Frank was unable to get a word in edgewise. Only days later did it occur to him that the sputtering host had refuted his own argument. If he had indeed taken risk, his success was—by definition—due in part to *random influences* entirely beyond his control.

A book of this kind must rely heavily on anecdotal evidence, and Frank makes ample use of "war stories" to demonstrate the impact of seemingly random events on his own and others' careers. Somewhat dramatically, he describes the misfortune that befell him one morning in 2007. Between sets of tennis, Frank had complained of nausea before losing consciousness and falling to the ground. Doctors later told him that he had suffered an episode of *sudden cardiac death*, instances of which are almost always fatal; the rare survivors are left severely impaired, both cognitively and otherwise. In Frank's case, however, an ambulance appeared almost immediately—summoned from the scene of a nearby traffic accident at which it had not been needed—enabling EMTs to administer timely emergency care even as he was being transported (first by ambulance and then by helicopter) to a regional hospital boasting a state-of-the-art cardiac care unit. Had there not been an idle ambulance mere yards from the court, the outcome would likely have been quite different. Because one was on hand, Frank's career continues!

Even luckier was actor James Doohan, who played Montgomery "Scotty" Scott on *Star Trek*. As a pilot and captain in combat with the Royal Canadian Artillery Regiment during World War II, he was struck by six bullets from friendly fire. One blew off his middle finger, four hit his leg, and one his chest. He survived, for another sixty years, only because the last-named hit the silver cigarette case in his shirt pocket!

Actor Al Pacino, according to Frank, owes much of his Hollywood success to one highly improbable casting decision. Studio executives wanted Robert Redford, Warren Beatty, or Ryan O'Neal for the role of Michael Corleone in Francis Ford Coppola's adaptation of Mario Puzo's best-selling novel, *The Godfather*. But Coppola wanted the unknown Pacino, who actually looked Sicilian. He also wanted Michael Corleone, rather than his father Don, to be the film's central character. What are the odds, Frank asks, that director Coppola would prevail over studio brass on both counts? And how might Pacino claim credit for either victory? He, one suspects, would be the first to concede that he caught a very lucky break in landing that career-defining role!



Success and Luck: Good Fortune and the Myth of Meritocracy. By Robert H. Frank. Courtesy of Princeton University Press.

Perhaps even luckier was Bryan Cranston, who played the leading role in *Breaking Bad*, one of the most successful TV dramas of all time. Previously an obscure middle-aged supporting actor, he won four Emmy Awards in the show's five seasons and is now one of the most sought-after actors in the profession. But he was offered the part only after John Cusack and Matthew Broderick turned it down. Was he not lucky that they did so?

Far more important, in the greater scheme of things, was the stroke of luck by which Microsoft came to own MS-DOS, the operating system designed for the original IBM personal computer. Ownership entitled the firm to collect a royalty on every "plug-compatible" PC sold. Unaware that such a device would soon occupy virtually every office desk in the developed world, IBM negotiators accepted Bill Gates' offer to acquire, modify, and *retain ownership* of the "quick and dirty operating system" QDOS, developed by Seattle Computer Products Inc. In accepting that offer, IBM signed away an asset that would end up being worth hundreds of billions of dollars.

Persuasive as such anecdotes are, Frank does not rely on them alone to make his case – he does some modeling as well. In particular, he simulates a winner-take-all tournament in which each of the many contestants receives three component scores between 0 and 100: one for talent, one for effort, and one for luck. Each component score $CS_?$ is drawn at random from a uniform distribution, and the three are combined into a final score *FS* as follows:

$$FS = (49 \times CS_{\text{talent}} + 49 \times CS_{\text{effort}} + 2 \times CS_{\text{luck}})/100.$$

Thus, 98% of a contestant's final score is determined by his effort and skill, while a mere 2% is due to luck. Yet in the presence of many contestants, luck proves instrumental in determining the winner. Frank explains this possibly surprising fact by observing the following: because many of the merit scores $(CS_{\text{effort}} + CS_{\text{talent}})/2$ will fall between 95 and 100 and be tightly spaced, the addition of a small luck component can cause the order of the final scores to differ from that of the merit scores.

In a series of tournaments with 100,000 contestants each, the average luck score of winners was 90.23, and 78.1% of tournament winners did not have the highest merit score; there was usually more than one contestant with a higher merit score than the ultimate winner. The higer-merit contestants' bad luck, combined with the winner's good fortune, determined the final outcome. In the book's appendix, Frank provides the results of various other tournaments in which the number of contestants varied from 1,000 to 10,000 to 100,000, while the weighting of the luck component varied from 1% to 2% to 5% to 10% to 20%, with qualitatively similar results in all cases. The winners always had high merit scores, but seldom the highest one. Most owed their success to a combination of good performance *and* good fortune!

One can quibble with Frank's tournament design, which drew component scores from a uniform distribution rather than the normal distributions that ordinarily govern performance scores. But one could easily correct that oversight by replacing each of his component scores with sums of, say, three uniformly-distributed random variables, since the *n*-fold convolution of uniform distributions converges rapidly to the normal distribution. Frank's design also fails to distinguish the one big break actors Pacino, Doohan, and Cranston received from the series of small incremental breaks likely to spur a typical climb to the top of the corporate ladder. But his point is well and clearly made, and lends strong support to his main contention that while a host of individuals exhibit both talent and hard work, relatively few manage to parlay those assets into worldly success. Plenty of equally talented and hardworking people never do manage to grasp the brass ring.

Finally, it should be mentioned that Frank is intimately familiar with so-called "happiness literature," which seeks to determine how happy people are in various parts of the world and walks of life. In it he finds evidence that people who acknowledge luck as a significant contributor to worldly success, including their own, are on the whole happier than those who deny its influence, and are therefore less reluctant to share their good fortune by paying taxes and engaging in philanthropy.

Success and Luck is an important book, which takes a plausible approach to a difficult problem of genuine significance. It deserves to be widely read and publicly discussed.

James Case writes from Baltimore, Maryland.

1 http://video.foxbusiness.com/v/3887675/luck-is-the-real-key-to-success/?#sp=show-clips

Professional Opportunities and Announcements

Send copy for classified advertisements and announcements to: ***marketing@siam.org****; For details 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****.*

Institute for Advanced Study

School of Mathematics

The School of Mathematics at the Institute for Advanced Study has a limited number of memberships with financial support for research during the 2017-18 academic year.

The School frequently sponsors special programs. However, these programs comprise no more than one-third of the memberships so that each year a wide range of mathematics is supported.

Candidates must give evidence of ability in research comparable at least with that expected for the Ph.D. degree, but otherwise can be at any career stage. Successful candidates will be free to devote themselves full time to research.

About half of our members will be postdoctoral researchers within five years of their Ph.D. We expect to offer some two-year postdoctoral positions.

Up to eight von Neumann Fellowships will be available for each academic year. To be eligible for the von Neumann Fellowships, applicants should be at least five, but no more than 15, years following the receipt of their Ph.D.

The **Veblen Research Instructorship** is a three-year position in partnership with the Department of Mathematics at Princeton University. Three-year instructorships will be offered each year to candidates in pure and applied mathematics who have received their Ph.D. within the last three years. Usually the first and third year of the instructorship will be spent at Princeton University and will carry regular teaching responsibilities. The second year is spent at the Institute and dedicated to independent research of the instructor's choice. Candidates interested in a Veblen Instructorship position may apply directly at the IAS website (**https://application.ias.edu**) or they may apply through MathJobs. If they apply at MathJobs, they **must** also complete the application form at **https://applications.ias.edu**, but do not need to submit a second set of reference letters. Questions about the application procedure should be addressed to **applications@math.ias.edu**.

Also, the School of Mathematics is looking for highly-qualified applicants in the field of computer-assisted formalization of mathematics, univalent foundations, and homotopy type theory and is expecting to offer two or more memberships in this area.

In addition, there are also **two-year postdoctoral positions** in computer science and discrete mathematics offered jointly with the following institutions: The Department of Computer Science at Princeton University (**http://www.cs.princeton.edu**), DIMACS at Rutgers, The State University of New Jersey (**http://www.dimacs.rutgers.edu**), and the Simons Foundation Collaboration on Algorithms and Geometry (**https://www.simonsfoundation.org/mathematics-and-physical-science/algorithms-and-geometry-collaboration/**).

School term dates for 2017-18 academic year are: term I, Monday, September 25 to Friday December 22, 2017; term II, Monday, January 15, 2018, to Friday, April 13, 2018.

During the 2017-18 year, the School will have a special program on Locally Symmetric Spaces: Analytical and Topological Aspects. Akshay Venkatesh of Stanford University will be the Distinguished Visiting Professor.

The topology of locally symmetric spaces interacts richly with number theory via the theory of automorphic forms (Langlands program). Many new phenomena seem to appear in the non-Hermitian case (e.g., torsion cohomology classes, relations with mixed motives and algebraic K-theory, derived nature of deformation rings). One focus of the program will be to try to better understand some of these phenomena.

Much of our understanding of this topology comes through analysis ("Hodge" theory). Indeed, harmonic analysis on locally symmetric spaces plays a foundational role in the theory of automorphic forms and is of increasing importance in analytic number theory. A great success of such harmonic analysis is the Arthur-Selberg trace formula; on the other hand, the analytic aspects of the trace formula are not fully developed, and variants such as the relative trace formula are not as well understood. Thus, analysis on such spaces, interpreted broadly, will be another focus of the program.

California Institute of Technology

Department of Computing and Mathematical Sciences

The Department of Computing and Mathematical Sciences (CMS) at the California Institute of Technology invites applications for the position of lecturer in computing and mathematical sciences. This is a (non-tenure-track) career teaching position, with full-time teaching responsibilities. The start date for the position is September 1, 2017, and the initial term of appointment can be up to three years.

The lecturer will teach introductory computer science courses including Data Structures, Algorithms, and Software Engineering, and will work closely with the CMS faculty on instructional matters. The ability to teach intermediate-level undergraduate courses in areas such as software engineering, computing systems, or compilers is desired. The lecturer may also assist in other aspects of the undergraduate program, including curriculum development, academic advising, and monitoring research projects. The lecturer must have a track record of excellence in teaching computer science to undergraduates. In addition, the lecturer will have opportunities to participate in research projects in the department. An advanced degree in computer science or related field is desired but not required.

Please view the application instructions and apply online at **https://applications.caltech.edu/job/cmslect**.

The California Institute of Technology is an Equal Opportunity/Affirmative Action Employer. Women, minorities, veterans, and disabled persons are encouraged to apply.

California Institute of Technology

Department of Computing and Mathematical Sciences

The Department of Computing and Mathematical Sciences (CMS) at the California Institute of Technology (Caltech) invites applications for tenure-track or tenured faculty positions. CMS is a unique environment where innovative, interdisciplinary, and foundational research is conducted in a collegial atmosphere. Candidates in all areas of computing and mathematical sciences are invited to apply, including (but not limited to) learning and computational statistics, security and privacy, networked and distributed systems, optimization and computational mathematics, control and dynamical systems, theory of computation and algorithmic economics, scientific computing, etc. Additionally, we are seeking candidates who have demonstrated strong connections to other fields, including the mathematical, physical, biological, and social sciences.

A commitment to world-class research, 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 computer science, applied mathematics, or related field.

Applicants are encouraged to have all their application materials on file by October 21st, 2016, but applications will be accepted until the end of December. For a list of documents required and full instructions on how to apply online, please visit **http://www.cms.caltech.edu/search**.

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

Caltech is an Equal Opportunity/Affirmative Action Employer. Women, minorities, veterans, and disabled persons are encouraged to apply.

Georgia Institute of Technology

School of Mathematics

The School of Mathematics at Georgia Tech is accepting applications for faculty positions at all ranks and in all areas of pure and applied mathematics and statistics. Applications by highly-qualified candidates, and especially those from groups underrepresented in the mathematical sciences, are particularly encouraged. See **www.math.gatech.edu/resources/employment** for more details and application instructions.

University of Michigan

Department of Mathematics and Department of Molecular, Cellular, and Developmental Biology

The Department of Mathematics and the Department of Molecular, Cellular, and Developmental Biology (MCDB) in the College of Literature, Science, and the Arts at the University of Michigan solicit applications for faculty positions in mathematical/computational biology at the assistant professor level, but appointment at a more senior level is possible for applicants with suitable experience. We encourage applications from scientists with a strong background in the life sciences who use mathematical modeling, or apply computational approaches to large datasets to understand basic cellular, genetic, developmental, and/or physiological processes. We are most interested in candidates who not only use but also develop cutting-edge models and tools from applied, computational, and/or interdisciplinary mathematics to solve real-world problems in the biological sciences. The faculty position will be tenure track or tenured with a university year appointment starting September 1, 2017, or January 1, 2018. Successful candidates will be expected to establish a vigorous, extramurally-funded research program and to be involved with instruction of both undergraduate and graduate students. For further information about research areas in mathematics please visit **https://lsa.umich.edu/math**, and for MCDB **http://lsa.umich.edu/mcdb**.

All applications must be submitted online at **http://www.mathjobs.org**. You will be asked to upload the following materials: A cover letter, a curriculum vitae, a brief summary of recent research accomplishments and statement of future research plans, a statement of teaching philosophy and experience, and evidence of teaching excellence for those who have teaching experience. Candidates for appointment at the assistant professor level should provide names and contact information for at least three references, as instructed in the online application form. To ensure full consideration, all materials should be received by October 14, 2016.

Women and underrepresented minorities are encouraged to apply. The University of Michigan is supportive of the needs of dual career couples and is an equal opportunity/affirmative action employer.

Michigan State University

Department of Computational Mathematics, Science and Engineering

Join Michigan State University's Global Impact Initiative, designed to address the grand challenges through the creation of over 100 new faculty positions in some of the most promising and exciting fields of research. We welcome applicants from diverse backgrounds. MSU offers an inclusive and collaborative work environment. To learn more visit **http://research.msu.edu/global-impact**.

The Department of Computational Mathematics, Science and Engineering (CMSE), a newly-created department at Michigan State University, invites applications from outstanding candidates for a tenure-stream, open-rank faculty position in the broad area of data science. The anticipated start date is August 16, 2017.

In service to the Global Impact Initiative, the Department of CMSE will be hiring eight faculty in computational and data science over the next two years, with the goal of growing the department to roughly 30 faculty.

A significant area of research focus within CMSE will be on the synergy between algorithms for computational modeling and data science in physical, biological, and engineering applications. The majority of positions within CMSE will be jointly held with other departments on campus, with tenure home in CMSE. Furthermore, the new department has a mandate to develop an innovative curriculum at both the graduate and undergraduate levels that expands upon the role of algorithm development, massively parallel and heterogeneous computing, and the use of computational tools in problem solving.

Exceptional candidates from all areas of data science will be considered. Particular attention will be given to algorithm development in approximate Bayesian computations; statistical learning and inference; applied harmonic analysis; data sketching/compression and data recovery; distributed and parallel algorithms in data science, as applied to materials science; Earth-system science; computational biology; and data-driven engineering design.

Applicants are required to have a Ph.D. in either math, statistics, computer science, or related fields. Faculty in CMSE are expected to develop a world-leading research program, mentor graduate students, and participate in the development and implementation of the new computational and data science curriculum.

Apply to this job via MSU's online job application website: **https://jobs.msu.edu**. Apply to position #4090. Applications should include a cover letter, CV, statement of research plans, and a one-page teaching statement, all in a single PDF file. In addition, three letters of recommendation should be submitted electronically through this application system. Applications received by November 14, 2016, will receive full consideration, but the search will continue until the positions are filled. Questions regarding the position may be directed to Professor B. Shanker (bshanker@msu.edu), Chair of the Search Committee.

Michigan State University has been advancing knowledge for more than 160 years. A member of the Association of American Universities, MSU is a research-intensive institution with 17 degree-granting colleges. MSU is an affirmative action, equal opportunity employer and is committed to achieving excellence through cultural diversity. The University actively encourages applications and/or nominations of women, persons of color, veterans and persons with disabilities, and we endeavor to facilitate employment assistance to spouses or partners of candidates for faculty and academic staff positions. Job applicants are considered for employment opportunities, and employees are treated without regard to their race, color, religion, sex, sexual orientation, gender identity, national origin, disability, or veteran status.

Michigan State University

Department of Computational Mathematics, Science and Engineering

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The Department of Computational Mathematics, Science and Engineering (CMSE), a newly-created department at Michigan State University, invites applications from outstanding candidates for a tenure-system, open-rank faculty position in the broad area of inverse problems and imaging. The anticipated start date is August 16, 2017.

In service to the Global Impact Initiative, the Department of CMSE will be hiring eight faculty in computational and data science over the next two years, with the goal of growing the department to roughly 30 faculty.

Exceptional candidates from all areas of inverse problem and imaging will be considered, with particular attention to algorithm and theory developments for applications in medical imaging, geoscience, remote sensing, and other related inversion and imaging problems.

Research within CMSE will focus on the synergy between algorithms for computational modeling and data science in applications by the creation of joint positions in physical, biological, and engineering departments with tenure home in CMSE. The department is developing an innovative graduate and undergraduate curriculum in algorithm development, massively parallel and heterogeneous computing, and the use of computational tools in problem solving.

Applicants are required to have a Ph.D. in either mathematics, geoscience, biomedical engineering, or other computational related fields. Faculty in CMSE are expected to develop a world-leading research program, mentor graduate students, and participate in the development and implementation of the new computational and data science curriculum.

Online application is required via MSU's online job application website: **https://jobs.msu.edu**. Apply to Position #4100. Applications should include a cover letter, CV, statement of research plans, and a one-page teaching statement, all in a single PDF file. In addition, three letters of recommendation should be submitted electronically through this application system. Applications received by November 14, 2016, will receive full consideration, but the search will continue until the positions are filled. Questions regarding the position may be directed to Professor Jianliang Qian (jqian@msu.edu), Chair of the Search Committee.

Michigan State University has been advancing knowledge for more than 160 years. A member of the Association of American Universities, MSU is a research-intensive institution with 17 degree-granting colleges. MSU is an affirmative action, equal opportunity employer and is committed to achieving excellence through cultural diversity. The University actively encourages applications and/or nominations of women, persons of color, veterans and persons with disabilities. Also, we endeavor to facilitate employment assistance to

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

Professional Opportunities

Continued from page 10

spouses or partners of candidates for faculty and academic staff positions.

University of Colorado Denver

Department of Mathematical and Statistical Sciences

The Department of Mathematical and Statistical Sciences at the University of Colorado Denver invites applications for a tenure-track assistant professor position starting in August 2017. The candidate should have research interest in an area on the interfaces of computational mathematics and probability and statistics, such as numerical solutions of stochastic differential equations, stochastic analysis, uncertainty quantification, data assimilation, etc. The regular teaching load is four courses per year, which may be reduced for an initial period. The candidate will be expected to develop a strong independent research program with external funding, teach a variety of courses at both the graduate and the undergraduate levels, and mentor student research. The full announcement is at **https://www.cu.edu/cu-careers**, requisition 06834, or **http://math.ucdenver.edu/ad**.

Sandia National Laboratories

Center for Computing Research and Computer Sciences and Information Systems Center

Sandia National Laboratories' Center for Computing Research (NM) and the Computer Sciences and Information Systems Center (CA) are now accepting applications for the 2017 John von Neumann Postdoctoral Research Fellowship in Computational Science. This prestigious postdoctoral fellowship is supported by the Applied Mathematics Research Program in the U.S. Department of Energy's Office of Advanced Scientific Computing Research.

The John von Neumann Fellowship provides an exceptional opportunity for innovative research in computational mathematics and scientific computing on advanced computing architectures, with application to a broad range of science and engineering problems of national importance. This 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.

Applications will be accepted through December 1, 2016. To apply, visit **sandia.gov/careers** and search for job #654914.

Carnegie Mellon University

Tepper School of Business

The Tepper School of Business at Carnegie Mellon University seeks candidates for a tenure-track faculty position in operations research at the assistant professor level, beginning in September 2017. Applicants are expected to have a Ph.D. in operations research or a related field at the time of appointment, a demonstrated potential for outstanding research, and strong teaching skills.

The specialty of the candidate may be in the broad area of optimization with connections to business analytics and machine learning. The ideal candidate will be able to contribute to the school's analytical approach to business education, and engage in cross-disciplinary research activities within the Tepper School and Carnegie Mellon University.

Carnegie Mellon University seeks to meet the needs of dual-career couples and is a member of the Higher Education Recruitment Consortium (HERC) that assists with dual-career searches.

Applicants should submit an application letter, curriculum vitae, up to three publications or working papers, research and teaching statements, and three recommendation letters. Questions about the application can be addressed to Mr. Philip Conley at orgroup@andrew.cmu.edu or 412-268-6212.

To receive full consideration, applications must be submitted by **January 1, 2017**.

Application Procedure: Faculty applications and all supporting documents must be submitted to **https://apply.interfolio.com/37613**.

Carnegie Mellon University is an equal opportunity employer and is committed to increasing the diversity of its community on a range of intellectual and cultural dimensions. Carnegie Mellon welcomes faculty applicants who will contribute to this diversity through their research, teaching, and service, including women, members of minority groups, protected veterans, individuals with disabilities, and others who would contribute in different ways.

The Chinese University of Hong Kong, Shenzhen

School of Science and Engineering

Located in the Longgang District of Shenzhen, the Chinese University of Hong Kong, Shenzhen [CUHK(SZ)] is a research-intensive university established in 2014 through a Mainland-Hong Kong collaboration, with generous support from the Shenzhen Municipal Government. It inherits the fine academic traditions of the Chinese University of Hong Kong and will develop its academic programmes in phases and offer courses in the Schools of Science and Engineering, Management and Economics, and Humanities and Social Science. The language of instruction will be in both English and Chinese, and the students will receive degrees of the Chinese University of Hong Kong.

Post Specification: The School of Science and Engineering (www.cuhk.edu.cn/en/Xueyuan/ligong.html) invites applications for faculty positions in all areas of **statistical science, data science, mathematics, financial engineering and quantitative finance**, and **bioinformatics**. Applications in other areas will also be considered.

Junior applicants should have **(i)** a Ph.D. degree (by the time of reporting for duty) in related fields and **(ii)** high potential in teaching and research. Candidates for associate and full professor posts are expected to have demonstrated academic leadership and strong commitment to the highest standards of excellence. Appointments will normally be made on contract basis for up to three years initially, leading to longer-term appointment or tenure later, subject to review. Exceptional appointments with tenure will be considered for candidates of proven ability.

Salary and Fringe Benefits: Salary will be comparable to international standards, commensurate with experience and accomplishments. Appointments will be made under the establishment of CUHK(SZ), and employee benefits will be provided according to the relevant labor laws of Mainland China as well as CUHK(SZ) regulations. Subsidies from various government sponsored talent programs will also be made available for eligible candidates. See http://www.cuhk.edu.cn/UploadFiles/talentsProgramoutline.pdf.

Applications (with CV and contact information of three referees) should be emailed to Talents4SSE@cuhk.edu.cn.

DEPARTMENT OF AEROSPACE ENGINEERING - Open Rank Faculty Search College of Engineering
University of Illinois at Urbana-Champaign

The Department of Aerospace Engineering at the University of Illinois at Urbana-Champaign seeks highly qualified candidates for multiple faculty positions in all areas of aerospace engineering, with emphasis on the areas of orbital mechanics, space systems, multi-functional composites, and additive manufacturing. Preference will be given to qualified candidates working in emerging areas of aerospace engineering whose scholarly activities have high impact. Please visit **http://jobs.illinois.edu** to view the complete position announcement and application instructions. Full consideration will be given to applications received by **December 16, 2016**. Applications received after that date may be considered until the positions are filled.

The University of Illinois conducts criminal background checks on all job candidates upon acceptance of a contingent offer.

Illinois is an EEO Employer/Vet/Disabled - www.inclusiveillinois.illinois.edu and committed to a family-friendly environment (http://provost.illinois.edu/worklife/index.html).

AEROSPACE ENGINEERING
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Tenure/Tenured Track ORIE Faculty
Cornell University, Ithaca, NY

Cornell is a community of scholars, known for intellectual rigor and engaged in deep and broad research, teaching tomorrow's thought leaders to think otherwise, care for others, and create and disseminate knowledge with a public purpose.

Cornell University's School of Operations Research and Information Engineering (ORIE) seeks to fill multiple tenured/tenure-track faculty positions for its Ithaca campus. Applicants with research interests in e-commerce- and healthcare-related areas of supply chain logistics, and in integer programming, will receive primary consideration, although we welcome strong applicants from all research areas represented within ORIE. One of the faculty positions may include responsibilities within Cornell's Systems Engineering Program.

Requisite is a strong interest in the broad mission of the School, exceptional potential for leadership in research and education, an ability and willingness to teach at all levels of the program, and a PhD in operations research, mathematics, statistics, or a related field by the start of the appointment. Salary will be appropriate to qualifications and engineering school norms.

Cornell ORIE is a diverse group of high-quality researchers and educators interested in probability, optimization, statistics, simulation, and a wide array of applications such as e-commerce, supply chains, scheduling, manufacturing, transportation systems, health care, financial engineering, service systems and network science. We value mathematical and technical depth and innovation, and experience with applications and practice. Ideal candidates will have correspondingly broad training and interests. ORIE participates in particular in Cornell's interdisciplinary Systems Engineering Program.

Please apply online at **https://academicjobsonline.org/ajo/jobs/7553** with a cover letter, CV, statements of teaching and research interests, sample publications, at least three reference letters and, for junior applicants, a doctoral transcript. Applicants attending the INFORMS annual meeting are strongly encouraged to submit all application materials by October 30, 2016. All applications completed by November 15, 2016 will receive full consideration, but candidates are urged to submit all required material as soon as possible. Applications will be accepted until the positions are filled.

ORIE and the College of Engineering at Cornell embrace diversity and seek candidates who can contribute to a welcoming climate for students of all races and genders. Cornell University seeks to meet the needs of dual career couples, has a Dual Career program, and is a member of the Upstate New York Higher Education Recruitment Consortium to assist with dual career searches. Visit http://www.unyherc.org/home/ to see positions available in higher education in the upstate New York area. Diversity and Inclusion are a part of Cornell University's heritage. We are a recognized employer and educator valuing AA/EEO, Protected Veterans, and Individuals with Disabilities. We strongly encourage qualified women and minority candidates to apply.

Find us online at http://hr.cornell.edu/jobs or
Facebook.com/CornellCareers

Cornell University is an innovative Ivy League university and a great place to work. Our inclusive community of scholars, students and staff impart an uncommon sense of larger purpose and contribute creative ideas to further the university's mission of teaching, discovery and engagement. Located in Ithaca, NY, Cornell's far-flung global presence includes the medical college's campuses on the Upper East Side of Manhattan and in Doha, Qatar, as well as the new CornellNYC Tech campus to be built on Roosevelt Island in the heart of New York City.

Diversity and inclusion have been and continue to be a part of our heritage.
Cornell University is a recognized EEO/AA employer and educator.

丘成桐数学科学中心
Yau Mathematical Sciences Center

Yau Mathematical Sciences Center
Tsinghua University, Beijing, China

Positions:

- **Professorship;**
- **Associate Professorship;**
- **Assistant Professorship (tenure-track).**

The YMSC invites applications for the above positions in the full spectrum of mathematical sciences: ranging from pure mathematics, applied PDE, computational mathematics to statistics. The current annual salary range is between 0.25-1.0 million RMB. Salary will be determined by applicants' qualification. Strong promise/track record in research and teaching are required. Completed applications must be electronically submitted, and must contain curriculum vitae, research statement, teaching statement, selected reprints and /or preprints, three reference letters on academic research and one reference letter on teaching(Reference letters must be hand signed by referees), sent electronically to

msc-recruitment@math.tsinghua.edu.cn

The review process starts in December 2016, and closes by April 30, 2017. Applicants are encouraged to submit their applications before December 31, 2016.

Tenure-Track Faculty Position in Applied Mathematics

The ***Department of Mathematics and Statistics***, Faculty of Arts and Science at ***Queen's University***, Kingston, Canada, invites applications for a **Tenure-track faculty position in Applied Mathematics and Mathematics and Engineering** at the rank of Assistant Professor with a starting date of July 1, 2017. In areas related to Mathematics and Engineering, there are presently prominent research groups in Geometric Mechanics, Control Theory, and Information and Communication Theory. Candidates with expertise in any of the following areas are strongly encouraged to apply:

- **Mathematical Fluid and Continuum Mechanics,**
- **Partial Differential Equations,**
- **Numerical Analysis, and**
- **Control of Mechanical Systems**

For more information about the Mathematics and Engineering program, please see http://www.mast.queensu.ca/meng/. A successful candidate will be expected to work in any of these or complementary research areas, and to contribute to both the graduate and undergraduate programs.
A candidate who joins the Mathematics and Engineering group will be expected to obtain a license as a Professional Engineer; an undergraduate degree in engineering is a strong asset towards obtaining the license. For the full position announcement, please visit:

http://www.mast.queensu.ca/positions/

Queen's
UNIVERSITY

AIMS Advances Mathematics Education in Africa

By Barry Green

This past August, the African Institute for Mathematical Sciences (AIMS) opened its newest centre in Kigali, Rwanda. There was great excitement when 46 talented young African students arrived from all over the continent to begin a special one-year master's programme in the mathematical sciences, taught by local and international lecturers in a 24/7 environment.

There are six AIMS centres across Africa: one in South Africa,[1] which opened in 2003, and others in Senegal, Ghana, Cameroon, Tanzania, and now Rwanda. These centres train over 300 students each year. AIMS' Next Einstein Initiative[2] is working to establish 15 centres of excellence across Africa by 2023, thereby building a network of gifted young Africans in tune with the broad use of the mathematical sciences and able to contribute to new opportunities for growth in Africa.

Established in 2003, AIMS is the first pan-African network of centres of excellence in the mathematical sciences. Its model prioritises international-class education of Africa's most valuable resource—its young people—for the transformation of the continent. AIMS has graduated more than 1,200 students from 42 African countries to date, 31% of them being women.

Each year over 3,000 young graduates apply for this programme, and it is our conviction that Africa has the pipeline to produce the next Einstein. The continent has what it takes to make breakthrough discoveries, either individually or collectively, that are relevant in Africa but also of global value and recognition regarding science and its use in society. AIMS is working to fulfill this potential, aware that mathematics underpins most of modern life, from information and communication technology to genetics, medicine, finance, demographics, and planning. In this way AIMS is filling the skills gap in the mathematical sciences, which will directly contribute to the development of the continent and drive Africa's transformation.

The training programme at AIMS focuses on developing scientific, technical, and entrepreneurial competence as well as creating a critical mass of well-rounded scientists with excellent problem-solving skills, capable of creative thinking and genuine innovation. AIMS students learn professional and employable skills, and are also trained in entrepreneurial methods to broaden their career preparedness for paths outside academia.

Our core programme, for which full scholarships are provided, is taught by world-class lecturers from both Africa and abroad in a continuous learning environment.

Dovetailing with this programme, we have introduced the AIMS Industry Initiative,[3] which seeks to maximise the opportunities and potential for the mathematical sciences to contribute to African economies via human capital, knowledge transfer, and applied scientific research and technological excellence. The initiative links the mathematical sciences to the needs of industry, focusing on eliminating the skills gap in Africa. AIMS is also piloting a cooperative programme at our centre in AIMS Senegal. This programme seeks to enhance the competencies of our students and graduates by providing them with opportunities to gain real-world experience with international and local partners, which will help them make a notable impact on Africa's economic, academic, and governmental capacity.

Professor Neil Turok, founder of AIMS and director of the Perimeter Institute for Theoretical Physics, chats with students at the South African centre. Photo courtesy of AIMS.

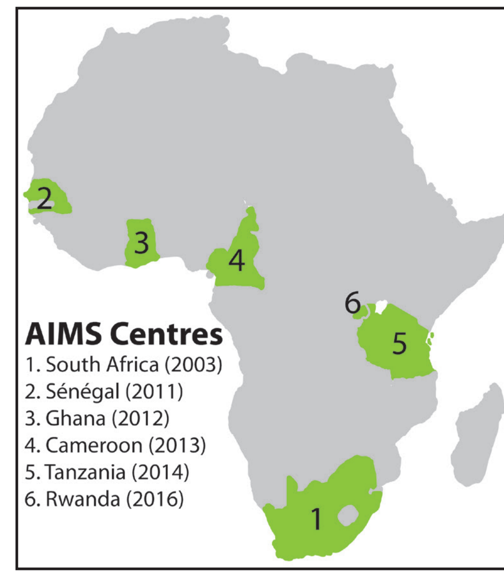
The core AIMS training programme is part of a broader project for development that also involves research, outreach, and community engagement. Thus, a key pillar of the institute's strategy is the facilitation of high-quality research that addresses challenges in African development. Each centre is expected to engage in relevant, multidisciplinary research. AIMS provides outstanding researchers the opportunity to conduct their work surrounded by peers in a world-class environment designed to inspire innovation and creativity. AIMS students and alumni are also able to interact with researchers through research projects, post-AIMS bursaries, and research-related workshops.

AIMS' outreach and community engagement initiatives are committed to growing the pipeline of students progressing to secondary and tertiary mathematics and science education, and decreasing the failure and drop-out rate of mathematics students at all levels. Through innovative pedagogical approaches, the use of technology, and continually-updated curricula, the AIMS teacher training programmes focus on strengthening the mathematics teacher capacity and professional development of teachers. These teachers can then provide as many school learners in Africa as possible with a quality education in maths and science, investing in the future thinkers who will lead Africa's development.

The AIMS Schools Enrichment Centre (AIMSSEC)[4] in South Africa has trained over 1,700 teachers with its Mathematical Thinking Course. The teacher training program in Cameroon—supported by The MasterCard Foundation—hopes to train 1,920 pre-service teachers and 1,200 in-service teachers over the next five years, reaching 1.7 million school children.

The AIMS Women in STEM Initiative (AIMSWIS)[5] is dedicated to accelerating progress for African women in science, technology, engineering, and mathematics (STEM) through evidence-based reporting and advocacy, leveraging of increased investments, adoption of best practices, engagement of men, and collaboration with African women in the STEM pipeline.

AIMS is keenly aware that it has many partners with which to work and is part of a growing renewal in Africa. The Next Einstein Forum (NEF),[6] an initiative of AIMS and the Robert Bosch Stiftung,[7] was launched in 2013 as a platform to bring together relevant stakeholders and policy-makers—from the scientific and academic sector, governments, science funding agencies, industry, media, and civil society—to showcase Africa's remarkable progress in science. By creating a community of scientists, NEF is catalysing action to translate these scientific advances into human benefit.



There are six AIMS centres throughout Africa. The South African centre opened in 2003, while the Rwandan centre opened just this year. Image courtesy of AIMS.

In collaboration with the Robert Bosch Stiftung and the government of Senegal, AIMS co-hosted the first NEF Global Gathering in March 2016[8] in Dakar, Senegal. The gathering brought together more than 1,000 global scientific and industry thought-leaders, political leaders, and young scientists to establish a clear roadmap of Africa's future transformation by leveraging science, technology and innovation. The next Global Gathering will be held in Kigali, Rwanda, in 2018.

The spirit of AIMS distinguishes it from other institutions; AIMS is more than just the math. The organization has a caring side, concerned with the development of people and the inspiration of empowerment through understanding.

One in seven people, or 15% of today's population, is African. In 2050, a little over a generation from now, 40% of the world's youth population will be African. These numbers mean that the world will look to Africa for talent. If we increase the pipeline of students pursuing STEM fields, both in research and industry, Africa has the potential to transform and inspire the world. African countries do not lack talented potential mathematicians. But without increased investment and more conducive education policy, few of them will reach their potential.

Barry Green is the director of the African Institute for Mathematical Sciences South Africa and Chief Academic and Research Officer for the AIMS Global Network.

1 http://aims.ac.za/
2 http://www.nexteinstein.org/
3 http://www.nexteinstein.org/the-industry-initiative-2/
4 http://aimssec.ac.za/
5 http://www.nexteinstein.org/aimswis/
6 http://nef.org/
7 http://www.bosch-stiftung.de/content/language2/html/index.asp
8 http://nef.org/tag/nef-global-gathering-2016/

46 bright young African students from all over the continent will partake in a special one-year master's programme at the AIMS centre in Rwanda, which opened in 2016. They are the centre's inaugural group, pictured here with Thierry Zomahoun, President and CEO of the AIMS Global Network. Photo courtesy of AIMS.