Newsjournal of the Society for Industrial and Applied Mathematics

siam news

Volume 47/ Number 5
June 2014

Simons Foundation Creates Center in Data Science

Data science is a hot field. New institutes have been created at Berkeley, Columbia, NYU, Stanford, and elsewhere, with funding from the Sloan Foundation, the Moore Foundation, and the Simons Foundation; it's almost impossible to keep track of the educational programs emerging in the field. Quite naturally, many of the new institutes and degree programs place a heavy emphasis on computer science (machine learning, say) or statistics.

In mid-May, hoping to learn about developments in the field and, in particular, the role of applied mathematics in it, SIAM News *visited Leslie Greengard, director of the not yet one-year-old Simons Center for Data Analysis in New York City's Flatiron District.*

About a year ago, as James Simons was preparing to add an internal research center in data science to the Simons Foundation's far-reaching programs in science and mathematics, Leslie Greengard, a few subway stops downtown at the Courant Institute, was looking to do something new. With a PhD in computer science and an MD (received at the same time), his thoughts were turning to the biosciences, actually a return to his early research interests, and in particular to instrumentation, in keeping with his work in computational science.

With his background and interests, Greengard is at home in the worlds and, notably, the languages of both the mathematical and the life sciences. In July, in a talk at the Simons Foundation, which has extramural programs in mathematics and physical science, the life sciences, and autism research, he touched on some of the exciting research avenues then on his mind.

On September 1, he became the founding director of the Simons Center for Data Analysis. Officially, he now spends two thirds of his time at SCDA, one third at Courant.

Clearly, Greengard has succeeded in his quest for something new, beginning with one of his first concrete tasks: deciding on the form a functioning internal research lab would take. Modeled after the "old Bell Labs," SCDA aims to house between 30 and 40 researchers, with the possibility of year-long visits by senior people.

Like Bell Labs, the Simons setting offers almost constant exposure to good problems, in part via visiting investigators from the Simons extramural research programs. Although SCDA researchers will be free to pursue their own interests, it makes sense for staff scientists to make significant contact in their work with experimental efforts in neuroscience, genomics, and a wide variety of other fields supported by the Simons Foundation.

See **Data Science** *on page 2*

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

Behind the Scenes of ICIAM

Near the beginning of her two-year term as SIAM president (2013–14), Irene Fonseca identified two top priorities: internationalization and industry. These are precisely at the two poles of ICIAM ("which has two I's"), she says. For SIAM ("which has only one I, but I double it!"), "being part of ICIAM is fundamental to bridges to the rest of the world." Few would agree more with the value of such bridges than Barbara Keyfitz and Maria Esteban, president and president-elect, respectively, of ICIAM.

Fonseca, Keyfitz, and Esteban were among the distinguished visitors from around the world who gathered at the Mathematical Biosciences Institute at Ohio State University, May 15 and 16, to attend the annual board meeting of the International Council for Industrial and Applied Mathematics. At the request of *SIAM News*, Keyfitz (a professor of mathematics at OSU), made arrangements for a taped lunchtime conversation among the three during the workshop that preceded the meeting.

As anyone who has attended ICIAM will know—the most recent congresses were in Vancouver (2011) and Zurich (2007)—ICIAM offers prodigious opportunities for bridge- and network-building at the individual level, and up through the society/national/international levels. Mathematical scientists from all five continents take part,

See **ICIAM** *on page 3*

Three strong believers in the importance of the International Congress on Industrial and Applied Mathematics took a break during the most recent meeting of the ICIAM board to discuss their activities and the experiences they envision for those who attend ICIAM 2015, in Beijing. From left, SIAM president Irene Fonseca of Carnegie Mellon University, ICIAM president Barbara Keyfitz of Ohio State University, and ICIAM president-elect Maria Esteban of the applied mathematics research center CEREMADE, at the University of Paris–Dauphine.

"Bike Tracks," Quasi-magnetic Forces, And the Schrödinger Equation

By Mark Levi

In an invited talk at the 2013 SIAM Conference on Applications of Dynamical Systems, Mark Levi described a recently discovered connection between two distinct objects—the stationary Schrödinger equation and "bicycle tracks." A request from SIAM News *for an article based on the talk elicited the following well-illustrated article.*

The stationary Schrödinger equation

$$\ddot{x} + p(t)\,x = 0, \qquad (1)$$

where p is the given potential, arises in many branches of mathematics, physics, and engineering and has been studied for well over a century. Known also as Hill's equation, it comes up in studies of the spectrum of the hydrogen atom, in celestial mechanics, particle accelerators, forced vibrations, wave propagation, and many other problems. Hill's equation plays a central role in explaining the complete integrability of the Korteweg–de Vries equation: One of the most remarkable mathematical discoveries of the last century is that the eigenvalues of the Schrödinger operator remain fixed if the potential p evolves according to the KdV equation.

The 1989 Nobel Prize in Physics was awarded to W. Paul for his invention of the Paul trap—an electromagnetic trap that suspends charged particles. The mathematical substance of Paul's discovery amounts to an observation on Hill's equation, as Paul explained in his Nobel lecture [10]. (As an alternative to Paul's computational explanation, a geometrical explanation of the workings of the Paul trap can be found in [5].) The stability of Kapitsa's famous inverted pendulum (demonstrated experimentally by Stephenson in 1908, about half a century before Kapitsa's paper) is also explained by the properties of Hill's equation. Incidentally, a *topological* explanation of this counterintuitive effect can be found in [6].

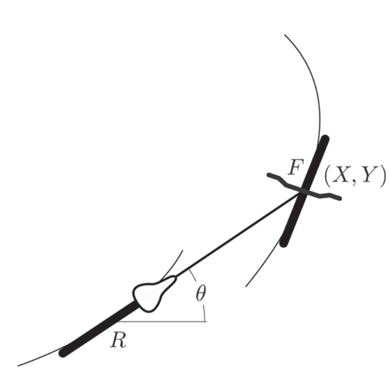


Figure 1. *Idealized bike.*

The long history of Hill's equation is reflected in the rich classical literature of the 18th and 19th centuries on the eigenfunctions of special second-order equations (including polynomials of Lagrange, Laguerre, Chebyshev, and Airy's function), as well as in more recent work on inverse scattering and on the geometry of "Arnold tongues" [1,2,9,11].

Introducing bike tracks, the second partner in the new relationship, Figure 1 shows an idealized bike—a segment RF of constant length that can move in the plane as follows: The front F is free to move along any path, while the velocity of the rear end R is constrained to the direction RF—that is, the rear wheel doesn't sideslip. Figure 2 shows some examples.

The tire track problem does not have the

See **Bike Tracks** *on page 4*

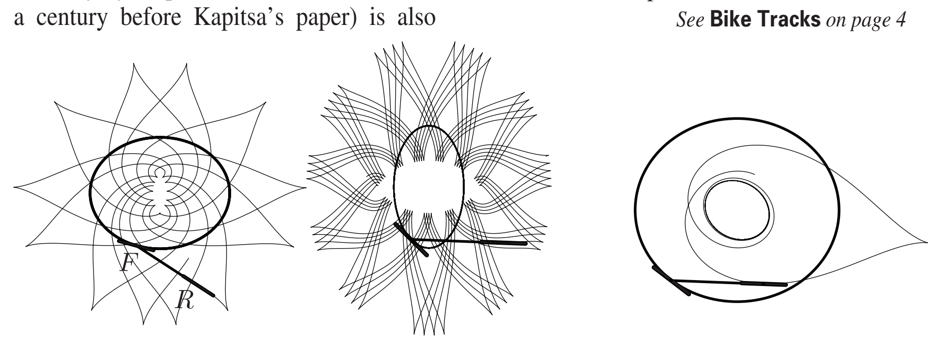


Figure 2. *Some paths of the rear wheel as the front wheel traces out the heavier path multiple times.*

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

siam news
Volume 47/ Number 5/ June 2014

Data Science

continued from page 1

The new center, Greengard emphasizes, "is concerned with data science that is closely connected to an underlying scientific model." In choosing the right problems to work on and in assembling a critical mass of researchers, this is the principle that guides his thinking.

SCDA's 30–40 researchers, he says, will make up five groups—two devoted to infrastructure (mathematics and computer science, and software development) and the three others to the somewhat overlapping areas of genomics, systems biology, and neuroscience. To date, he has made three senior hires: Ian Fisk (most recently computing coordinator, CMS/CERN), deputy director for computing; Nick Carriero (most recently senior research scientist in computer science and co-director, W.M. Keck biotech lab high performance computing resource, Yale School of Medicine), group leader for software development; and Dmitri Chklovskii (most recently leader of a group at Janelia Farm Research Campus), group leader for neuroscience.

Greengard currently spends a lot of his time thinking about problems and research areas that promise to meet his, and Simons's, expectations for SCDA. Beyond the usual academic motivation of furthering science, SCDA's mission includes the development of tools that are likely to find wide use. The center "will be partly a software shop," Greengard says. Internally funded by the Simons Foundation, SCDA researchers will be collaborating with colleagues in both experimental and theoretical disciplines across academic, government, and industrial research labs. Those connections will be built in part around the creation of new algorithms and in part around the development of new software tools and frameworks.

Always animated, Greengard becomes even more so in discussing promising problems for SCDA to take on. While active projects in genomics and bioinformatics are under way at the foundation, most of those he describes for *SIAM News* touch on problems that arise in neuroscience and structural biology, where new experimental techniques are yielding vast streams of data. He mentions the much-needed development of standards for processes that are not now standardized.

A case in point is the analysis of spikes produced on insertion of an electrode, or more interestingly a multi-electrode array, in the brain. The first task in analyzing the data is to determine which of an unknown number of neurons is giving rise to which spike. This process of disambiguation ("spike sorting") is typically based on the subtly different shapes corresponding to different neurons. At present, Greengard points out, each lab processes data in its own way, generally aided by a variety of academic and commercial software packages. The raw data, however, tends not to be publicly available. What's needed, and what he considers a worthy project for SCDA, is

As SCDA director, "I'm in noncompete mode with everybody," says Leslie Greengard. In confirmation, he points to the center's first published paper, of which he is one of several authors (including David Hogg of NYU's Center for Data Science). The subject, Greengard's recent immersion in neuroscience notwithstanding, is exoplanets.

a platform where people make their data available (for reproducibility) and where scientists can easily develop and test new algorithms. Greengard hopes that the same platform will be useful for EEG and MEG data analysis as well—despite differences in the specific computational tasks, much of the software and data-handling infrastructure will be the same.

He also mentions cryo-electron microscopy as a biologically important and mathematically compelling area of research. "Even though the field is now several decades old, new microscopes and new electron detectors have made this an exciting research area." Cryo-EM (also called single-particle EM) is a way to determine the three-dimensional structure of proteins without the need for crystallization, making it a much more accessible and high-throughput modality. Beginning with noisy projection data from frozen configurations of the proteins in unknown orientations, the mathematical problem is to determine the corresponding atomic-resolution structure. In the course of the experiment, the electron beam distorts not only the proteins, but the entire ice sheet in which they're embedded.

Greengard views the development of next-generation tools for cryo-EM as a "great poster child for computational science." Success will involve "physical modeling, Fourier analysis, numerical analysis, and data science all rolled into one." He has been discussing the problem with Amit Singer of Princeton, one of a group of mathematicians who have been working in the area for some time (and an invited speaker on the subject at the 2012 SIAM Conference on Imaging Science). "It's a great match of modern computational science with a biologically important problem," Greengard says, "and a great example of the kinds of problems we intend to focus on."

SCDA will also work with the Simons Collaboration on the Global Brain, an initiative launched by the Simons Foundation that involves some of the key researchers in the field, including David Tank of Princeton, Larry Abbott of Columbia, William Newsome of Stanford, Anthony Movshon of NYU, and Gerald Fischbach, chief scientist and fellow of the foundation. With ties to the major US BRAIN initiative (Brain Research through Advancing Innovative Neurotechnologies), this exemplifies the major problems in data science, all requiring new methods and algorithms, to be tackled by SCDA scientists.

Greengard will give this year's John von Neumann Lecture ("Fast, Accurate Tools for Physical Modeling in Complex Geometry") in July at the SIAM Annual Meeting in Chicago. He suggested an alternative, snappier title during the SIAM News *visit: "Anatomy of a Problem."*

SIAM Education Committee Releases Timely Report on Undergraduate Programs

The SIAM Education Committee has released a new report, *Undergraduate Degree Programs in Applied Mathematics*.* Designed to serve as a resource for people interested in starting new programs or developing existing ones, the report was initiated by Education Committee chair Peter Turner and developed by Rachel Levy, Byong Kwon, Edmond Chow, Maeve McCarthy, and Katherine Socha.

The report describes components of existing programs in applied mathematics, based on surveys of representative programs. It includes discussions of course requirements, capstone requirements, industrial opportunities, student research opportunities, student recruitment, attrition, resources, K–12 outreach, postgraduation opportunities, and the challenges of initiating a new program.

The new report builds on *The Mathematical Sciences in 2025* (Board on Mathematical Sciences and Their Applications, 2013), which places significant emphasis on applied mathematics and mathematical modeling. Modeling and applications can motivate undergraduates to study mathematics, especially those whose primary interest is in using their mathematical skills in such applied settings as the physical sciences and engineering, geoscience, and life and social sciences that will vary according to institutional interests. The emphasis on modeling and applications is seen as important not only for the students' undergraduate studies per se, but also as part of their preparation for careers outside academia.

*www.siam.org/reports/.

Modeling in the undergraduate curriculum was also a major theme of two recent SIAM–NSF workshops in the Modeling across the Curriculum project. Recommendations from reports on those workshops are also relevant to the discussion of undergraduate applied math programs. The first report can be found at www.siam.org/reports/modeling_12.pdf; the second will be available this summer.

The ideas in the new report also resonate with the NSF–funded INGenIOuS program (Investing in the Next Generation through Innovative and Outstanding Strategies), a collaborative effort of the AMS, ASA, MAA, and SIAM. This program explores preparation for careers outside academia, including ways to bridge gaps between business/industry/government and academia, and to improve students' preparation for non-academic careers, build public awareness of the role of mathematics and statistics in both STEM and non-STEM careers, diversify incentives, rewards, and mechanisms for conferring recognition in academia, develop new curricular pathways, and build and sustain professional communities.

Synergies with several other activities enhance the new report. PIC Math (Preparation for Careers in Industry), a joint MAA/SIAM program, helps make faculty and their students more aware of non-academic careers in applied mathematics. TPSE Math (Transforming Post-Secondary Education in Mathematics), founded by some of the contributors to *Math 2025*, emphasizes the importance of modeling and applications to a relevant undergraduate experience. MAA (with input from ASA and SIAM) is leading the development of a new project: Vision for Undergraduate Math in 2025. Representatives of the SIAM Education Committee are participants in the planning for all these activities, and the new report should be a valuable resource for all.—*Rachel Levy, Harvey Mudd College, and Peter Turner, Clarkson University.*

siam news

ISSN 1557–9573.

Super-sized Study Groups with Industry: A Nonlinear Increase in Problem-solving Effectiveness

By Chris Breward and John Ockendon

Marking a milestone for industrial mathematics, the University of Oxford staged the 100th European Study Group with Industry during the week of April 7–11. This "Super-Sized Study Group" saw 200 participants attack ten problems of economic or social importance to the presenters, who represented sectors as diverse as manufacturing, agrifood, industrial processes, image processing, safety and security, and transport.

The interests of large multinationals, government agencies, and rapidly growing startups were all accommodated. The industrial reaction was more positive than ever: CrowdEmotion, a BBCWorldwide Labs startup, implemented a Study Group-generated algorithm in its software by the end of the final afternoon, and others were already discussing avenues for future collaboration. The registration fee was clearly no deterrent for the industrial participants.

The Study Group followed the tried and tested format of problem presentation, self-organised brainstorming, and reporting back. The mathematics evolved in the course of the week, following the universal Study Group pattern of repeated rephrasing of the raw problem in light of mathematical modelling until it made good scientific sense and would yield valuable practical insights. You would have to be present to grasp how tortuous this process can be, but the three following examples (and the accompanying photo) should give some idea.

■ ■ ■

Raw Problem. A contaminant is released onto an urban surface, such as concrete or carpet. What is the best way to clean it up?
Processed Modelling Problem. Model the penetration of the contaminant into a porous substrate and the effect of a subsequent application of a chemically active cleanser to the substrate.

This led to a novel analysis of chemical reactions at the interface between two liquids in a porous medium. The key new insight was that cleansing is better when the reaction products are soluble in the cleanser rather than in the contaminant material. "The week was a great success," said Anthony Arkell and Hasmitta Stewart of the UK Government Decontamination Service. "The outcomes . . . will allow us to target further research and development and provide better advice in the interim."

Raw Problem. How can video searching be made quicker and more accurate?
Processed Modelling Problem. Identify models for colour perception most appropriate for jpeg and minimise the occurrence of subsequent encryption-generated artefacts.

This reminded the academic participants of the beautiful mathematical (geometrical) models of colour vision and provided new challenges for image processing. Suggested along the way were new algorithms for decompressing jpeg files that would make objects recognisable by sharpening the edges in the image and reducing computer-generated artefacts. "We now have a clear insight into how we may advance the state-of-the-art in automated scene analysis," said Glynn Wright, CEO of the small company Aralia. "Some of the results promise to be of considerable significance to virtually everyone who uses digital images."

Raw Problem. Design fibrous filters that optimise droplet removal from a two-phase gas/liquid flow.
Processed Modelling Problem. Model liquid transport along the exterior of fibres in networks and incorporate pinning and droplet formation.

Work on this problem provided a brand new twist to the theory of filters because of the high mobility of the filtrate. Proposed models ranged from generalised lubrication theories to Markov chains. Mark Hurwitz, from the multinational Pall Corporation, said that he was "highly gratified by the interest shown in our coalescence problem and the intense effort made by so many talented mathematicians. In a single week my thinking about this complicated subject has been significantly clarified, and the array of modelling approaches developed provide a powerful roadmap for further research."

"Do the simplest problem first." The process of a Study Group from raw problem to a useful outcome for the presenter can be tortuous.

■ ■ ■

Since their inception at Oxford in 1968, Study Groups have established themselves globally as a powerful mechanism for bringing mathematical thinking to bear on industrial problems (see http://www.maths-in-industry.org/, which lists about 20 Study Groups yearly and will contain detailed reports on the ESGI100 problems in due course). Recent innovations include communications via social media and, especially important, the concept of pre-Study Group student modelling camps as pioneered in North America.

Most Study Groups involve about five problems and 50–70 participants, the majority of whom are early-career researchers. The dramatic outcome at ESGI100 was the result of the scaling up in the number of participants and the corresponding nonlinear increase in the number of interactions, enabling brainstorming sessions to enhance both the novelty of the mathematics that was applied and the impact of the resulting new insights on the industrial problems. Somehow, people did not get lost in the crowd and managed to self-assemble into small teams within which leaders emerged to coordinate their outputs. The success of such brainstorming could be a great topic for psychological study!

An event on this scale could not have happened without strong support from many sources, including, crucially, the Smith Institute for Industrial Mathematics and System Engineering (http://www.smithinst.co.uk/). It provided the key infrastructure for drawing in the problems, and its wide network of leading academics, industrialists, and government policy-makers helped organise a panel discussion on the future of industrial mathematics.

The wide-ranging panel discussion identified a number of routes for enhancing the profile of industrial mathematics in the corridors of power, making it clear that the success of the subject crucially depends on the enthusiasm and commitment of early-career researchers. If such researchers are to be identified and encouraged, academics must continue to demonstrate the attractiveness of careers in which mathematicians can put their skills to genuine practical use in industry and society. The numerous Study Groups that occur throughout the world provide a forum that highlights how exciting and rewarding such careers can be.

Chris Breward and John Ockendon are from the Oxford Centre for Industrial and Applied Mathematics, Mathematical Institute, University of Oxford.

ICIAM

continued from page 1

and the invited talks and prizes represent work at the highest levels of the field.

What Does the ICIAM President Do?

The ICIAM president and the board, which is made up of representatives of participating societies, are responsible for the high quality of ICIAM, beginning with selection of the site—Beijing in 2015, Valencia in 2019. The rigorous process of choosing a site continues through the formation of a 20-member scientific program committee, which in turn chooses the 27 invited speakers. A proposed slate of speakers (or for that matter the proposed make-up of the scientific program committee), according to Keyfitz, rarely wins board approval on the first try.

That ICIAM invited speakers do outstanding work and are leaders in their areas is a given. Beyond that, the list of invited speakers must be balanced—mathematically and geographically—and it must be diverse with respect to academic vs. industrial work, gender, type of academic institution. . . . Giving an invited talk at ICIAM is an honor, conferring considerable prestige on the speaker. The list of invited speakers for Beijing can be found at www.iciam2015.cn/newsletter-invited+speakers.html.

Five ICIAM prizes—Collatz, Lagrange, Maxwell, Su Buchin, and Pioneer—are awarded at each congress. In Beijing for the first time, Keyfitz says, the prize recipients will have the opportunity to speak (30 minutes each); each recipient plans to attend the meeting and is eager to use the time to present his/her work. The prizes and talks will be part of the opening ceremonies. Having recently overseen the selection of the 2015 prize recipients, Keyfitz testifies to the intense, thorough, and time-consuming scrutiny directed to all nominees. When she succeeds Keyfitz in 2015, Esteban will bring to the job her experience as a member of the Abel Prize Committee.

How Does ICIAM Differ from the ICM?

An invitation to give a plenary or other invited talk at the International Congress of Mathematicians, which dates back to 1897 (when the first one was held in Zurich), is considered one of the most significant recognitions a mathematician can receive. Almost all ICM speakers are invited, Esteban points out.

"You go to the ICM to listen, to ICIAM to speak," Keyfitz says.

Among the events most closely associated with the ICM is the presentation of prizes, including the Fields Medals. The names of the prize recipients are a closely held secret, revealed only during the ICM. For ICIAM, the names of the 2015 prize recipients will be announced in mid-September.

An important distinction from the ICM is the bottom-up nature of ICIAM minisymposia. For ICIAM, it's the community that proposes minisymposia, almost all of which are accepted. The presence of the community is clearly felt in the minisymposia, which in a sense are the heart of the congress. Keyfitz, Esteban, and Fonseca encourage readers to propose minisymposia for Beijing.

ICIAM is rapidly attaining the level of prestige associated with participation in the venerable ICM, they believe. In its relatively short history—the first ICIAM was held in Paris in 1987—the high standards of ICIAM member societies, host countries, and scientific program committees have led to steady increases in the recognition accorded invited speakers at ICIAM.

What Industry-related Activities Are Planned for ICIAM 2015?

As a leader in launching the EU-MATHS-IN project, Esteban is deeply invested in the subject of industrial math. Even with several minisymposia devoted to the subject on the ICIAM program, she sees "a need to increase the presence of industrial math at ICIAM."

In Europe, she says, realizing that different countries approach industrial math in different ways, "we decided to sit down together and see what works and what doesn't. Maybe this European experience could be amplified at the world level." Europe is relatively homogeneous, even counting Eastern Europe, compared with the rest of the world. Increasing the impact of mathematics on society in countries that haven't thought about or tried to improve the way they organize industrial math is a challenge, one that's well worth taking on!

One of the main reasons to attend an international meeting is to share and learn from the experiences of others. ICIAM could become a great forum to make industrial mathematics known, Fonseca says.

■ ■ ■

In engaging in the community-oriented activities touched on in this narrative version of their conversation at MBI, Fonseca, Esteban, and Keyfitz maintain a delicate balance with the well-respected research for which each is known.

Esteban, perhaps less familiar than Keyfitz and Fonseca to many in the SIAM community, in a sense speaks for all three when she writes in an email message to *SIAM News*:

"At especially busy times, I cannot think about my research for weeks. . . . But when you are involved in some research project that is going well, you manage to find time. . . .

"When I started my career, I saw myself doing research, and not more. I never thought that I would spend so much time in extra-research activities. . . ."

In one way or another, she continues, "I started doing this at my university, and then I got involved in [the French applied mathematics society] SMAI, and from this I jumped to the European scale by getting involved in some committees in the European Mathematical Society, and finally came ICIAM and other international engagements that I have or have had in the past. I suppose that at some point I kind of liked some of the things that can be achieved by doing this kind of work."

Readers interested in learning more about ICIAM and the status of the program for ICIAM 2015, which will be held in Beijing, August 10–14, are encouraged to visit www.iciam2015.cn/—and to propose minisymposia.

Mathematics as Play

Math Bytes: Google Bombs, Chocolate-Covered Pi, and Other Cool Bits in Computing. By Tim Chartier, Princeton University Press, Princeton, New Jersey, 2014, 152 pages, $24.95.

BOOK REVIEW

By Philip J. Davis

Of what use is mathematics? Over the years, answers have ranged widely. In *The Handmaiden of the Sciences* (1937), E.T. Bell was reflecting a common opinion. Earlier, Bertrand Russell considered mathematics the cat's meow because of its logic. Another opinion has God as a mathematician who created the cosmos along mathematical lines.*

It is also the case that the use of mathematics has been panned and subjected to derision: Recently, path-breaking but controversial French economist Thomas Piketty berated his profession for its "childish passion" for mathematical economics and neglect of its history. Other have looked on the knowledge and use of mathematics as an ego trip.

So who needs mathematics? How much math does a checkout clerk in the supermarket need to know? Does your primary care physician need to know any mathematics other than, perhaps, the qualitative distinction between low- and high-dose aspirin tablets? Is 81 mg vs. 325 mg of any importance to a physician other than as identifiers for prescriptions?

And yet, during a recent hospitalization for several days, I was impressed by the extent to which medical diagnosis and practice have been computerized, chipified, graphisized, netisized by pieces of hardware/software to which I had been hooked up. I began to feel that as far as the doctors and nurses were concerned, my identity had been replaced by a vector of numbers. Talk about identity theft!

How much and what mathematics should be required for a diploma are currently hot topics in educational circles and in the media. NECAP (the New England Common Assessment Program in K–12 math, reading, and writing) has both elicited praise and aroused fury.

All this points to mathematics as utilitarian: for use in analyzing and describing, interpreting, planning, constructing, predicting, prescribing, preventing, teaching, and—alas—occasionally in doing damage.

Yet mathematics has another face, one that I became aware of long ago as a 6th grader. One day, on the top of the family piano, I found four old volumes, bearing the title *Rational Recreations*: *in which the principle of numbers and natural philosophy are clearly and copiously elucidated by a series of entertaining interesting experiments. Among which are all those commonly performed with the cards.* By William Hooper, MD, they were published in London, in 1787.

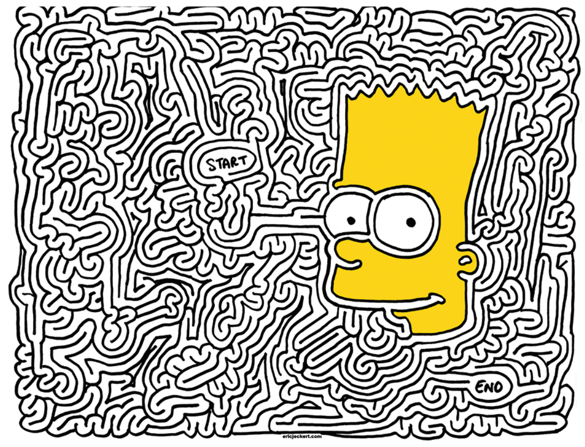
I assume that my older brother, who was then a graduate student at MIT, found and bought these books because he was amused by their experiments in physics (pneumatics, hydrology, pyrotechnics). Many of the card tricks in the books have mathematical underpinnings. Then there are numerical tricks that go like this: Think of a number (but don't tell me); do this and that, and tell me what your number is now. Then your number was such and such.

Mathematical play, though rarely imposed by physical necessity or moral duty, can lead to insight and development. Nathalie Sinclair, in *Mathematics and the Aesthetic,* writes that

> "[Johan] Huizinga [in a path-breaking study of human play] alluded to the possibility that in 'mathematical play', the mathematician is aesthetically exploring certain structures or trying to impose or reveal structures and patterns."

Tim Chartier, a professor of mathematics at Davidson College, has put together a delightful book of recreational mathematics. His presentation of a large array of topics is accompanied by excellent graphics, many in color. The book has plenty of competition—the recent Dover catalog for mathematics and science lists easily 50 books under "recreational mathematics." But Chartier has his own, often novel selections, which should attract wide popular attention. Among them are: the game of 30 questions, creating fractal islands, ranking athletic teams (or, in the case of Google's PageRank, web pages), image identification and alteration, the topology of doodling, painting via number theory, a game called google-opoly, Bart Simpson as a maze, and many, many others.

In sum, a fun book.



Bart Simpson as a maze. From Math Bytes.

Books Mentioned in this Review

William Hooper, *Rational Recreations*; a free online version is available at books.google.com/books/about/Rational_Recreations.html?id=iOQ4AAAAMAA.

Johan Huizinga, *Homo Ludens: A Study of the Play-Element in Human Culture*, Beacon Press, 1971.

Nathalie Sinclair, David Pimm, and William Higginson, eds., *Mathematics and the Aesthetic: New Approaches to an Ancient Infinity*, Canadian Mathematical Society Books in Mathematics, Springer, 2006.

Philip J. Davis, professor emeritus of applied mathematics at Brown University, is an independent writer, scholar, and lecturer. He lives in Providence, Rhode Island, and can be reached at philip_davis@brown.edu.

*See my article "A Brief Look at Mathematics and Theology," *Humanistic Mathematics Network Journal*, (27) 2004.

Bike Tracks

continued from page 1

pedigree of the Schrödinger equation, nor does it have the same rich history. Still, the problem has been studied since at least the 1870s (see [3] and references therein). It arises in differential geometry, and also as a model problem in engineering applications; a brief review and further discussion can be found in [4]. (Amusingly, the bicycle can be used to measure areas enclosed by planar curves: The actual device, the Prytz planimeter, is named after its inventor Holger Prytz, a 19th-century Danish cavalry officer.) A beautiful observation of R. Foote [3] gave rise to further developments, including a solution of Menzin's conjecture from 1908 [8].

To describe the connection between the Schrödinger equation and the tire track problem, I specify a recipe that assigns, to every Schrödinger potential $p(t)$, the path $(X(t), Y(t))$ of the front wheel in such a way that the Schrödinger equation and the "bicycle equation" are equivalent via an explicit transformation, as explained below.

To understand how the Schrödinger potential p generates the front wheel path, consider a particle of mass $m = 1$ whose speed v is a prescribed function of time, and whose direction of motion is determined by the force

$$F_N = a_N = v(2 - v) \qquad (2)$$

acting in the direction normal to the velocity vector (see Figure 3). Unlike the true magnetic force, this magnetic-like force is not linear in v. We can think of our particle as a rocket with the "thrust" force acting tangentially to the path, and with the normal "magnetic" force (2) determined by v. Given $v = v(t)$, the law (2) determines the path $(X(t), Y(t))$ of the particle completely, provided that we fix the initial point and the initial direction. As an example, if we hold v constant, we get uniform circular motion, except in the case of $v = 0$ or 1, when uniform rectilinear motion results. Figure 4 shows trajectories for $v = \alpha + \beta/(1 + t^2)$ and $v = \alpha + \beta \cos t$. Trajectories for v of the form $v = \alpha + \beta \cos t + \gamma \cos 2t$ with various choices of α, β, γ are shown in Figure 5.

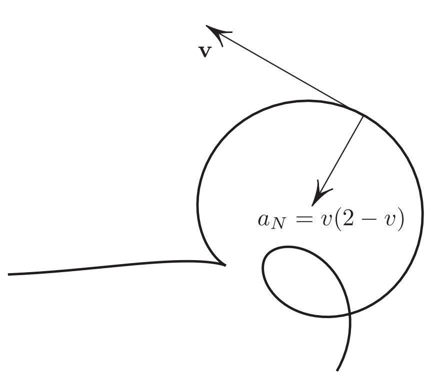


Figure 3. *A quasi-magnetic force.*

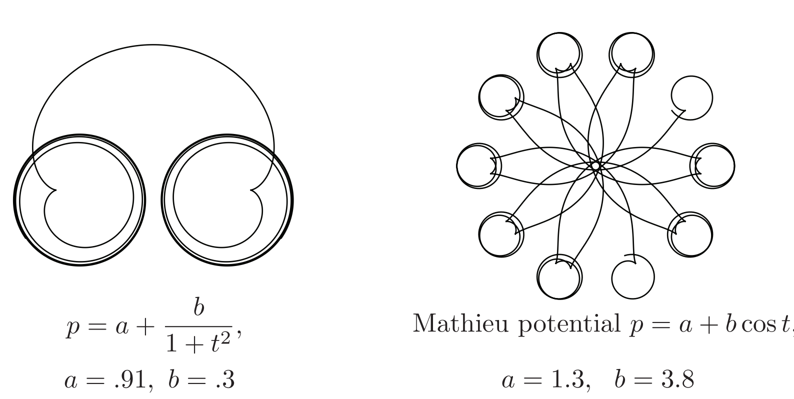


Figure 4. *Paths of a particle subject to the strange quasi-magnetic force for various choices of speed $v = v(t)$. Each of these paths corresponds to a Schrödinger potential $p = p(t) = 1 - v(t)$.*

Given a Schrödinger potential $p = p(t)$, we define $v = v(t) = 1 - p$. With v thus prescribed, consider the motion $(X(t), Y(t))$ of the "magnetic" particle, as outlined in the preceding paragraph. If we now think of $(X(t), Y(t))$ as the path of the front wheel F, as shown in Figure 1, we find that the angles θ of the bike and the solutions x of the Schrödinger equation are related via the transformation

$$\theta = 2 \arg(x + i\dot{x}) + \varphi, \qquad (3)$$

where $\varphi = t + \int_0^t p(s)\, ds$. With the transformation (3), we have converted one problem into another. More explicit details on the equivalence can be found in [7].

To summarize, each Schrödinger potential p can be represented as a front wheel path of an equivalent "bike" problem, as illustrated in Figures 4 and 5; in the former, the potential $p = 1 - v$. In conclusion, the equivalence described raises the interesting prospect of translating known results obtained for one problem to better understand the other.

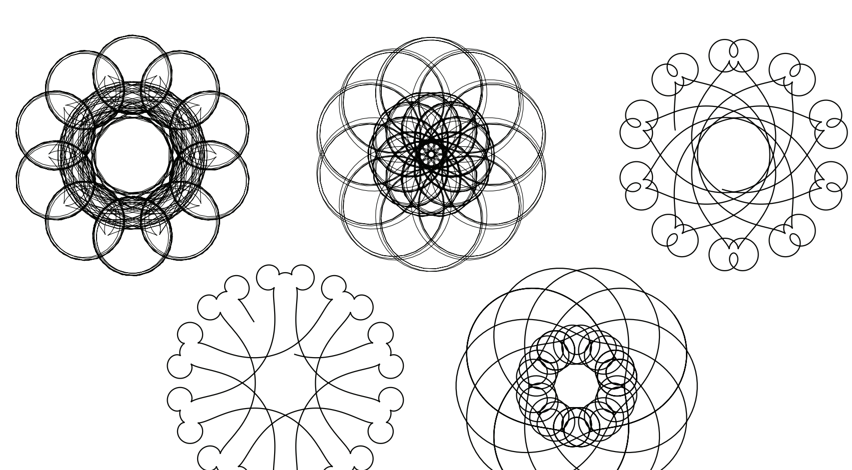


Figure 5. *Schrödinger potentials $p = a + b \cos t + c \cos 2t$ represented as equivalent bike paths for different choices of a, b, c.*

Acknowledgments

The author's research was supported by NSF grant DMS–0605878.

References

[1] V.I. Arnold, *Remarks on the perturbation theory for problems of Mathieu type*, Russ. Math. Surveys, 38 (1983).

[2] H.W. Broer and C. Simo, *Resonance tongues in Hill's equations: A geometric approach*, J. Differential Equations, 166:2 (2000), 290–327.

[3] R.L. Foote, *Geometry of the Prytz planimeter*, Rep. Math. Phys., 42:1–2 (1998), 249–271.

[4] R.L. Foote, M. Levi, and S. Tabachnikov, *Tractrices, bicycle tire tracks, hatchet planimeters, and a 100-year-old conjecture*, Amer. Math. Monthly, 120:3 (2013), 199–216.

[5] M. Levi, *Geometry and physics of averaging with applications*, Phys. D, 132 (1999), 150–164.

[6] M. Levi, *Stability of the inverted pendulum—A topological explanation*, SIAM Rev., 30 (1988), 639–644.

[7] M. Levi, *Schrödinger's equation and bike tracks—A connection,* 2014; http://arxiv.org/pdf/1405.1741.pdf.

[8] M. Levi and S. Tabachnikov, *On bicycle tire tracks geometry, Menzin's conjecture, and oscillation of unicycle tracks*, Exp. Math., 18:2 (2009),173–186.

[9] D.M. Levy and J.B. Keller, *Instability intervals of Hill's equation*, Comm. Pure Appl. Math., 16 (1963), 469–476.

[10] W. Paul, *Electromagnetic traps for charged and neutral particles*, Rev. Modern Phys., 62 (1990), 531–540.

[11] M.I. Weinstein and J.B. Keller, *Asymptotic behavior of stability regions for Hill's equation*, SIAM J. Appl. Math., 47 (1987), 941–958.

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

Where Are Our Free Student Members Today?

TALK OF THE SOCIETY

By James Crowley

SIAM offers free memberships to almost all interested students. Only a small fraction of these student members go on to become professional (paying) members of SIAM. Because the SIAM Board of Trustees allocates a lot of money to provide the free student memberships, we naturally wonder why the fraction who later become full members is so small. To answer the question, we conducted a small study, sampling a group of former SIAM student members to learn where they are now. The study is illuminating with respect not only to the SIAM membership, but also to the early career paths of people who were once SIAM student members.

Remarkably, a total of 22,625 individuals have had free SIAM student memberships at some time in their careers. During the period from 2003 to 2013, 18,480 individuals had free student memberships. To put this in perspective: US academic institutions produce about 1000–1500 PhDs per year across the mathematical sciences. Also in 2003–2013, 1325 of SIAM's paying members had had free student memberships at some time.

Why don't more student members convert to paying members? What happens to these free student members? Where do they go? What do we know about their subsequent career paths?

Here's the succinct answer to the last question: very little. Hence our small study, for which we took a sample of individuals who had free student memberships in 2005 and attempted to learn, from our own records and from publicly available sources, something about the individuals' careers. In this information, we hoped to find clues that would help us answer the other questions.

The Study

We did not intend to conduct a rigorous, statistically valid study. Rather, we gathered information from our own records and public sources (the web and LinkedIn) for a relatively small sample: 218 randomly selected individuals who had free student memberships in 2005. From our records we obtained the years and types (student, postgraduate, regular) of the individuals' SIAM memberships. We also attempted to find, either from our records or from public sources, the highest degree earned, the year and the institution that awarded it, and the student's major field. Finally, we searched public records for information about individuals' employment after graduation—job title(s) and employer(s), which we categorized by type.

For many students, involvement in SIAM comes through chapters at their universities. Pictured here are members of the University of Manchester chapter in early May, at their 2014 student conference. Courtesy of Nicholas Higham.

To protect the privacy of individuals, we report only generic data. All data reported is as of the end of 2013.

One of the interesting things about data in today's world is that most people can be found on the Internet, and quite a bit of their history is available.

Inspection of general membership data for the 218 individuals in the study revealed that they had free SIAM memberships for an average of about 3.7 years; for students in doctoral programs in applied math, the average was slightly higher, at 3.9 years.

The Bottom Line

The probability of an individual who had a free student membership in 2005 becoming a paying member at any time in the future is .17. The probability of such an individual still being a SIAM member (of any kind) is .11. It is these rather low numbers that led us to embark on our study of student members who did not convert to regular SIAM membership after completing their studies.

We began by looking for the highest degrees attained by the 218 individuals in our sample. For those whose highest degree could be determined, the breakdown was: bachelor's (6), master's (36), PhD or the equivalent (161).

We looked further into each category to see if we could learn what happened to the individuals who did not become SIAM members after completing their studies.

Easiest First: Terminal Master's Degrees

When we mention SIAM student members, our first thought might be of students in standard doctoral degree programs. That is the case for many SIAM student members, but not all. Some complete terminal master's degrees and find employment outside academia. And some who were student members in 2005 were still in degree programs in 2013.

What is the probability that someone with a terminal master's degree becomes a paying SIAM member at some point? The answer, unfortunately, is close to zero. Not one of the 36 master's students in our sample became a paying SIAM member.

Where did those 36 individuals go? Of the 26 for whom we could find information: Two teach at community colleges; two are computer technicians (full-time) at the universities where they studied; five are still students; 12 work in industry; and three took jobs in national labs. Following less expected paths, two are now technical/science writers.

Those working in industry have what appear to be good technical jobs, at companies that include Fluke Networks

See **Student Members** *on page 6*

Student Members

continued from page 5

and Ericsson (Sweden); Comstock Canada Ltd.; and Signal Innovations Group, Nestle USA, Blue Cross, Northrop Grumman, Bloomberg, and Shell Upstream (all in the US).

Many of those with master's degrees are "code warriors"—writing computer code or managing groups that do, with job titles like software development engineer or software designer. Their work does not tend to involve numerical algorithms or scientific computing, and SIAM thus becomes less relevant to their work experience. Others in this group work in fields closer to SIAM, using, for example, optimization techniques for scheduling or demand planning. Job titles include demand planner, planner and scheduler, financial software developer, software engineer, actuary, computer technician, and data security analyst.

It is worth pointing out that people with terminal master's degrees are not necessarily dropouts from PhD programs. Providing confirmation are individuals with multiple master's degrees in fields relevant to their work.

Bachelor's Degrees

SIAM does have student members who are undergraduates, perhaps through the student chapters at their universities. The very small size of our sample makes it hard to distinguish trends. One person became a fairly well-known science fiction writer, and another is teaching at a community college. It seems fair to say that people who are undergraduates in math or related disciplines go on to pursue diverse careers.

Doctoral Degrees

We are most interested in the group who eventually received PhDs, as these are the individuals most likely to become regular SIAM members. Of the 218 individuals in the study, we know that at least 160 (73.4%) received PhDs in SIAM-related disciplines. There may be a few more, but we suspect that a large proportion of those who could not be found on the web did not complete PhD programs.

The 160 who were identified as receiving PhDs represent a diverse set of departments/majors: mathematics (42); applied mathematics (32); computer science (21); and mechanical and electrical engineering (11 each). The remaining individuals were scattered among operations research, aeronautical or astronautical engineering, materials science, earth sciences, nuclear engineering, biomedical engineering, and others. Indeed, SIAM student members are a diverse lot.

We were unable to identify where 17 (10.6%) of them went. Some clearly left the discipline; one, for example, went to vet school and now works at an animal hospital. Of the 143 whose paths to relevant careers could be tracked, 60.1% were in academia, 30.1% in industry, 3.5% in national labs, 3.5% in medical centers; one each (.7%) was working in government, national academies, or not-for-profit organizations, or was unemployed. The actual percentage of unemployed subjects is likely to be higher—they could be among those who could not be found in public sources.

Of the 86 in academia, 19 were in small colleges/universities, and 63 were at institutions that grant advanced degrees in a relevant discipline. Of the individuals at PhD-granting institutions, a fairly large number were still in what appear to be temporary positions (as postdocs, visiting lecturers, or research associates). Only 30 individuals listed positions with titles like associate or assistant professor; for nine of them, the position title could not be identified.

Each year, representatives of SIAM student chapters share their experiences over breakfast at the SIAM Annual Meeting. Shown here are participants in the 2013 event in San Diego. Photo by Susan Whitehouse.

Forty-two of the PhDs (19.3% of the total sample, 26% of the PhDs, 29.4% of those we could identify) were working in industry. The companies occupy a diverse set of industrial sectors: computer hardware, consumer products, consulting, engineering, banking/finance, health care, Internet services, manufacturing, petrochemicals, software, and telecommunications. The others were in miscellaneous fields—one person, for example, was working at a field station for a geophysics company.

Given the relatively large number of individuals in this group, we wanted to know the probability of a PhD who took a job in industry becoming a paying SIAM member at any time. The answer: .09. And of such an individual still being a SIAM member: .07. Obviously, our retention of PhDs who find employment in industry lags behind that for people who stay in academia.

The department/major of an individual's degree also makes a difference: Those with PhDs in applied mathematics are more likely to remain SIAM members after receiving their degrees than those in other fields. The probability that an individual with a PhD in applied mathematics remains a SIAM member after completing the degree is .25; the probability drops to .21 for PhDs in mathematics or computer science, to less than .1 for electrical or mechanical engineering.

What Did We Learn?

While the conversion rate of free student memberships to regular (paying) memberships after graduation seems low, we believe that there are reasonable explanations. Certainly, completion of a relevant graduate degree is important. An individual's major, and type of employment after receiving a degree, play a role; people in jobs unrelated to areas covered by SIAM are unlikely to continue as members.

Clearly, those who are working or closely involved in SIAM-related areas are more likely to continue in SIAM. To approach this hypothesis from another angle, we looked at 32 individuals who received student travel awards in 2005 or 2006, on the assumption that people who participated in SIAM conferences as students would be more closely engaged in SIAM-related endeavors.

Of this group, eight were never SIAM student members (student membership is not required to compete for a travel award); 15 (47%) eventually became paying SIAM members, and nine are still paying SIAM members. This is a much higher conversion rate than that for our free student members. The reason is most likely that SIAM activities are more aligned with the interests of conference-goers.

SIAM student members can be first-year graduate students, who often change direction or move on to other activities before completing degrees. Some take jobs of various types in industry, where SIAM programs may be less relevant. They form a very diverse group. Those who do complete degrees and find jobs for which SIAM is relevant to their careers have a much higher probability of retaining their association with SIAM.

Professional Opportunities

Send copy for classified advertisements to: Advertising Coordinator, SIAM News, *3600 Market Street, 6th Floor, Philadelphia, PA 19104–2688; (215) 382–9800; fax: (215) 386–7999; marketing@siam.org. The rate is $2.85 per word (minimum $350.00). Display advertising rates are available on request.*

Advertising copy must be received at least four weeks before publication (e.g., the deadline for the September 2014 issue is July 31, 2014).

Advertisements with application deadlines falling within the month of publication will not be accepted (e.g., an advertisement published in the September issue must show an application deadline of October 1 or later).

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 COMPUTATIONAL ENGINEERING & SCIENCES

The *Institute for Computational Engineering and Sciences (ICES)* at *The University of Texas at Austin* is searching for exceptional candidates with expertise in computational science and engineering to fill several Moncrief endowed faculty positions at the Associate Professor level and higher. These endowed positions will provide the resources and environment needed to tackle frontier problems in science and engineering via advanced modeling and simulation. This initiative builds on the world-leading programs at ICES in Computational Science, Engineering, and Mathematics (CSEM), which feature 16 research centers and groups as well as a graduate degree program in CSEM. Candidates are expected to have an exceptional record in interdisciplinary research and evidence of work involving applied mathematics and computational techniques targeting meaningful problems in engineering and science. For more information and application instructions, please visit: www.ices.utexas.edu/moncrief-endowed-positions-app/. This is a security sensitive position. The University of Texas at Austin is an Equal Employment Opportunity/Affirmative Action Employer.

THE UNIVERSITY OF TEXAS AT AUSTIN

NSF's Math Sciences Innovation Incubator Supports Multidisciplinary Research Collaborations

The Division of Mathematical Sciences at the National Science Foundation aims to enhance the synergistic relationships between the mathematical sciences and other NSF-supported disciplines through the Mathematical Sciences Innovation Incubator activity. The MSII activity encourages and supports new research collaborations among mathematical scientists and other scientists and engineers working in NSF-supported research areas of high national priority by:

- facilitating DMS co-review and co-funding of multi-disciplinary research collaborations involving mathematical scientists;
- providing leverage for investments of non-DMS NSF programs in projects that include mathematical scientists; and
- providing a uniform mechanism through which collaborative research teams involving mathematical scientists can request DMS co-review.

For more information, readers can visit the MSII page (http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505044&org=DMS). A more detailed announcement can also be found at http://www.nsf.gov/pubs/2014/nsf14063/nsf14063.jsp.

Announcements

Send copy for announcements to: Advertising Coordinator, SIAM News, *3600 Market Street, 6th Floor, Philadelphia, PA 19104–2688; (215) 382–9800; marketing@siam.org. The rate is $1.85 per word (minimum $275.00). Announcements must be received at least one month before publication (e.g., the deadline for the September 2014 issue is July 31, 2014).*

Tenth Mississippi State Conference on Differential Equations and Computational Simulations
October 23–25, 2014
Mississippi State University
Starkville, MS

The Tenth Mississippi State Conference on Differential Equations and Computational Simulations will be held from October 23 to 25, 2014, at Mississippi State University. This interdisciplinary conference will provide a joint forum in which mathematicians, scientists, and engineers from industries, federal laboratories, and academia can exchange research and development ideas. An overall goal of this conference is to promote research and education in mathematical and computational analysis of theoretical and applied differential equations. In addition to the ten principal lectures, there will be sessions for 20-minute contributed talks. This conference is dedicated to Ratnasingham Shivaji in celebration of his 60th birthday, his outstanding contributions to differential equations, and his service to Mississippi State University.

Conference participants are encouraged to submit full length manuscripts after the conference. Reviewed manuscripts will be published as a special issue of the *Electronic Journal of Differential Equations*.

The deadline for pre-registration and abstract submission is September 5, 2014.

Funding for travel, provided by a grant from the National Science Foundation, is available to help support graduate students/recent PhDs with expenses.

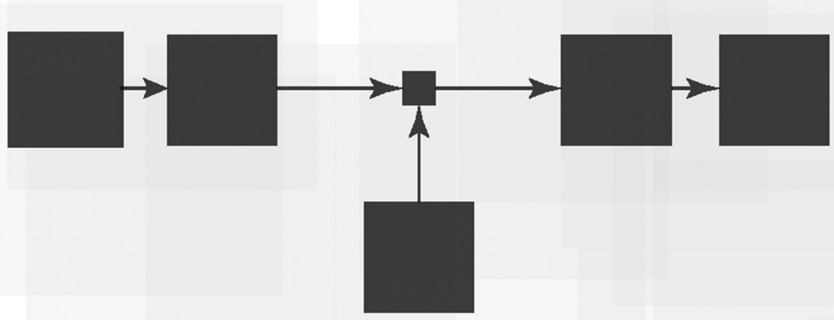
Information regarding the conference and online registration and abstract submission is available at http://www.ccs.msstate.edu/deconf/de2014/.

SPCodingSchool

January 19th to 30th 2015 – Campinas, Brazil

SP Coding and Information School

The SPCodingSchool is a two week long school on coding and information theory which will be held in Brazil January 19 to 30, 2015. Leading researchers in these areas will give both introductory and advanced courses. Students (up to 90) will be fully supported by Fapesp (including flight tickets and a grant to cover other expenses).



Where: University of Campinas (Unicamp), Campinas - Brazil
When: January 19, 2015 to January 30, 2015
Intended audience: Graduate students in Mathematics, Electrical Engineering or Computer Science. A small amount of grants may be given to advanced undergraduates and new doctors.
Financial support: flight tickets + generous grant to all selected students (up to 90, including international students).
Website: http://www.ime.unicamp.br/spcodingschool
Contact: spcodingschool2015@gmail.com

SPEAKERS

Alexander Barg (University of Maryland), Amin Shokrollahi (EPFL - Switzerland), Chandra Nair (Chinese University of Hong Kong), Danilo Silva (UFSC - Brazil), Emmanuel Abbe (Princeton - United States,TBC), Frédérique Oggier (Nanyang Technological University - Singapore), Henk Van Tilborg (TUE - Nederlands), Jean-Claude Belfiore (Télécom Paris Tech - France), João Barros (Universidade do Porto - Portugal), Madhu Sudan (Microsoft Research - United States,TBC), Max Costa (Unicamp - Brazil), Michelle Effros (Caltech - United States), Ninoslav Marina (Haute Ecole ARC - Switzerland), Ram Zamir (Tel Aviv University - Israel), Reginaldo Palazzo Jr. (Unicamp - Brazil), Sueli I. R. Costa (Unicamp - Brazil), Valdemar C. da Rocha Jr. (UFPE - Brazil).

Designers Fine-tune the Aerodynamics of World Cup Soccer Balls

By James Case

The FIFA World Cup of football (soccer in the US) has been contested quadrennially since 1930, with a gap between 1938 and 1950 because of World War II. In the early years, the host country furnished the official match balls, which were sometimes of disputed quality. Adidas, which began making soccer balls in 1963, won the contract to furnish the official World Cup ball in 1970, and has yet to relinquish it. That year's ball, dubbed the "Telstar," was the first to consist of 12 black pentagonal leather panels and 20 hexagonal white ones, stitched together to resemble a truncated icosahedron, or "buckyball." The blend of black and white panels made the redesigned balls especially visible on the black and white TV screens of the day.

Until 1954, soccer balls consisted of a dozen roughly rectangular panels. The balls for that year's World Cup in Switzerland were the first to be made of 18 such panels, in an effort to produce a more nearly spherical ball better able to hold its shape under game conditions. Because leather balls absorb water when used in the rain, and because the added weight causes head and neck injuries, repeated efforts were made to develop satisfactory rubber balls, as well as water-resistant coatings for leather ones. For the 1982 World Cup, played in Spain, Adidas supplied the Tango ball, which had rubber inlays over the seams to make the surface smoother and to keep water from seeping in. But the rubber wore unevenly during play, and the balls had to be replaced as the games went on. That was the last genuine leather ball used in World Cup play; subsequent models were made of polyurethane. The Fevernova, used in the World Cup sponsored by Korea and Japan in 2002, was the last to use the 32-panel buckyball configuration.

For the 2006 World Cup, held in Germany, Adidas introduced the radical Teamgeist design, whose 14 "thermally bonded" panels were intended to create a smooth, consistent kicking surface, making the trajectory more nearly independent of the part of the ball that was kicked. The Teamgeist was followed four years later by the even more radical Jabulani, whose eight "spherically molded" and thermally bonded panels were intended to provide the smoothest and least deformable ball yet.

But the Jabulani was wildly unpopular with goalkeepers, who complained that balls kicked hard and without spin followed erratic paths, similar to those of a knuckleball in baseball, making them hard to catch. This is clearly unfair—some of the paths followed by such a ball will be far more erratic than others, increasing the role of chance relative to skill in the outcome of games. The ball selected for the 2014 World Cup in Brazil—the Brazuca—has been subjected to extensive wind tunnel testing, in an effort to confirm that its design reduces, without completely eliminating, this "knuckling effect," a purely aerodynamic phenomenon. (The name Brazuca was chosen by public vote in Brazil, with more than a million citizens participating.)

When launched on a given trajectory, spinning balls are subject to the aerodynamic forces lift and drag. Drag acts in the direction opposite to that of the velocity vector, lift in a direction orthogonal to both the velocity vector and the ball's axis of rotation. Despite the lack of any axis of rotation, spinless balls remain subject to normal forces acting in directions orthogonal to the velocity vector. And these forces, having no obvious preference among the available directions, tend to change abruptly and unpredictably in both direction and magnitude, thereby producing the erratic trajectories so vexing to catchers and goalkeepers.

Stanley Corsin, a professor of mechanics at Johns Hopkins University, studied such trajectories during the 1950s, in part by dropping spinless ping pong balls down the three-story stairwells outside his office in Maryland Hall. He also persuaded Hoyt Wilhelm, then of the Baltimore Orioles and one of the most accomplished knuckleball pitchers in baseball history, to participate in a series of tests conducted at the Army's Aberdeen Proving Ground.

The recent comparative wind tunnel tests on the Jabulani and Brazuca balls measured both drag and normal forces. It has long been known that almost any smooth convex projectile will experience a relatively sudden and rather dramatic increase in drag as its speed is reduced by atmospheric friction. This "drag crisis" kicks in at higher speeds for perfectly smooth balls than for those with appreciably rougher surfaces. Indeed, Adidas was obliged to roughen the surface of the Jabulani ball prior to the 2010 World Cup in an effort to make it follow trajectories similar to those of its predecessors. Significantly, the six-panel Brazuca has 68% more total seam length (and therefore roughness) than the eight-panel Jabulani.

With regard to drag, the results of the recent wind tunnel experiments shown in Figure 1 are typical of various orientations. The drag coefficients for all three balls tested increased from less than 0.2 to more than 0.4 in relatively short order, assuming an intermediate value of 0.3 at airspeeds of about 12 meters per second for the Brazuca, about 17.5 m/s for the Jabulani, and about 22 m/s for a perfectly smooth ball of the same size. Such experiments had to be performed several times over, as non-uniform balls perform differently in different orientations. However, the companion results tend to confirm the expectation that the Brazuca ball is subject to significantly weaker drag forces at intermediate speeds—say 10 to 20 m/s—than the Jabulani, while the drag on both is roughly equal at speeds above 25 m/s.

Obtaining measurements of the normal forces, which are far smaller than the drag force, is more delicate. The wind tunnel experiments were conducted by Takeshi Asai and Sungchan Hong of the University of Tsukuba, in Japan, who recorded the results on a personal computer using an analog-to-digital converter with a sampling rate of 1000 Hz in test runs slightly more than eight seconds in duration. The normal forces on the two balls were measured in two different orientations (A and B) at airspeeds of 20 and 30 m/s. The results of the lower-speed tests are shown in Figure 2. Clearly, the normal forces, together with the range over which they varied, were far smaller on the Brazuca than on the Jabulani ball, in both orientations. Thus, goalkeepers in Brazil can anticipate weaker "knuckleball" effects on intermediate-speed kicks.

The results for the higher speed were less definitive, with the forces buffeting the Jabulani somewhat weaker and less variable in orientation A, but significantly stronger and more variable in orientation B. Yet because the strongest and most variable normal forces observed in any of the tests were those affecting the Jabulani in orientation B, it is at least possible that the Brazuca will outperform its predecessor on high-speed kicks as well. Results of the wind tunnel tests were forwarded for analysis to John Eric Goff, a professor of physics at Lynchburg College in Virginia and the author of a well-known book* on the physics of sports. He fit the variable drag coefficient data from Figure 1 to curves of the form

$$C_D(s) = a + \frac{b}{\left[1+e^{(s-\mu)/\sigma}\right]},$$

where the constants a, b, μ, and σ are parameters to be chosen, and constructed sample trajectories for both balls by integrating numerically the equations of motion

$$\ddot{x} = -\beta f(s)\dot{x} \text{ and } \ddot{y} = -\beta f(s)\dot{y} - g,$$

in which $\beta = \rho A/2m$, $s = \sqrt{\dot{x}^2 + \dot{y}^2}$, and $f(s) = sC_D(s)$. From this he concluded that the two balls would follow quite similar paths when launched at speeds approximating 30 m/s, but significantly different ones when launched at lower speeds.

Impressive as all this is, more could be done, for both soccer balls and baseballs. The availability of high-resolution time series data of the sort depicted in Figure 2 suggests that the addition of stochastic terms $u(t)$ and $v(t)$ to the right-hand sides of the foregoing equations of motion would permit the simulation of quite realistic knuckleball trajectories. In this way, it might be possible to test the long-standing hypothesis that knuckling effects are greatest on balls launched at or just slightly above the speeds at which the slope of the graph of $C_D(s)$ is greatest.

**Gold Medal Physics*, Johns Hopkins University Press, Baltimore, 2009.

James Case writes from Baltimore, Maryland.

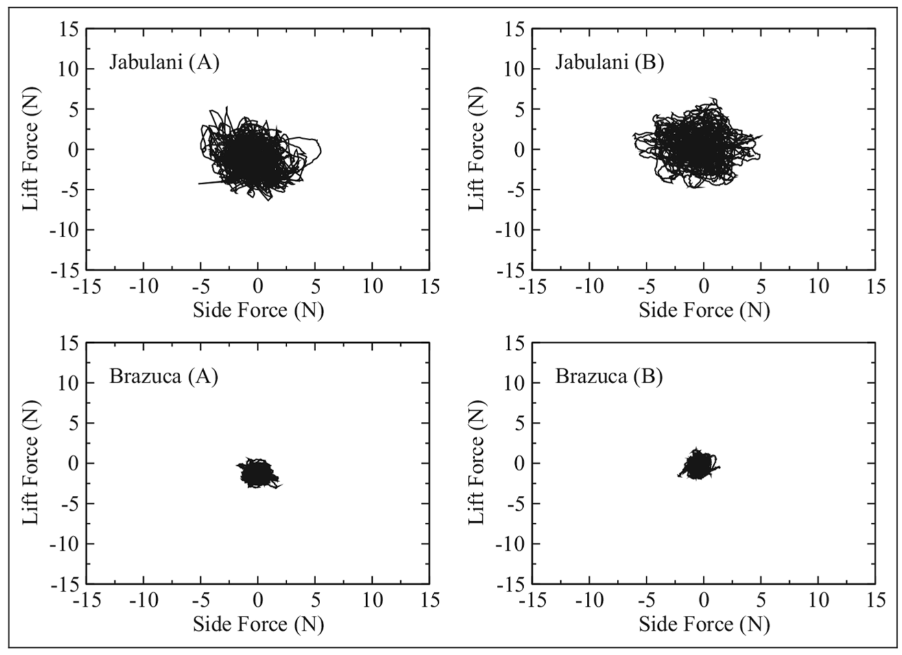


Figure 2. *Lift and side forces at an air speed of 20 m/s in studies of knuckleball effects for Brazuca and Jabulani balls in different orientations.*

Winning designs. Above, Telstar (Mexico, 1970) was the first official World Cup ball and the first to be based on a truncated icosahedron, or buckyball. Top right, Jabulani (South Africa, 2010). Right, Brazuca, the official ball of the 2014 World Cup match, which begins June 14 in Brazil. Reacting to complaints from 2010 players, Brazuca designers set out to reduce, without completely eliminating, the Jabulani's "knuckling effect."

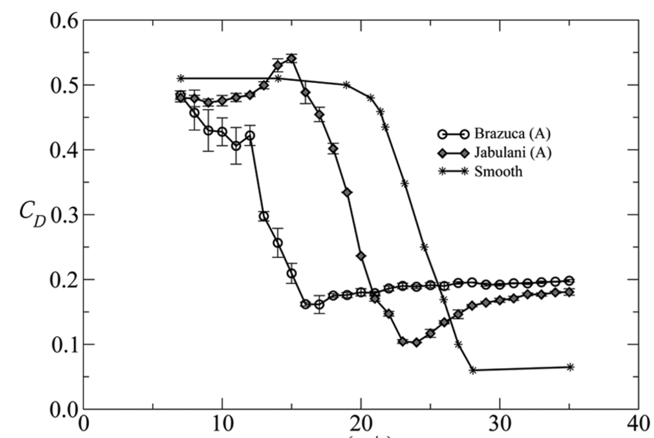


Figure 1. *Wind tunnel experimental drag coefficient results for Brazuca and Jabulani soccer balls, with error bars showing experimental uncertainty. Drag data for a soccer ball-sized smooth sphere is shown for comparison. Figures 1 and 2 reprinted with permission from J.E. Goff, T. Asai, and S. Hong, "A Comparison of Jabulani and Brazuca Non-spin Aerodynamics,"* Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, *March 2014; doi: 10.1177/1754337114526173; http://pip.sagepub.com/content/early/2014/03/17/1754337114526173.*