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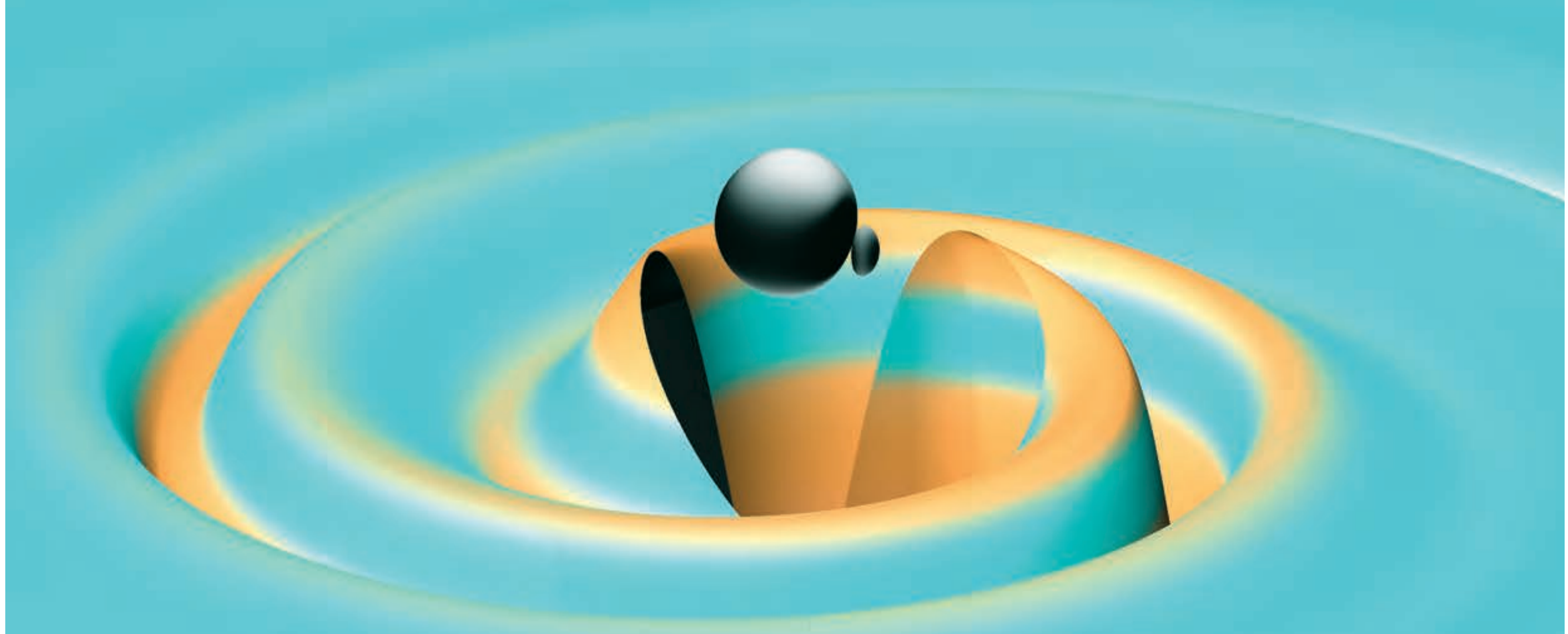
Notices

of the American Mathematical Society

August 2017

Volume 64, Number 7



AMERICAN MATHEMATICAL SOCIETY

Gravitational waves are produced by black holes spiraling inward (see page 674).

Notices
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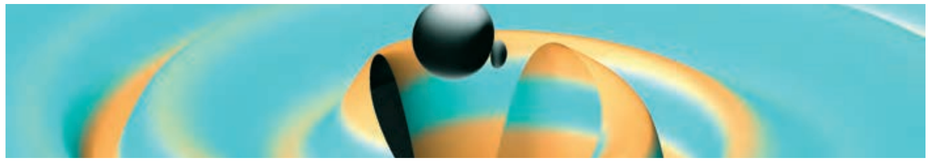

August 2017

FEATURED

*This season of the Perseid meteor shower August 12 and the third sighting in June make our cover feature on the discovery of gravitational waves stirring and profound. Later in the issue, James Tanton tells you how to prepare for Global Math Week, coming in October. Enjoy the summer while you can. —**Frank Morgan, Editor-in-Chief***

FROM THE AMS SECRETARY

COMMENTARY

ALSO IN THIS ISSUE

Notices
of the American Mathematical Society

IN EVERY ISSUE

Cover: The gravitational waves first detected December 26, 2015, came from the spiraling merger of two black holes. The cover image is from a video that shows numerical simulation of the event GW151226 associated to a binary black-hole coalescence.
Credits: Numerical-relativistic Simulation: S. Ossokine, A. Buonanno (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetimes Project.
Scientific Visualization: T. Dietrich, R. Haas (Max Planck Institute for Gravitational Physics).

Notices
of the American Mathematical Society

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LETTERS TO THE EDITOR

Online Survey of Publishing Issues

In 2016 I circulated an online survey of mathematicians, to elicit opinions on various issues related to journal publishing. The survey, which was terminated after 1,000 responses, was propagated via mailing lists (for example, by the European Mathematical Society but not by the AMS) and via direct e-mails to pseudo-randomly chosen departments and societies in order to reach a wide cross-section of the international mathematical community. The raw data is available at `https://figshare.com/projects/Survey_of_mathematical_publishing/16944`, and an analysis of the results by Cameron Neylon, David M. Roberts, and me appears in the March 2017 issue of the *Newsletter of the EMS*.

The results show widespread appetite for change. On a five-point scale, from one being "the status-quo is completely acceptable" and five being "almost all [journals] need serious work," 78 percent of respondents selected three, four, or five. Free-form comments concentrated heavily on peer review quality, administrative efficiency, price, and access, and almost 200 journals from fifty-seven publishers were mentioned by name as needing serious improvement. When asked what should happen if efforts by editors to reform a journal are blocked by the publisher, over half of respondents favored resignation, with 29 percent suggesting the editors join a better journal and 32 percent supporting creation of a new journal. Only 4.5 percent favored settling for the status quo. Respondents showed substantial support for innovations such as banning monetary payments to editors (43 percent) and editorial term limits (30 percent), credit for referees, open access, open refereeing, and election of editors. The results also show that reputation of journals is strongly believed to follow from peer review quality and editorial board research quality, while the identity of the publisher is almost negligibly important.

Interestingly, when asked what they thought the opinion of the community was on all these issues, respondents consistently rated themselves as much more progressive than the community at large. I hope that making this public will help dispel some of the myths around journal reform and encourage editors, readers, and authors to investigate changes to the status quo. I am currently involved in several projects to improve the current journal system, notably MathOA (`mathoa.org`), and welcome feedback from fellow AMS members.

Mark C. Wilson
University of Auckland
Department of Computer Science
`mcw.blogs.auckland.ac.nz`

(Received March 29, 2017)

The Daughters of John Adams

On the Back Page (Volume 64, Number 5, May 2017 issue), the editor inserts "and daughters!" into John Adams's statement, "I must study politics and war that my sons may have liberty to study mathematics and philosophy." The implication seems to be that Adams must have intended to include his daughters, even if he did not mention them explicitly, but this may be an overly generous assumption. Adams penned that line four years after Abigail Adams's famous exhortation to "remember the ladies," and so he was not unaware of the issue of women's education, but he did not make the issue a political priority. Abigail Adams Smith, the only one of his daughters to survive to adulthood, received no formal education.

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(Received May 28, 2017)

EDITOR'S NOTE. Or maybe our implication is that Adams *should have* included his daughters!

**We invite readers to submit letters to the editor to* `notices-letters@ams.org` *and post commentary on the* Notices *webpage* `www.ams.org/notices`.

American Mathematical Society

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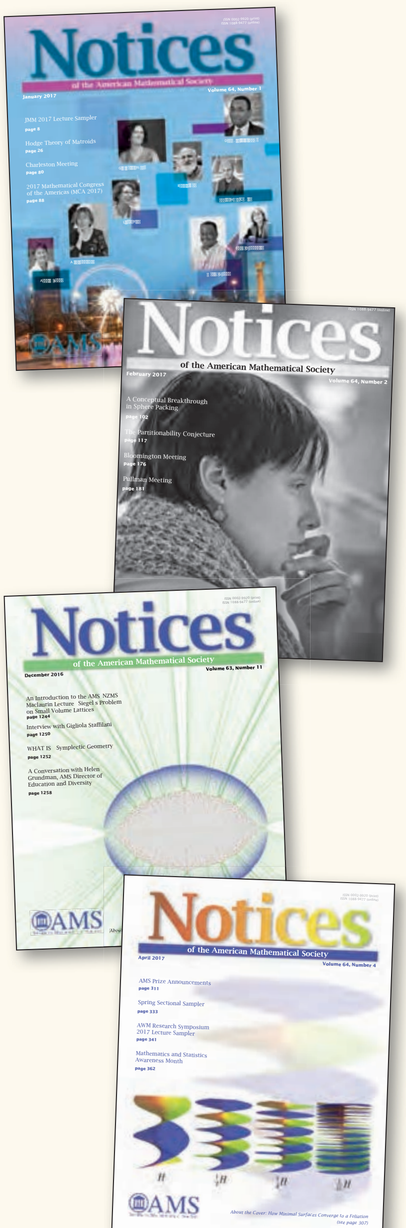
Call for Applications & Nominations

Chief Editor of the *Notices*



Applications and nominations are invited for the position of Chief Editor of the *Notices of the American Mathematical Society*, to commence with the January 2019 issue. The Society seeks an individual with strong mathematical research experience, broad mathematical interests, and a commitment to communicating mathematics to a diverse audience at a wide range of levels. The applicant must demonstrate excellent written communication skills.

The Chief Editor has editorial responsibility for a major portion of the *Notices* within broad guidelines. The goal of the *Notices* is to serve all mathematicians by providing a lively and informative magazine containing exposition about mathematics and mathematicians, and information about the profession and the Society.

The Chief Editor is assisted by a board of Associate Editors, nominated by the Chief Editor, who help to fashion the contents of the *Notices* and solicit material for publication. Some writing, and all publication support, will be provided by AMS staff. The Chief Editor will operate from her or his home base. Compensation will be negotiated for this half-time position and local part-time secretarial support will be provided. In order to begin working on the January 2019 issue, some editorial work would begin in early 2018.

Nominations and applications (including curriculum vitae) should be sent to the Chair of the Search Committee, Executive Director Catherine A. Roberts, at `exdir@ams.org`. Confidential inquiries may also be sent directly to Catherine A. Roberts or to any other member of the Search Committee (David Jerison, Mary Pugh, Kenneth Ribet, or Carla Savage).

To receive full consideration, nominations and applications should be sent on or before **September 15, 2017**.

The Travel Ban: Affected Mathematicians Tell Their Stories

Alexander Diaz-Lopez, Allyn Jackson, and Stephen Kennedy

On Friday, January 27, 2017, Donald Trump signed Executive Order 13769 banning entry into the United States by citizens of seven Middle Eastern nations. Innocent people were detained and expelled; families were divided; chaos, confusion, and discord were widespread. On Monday, January 30, the AMS Trustees issued a statement opposing the ban (see sidebar on page 680). *Notices* sought out individuals directly affected by the ban, and we report their stories here. The publication schedule of *Notices* undoubtedly means that these colleagues' situations will have changed by the time their stories appear in print.

Hamed Razavi, a recent Michigan PhD and an Iranian citizen, was prevented by the ban from returning to Ann Arbor to collect the Sumner Myers Prize.

Hamed Razavi is a postdoctoral researcher at the biorobotics laboratory of the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland. Razavi is an Iranian citizen with a bachelor's degree in mathematics and mechanical engineering and a master's in the latter discipline from Shiraz University. He came to the United States in 2010 and earned a PhD from the University of Michigan in applied mathematics in 2016.

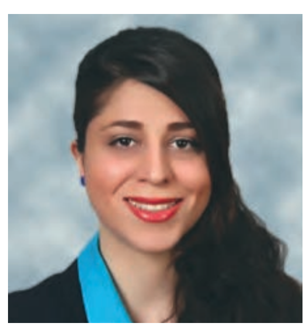
Razavi works in control theory. In his thesis, he developed a mathematical theory to design algorithms for stable periodic walking of legged robots. His work at EPFL is focused on implementing that theory. His PhD thesis was awarded Michigan's Sumner Myers Prize for the best mathematics dissertation of 2016. That prize was to be awarded this spring at a ceremony in Ann Arbor at which Razavi would describe his work. His visa application to attend that ceremony was in process when the executive order was issued. The uncertainty about his ability to enter the US forced him to deliver the lecture and receive his prize via a livestream from Lausanne on March 24.

"could negatively affect the US status in science"

—H. Razavi

Major conferences in Razavi's field are regularly held in the United States; he assumes that these are now closed to him. He had considered academic employment in the United States at the conclusion of his current postdoctoral position but assumes this option is also closed to him.

Razavi's main concern is not his own future. He is more worried about younger Iranian and Middle Eastern would-be mathematicians and scientists who will not have the opportunity for US visits and educations. He is worried about the people in the United States who might, with no warning, be cut off from families and friends again. He points too to the damage being done to the reputation and practice of US science, saying, "It is not only about the specific people that the travel ban has affected, it is also about the atmosphere that it has generated which could negatively affect the US status in science."



Behesteh Tolouei Rakhshan is a graduate student at Purdue. Her Iranian fiancé is unable to join her in the United States.

Beheshteh Tolouei Rakhshan, originally from Iran, has been a PhD student in applied mathematics at Purdue University since the fall of 2016. Because she has multiple sclerosis, she must try to avoid

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strong mental pressure and stress, which can seriously affect her physical well-being.

Since November 2013 she has been engaged to an Iranian man. The two studied at the same university in Iran and together began the application process for further study in the United States. She was accepted at Purdue, and he was accepted in applied mathematics at Georgia State University. Although they would be geographically separated, they resolved to meet every chance they could. This resolution helped Rakhshan both emotionally and physically to have the strength she needed for her studies.

Rakhshan received her F1 Visa at the United States embassy in Armenia. However, her fiancé's five visa applications were denied under Section 214(b), meaning that he did not demonstrate sufficiently strong and long-term ties outside the United States. The denials all occurred before the executive order. Now, with the executive order in place, the young couple fear they will never be able to carry out their plans. Unable to see her fiancé or her family, Rakhshan is considering leaving the United States to continue her education elsewhere. This would not be an easy decision, since she worked hard in Iran to save enough money to come to the United States and realize her educational goals. Her illness, together with the emotional stress she has endured, have left her without the concentration needed for her mathematical work.

Nima Rasekh is a graduate student at Illinois. His wife was trapped outside the country by the travel ban.

Nima Rasekh is a fourth-year graduate student at the University of Illinois at Urbana–Champaign studying homotopy theory, specifically higher category theory. Rasekh is an Iranian citizen who spent his childhood in Germany and attended high school and university in Shiraz, Iran. Rasekh spent one year at the University of Western Ontario, earning a master's degree, before moving to the United States and UIUC in fall 2013.

On the day that the travel ban was issued, Rasekh's wife, an Iranian citizen with a valid US Visa, was in Iran visiting family. The ban would prevent her from returning. He describes his life and state of mind as "completely upended" as he contemplated finishing his studies apart from her for he knew not how long. The stress and uncertainty made it difficult to work. When Judge Robarts of the district court stayed the executive order, Rasekh immediately bought a plane ticket for his wife to return, and, fortunately, she made it home. "The other lasting effect is that it just makes doing math more difficult, as I am now forced to spend a portion of every day to read news and see whether there is another executive order that will significantly affect my life," he said.

"I was hoping I could play a part in changing these conceptions."

—N. Rasekh

Rasekh plans to graduate next year and hopes for a postdoc with a strong homotopy theory group. He feels reasonably secure about being able to stay in the United States to finish his degree. But he has decided that he must focus his job search outside the United States given the uncertainty of his status here. He points out the logistical difficulty of looking for a job outside the country while simultaneously being unable to leave the country because of possible difficulty in returning. For that same reason he has stopped considering conference travel outside the United States.

Rasekh stresses that he doesn't feel that he has been particularly harmed by the ban. He is more worried about others: refugees in dire danger being denied safety, other foreigners being denied the educational opportunities he has enjoyed. He worries too about the misconceptions in the United States that lead to such policies. "There seem to be a lot of misunderstandings in this society when it comes to Iranian or in general Middle Eastern people," he said. "I was hoping I could play a part in changing these conceptions."

Camelia Karimianpour is a postdoc at Michigan whose sister was stranded in Tehran after attending their father's funeral.

Camelia Karimianpour is postdoctoral assistant professor at the University of Michigan working in representation theory of p-adic groups. She was born and grew up in Tehran and attended the University of Tehran for her undergraduate education. Her master's and PhD are from the University of Ottawa. She interrupted her graduate education to teach high school mathematics in Tehran for two years. She returned to Ottawa and earned her PhD under Monica Nevins and Hadi Salmasian with a thesis titled "The Stone-von Neumann construction in branching rules and minimal degree problems."

Karimianpour is concerned about her ability to travel outside the United States. She believes it would be "very risky" to leave the United States, though she had been anticipating traveling for conferences and collaborations to both Canada and Europe.

Much of Karimianpour's family remains in Tehran. She now feels unable to visit them, and, of course, they cannot visit her. She has a sister and brother-in-law who live in Philadelphia. In November of last year Karimianpour and her sister traveled to Iran for their father's funeral. Karimianpour returned to the United States before the ban was put in place, but her sister remained behind in Iran for an

> *"long-term effect [on] the way mathematicians, and science in general, progress"*
> *—C. Karimianpour*

extended visit. As of this writing, Karimianpour's sister remains stranded in Tehran, unable to return home to Philadelphia, because embassies will not schedule appointments to renew visas for citizens of the seven countries excluded by the ban.

As was the case with every affected mathematician with whom we talked, Karimianpour was more concerned about the effect on others and on mathematics itself than she was about her own situation. "I think we all know the progress of math benefits enormously from bright mathematicians regardless of their race, religion, or nationality. There is no doubt that limiting the access of certain bright minds to some of the elite institutions of mathematics will have a long-term effect [on] the way mathematicians, and science in general, progress." She cited two specific potential harms. First, talented young foreign mathematicians, who already have to separate from their families and friends and endure an arduous and extreme visa process, might be less willing to do that to face a tenuous future in the United States. And second, foreign mathematicians who are unaffected by the ban might just decide, either out of solidarity or a desire to avoid mistreatment at the border, to avoid scientific travels to the United States.

Photo Credits

Photo of Hamed Razavi is courtesy of Hamed Razavi.

Photo of Beheshteh Tolouei Rakhshan is courtesy of Illia Photo and Film Studio.

Photo of Nima Rasekh is courtesy of Nima Rasekh.

Photo of Camelia Karimianpour is courtesy of Camelia Karimianpour.

AMS Council Statement on Immigration[1]

The Council reaffirms its policy on immigration[2], adopted in March of 1997.

Mathematical sciences profit enormously from unfettered contact between colleagues from all over the world. The United States is a destination of choice for international students who wish to study mathematics; the US annually hosts many conferences attracting global participation. Our nation's position of leadership in mathematics depends critically upon open scientific borders. We urge our colleagues to support efforts to maintain the international collegiality, openness, and exchange that strengthens the vitality of the mathematics community, to the benefit of our nation and the world.

Note: *This Statement was adopted by the AMS Council in April 2017.*

Statement by AMS Board of Trustees[3]

The members of the Board of Trustees of the American Mathematical Society wish to express their opposition to the Executive Order signed by President Trump that temporarily suspends immigration benefits to citizens of seven nations.

For many years, mathematical sciences in the USA have profited enormously from unfettered contact with colleagues from all over the world. The United States has been a destination of choice for international students who wish to study mathematics; the US annually hosts hundreds of conferences attracting global participation. Our nation's position of leadership in mathematics depends critically upon open scientific borders. By threatening these borders, the Executive Order will do irreparable damage to the mathematical enterprise of the United States.

We urge our colleagues to support efforts to maintain the international collegiality, openness, and exchange that strengthens the vitality of the mathematics community, to the benefit of everyone.

We have all signed the online petition of academics[4] opposing the ban. We encourage our colleagues to consider joining us in signing it and in asking the Administration to rescind the Executive Order.

Robert Bryant, president of the AMS
Kenneth Ribet, president-elect of the AMS
Ruth Charney
Ralph Cohen
Jane Hawkins
Bryna Kra
Robert Lazarsfeld
Zbigniew Nitecki
Joseph Silverman
Karen Vogtmann

Note: *The AMS Board of Trustees made this statement on January 30, 2017, while Robert Bryant was AMS president. Bryant's presidential term ended two days later; he was succeeded by Kenneth Ribet.*

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[1] *April 2017 Council Statement:* www.ams.org/about-us/governance/policy-statements/statements-immigration-0417

[2] *March 1997 AMS Policy Statement:* www.ams.org/about-us/governance/policy-statements/sec-immigration

[3] *Board of Trustees Statement:* www.ams.org/news?news_id=3305

[4] *Academics Petition:* https://notoimmigrationban.com/

OPINION

International Mobility and US Mathematics

Moon Duchin

Note: The opinions expressed here are not necessarily those of Notices.
Responses on the Notices *webpage are invited.*

ABSTRACT. United States mathematical history has been shaped by social, political, and religious flows around the world. Policies fostering international exchange and mobility are essential for a healthy mathematical community.

By any account, the United States is now a world superpower on the mathematical stage. In mathematics, as in many fields, the US rose to its current prominence on the strength of flows of ideas and of people across its borders in both directions. A special role was played by immigration, as people moved around the world on strong religious and political currents.

An immigrant arguably started it: J. J. Sylvester came to the United States because his advancement was limited in Britain: a brilliant Second Wrangler of the Cambridge Tripos, he was barred from receiving a Cambridge degree by the university's (Anglican) Articles of Faith. Neither Sylvester, being Jewish, nor his contemporary Augustus De Morgan, being a "Dissenter," could be fellows or professors at Oxford or Cambridge at the time. De Morgan went only as far afield as University College London, but Sylvester ultimately struck out for the United States on two separate occasions. Here he infused US mathematics with energy and ambition and founded the nation's first mathematical journal, the *American Journal of Mathematics*, still a top journal today.

Later, turmoil in Europe completely reshaped American mathematics. Hitler rose to power in February 1933, and by April an order was issued purging Jewish citizens from national service, which included university employment. In the months and years that followed, Jewish mathematicians and other scattered undesirables and malcontents fled the Fascists. American universities seized the opportunity to raise their level of mathematics to rival the traditional European powerhouses, and US mathematics has never looked back. Einstein may be the most famous scientific name to come to our shores in those years, but Gödel, Noether, Weyl, Artin, Siegel, Bers, Courant, and von Neumann all participated in the great transformation [1]. The reception of this new crop of mathematicians was uneven, but the indisputable long-term effect was the crystallization in the United States of the strongest mathematical community in the world.

Partly as a function of its new internationalism, post-WWII America continued to attract immigrants from all over the world at the highest levels of mathematics. New research centers like the Institute for Advanced Study (founded 1930) and the Courant Institute (founded 1935) were flourishing by midcentury with a rich mix of native-born and immigrant scholars. The postwar decades brought A. Borel, Calderón, Chern, Chow, Harish-Chandra, and Hironaka, among many others, and a constant flow of visitors.

Three brief profiles will help to illustrate both the attractive force of American mathematics across the twentieth century and the stultifying effects of nationalist insularity around the world.

Chinese mathematical immigration spanned the full century, building from a trickle to a rapid flow. In 1907 Teddy Roosevelt agreed to accept political reparation money from China for the bloody, anti-Christian, nativist Boxer Rebellion in the form of the Boxer Indemnity Scholarship program: educational scholarships for Chinese students to study in the United States. By the 1930s, Chern reports that this had become a natural place for the best Chinese students to come, though he himself chose

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Europe for his studies and only came to the States when his mathematical isolation in postwar China caused him to reach out for other options [3]. Chern returned continually to China in efforts to build up a strong tradition for mathematics, but his and many colleagues' hopes were dashed amidst the repression and anti-intellectualism of the Cultural Revolution, and the work had to be begun anew in the 1980s. Meanwhile, a generation of Chinese mathematicians, most notably S.-T. Yau, had set up in the US and helped establish the pipeline of Chinese talent that today accounts for more than one in ten students in the top tier of American doctoral programs.

The aftershocks of the 1917 Russian Revolution brought us refugees and other escapees who developed pure and applied mathematics in the States, including Lefschetz, Tamarkin, Timoshenko, and Zariski. Later, it became difficult to leave the Soviet Union or even to communicate freely with the outside mathematical world. Political efforts on behalf of Soviet colleagues grew in the US through the Cold War period. In the 1970s and 1980s came a vanguard of Soviet emigrants, including Bernstein, Gromov (first to the US and later to France), Kazhdan, Ratner, Margulis, and Zelmanov, who were allowed to leave the USSR under an ostensible policy of Jewish "repatriation" that only gestured towards Israel. After the collapse of the Soviet Union in 1992, hundreds of mathematicians flooded from the Soviet bloc into other countries, many of course coming to the United States. The effects were dramatic: according to an AMS survey, immigrants from Eastern Europe and the former USSR made up 10%–13% of all new faculty hires in mathematics in 1991–92 [2].

Iran has a storied mathematical tradition with ancient and medieval Persian antecedents, and the twentieth century saw the establishment of modern universities and renewed mathematical institutions. The 1979 Iranian Revolution was devastating for intellectuals, with its own Cultural Revolution purging academics and keeping universities closed for years in the early 1980s. In mathematics Iran rebuilt a global profile with a key role played by the International Mathematical Olympiad—Iran first formed a team in the mid-1980s and became a powerhouse by the 1990s, winning outright in 1998. IMO credentials and quietly relaxed US immigration rules have made it possible for a steady stream of preeminent Iranian mathematicians to come to the States for graduate study since the 1990s, including leading young figures in geometric topology, algebraic geometry, ergodic theory, number theory, dynamics, and many other fields. This wave included Maryam Mirzakhani—first as a graduate student, then a postdoc, and now a professor and one of two American immigrants to receive Fields Medals in 2014.

To quantify the global draw of United States mathematics, consider a recent demographic analysis of one of the field's top midcareer honors, a speaking invitation at the International Congress of Mathematicians. Martin Andler conducted a study of the global displacements of the 206 mathematicians so honored at the 2014 ICM in Seoul [4]; his report confirms the leading position of US mathematics and the vital role of immigration. Only 26 of 206 speakers were born in the United States, but 85 received a US PhD and 76 have permanent jobs here, where their research programs and their teaching and training activities are fundamental elements of our continued mathematical excellence.

Generations of immigrants have made American mathematics what it is today: a world-historical magnet for talent and innovation. Some people come to the United States fleeing authoritarianism and violence; others are simply looking to a stable, open society for intellectual opportunity. Not just immigration, but, more generally, *mobility* makes the scientific community stronger through collaboration and intellectual exchange. The lessons of 150 years teach us clearly that our mathematical leadership depends on our hard-won tradition of internationalism. Science withers in closed societies.

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[1] Lipman Bers, The migration of European mathematicians to America, *A Century of Mathematics in America, Part I*, Hist. Math., 1, Amer. Math. Soc., Providence, RI, 1988, pp. 231–243. MR1003172

[2] George J. Borjas and Kirk B. Doran, The collapse of the Soviet Union and the productivity of American mathematicians, *The Quarterly Journal of Economics*, **127** (2012) no. 3, 1143–1203.

[3] Allyn Jackson, Interview with Shiing Shen Chern, *Notices Amer. Math. Soc.* **45** (1998), no. 7, 860–865. MR1633718

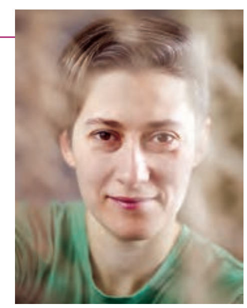
[4] Martin Andler, Who are the Invited Speakers at ICM 2014? *European Math Society Newsletter*, no. 92, June 2014.

Photo Credit

Photo of Moon Duchin is courtesy of Tufts University.

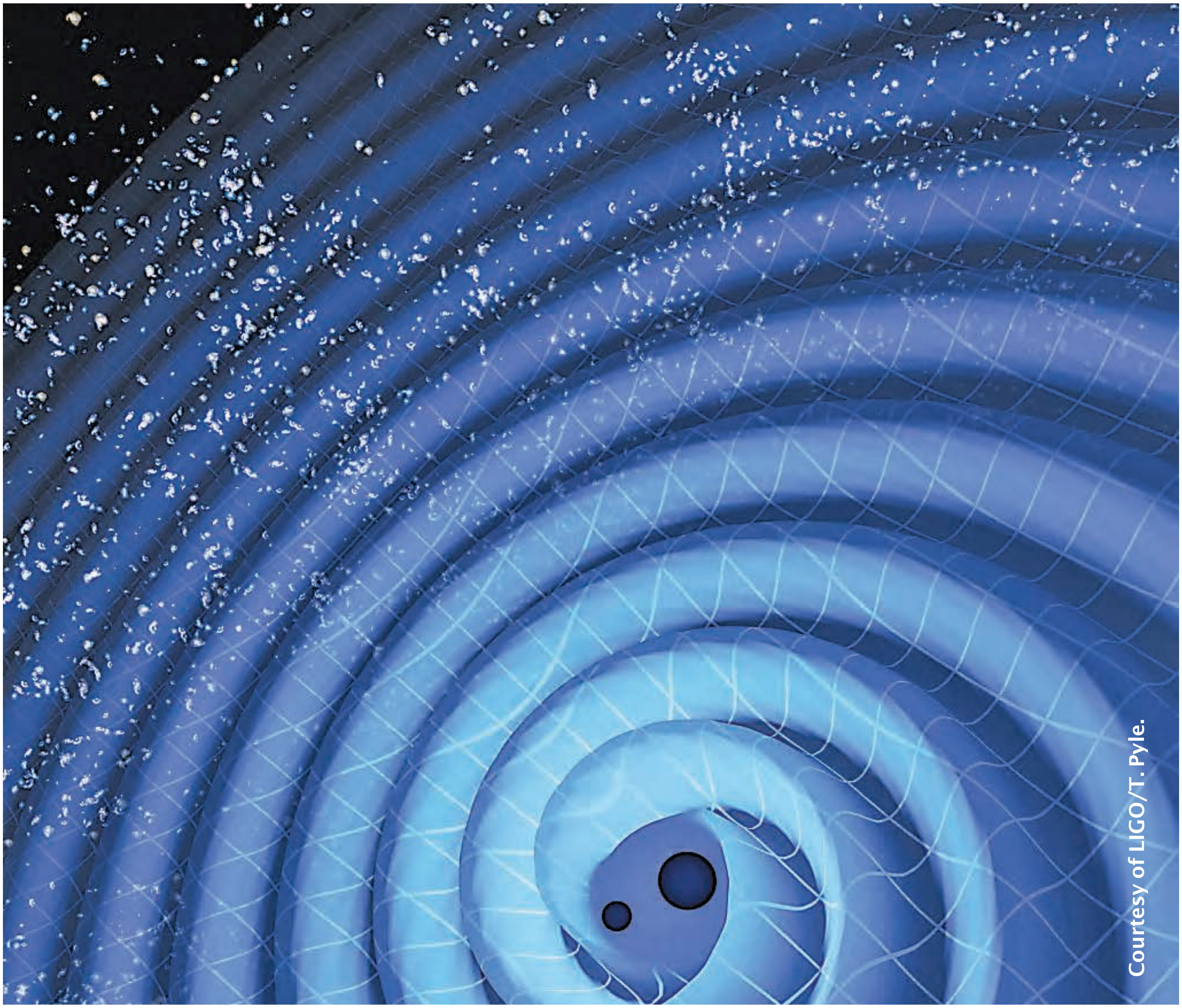
ABOUT THE AUTHOR

Moon Duchin is associate professor of mathematics at Tufts University and serves as director of the Program in Science, Technology, and Society. She is a member of the AMS Committee on Human Rights of Mathematicians.



Moon Duchin

THE MATHEMATICS OF GRAVITATIONAL WAVES



This illustration shows the merger of two black holes and the gravitational waves that ripple outward as the black holes spiral toward each other. The black holes—which represent those detected by LIGO on December 26, 2015—were 14 and 8 times the mass of the sun, until they merged, forming a single black hole 21 times the mass of the sun. In reality, the area near the black holes would appear highly warped, and the gravitational waves would be difficult to see directly.

A Two-Part Feature

Introduction by Christina Sormani

The Mathematics of Gravitational Waves

A little over a hundred years ago, Albert Einstein predicted the existence of gravitational waves as a possible consequence of his theory of general relativity. Two years ago, these waves were first detected by LIGO. In this issue of *Notices* we focus on the mathematics behind this profound discovery.

Einstein's prediction of gravitational waves was based upon a linearization of his gravitational field equations, and he did not believe they existed as solutions to the original nonlinear system of equations. It was not until the 1950s that the mathematics behind Einstein's gravitational field equations was understood well enough even to define a wave solution. Robinson and Trautman produced the first family of explicit wave solutions to Einstein's nonlinear equations in 1962. Our first article, written by C. Denson Hill and Paweł Nurowski, describes this story of how the theoretical existence of gravitational waves was determined.

Christina Sormani is a Notices *editor. Her e-mail address is* `sormanic@member.ams.org`.

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Our second article, by Lydia Bieri, David Garfinkle, and Nicolás Yunes, describes the mathematics behind gravitational waves in more detail, beginning with a description of the geometry of spacetime. They discuss Choquet-Bruhat's famous 1952 proof of existence of solutions to the Einstein equations given Cauchy data. They then proceed to the groundbreaking work of Christodoulou-Klainerman and a description of the theory behind gravitational radiation: the radiation of energy in the form of gravitational waves.

Numerical methods are used to predict the gravitational waves emanating from specific cosmological events like the collision of black holes. Starting in Section 4 of their article, Bieri et al. describe these numerical methods beginning with linearized theory and the post-Newtonian approximation first developed by Einstein. They then describe the inward spiraling (as on the cover of this issue) of two black holes coming together and the resulting waves that occur as the black holes merge into one. They close with a description of the LIGO detector and how its measurements corroborated the predictions of the numerical teams. Ultimately the LIGO detection of gravitational waves not only validated Einstein's theory of general relativity, but also the work of the many mathematicians who contributed to an understanding of this theory.

Part one by C. Denson Hill and Paweł Nurowski

How the Green Light Was Given for Gravitational Wave Search

The recent detection of gravitational waves by the LIGO/Virgo team (B. P. Abbot et al. 2016) is an incredibly impressive achievement of experimental physics. It is also a tremendous success of the theory of general relativity. It confirms the existence of black holes, shows that binary black holes exist and that they may collide, and that during the merging process gravitational waves are produced. These are all predictions of general relativity theory in its fully nonlinear regime.

The existence of gravitational waves was predicted by Albert Einstein in 1916 within the framework of linearized Einstein theory. Contrary to common belief, even the very *definition* of a gravitational wave in the fully nonlinear Einstein theory was provided only after Einstein's death. Actually, Einstein advanced erroneous arguments against the existence of nonlinear gravitational waves, which stopped the development of the subject until the mid 1950s. This is what we refer to as the *red light* for gravitational wave research.

In this note we explain how the obstacles concerning gravitational wave existence were successfully overcome at the beginning of the 1960s, giving the *green light* for experimentalists to start designing detectors, which eventually produced the recent LIGO/Virgo discovery.

Gravitational Waves in Einstein's Linearized Theory

The idea of a gravitational wave comes directly from Albert Einstein. Immediately after formulating General Relativity Theory, still in 1916 Einstein [3] linearized his field equations

$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} = \kappa T_{\mu\nu} \tag{0.1}$$

by assuming that the metric $g_{\mu\nu}$ representing the gravitational field has the form of a slightly perturbed Minkowski metric $\eta_{\mu\nu}$,

$$g_{\mu\nu} = \eta_{\mu\nu} + \epsilon h_{\mu\nu}.$$

Here $0 < \epsilon \ll 1$, and his linearization simply means that he developed the left hand side of (0.1) in powers of ϵ and neglected all terms involving ϵ^k with $k > 1$. As a result of this linearization Einstein found the field equations of *linearized* general relativity, which can conveniently be written for an unknown

$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h_{\alpha\beta}\eta^{\alpha\beta}$$

as

$$\Box\bar{h}_{\mu\nu} = 2\kappa T_{\mu\nu}, \qquad \Box = \eta_{\mu\nu}\partial^\mu\partial^\nu.$$

These equations, outside the sources where

$$T_{\mu\nu} = 0,$$

constitute a system of decoupled relativistic wave equations

$$\Box h_{\mu\nu} = 0 \tag{0.2}$$

for each component of $h_{\mu\nu}$. This enabled Einstein to conclude that *linearized* general relativity theory admits solutions in which the perturbations of Minkowski spacetime $h_{\mu\nu}$ are plane waves traveling with the speed of light. Because of the *linearity*, by superposing plane wave solutions with different propagation vectors k_μ, one can get waves having any desirable wave front. Einstein named these *gravitational waves*. He also showed that within the linearized theory these waves carry energy, and he found a formula for the energy loss in terms of the third time derivative of the quadrupole moment of the sources.

Since far from the sources the gravitational field is very weak, solutions from the linearized theory should coincide with solutions from the full theory. Actually the wave detected by the LIGO/Virgo team was so weak that it was treated as if it were a gravitational plane wave from the linearized theory. We also mention that essentially all visualizations of gravitational waves presented during popular lectures or in the news are obtained using linearized theory only.

The Red Light

We focus here on the fundamental problem posed by Einstein in 1916, which bothered him to the end of his life. The problem is: Do the fully nonlinear Einstein equations admit solutions that can be interpreted as gravitational waves?

If "yes," then far from the sources, it is entirely reasonable to use linearized theory. If "no," then it makes no sense to expend time, effort, and money to try to detect such waves: solutions from the linearized theory are not physical; they are artifacts of the linearization.

If the answer is "no" we refer to it as a "red light" for gravitational wave search. This red light can be switched to "green" only if the following subproblems are solved:

(1) What is a definition of a *plane* gravitational wave in the full theory?
(2) Does the so defined plane wave exist as a solution to the full Einstein system?
(3) Do such waves carry energy?
(4) What is a definition of a gravitational wave with *nonplanar front* in the full theory?
(5) What is the energy of such waves?
(6) Do there exist solutions to the full Einstein system satisfying this definition?

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(7) Does the full theory admit solutions corresponding to the gravitational waves emitted by bounded sources?

To give a green light here, one needs a satisfactory answer to all these subproblems. Let us explain: Suppose that only the questions (1)–(3) had been settled in a satisfactory manner. Could we have a green light? The answer is no, because, contrary to the linear theory, unless we are very lucky, there is no way of superposing plane waves to obtain waves with arbitrary fronts. Thus the existence of a plane wave does not mean the existence of waves that can be produced by bounded sources, such as for example binary black hole systems.

Search for Plane Waves in the Full Theory

Naive Approach

A naive answer to our question (1) could be: a gravitational plane wave is a spacetime described by a metric, which in some coordinates (t, x, y, z), with t being timelike, has metric functions depending on $u = t - x$ only; preferably these functions should be sin or cos. This is not a good approach as is seen in the following example:

Consider the metric

$$\begin{aligned} g =&(\eta_{\mu\nu} + h_{\mu\nu})\mathrm{d}x^\mu \mathrm{d}x^\nu = \mathrm{d}t^2 - \mathrm{d}x^2 - \mathrm{d}y^2 - \mathrm{d}z^2 \\ &+ \cos(t-x)\Big(2+\cos(t-x)\Big)\mathrm{d}t^2 \\ &- 2\cos(t-x)\Big(1+\cos(t-x)\Big)\mathrm{d}t\mathrm{d}x \\ &+ \cos^2(t-x)\mathrm{d}x^2. \end{aligned}$$

We see here that the terms after the first row give the perturbation $h_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu$ of the Minkowski metric $\eta = \eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = \mathrm{d}t^2 - \mathrm{d}x^2 - \mathrm{d}y^2 - \mathrm{d}z^2$. They are *oscillatory*, and one sees that the *ripples of the perturbation move with the speed of light*, $c = 1$, along the x-axis. A closer look shows also that the coefficients $h_{\mu\nu}$ of the perturbation satisfy the wave equation (0.2) (since they depend on a single null coordinate u only), and more importantly, that the full metric g has Ricci curvature 0 (is "*Ricci flat*").

Thus the above metric is not only an example of a "gravitational wave" in the linearized Einstein theory, but also it provides an example of a solution of the vacuum Einstein equations $R_{\mu\nu} = 0$ in the *fully nonlinear* Einstein theory. With all this information in mind, in particular having in mind the sinusoidal change of the metric with the speed of light in the x direction, we ask: is this an example of a plane gravitational wave?

The answer is *no*, as we created the metric g from the flat Minkowski metric $\eta = \mathrm{d}\bar{t}^2 - \mathrm{d}x^2 - \mathrm{d}y^2 - \mathrm{d}z^2$ by a *change of the time coordinate*: $\bar{t} = t + \sin(t - x)$. In view of this, the metric g is just the flat Minkowski metric, written in nonstandard coordinates. As such it does not correspond to any gravitational wave!

The moral from this example is that attaching the name of a "gravitational wave" to a spacetime that just satisfies an intuitive condition in some coordinate system is a wrong approach. As we see in this example we can always introduce a sinusoidal behaviour of the metric coefficients and their 'movement' with speed of light, by an appropriate change of coordinates.

Figure 1. Herman Bondi (left) here pictured with Peter G. Bergmann at the Jabłonna Relativity Conference, 1962, was one of the first to establish the possibility of planar gravitational waves.

We need a mathematically precise definition of even a plane wave.

Red Light Switched on: Einstein and Rosen

The first ever attempt to define a plane gravitational wave in the full theory is due to Albert Einstein and Nathan Rosen [4]. It happened in 1937, twenty years after the formulation of the concept of a plane wave in the linearized theory. They thought that they had found a solution of the vacuum Einstein equations representing a plane polarized gravitational wave. They observed that their solution had certain singularities and as such must be considered as *unphysical*. Their opinion is explicitly expressed in the subsequent paper of Rosen [7], which has the following abstract:

The system of equations is set up for the gravitational and electromagnetic fields in the general theory of relativity, corresponding to plane polarized waves. It is found that all nontrivial solutions of these equations contain singularities, so that one must conclude that strictly plane polarized waves of finite amplitude, in contrast to cylindrical waves, cannot exist in the general theory of relativity.

The Einstein-Rosen paper [4] was refereed by Howard P. Robertson, who recognized that the singularities encountered by Einstein and Rosen are merely due to the wrong choice of coordinates and that, if one uses correct coordinate patches, the solution may be interpreted as a cylindrical wave, which is nonsingular everywhere except on the symmetry axis corresponding to an infinite line source. This is echoed in Rosen's abstract quoted above in his phrase "in contrast to cylindrical waves," and is also mentioned in the abstract of the earlier Einstein-Rosen paper [4], whose first sentence is: *The rigorous solution for cylindrical gravitational waves is given.* Nevertheless, despite the clue given to them by Robertson, starting from 1937, neither Einstein nor Rosen believed that physically acceptable plane gravitational waves were admitted by the full Einstein theory. This belief of Einstein affected the views of his collaborators, such as Leopold Infeld, and more generally many other relativists. If a plane gravitational wave is not admitted by the theory, and if this statement comes from, and is fully supported by, the authority of Einstein, it was hard to believe at any fundamental level that the predictions of the linearized theory were valid.

Towards the Green Light: Bondi, Pirani, and Robinson

It is now fashionable to say that a new era of research on gravitational waves started at the International Conference on Gravitation held at Chapel Hill on 18–23 January 1957. To show that not everybody was sure about the existence of gravitational waves during this conference we quote Herman Bondi [1], one of the founding fathers of gravitational wave theory:

Polarized plane gravitational waves were first discovered by N. Rosen, who, however, came to the conclusion that such waves could not exist because the metric would have to contain certain physical singularities. More recent work by Taub and McVittie showed that there were no unpolarized plane waves, and this result has tended to confirm the view that true plane gravitational waves do not exist in empty space in general relativity. Partly owing to this, Scheidegger and I have both expressed the opinion that there might be no energy-carrying gravitational waves at all in the theory.

The last sentence in the quote refers to Bondi's opinion expressed during the Chapel Hill Conference. Interestingly, the quote is from Bondi's *Nature* paper announcing the discovery of a singularity-free solution of a plane gravitational wave that carries energy, received by the journal on March 24, 1957. A dramatic change of opinion between January and March of the same year!

Bondi in the *Nature* paper invokes the solution of Einstein's equations found in the context of gravitational waves by Ivor Robinson. This paper, and the subsequent paper written by Bondi, Felix Pirani, and Robinson [2], answers in positive our problems (1), (2), and (3).

In particular (1) is answered with the following definition of a *plane wave in the full theory*: The gravitational plane wave is a spacetime that (a) satisfies vacuum Einstein's equations $R_{\mu\nu} = 0$ and (b) has a 5-dimensional group of isometries. The motivation for this definition is the fact that a plane electromagnetic wave has a 5-dimensional group of symmetries. Bondi, Pirani, and Robinson do *not* assume that the 5-dimensional group of isometries is isomorphic to the symmetry of a plane electromagnetic wave. They inspect all Ricci flat metrics with symmetries of dimension greater than or equal to 4 given by A. Z. Petrov (1957), and find exactly one class of solutions with the same 5-dimensional group of isometries, which by a miracle *is* isomorphic to the symmetry group of the electromagnetic field.

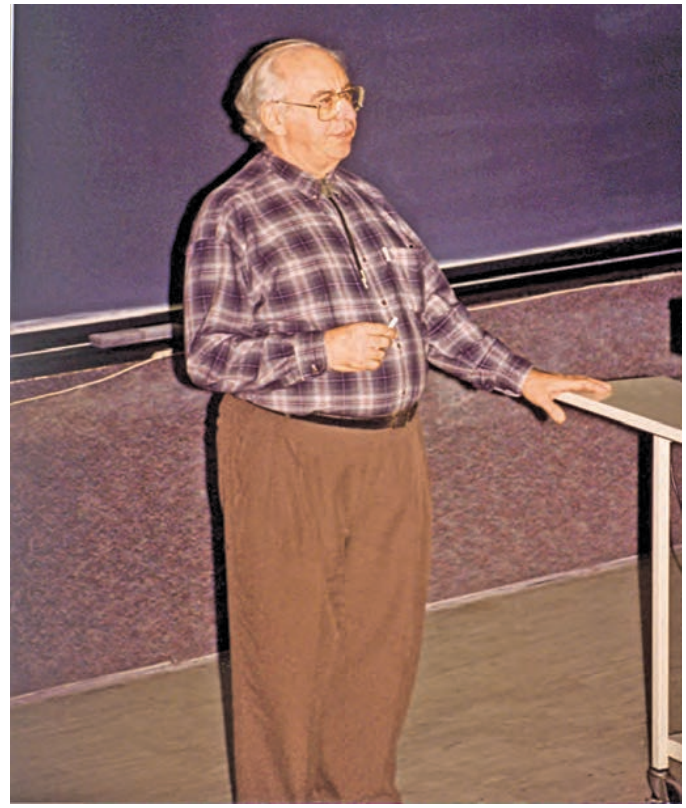


Figure 2. Ivor Robinson, shown here during Journées Relativistes in Dublin, 2001, was an independent discoverer of an exact solution describing planar gravitational waves.

It follows that the class of metrics obeying the Bondi-Pirani-Robinson definition of a plane gravitational wave depends on two *free functions of one variable* that can be interpreted as the wave amplitude and the direction of polarization. Using these free functions Bondi, Pirani, and Robinson obtained a *sandwich wave*, i.e. a gravitational wave that differs from the Minkowski spacetime only in a 4-dimensional strip moving in a given direction with the speed of light. They used this sandwich wave and analyzed what happens when it hits a system of test particles. It follows that the wave *affects* their motion, which leads to the conclusion that *gravitational plane waves in the full theory carry energy*.

In this way, the *Nature* paper of Bondi [1], together with the later paper of Bondi, Pirani, and Robinson [2], *solves our problems* (1), (2) *and* (3): the plane wave in the full theory is defined, it is realized as a class of solutions of Einstein field equations $R_{\mu\nu} = 0$, and it carries energy, since passing through the spacetime in a form of a sandwich it affects test particles.

As a last comment in this section we mention that the Bondi-Pirani-Robinson gravitational plane waves, sought

Figure 3. Felix Pirani, shown here in 1937, when Einstein and Rosen were writing their controversial paper, and in May 2015, a few months before his death, collaborated with Bondi and Robinson and gave an algebraic local criterion for gravitational waves.

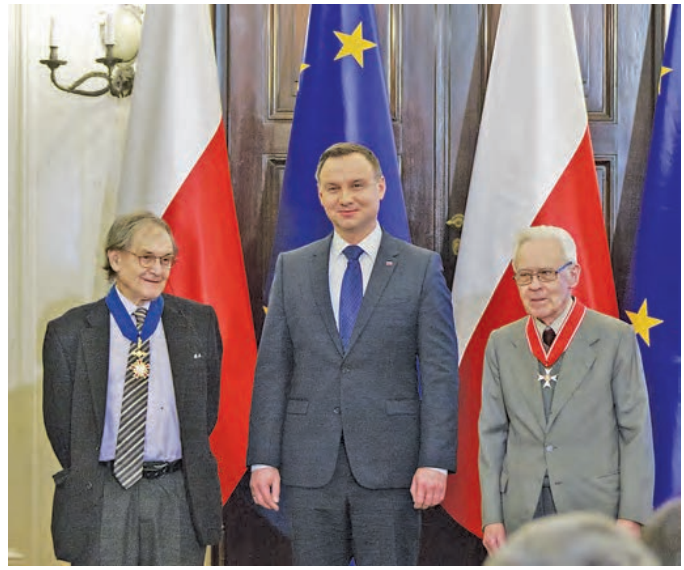


Figure 4. Roger Penrose (left), President of the Republic of Poland Andrzej Duda (center), and Andrzej Trautman at the ceremony at which Penrose got the highest Polish medal of merit for a foreigner and Trautman for a Pole, Warsaw 2016. Penrose and Trautman developed a nonlocal theory of radiation.

with great effort by physicists for forty years, were actually discovered already in 1925 by a *mathematician*, H. W. Brinkmann. He discovered what are known as *pp-waves*, a class of Ricci flat metrics having radiative properties, which include Bondi-Pirani-Robinson plane waves as a special case. His discovery was published in English in *Mathematische Annalen* **94** (1925), 119–145. If only there had been better communication between mathematicians and physicists.

General Gravitational Waves

Closer to the Green: Pirani

The development of the theory of gravitational waves at the turn of the 1950s and 1960s was very rapid. The story, as we are presenting it here now, is more topical than chronological, so, breaking the chronology, we will now discuss an important paper of Felix Pirani [5], which appeared before Bondi's *Nature* announcement of the existence of a plane wave in Einstein's theory. It is also worthwhile to note that Pirani's paper [5] was submitted a few months *before* the Chapel Hill conference. For us, this paper is of fundamental importance, since, among other things, it gives the first attempt at a purely geometric *definition of a gravitational wave spacetime*.

Pirani argues that gravitational radiation should be detectable by analysis of the Riemann tensor. He suggests that a spacetime containing gravitational radiation should be *algebraically special*. This suggestion uses the so-called *Petrov classification* of gravitational fields. At every point it consists in the enumeration of the distinct *eigendirections* of the Weyl tensor (the traceless part of the Riemann tensor). These eigendirections are called *principal null directions* (PNDs). If at a point all four PNDs are distinct, the spacetime at this point is called *algebraically general*. If at least two of the PNDs coincide, the spacetime at this point is called *algebraically special*. At each point various coincidences of PNDs may occur, resulting in the stratification of the algebraically special spacetime points into four *Petrov types*: type II (two PNDs coincide, the other two are distinct), type III (three PNDs coincide), type N (four PNDs coincide), and type D (four PNDs are grouped in two different pairs of coinciding PNDs). Pirani's suggestion that spacetimes containing radiation should be algebraically special *everywhere* was not very precise, as all the Petrov types (II, III, D, N) had not yet been correctly spelled out (the fully correct Petrov classification was given later by Roger Penrose in 1960).

Pirani's intuition about the importance of algebraic speciality in the theory of gravitational waves was brilliant. However, he was wrong in insisting on algebraical speciality of radiative spacetimes everywhere. We know now ([9], p. 411, eq. (21)) that the Weyl tensor of a radiative spacetime must be of type N very *far from the sources*, or better said, *asymptotically*.

Switching on Green: Radiation is Nonlocal

Pirani's algebraic speciality condition for a gravitational wave spacetime refers to pointwise defined objects—the PNDs. As the Weyl tensor can change its algebraic type from point to point, the criterion is local. On the other hand, even in Maxwell theory, radiation is a nonlocal phenomenon. To illustrate this we recall a well-known conundrum:

Q: Does a unit charge hanging on a thread attached to the ceiling of Einstein's lift radiate or not?
A: Well… viewed by an observer in the lift—NO!, as it is at rest; but, on the other hand, viewed by an observer on the Earth—YES!, as it falls down with constant acceleration $\vec{g}$.

Here, the confusion in the answers is of course due to the fact that one tries to apply a *purely local* physical law—the equivalence principle[1]—to the very nonlocal phenomenon, which is radiation in electromagnetic theory.

This gives a hint as to how to define what radiation is in general relativity. One can not expect that in this nonlinear theory radiation can be defined in terms of local notions. This point is raised and consequently developed by Andrzej Trautman, in two papers [8, 9] submitted to *Bulletin de l'Academie Polonaise des Sciences*, behind the Iron Curtain, in April 1958. This led him to finally solve our problems (4)–(5), [9], and (6)–(7), [6], thereby switching the red light to green.

It is worthwhile to mention that although Trautman's two papers [8, 9] were published behind the Iron Curtain, their results were exposed to the Western audience. In the next two months after their submission to the Polish *Bulletin* (May–June, 1958) Trautman, on the invitation of Felix Pirani, gave a series of lectures at King's College London presenting their theses. The audience of his lectures included H. Bondi and F. Pirani, and the lectures were mimeographed and spread among Western relativists.

Another interesting thing is that Trautman's two papers were an abbreviated version of his PhD thesis. It had two supervisors: the official one—Leopold Infeld, the closest collaborator of Albert Einstein, who following Einstein did not believe in gravitational waves, and the unofficial one—Jerzy Plebański, for whom the existence of gravitational waves was obvious. It was Plebański who proposed gravitational waves as a subject of Trautman's PhD. Despite Infeld's disbelief in gravitational waves, Trautman obtained his PhD under Infeld.

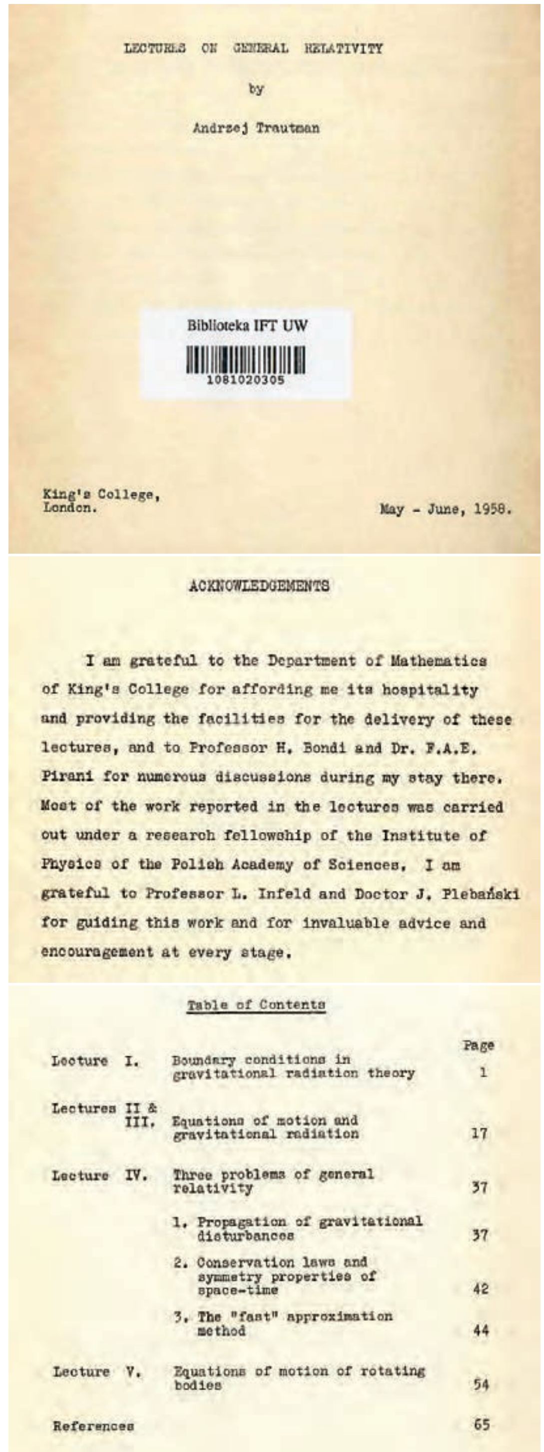
Green Light: Trautman

Trautman's general idea in defining what a gravitational wave is in the full Einstein theory was to say that it should satisfy certain boundary conditions at infinity. More precisely, from all spacetimes, i.e. solutions of Einstein's equations in the full theory, he proposed to select only those that satisfied boundary conditions at infinity, which were his *generalizations* of Sommerfeld's radiation conditions. These are known in the linear theory of a scalar field, and Trautman [8, 9] generalizes them to a number of *physical theories*. He reformulates Sommerfeld's radiation boundary conditions for the scalar inhomogeneous wave equation into a form that is then generalized to other field theories. As an example he shows how this generalization works in Maxwell's theory and that it indeed selects the outgoing radiative Maxwell fields from all solutions of Maxwell's equations.

In the next paper [9] Trautman does the same for Einstein's general relativity. Trautman defines the *boundary conditions to be imposed on gravitational fields due to isolated systems of matter*. This is the first step in solving our problems (4) and (5).

He then passes to the treatment of our problem (5). He uses the *Freud superpotential* 2-form $\mathcal{F}$ to split the Einstein tensor E into $E = \mathrm{d}\mathcal{F} - \kappa\mathfrak{T}$ so that the Einstein equations $E = \kappa T$ take the form

$$\mathrm{d}\mathcal{F} = \kappa(T + \mathfrak{T}).$$



LECTURES ON GENERAL RELATIVITY

by

Andrzej Trautman

Biblioteka IFT UW

1081020305

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Figure 5. The first three pages of Trautman's mimeographed King's College Lectures, which carried Trautman's work behind the Iron Curtain to Western relativists.

[1] *The inability to locally distinguish between gravitational and inertial forces.*

Figure 6. A blackboard discussion between Trautman's two advisors, Jerzy Plebański (left) and Leopold Infeld, at the Institute of Theoretical Physics of University of Warsaw. Ironically, Trautman got his PhD on gravitational waves as recommended by Plebański under Infeld, who didn't believe in them.

Figure 7. Andrzej Trautman established gravitational waves in the full Einstein theory.

Here T is the energy-momentum 3-form, and κ is a constant related to the gravitational constant G and the speed of light c via $\kappa = \frac{8\pi G}{c^4}$ (in the following we work with physical units in which $c = 1$).

Since $\mathfrak{T}$ is a 3-form totally determined by the geometry, it is interpreted as the energy-momentum 3-form of *pure gravity*. The closed 3-form $T + \mathfrak{T}$ is then used to define the 4-momentum $P^\mu(\sigma)$ of a *gravitational field attributed to every space-like hypersurface* σ of a spacetime satisfying his radiative boundary conditions. He shows that $P^\mu(\sigma)$ is *finite* and *well defined*, i.e. that it does not depend on the coordinate systems adapted to the chosen boundary conditions. Using his boundary conditions he then calculates how much of the gravitational energy $p^\mu = P^\mu(\sigma_1) - P^\mu(\sigma_2)$ contained between the spacelike hypersurfaces σ_1 (initial one) and σ_2 (final one) *escapes to infinity*.

Finally, he shows that p^0 is *nonnegative*, saying that radiation is present when $p^0 > 0$.

Taken together, everything we have said so far about Trautman's results, *solves our problems* (4) and (5): What in popular terms is called a *gravitational wave in the full GR theory* is a *spacetime satisfying Trautman's boundary conditions with* $p^0 > 0$; the *energy of a gravitational wave* contained between hypersurfaces σ_1 and σ_2 is given by p^0.

Trautman proves only that $p^0 \geq 0$. If the inequality were sharp, $p^0 > 0$, this would give a proof of the statement that spacetimes satisfying Trautman's boundary conditions, or better said, the gravitational waves associated with them, *carry energy*. Trautman does not have such a proof. To handle this problem, one can try to find an example of an *exact solution* to the Einstein equations satisfying Trautman's boundary conditions, and to show that in this example p^0 is *strictly* greater than zero. This approach is taken by I. Robinson and Trautman [6], and we will comment on this later.

As regards Trautman's paper [9], it is worthwhile to mention that Trautman shows there two other interesting things implied by his boundary conditions. The first of them is the fact that in the presence of electromagnetic radiation a spacetime satisfying his boundary conditions has far from the sources Ricci tensor in the form of a *null dust* $R_{\mu\nu} = \rho k_\mu k_\nu$, with k a *null vector*. This in particular means that the electromagnetic/gravitational radiation in his spacetimes travels with the speed of light. The second interesting feature he shows is that *far from the sources the Riemann tensor of a spacetime satisfying his radiative boundary conditions is of Petrov type N*. Since far from the sources $Riemann = Weyl$, this verifies the *intuition* of Pirani [5]: spacetimes satisfying radiative boundary conditions satisfy the algebraic speciality criterion, and from all the possibilities of algebraic speciality they choose a type N Weyl tensor as the leading term at infinity. This was later developed into the celebrated *peeling-off theorem* attributed to Ray Sachs.

The last two of our problems (6)–(7) were addressed by I. Robinson and Trautman [6]. There they *found a large class of exact solutions* of the full system of Einstein equations satisfying Trautman's boundary conditions.

Figure 8. Paul A. M. Dirac with Trautman and Infeld during the 1962 Jabłonna Conference.

The solutions describe waves with *closed fronts* so *they can be interpreted as coming from bounded sources.*

These solutions solve our last two problems (6) *and* (7). For some of them $p^0 > 0$, so they correspond to gravitational waves that *do carry energy*.

To conclude, we say that the Bondi-Pirani-Robinson papers [1, 2] and the Trautman-Robinson papers [9, 6] solve all our problems (1)–(7), giving the green light to further research on gravitational radiation. We will not comment on these further developments since they are well documented; see e.g. D. Kennefick's recent book *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves.*

Figure 9. Ivor Robinson and Andrzej Trautman, shown here in Trieste in the late 1980s, found a large class of exact solutions for gravitational waves with closed fronts in the full Einstein theory.

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Part two by Lydia Bieri, David Garfinkle, and Nicolás Yunes

Gravitational Waves and Their Mathematics

Introduction

In 2015 gravitational waves were detected for the first time by the LIGO team [1]. This triumph happened 100 years after Albert Einstein's formulation of the theory of general relativity and 99 years after his prediction of gravitational waves [4]. This article focuses on the mathematics of Einstein's gravitational waves, from the properties of the Einstein vacuum equations and the initial value problem (Cauchy problem), to the various approximations used to obtain quantitative predictions from these equations, and eventually an experimental detection.

General relativity is studied as a branch of astronomy, physics, and mathematics. At its core are the Einstein equations, which link the physical content of our universe to geometry. By solving these equations, we construct the spacetime itself, a continuum that relates space, time, geometry, and matter (including energy). The dynamics of the gravitational field are studied in the Cauchy problem for the Einstein equations, relying on the theory of nonlinear partial differential equations (pde) and geometric analysis. The connections between astronomy, physics, and mathematics are richly illustrated by the story of gravitational radiation.

In general relativity, the universe is described as a spacetime manifold with a curved metric whose curvature encodes the properties of the gravitational field. While sometimes one wants to use general relativity to describe the whole universe, often we just want to know how a single object or small collection of objects behaves. To address that kind of problem, we use the idealization of the isolated system: a spacetime consisting of just the objects we want to study and nothing else. We might consider the solar system as an isolated object, or a pair of black holes spiraling into one another until they collide. We ask how those objects look to a distant, far away observer in a region where presumably the curvature of spacetime is very small. Gravitational waves are vibrations in spacetime that propagate at the speed of light away from their source. They may be produced, for example, when black holes merge. This is what was detected by Advanced LIGO (aLIGO) and this is the focus of this article.

Gravitational waves are vibrations in spacetime propagating at the speed of light.

Figure 1. Albert Einstein predicted gravitational waves in 1916.

First we describe the basic differential geometry used to define the universe as a geometric object. Next we describe the mathematical properties of the Einstein vacuum equations, including a discussion of the Cauchy problem and gravitational radiation. Then we turn to the various approximation schemes used to obtain quantitative predictions from these equations. We conclude with the experimental detection of gravitational waves and the astrophysical implications of this detection. This detection is not only a spectacular confirmation of Einstein's theory, but also the beginning of the era of gravitational wave astronomy, the use of gravitational waves to investi-

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gate aspects of our universe that have been inaccessible to telescopes.[2]

The Universe as a Geometric Object

A spacetime manifold is defined to be a 4-dimensional, oriented, differentiable manifold M with a Lorentzian metric tensor, g, which is a nondegenerate quadratic form of index one,

$$g = \sum_{\mu,\nu=0}^{3} g_{\mu\nu} dx^\mu \otimes dx^\nu,$$

defined in T_qM for every q in M varying smoothly in q. The trivial example, the Minkowski spacetime as defined in Einstein's special relativity, is $\mathbb{R}^4$ endowed with the flat Minkowski metric:

$$g = \eta = -c^2dt^2 + dx^2 + dy^2 + dz^2. \tag{1}$$

Taking $x_0 = t$, $x_1 = x$, $x_2 = y$, and $x_3 = z$, we have $\eta_{00} = -c^2$, $\eta_{ii} = 1$ for $i = 1, 2, 3$, and $\eta_{\mu\nu} = 0$ for $\mu \neq \nu$. In mathematical general relativity we often normalize the speed of light, $c = 1$.

Schwarzschild spacetime describes a black hole.

The family of Schwarzschild metrics are solutions of the Einstein vacuum equations that describe spacetimes containing a black hole, where the parameter values are $M > 0$. Taking $r_s = 2GM/c^2$, it has the metric:

$$g = -c^2 \frac{\left(1 - \frac{r_s}{4\rho}\right)^2}{\left(1 + \frac{r_s}{4\rho}\right)^2} dt^2 + \left(1 + \frac{r_s}{4\rho}\right)^4 h, \tag{2}$$

where $\rho^2 = x^2 + y^2 + z^2$, $h = dx^2 + dy^2 + dz^2$, and G denotes the Newtonian gravitational constant. This space is asymptotically flat as $\rho \to \infty$.

The Friedmann-Lemaître-Robertson-Walker spacetimes describe homogeneous and isotropic universes through the metric

$$g = -c^2dt^2 + a^2(t)g_\chi, \tag{3}$$

where g_χ is a Riemannian metric with constant sectional curvature, χ, (e.g. a sphere when $\chi = 1$) and $a(t)$ describes the expansion of the universe. The function, $a(t)$, is found by solving the Einstein equations as sourced by fluid matter.

In an arbitrary Lorentzian manifold, M, a vector $X \in T_xM$ is called *null* or lightlike if

$$g_x(X, X) = 0.$$

At every point there is a cone of null vectors called the *null cone*, as in Figure 2. A vector $X \in T_xM$ is called *timelike* if

$$g_x(X, X) < 0,$$

and *spacelike* if

$$g_x(X, X) > 0.$$

In general relativity nothing travels faster than the speed of light, so the velocities of massless particles are null vectors whereas those for massive objects are timelike. A causal curve is a differentiable curve for which the tangent vector at each point is either timelike or null.

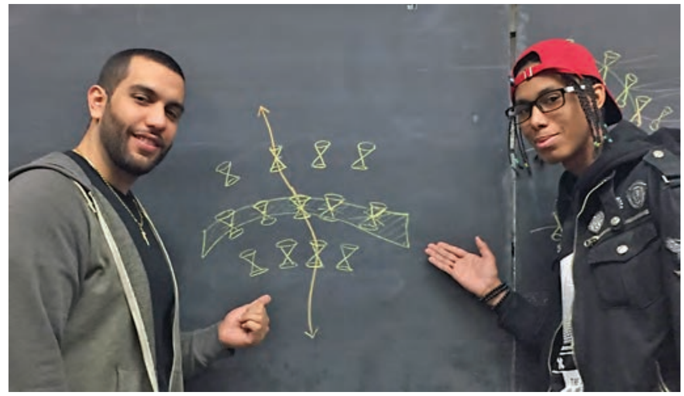

Figure 2. Light cones, a timelike curve, and a spacelike hypersurface as demonstrated by physics majors at Lehman College.

A hypersurface is called *spacelike* if its normal vector is timelike, so that the metric tensor restricted to the hypersurface is positive definite. A *Cauchy hypersurface* is a spacelike hypersurface where each causal curve through any point $x \in M$ intersects $\mathcal{H}$ exactly at one point. A spacetime (M, g) is said to be *globally hyperbolic* if it has a Cauchy hypersurface. In a globally hyperbolic spacetime, there is a time function t whose gradient is everywhere timelike or null and whose level surfaces are Cauchy surfaces. A globally hyperbolic spacetime is causal in the sense that no object may travel to its own past.

As in Riemannian geometry, curves with 0 acceleration are called geodesics. Light travels along null geodesics. Geodesics that enter the event horizon of a black hole as in Figure 3 never leave. Objects in free fall travel along timelike geodesics. They also can never leave once they have entered a black hole. When two black holes fall into each other, they merge and form a single larger black hole.

In curved spacetime, geodesics bend together or apart and the relative acceleration between geodesics is described by the Jacobi equation, also known as the geodesic deviation equation. In particular, the relative acceleration of nearby geodesics is given by the Riemann curvature tensor times the distance between them. The Ricci curvature tensor, $R_{\mu\nu}$, measures the average way in which geodesics curve together or apart. The scalar curvature, R, is the trace of the Ricci curvature.

Einstein's field equations are:

$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}\ , \tag{4}$$

where $T_{\mu\nu}$ denotes the energy-momentum tensor, which encodes the energy density of matter. Note that for

[2] *Editor's note: Don't miss the intriguing and most readable final sections of this article.*

Figure 3. The horizon of the black hole is depicted here as a cylinder with inward pointing light cones, as demonstrated by physics majors at Lehman College.

cosmological considerations, one can add $\Lambda g_{\mu\nu}$ on the left-hand side, where Λ is the cosmological constant. However, nowadays, this term is commonly absorbed into $T_{\mu\nu}$ on the right-hand side. Here we will consider the noncosmological setting. One then solves the Einstein equations for the metric tensor $g_{\mu\nu}$. If there are no other fields, then $T_{\mu\nu} = 0$ and (4) reduce to the Einstein vacuum equations:

$$R_{\mu\nu} = 0\,. \tag{5}$$

Note that the Einstein equation is a set of second order quasilinear partial differential equations for the metric tensor. In fact, when choosing the right coordinate chart (wave coordinates), taking $c = 1$, and writing out the formula for the curvature tensor, $R_{\mu\nu}$, in those coordinates, the equation becomes:

$$\Box_g g_{\alpha\beta} = N_{\alpha\beta} \tag{6}$$

where $\Box_g$ is the wave operator and $N_{\alpha\beta} = N_{\alpha\beta}(g, \partial g)$ denote nonlinear terms with quadratics in ∂g.

Quite a few exact solutions to the Einstein vacuum equations are known. Among the most popular are the trivial solution (Minkowski spacetime) as in (1); the Schwarzschild solution, which describes a static black hole, as in (2); and the Kerr solution, which describes a black hole with spin angular momentum. Note that the exterior gravitational field of any spherically symmetric object takes the form of (2) for $r > r_0$ where $r_0 > r_s$ is the radius of the object, so this model can be used to study the spacetime around an isolated star or planet. However, in order to understand the dynamics of the gravitational field and radiation, we have to investigate large classes of spacetimes. This can only be done by solving the initial value problem (Cauchy problem) for the Einstein equations, which will be discussed in the next section.

If there are matter fields, so that $T_{\mu\nu} \neq 0$, then these fields satisfy their own evolution equations, which have to be solved along with the Einstein field equations (4) as a coupled system. The scale factor, $a(t)$, of the Friedmann-Lemaître-Robertson-Walker cosmological spacetimes in (3) can then be found by solving a second order, ordinary

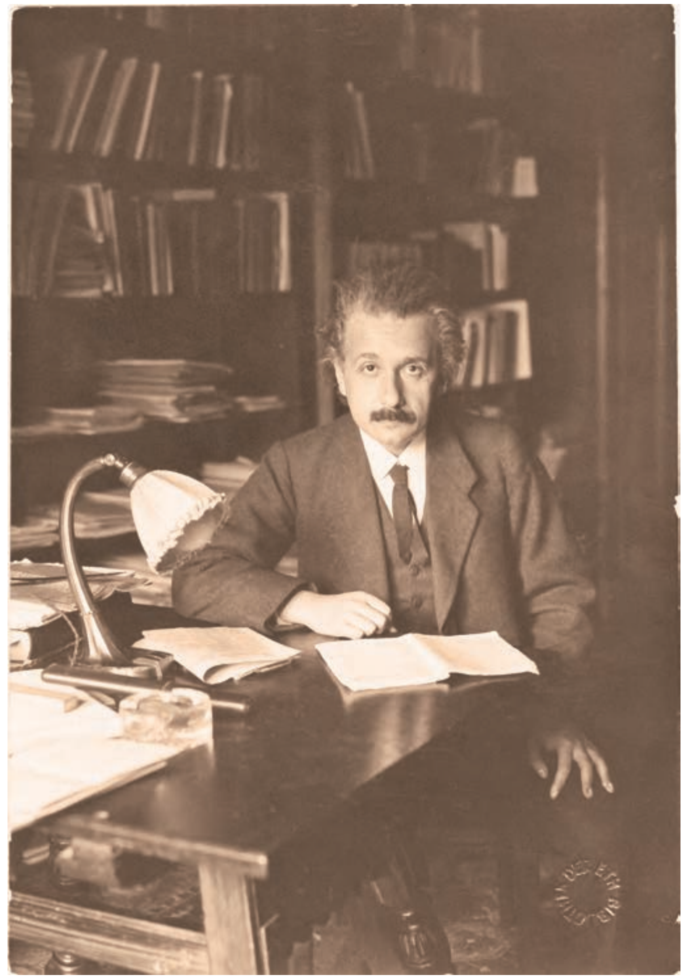

Figure 4. Albert Einstein

differential equation derived from (4). If a solution has a time where the scale factor vanishes, then the solution is said to describe a cosmos whose early phase is a "big bang."

The Einstein Equations

Beginnings of Cauchy Problem

In order to study gravitational waves, stability problems, and general questions about the dynamics of the gravitational field, we have to formulate and solve the *Cauchy problem*. That is, we are given as initial data a prescribed Riemannian manifold $\mathcal{H}$ with a complete Riemannian metric $\bar{g}_{ij}$ and a symmetric 2-tensor $\mathcal{K}_{ij}$ satisfying certain consistency conditions called the *Einstein constraint equations*. We then solve for a spacetime (M, g) that satisfies the Einstein equations evolving forward from this initial data set. That is, the given Riemannian manifold $\mathcal{H}$ is a spacelike hypersurface in this spacetime solution M, where $\bar{g}$ is the restriction of g. Furthermore, the symmetric two-tensor $\mathcal{K}_{ij}$ is the prescribed second fundamental form.

All the different methods used to describe gravitational radiation have to be thought of as embedded into the aim of solving the Cauchy problem. We solve the Cauchy problem by methods of analysis and geometry. However, for situations where the geometric-analytic techniques are not (yet) at hand, one uses approximation methods and numerical algorithms. The goal of the latter methods is to produce approximations to solutions of the Cauchy problem for the Einstein equations.

In order to derive the gravitational waves from binary black hole mergers, binary neutron star mergers, or core-collapse supernovae, we describe these systems by asymptotically flat spacetimes. These are solutions of the Einstein equations that at infinity tend to Minkowski space with a metric as in (1). Schwarzschild space is a simple example of such an isolated system containing only a single stationary black hole (2). There is a huge literature about specific fall-off rates, which we will not describe here. The null asymptotics of these spacetimes contain information on gravitational radiation (gravitational waves) out to infinity.

Recall that the Einstein vacuum equations (5) are a system of ten quasilinear, partial differential equations that can be put into hyperbolic form. However, with the Bianchi identity imposing four constraints, the Einstein vacuum system (5) constitutes only six independent equations for the ten unknowns of the metric $g_{\mu\nu}$. This corresponds to the general covariance of the Einstein equations. In fact, uniqueness of solutions to these equations holds up to equivalence under diffeomorphisms. We have just found a core feature of general relativity. This mathematical fact also means that physical laws do not depend on the coordinates used to describe a particular process.

The Einstein equations split into a set of evolution equations and a set of constraint equations. As above, t denotes the time coordinate whereas indices $i, j = 1, \dots, 3$ refer to spatial coordinates. Taking $c = 1$, the evolution equations read:

$$\frac{\partial \bar{g}_{ij}}{\partial t} = -2\Phi\mathcal{K}_{ij} + \mathcal{L}_X \bar{g}_{ij}, \tag{7}$$

$$\frac{\partial \mathcal{K}_{ij}}{\partial t} = -\nabla_i\nabla_j\Phi + \mathcal{L}_X\mathcal{K}_{ij}$$
$$+ (\bar{R}_{ij} + \mathcal{K}_{ij}\, tr\mathcal{K} - 2\mathcal{K}_{im}\mathcal{K}^m_j)\Phi \tag{8}$$

Here $\mathcal{K}_{ij}$ is the extrinsic curvature of the $t = const.$ surface $\mathcal{H}$ as above. The lapse Φ and shift X are essentially the g_{tt} and g_{ti} components of the metric, and are given by $T = \Phi n + X$ where T is the evolution vector field $\partial/\partial t$ and n is the unit normal to the constant time hypersurface. ∇_i is the spatial covariant derivative and $\mathcal{L}$ is the Lie derivative. However, the initial data $(\bar{g}_{ij}, \mathcal{K}_{ij})$ cannot be chosen freely: the remaining four Einstein vacuum equations become the following constraint equations:

$$\nabla^i\mathcal{K}_{ij} - \nabla_j\, tr\mathcal{K} = 0, \tag{9}$$

$$\bar{R} + (tr\mathcal{K})^2 - |\mathcal{K}|^2 = 0. \tag{10}$$

An *initial data set* is a 3-dimensional manifold $\mathcal{H}$ with a complete Riemannian metric $\bar{g}_{ij}$ and a symmetric 2-tensor $\mathcal{K}_{ij}$ satisfying the constraint equations ((9) and (10)). We will evolve an asymptotically flat initial data set $(\mathcal{H}, \bar{g}_{ij}, \mathcal{K}_{ij})$, that outside a sufficiently large compact set $\mathcal{D}$, $\mathcal{H}\setminus\mathcal{D}$ is diffeomorphic to the complement of a closed ball in $\mathbb{R}^3$ and admits a system of coordinates where $\bar{g}_{ij} \to \delta_{ij}$ and $\mathcal{K}_{ij} \to 0$ sufficiently fast.

It took a long time before the Cauchy problem for the Einstein equations was formulated correctly and understood. Geometry and pde theory were not as developed as they are today, and the pioneers of general relativity had to struggle with problems that have elegant solutions nowadays. The beauty and challenges of general relativity attracted many mathematicians, as for instance D. Hilbert or H. Weyl, to work on general relativity's fundamental questions. Weyl in 1923 talked about a "causally connected" world, which hints at issues that the domain of dependence theorem much later would solve. G. Darmois in the 1920s studied the analytic case, which is not physical but a step in the right direction. He recognized that the analyticity hypothesis is physically unsatisfactory, because it hides the propagation properties of the gravitational field. Without going into details, important work followed by K. Stellmacher, K. Friedrichs, T. de Donder, and C. Lanczos. The latter two introduced wave coordinates, which Darmois later used. In 1939, A. Lichnerowicz extended Darmois' work. He also suggested the extension of the 3 + 1 decomposition with nonzero shift to his student Yvonne Choquet-Bruhat, which she carried out.

Figure 5. Yvonne Choquet-Bruhat proved a local existence and uniqueness theorem for the Einstein equations.

Choquet-Bruhat, encouraged by Jean Leray in 1947, searched for a solution to the nonanalytic Cauchy problem of the Einstein equations, which turned into her famous result of 1952. There are many more players in this game that should be mentioned, but there is not enough space to do justice to their work. These works also built on progress in analysis and pde theory by H. Lewy, J. Hadamard, J. Schauder, and S. Sobolev among many others. Details on the history of the proof can be found in Choquet-Bruhat's survey article published in *Surveys in Differential Geometry 2015: One hundred years of general relativity*, and more historical background (including a discussion between Choquet-Bruhat and Einstein) is given in Choquet-Bruhat's forthcoming autobiography.

In 1952 Choquet-Bruhat [2] proved a local existence and uniqueness theorem for the Einstein equations, and in 1969 Choquet-Bruhat and R. Geroch [3] proved the global existence of a unique maximal future development for every given initial data set.

Theorem 1 (Choquet-Bruhat, 1952). *Let* $(\mathcal{H}, \bar{g}, \mathcal{K})$ *be an initial data set satisfying the vacuum constraint equations. Then there exists a spacetime* (M, g) *satisfying the Einstein vacuum equations with* $\mathcal{H} \hookrightarrow M$ *being a spacelike surface with induced metric* $\bar{g}$ *and second fundamental form* $\mathcal{K}$.

This was proven by finding a useful coordinate system, called wave coordinates, in which Einstein's vacuum equations appear clearly as a hyperbolic system of partial differential equations. The pioneering result by Choquet-Bruhat was improved by Dionne (1962), Fisher-Marsden (1970), and Hughes-Kato-Marsden (1977) using the energy method.

Global Cauchy Problem

Choquet-Bruhat's local theorem of 1952 was a breakthrough and has since been fundamental for further investigations of the Cauchy problem. Once we have local solutions of the Einstein equations, do they exist for all time, or do they form singularities? And of what type would the latter be? In 1969 Choquet-Bruhat and Geroch proved there exists a unique, globally hyperbolic, maximal spacetime (M, g) satisfying the Einstein vacuum equations with $\mathcal{H} \hookrightarrow M$ being a Cauchy surface with induced metric $\bar{g}$ and second fundamental form $\mathcal{K}$. This unique solution is called the *maximal future development* of the initial data set.

However, there is no information about the behavior of the solution. Will singularities occur or will it be complete? One would expect that sufficiently small initial data evolves forever without producing any singularities, whereas sufficiently large data evolves to form spacetime singularities such as black holes. From a mathematical point of view the question is whether theorems can be proven that establish this behavior. A breakthrough occurred in 2008 with Christodoulou's proof, building on an earlier result due to Penrose, that black hole singularities form in the Cauchy development of initial data, which do not contain any singularities, provided that the incoming energy per unit solid angle in each direction in a suitably small time interval is sufficiently large. This means that a black hole forms through the focussing of gravitational waves. This result has since been generalized by various authors, and the main methods have been applied to other nonlinear pdes.

The next burning question to ask is whether there is any asymptotically flat (and nontrivial) initial data with complete maximal development. This can be thought of as a question about the global stability of Minkowski space. In their celebrated work of 1993, D. Christodoulou and S. Klainerman proved the following result, which here we state in a very general way. The details are intricate and the smallness assumptions are stated for weighted Sobolev norms of the geometric quantities.

Theorem 2 (Christodoulou and Klainerman, 1993). *Given strongly asymptotically flat initial data for the Einstein vacuum equations* (5)*, which is sufficiently small, there exists a unique, causally geodesically complete and globally hyperbolic solution* (M, g)*, which itself is globally asymptotically flat.*

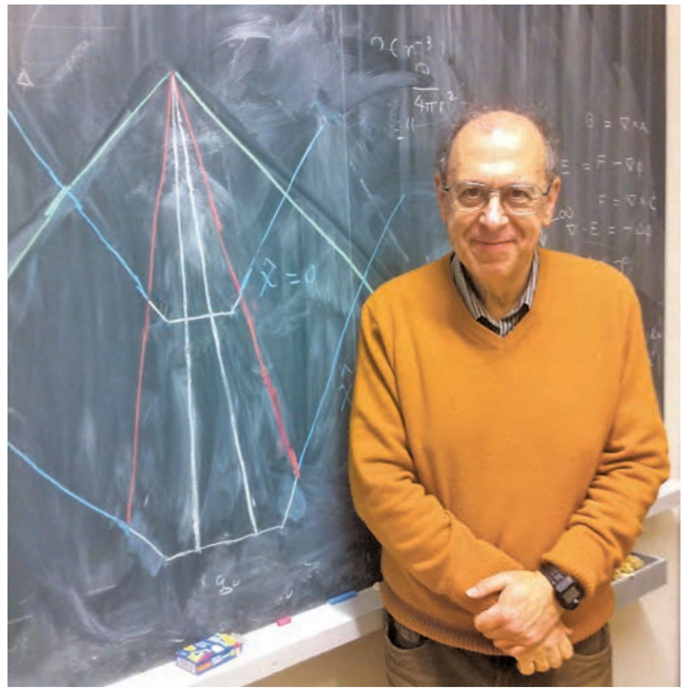

Figure 6. Demetrios Christodoulou proved (with Klainerman) the global nonlinear stability of the Minkowski space in general relativity, and he derived the *null memory effect of gravitational waves*, known as the *Christodoulou effect*.

The proof relies on geometric analysis and is independent of coordinates. First, energies are identified with the help of the Bel-Robinson tensor, which basically is a quadratic of the Weyl curvature. Then, the curvature components are estimated in a comparison argument using the energies. Finally, in a large bootstrap argument with assumptions on the curvature, the remaining geometric quantities are proven to be controlled. The proof comprises various new ideas and features that became important not only for further studies of relativistic problems but also in other nonlinear hyperbolic pdes.

The Christodoulou-Klainerman result of theorem 2 was generalized in 2000 by Nina Zipser for the Einstein-Maxwell equations and in 2007 by Lydia Bieri for the Einstein vacuum equations assuming less on the decay at infinity and less regularity. Thus, the latter result establishes the borderline case for decay of initial data in the Einstein vacuum case. Both works use geometric analysis in a way that is independent of any coordinates.

Next, let us go back to the pioneering results by Choquet-Bruhat and Geroch, and say a few words about

Figure 7. Lydia Bieri generalized the proof of nonlinear stability of Minkowski spacetime in general relativity to borderline decay of the data at infinity, and she has investigated gravitational radiation with memory; among the latter she (with Garfinkle) derived a contribution from neutrino radiation to the null memory effect.

further extensions of these works. A standard result ensures that for an Einstein vacuum initial data set $(\mathcal{H}_0, \bar{g}, \mathcal{K})$ with $\mathcal{H}_0$ allowing to be covered by a locally finite system of coordinate charts with transformations being C^1-diffeomorphisms, and

$$g_{mn}|_{\mathcal{H}_0} \in H^k_{loc} \ , \quad \partial_0 g_{mn}|_{\mathcal{H}_0} \in H^{k-1}_{loc} \ , \quad k > \frac{5}{2} \ , \tag{11}$$

there exists a unique globally hyperbolic solution with $\mathcal{H}_0$ being a Cauchy hypersurface. Several improvements followed, including those by Tataru, Smith-Tataru, and then by Klainerman-Rodnianski. The latter proved that for the same problem but with $k > 2$ there exists a time interval $[0, T]$ and a unique solution g such that $g_{mn} \in C^0([0,T], H^k)$ where T depends only on $||g_{mn}|_{\mathcal{H}_0}||_{H^k} + ||\partial_0 g_{mn}|_{\mathcal{H}_0}||_{H^{k-1}}$. Recently the L^2 curvature conjecture was proven by Klainerman-Rodnianski-Szeftel: under certain assumptions they relax the regularity condition such that the time of existence of the solution depends only on the

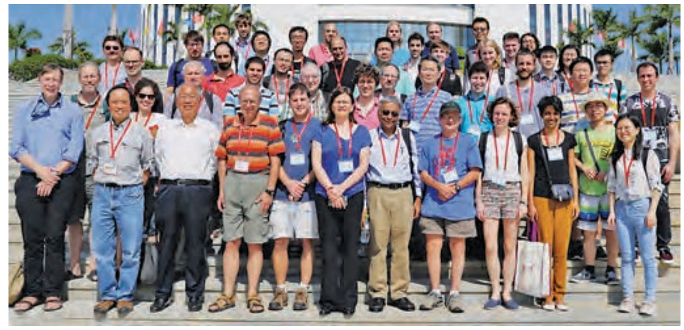

Figure 8. 2016 Conference

L^2-norms of the Riemann curvature tensor and on the gradient of the second fundamental form.

For our purposes, we want to know what the global existence theorem says about the properties of radiation, i.e. the behavior of curvature at large distances. In particular, because we expect gravitational radiation to propagate at the speed of light, we would like to study the behavior at large distances along outgoing light rays. This sort of question was addressed long before Christodoulou and Kainerman. However, these works assume a lot about the spacetimes considered. As a consequence, components of the Riemann curvature tensor show a specific hierarchy of decay in r. The spacetimes of the Christodoulou-Klainerman theorem do not fully satisfy these properties, showing only some of the fall-off but not all. In fact, Christodoulou showed that physical spacetimes cannot fulfill the stronger decay. The results by Christodoulou-Klainerman provide a precise description of null infinity for physically interesting situations.

Gravitational Radiation

In this section, we consider radiative spacetimes with asymptotic structures as derived by Christodoulou-Klainerman. The asymptotic behavior of gravitational waves near infinity approximates how gravitational radiation emanating from a distant black hole merger would appear when observed by aLIGO. Asymptotically the gravitational waves appear to be planar, stretching and shrinking directions perpendicular to the wave's travel direction.

As an example, let us consider the merger of two black holes. Long before the merger, the total energy of the two-black-hole spacetime, the so-called ADM energy or "mass," named for its creators Arnowitt-Deser-Misner, is essentially the sum of the masses of the individual black holes. During the merger, energy and momentum are radiated away in the form of gravitational waves. After the merger, once the waves have propagated away from the system, the energy left in the system, what is known as the Bondi mass, decreases and can be calculated through the formalism introduced by Bondi, Sachs, and Trautman.

Gravitational radiation travels along null hypersurfaces in the spacetime. As the source is very far away from us, we can think of these waves as reaching us (the experiment) at null infinity, which is defined as follows.

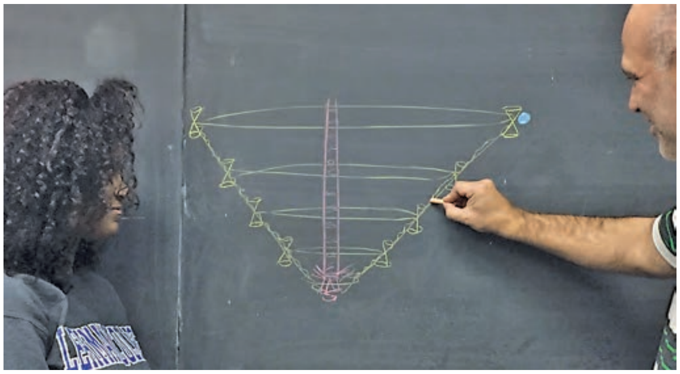

Figure 9. Gravitational waves demonstrated by Luis Anchordoqui of Lehman College. Here the horizon of the merging black holes is depicted in red and then the waves propagate at the speed of light towards Earth located at null infinity.

Definition 1. Future null infinity $\mathcal{I}^+$ is defined to be the endpoints of all future-directed null geodesics along which $r \to \infty$. It has the topology of $\mathbb{R} \times \mathbb{S}^2$ with the function u taking values in $\mathbb{R}$.

A null hypersurface C_u intersects $\mathcal{I}^+$ at infinity in a 2-sphere. To each C_u at null infinity is assigned a Trautman-Bondi mass $M(u)$, as introduced by Bondi, Trautman, and Sachs in the middle of the last century. This quantity measures the amount of mass that remains in an isolated gravitational system at a given retarded time, i.e. the Trautman-Bondi mass measures the remaining mass after radiation through $\mathcal{I}^+$ up to u. The Bondi mass-loss formula reads for $u_1 \leq u_2$

$$M(u_2) = M(u_1) - C \int_{u_1}^{u_2} \int_{S^2} |\Xi|^2 \, d\mu_{\overset{\circ}{\gamma}} du \tag{12}$$

with $|\Xi|^2$ being the norm of the shear tensor at $\mathcal{I}^+$ and $d\mu_{\overset{\circ}{\gamma}}$ the canonical measure on S^2. If other fields are present, like electromagnetic fields, then the formula contains a corresponding term for that field. In the situations considered here, it has been proven that $\lim_{u \to -\infty} M(u) = M_{ADM}$.

The effects of gravitational waves on neighboring geodesics are encoded in the Jacobi equation. This very fact is at the heart of the detection by aLIGO and is discussed in the section entitled Gravitational Wave Experiment. From this, we derive a formula for the displacement of test masses, while the wave packet is traveling through the apparatus. This is what was measured by the aLIGO detectors.

Now, there is more to the story. From the analysis of the spacetime at $\mathcal{I}^+$ one can prove that the test masses will go to rest after the gravitational wave has passed, meaning that the geodesics will not be deviated anymore. However, will the test masses be at the "same" position as before the wave train passed or will they be dislocated? In mathematical language, will the spacetime geometry have changed permanently? If so, then this is called the *memory effect* of gravitational waves. This effect was first computed in 1974 by Ya. B. Zel'dovich and A. G. Polnarev in the linearized theory, where it was found to be very small and considered not detectable at that time.

Figure 10. David Garfinkle has worked in many areas of general relativity; lately he has contributed significant results on the memory effect. He showed (with Bieri) that there are two types of memory.

In 1991 D. Christodoulou, studying the full nonlinear problem, showed that this effect is larger than expected and could in principle be measured. Bieri and Garfinkle showed that the formerly called "linear" (now ordinary) and "nonlinear" (now null) memories are two different effects, the former sourced by the difference of a specific component of the Weyl tensor, and the latter due to fields that do reach null infinity $\mathcal{I}^+$. In the case of the Einstein vacuum equations, this is the shear appearing in (12). In particular, the permanent displacement (memory) is related to

$$\mathcal{F} = C \int_{-\infty}^{+\infty} |\Xi(u)|^2 \, du \tag{13}$$

where $\mathcal{F}/4\pi$ denotes the total energy radiated in a given direction per unit solid angle. A very recent paper by P. Lasky, E. Thrane, Y. Levin, J. Blackman, and Y. Chen suggests a method for detecting gravitational wave memory with aLIGO.

Approximation Methods

To compare gravitational wave experimental data to the predictions of the theory, one needs a calculation of the predictions of the theory. It is not enough to know that solutions of the Einstein field equations exist; rather, one needs quantitative solutions of those equations to at least the accuracy needed to compare to experiments. In addition, sometimes the gravitational wave signal is so weak that to keep it from being overwhelmed by noise one must use the technique of matched filtering in which one looks for matches between the signal and a set of templates of possible expected waveforms. These quantitative solutions are provided by a set of overlapping approximation techniques, and by numerical simulations. We will discuss the approximation techniques in this section and the numerical methods in the section entitled Mathematics and Numerics.

Linearized Theory and Gravitational Waves. Since gravitational waves become weaker as they propagate away from their sources, one might hope to neglect the nonlinearities of the Einstein field equations and focus instead on the linearized equations, which are easier to work with. One may hope that these equations would provide an approximate description of the gravitational radiation for much of its propagation and for its interaction with the detector. In linearized gravity, one then writes the spacetime metric as

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \tag{14}$$

where $\eta_{\mu\nu}$ is the Minkowski metric as in (1) and $h_{\mu\nu}$ is assumed to be small. One then keeps terms in the Einstein field equations only to linear order in $h_{\mu\nu}$. The coordinate invariance of general relativity gives rise to what is called gauge invariance in linearized gravity. In particular, consider any quantity F written as $F = \bar{F} + \delta F$ where $\bar{F}$ is the value of the quantity in the background and δF is the first order perturbation of that quantity. Then for an infinitesimal diffeomorphism along the vector field ξ, the quantity δF changes by

$$\delta F \to \delta F + \mathcal{L}_\xi \bar{F},$$

where recall that $\mathcal{L}$ stands for the Lie derivative. Recall also that harmonic coordinates made the Einstein vacuum equations look like the wave equation in (6). We would like to do something similar in linearized gravity. To this end we choose ξ to impose the Lorenz gauge condition (not Lorentz!)

$$\partial_\mu \bar{h}^{\mu\nu} = 0,$$

where

$$\bar{h}_{\mu\nu} = h_{\mu\nu} - (1/2)\eta_{\mu\nu} h.$$

The linearized Einstein field equations then become

$$\Box \bar{h}_{\mu\nu} = -16\pi G T_{\mu\nu}, \tag{15}$$

where $\Box$ is the wave operator in Minkowski spacetime.

In a vacuum one can use the remaining freedom to choose ξ to impose the conditions that $h_{\mu\nu}$ has only spatial components and is trace-free, while remaining in Lorenz gauge. This refinement of the Lorenz gauge is called the TT gauge, since it guarantees that the only two propagating degrees of freedom of the metric perturbation are transverse $\partial^i h_{ij} = 0$ and (spatially) traceless $\eta^{ij} h_{ij} = 0$. The metric in TT gauge has a direct physical interpretation given by the following formula for the linearized Riemannian curvature tensor

$$R_{itjt} = -\frac{1}{2}\ddot{h}_{ij}^{TT}, \tag{16}$$

which sources the geodesic deviation equation, and thus encapsulates how matter behaves in the presence of gravitational waves. Combining Eq. (16) and the Jacobi equation, one can compute the change in distance between two test masses in free fall:

$$\triangle d^i(t) = \frac{1}{2} h_{ij}^{TT}(t) d_0^j$$

where d_0^j is the initial distance between the test masses.

The TT nature of gravitational wave perturbations allows us to immediately infer that they only have two polarizations. Consider a wave traveling along the z-direction, such that $h_{ij}^{TT}(t-z)$ is a solution of $\Box h_{ij}^{TT} = 0$. The Lorenz condition, the assumption that the metric perturbation vanishes for large r, the trace-free condition, and symmetries imply that there are only two independent propagating degrees of freedom:

$$h_+(t-z) = h_{xx}^{TT} = -h_{yy}^{TT}$$

and

$$h_\times(t-z) = h_{xy}^{TT} = h_{yx}^{TT}.$$

The h_+ gravitational wave stretches the x direction in space while it squeezes the y direction, and vice-versa. The interferometer used to detect gravitational waves has two long perpendicular arms that measure this distortion. Therefore, one must approximate these displacements in order to predict what the interferometer will see under various scenarios.

The Post-Newtonian Approximation

The post-Newtonian (PN) approximation for gravitational waves extends the linearized study presented above to higher orders in the metric perturbation, while also assuming that the bodies generating the gravitational field move slowly compared to the speed of light. The PN approach was developed by Einstein, Infeld, Hoffman, Damour, Deruelle, Blanchet, Will, Schaefer, and many others. In the harmonic gauge $\partial_\alpha(\sqrt{-g} g^{\alpha\beta}) = 0$ commonly employed in PN theory, the expanded equations take the form

$$\Box h^{\alpha\beta} = -\frac{16\pi G}{c^4}\tau^{\alpha\beta}, \tag{17}$$

where $\Box$ is the wave operator and

$$\tau^{\alpha\beta} = -(g)T^{\alpha\beta} + (16\pi)^{-1} N^{\alpha\beta},$$

with $N^{\alpha\beta}$ composed of quadratic forms of the metric perturbation.

These expanded equations can then be solved order by order in the perturbation through Green function methods, where the integral is over the past lightcone of Minkowski space for $x \in M$. When working at sufficiently high PN order, the resulting integrals can be formally divergent, but these pathologies can be bypassed or cured through asymptotic matching methods (as in Will's method of the direct integration of the relaxed Einstein equations) or through regularization techniques (as in Blanchet and Damour's Hadamard and dimensional regularization approach). All approaches to cure these pathologies have been shown to lead to exactly the same end result for the metric perturbation.

The metric perturbation is solved for order by order, where at each order one uses the previously calculated information in the expression for $N^{\alpha\beta}$ and also to find the motion of the matter sources, thus leading to an improved expression for $T^{\alpha\beta}$ at each order. In particular, the emission of gravitational waves by a binary system causes a change in the period of that system, and this change was used by Hulse and Taylor to *indirectly* detect gravitational waves through their observations of the binary pulsar. In this way, the PN iterative procedure provides a perturbative approximation to the solution to the Einstein equations to a given order in the feebleness of the gravitational interaction and the speed of the bodies.

Little work has gone into studying the mathematical properties of the resulting perturbative series. Clearly, the PN approximation should not be valid when the speed of the bodies becomes comparable to the speed of light or when the objects described are black holes or neutron stars with significant self-gravity. Damour, however, has shown that the latter can still be described by the PN approximation up to a given order in perturbation theory. Moreover, recent numerical simulations of the merger of binary black holes and neutron stars have shown that the PN approximation is accurate even quite late in the inspiral, when the objects are moving at close to a third of the speed of light.

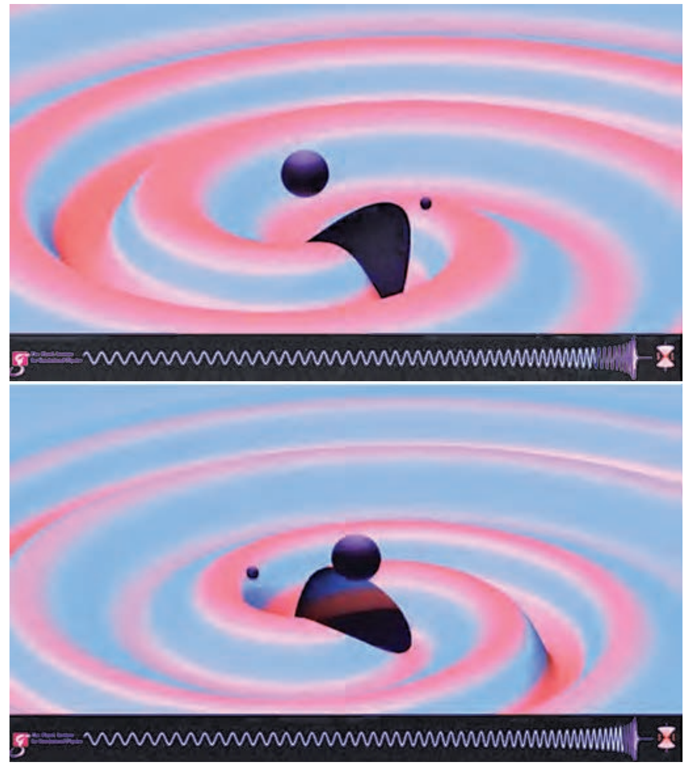

Figure 11. Numerical simulation of the late inspiral of an unequal-mass, black hole binary. Even late in the inspiral, the PN approximation for gravitational waves remains accurate.

Resummations of the PN Approximation

The accuracy of the approximate solutions can be improved by applying resummation techniques: the rewriting of the perturbative expansion in a new form (e.g. a Chebyshev decomposition or a Padé series) that makes use of some physical feature one knows should be present in the exact solution. For example, one may know (through symmetry arguments or by taking certain limits) that some exact result contains a first-order pole at a certain spacetime position, so one could rewrite the approximate solution as a Padé approximant that makes this pole explicit.

A particular resummation of the PN approximation that has been highly successful at approximating numerical solutions is the *effective one-body approach*. Recall that in Newtonian gravity, the motion of masses m_1 and m_2 under their mutual gravitational attraction is mathematically equivalent to the motion of a single mass μ in the gravitational field of a stationary mass M, where $M = m_1 + m_2$ and $\mu = (m_1 m_2)/M$. The effective one body approach similarly attempts to recast the motion of two black holes under their mutual gravitational attraction as the motion of a single object in a given spacetime metric.

More precisely, one recasts the two-body problem onto the problem of an effective body that moves on an effective external metric through an energy map and a canonical transformation. The dynamics of the effective body are then described through a (conservative) improved Hamiltonian and a (dissipative) improved radiation-reaction force. The improved Hamiltonian is resummed through two sets of square-roots of PN series, in such a way so as to reproduce the standard PN Hamiltonian when Taylor expanded about weak-field and slow-velocities. The improved radiation-reaction force is constructed from quadratic first-derivatives of the gravitational waves, which in turn are product-resummed using the Hamiltonian (from knowledge of the extreme mass-ratio limit of the PN expansion) and a field-theory resummation of certain tail-effects.

Once the two-body problem has been reformulated, the Hamilton equations associated with the improved Hamiltonian and radiation-reaction force are solved numerically, a significantly easier problem than solving the full Einstein equations. This resummation, however, is not enough because the improved Hamiltonian and radiation-reaction force are built from finite PN expansions. The very late inspiral behavior of the solution can be corrected by adding calibration coefficients (consistent with PN terms not yet calculated) to the Hamiltonian and the radiation-reaction force, which are then determined by fitting to a set of full, numerical relativity simulations.

The calibrated effective-one-body waveforms described above are incredibly accurate representations of the

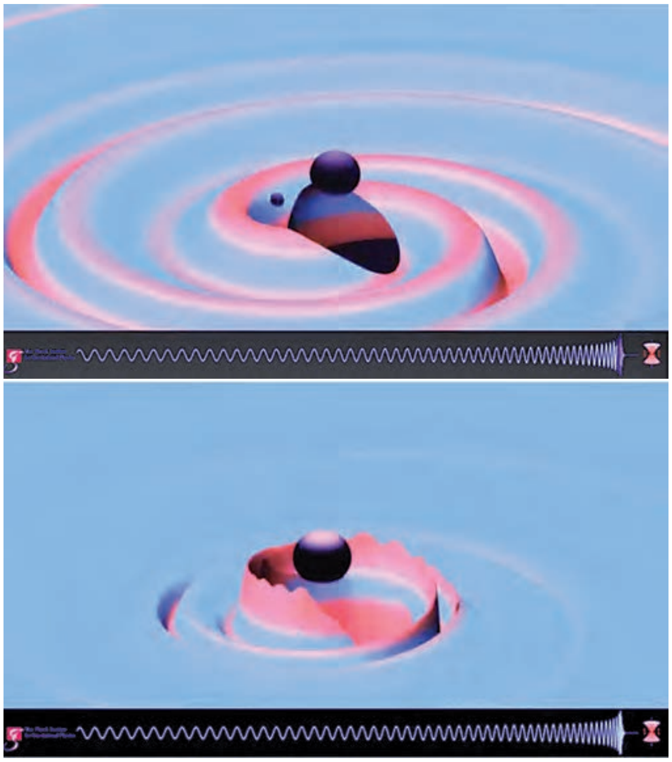

Figure 12. Numerical simulation of the merger of an unequal-mass, black hole binary. The effective-one-body approximation remains highly accurate almost up to the moment when the black holes horizons touch, when full numerical simulations are required.

gravitational waves emitted in the inspiral of compact objects, up to the moment when the black holes merge. They become accurate after the merger by adding on information from black hole perturbation theory that we describe next.

Perturbations About a Black Hole Background

After the black holes merge, they form a single distorted black hole that sheds its distortions by emitting gravitational waves and eventually settling down to a Kerr black hole. This "ringdown" phase is described using perturbation theory with the Einstein vacuum equations linearized around a Kerr black hole background. Teukolsky showed how to obtain a wave type equation for these perturbed Weyl tensor components from the Einstein vacuum equations. The result of the Teukolsky method is that the distortions can be expanded in modes, each of which has a characteristic frequency and exponential decay time. The ringdown is well approximated by the most slowly decaying of these modes. This ringdown waveform can be stitched to the effective-one-body inspiral waveforms to obtain a complete description of the gravitational waves emitted in the coalescence of black holes.

Mathematics and Numerics

In numerical relativity, one creates simulations of the Einstein field equations using a computer. This is needed when no other method will work, in particular when gravity is very strong and highly dynamical (as it is when two black holes merge).

The Einstein field equations, like most of the equations of physics, are differential equations, and the most straightforward of the techniques for simulating differential equations are finite difference equations. In the one-dimensional setting, one approximates a function $f(x)$ by its values on equally spaced points

$$f_i = f(i\delta) \text{ for } i \in \mathbb{N}.$$

One then approximates derivatives of f using differences

$$f' \approx (f_{i+1} - f_{i-1})/(2\delta)$$

and

$$f''(i) \approx (f_{i+1} + f_{i-1} - 2f_i)/\delta^2.$$

For any pde with an initial value formulation one replaces the fields by their values on a spacetime lattice, and the field equations by finite difference equations that determine the fields at time step $n+1$ from their values at time step n. Thus the Einstein vacuum equations are written as difference equations where the step 0 information is the initial data set.

One then writes a computer program that implements this determination and runs the program. Sounds simple, right? So what could go wrong? Quite a lot, actually. It is best to think of the solution of the finite difference equation as something that is supposed to converge to a solution of the differential equation in the limit as the step size δ between the lattice points goes to zero. But it is entirely possible that the solution does not converge to anything at all in this limit. In particular, the coordinate invariance of general relativity allows one to express the Einstein field equations in many different forms, some of which are not strongly hyperbolic. Computer simulations of these forms of the Einstein field equations generally do not converge.

Another problem has to do with the constraint equations. Recall that initial data have to satisfy constraint equations. It is a consequence of the theorem of Choquet-Bruhat that if the initial data satisfy those constraints then the results of evolving those initial data continue to satisfy the constraints. However, in a computer simulation the initial data only satisfy the finite difference version of the constraints and therefore have a small amount of constraint violation. The field equations say that data with zero constraint violation evolve to data with zero constraint violation. But that still leaves open the possibility (usually realized in practice) that data with small constraint violation evolve in such a way that the constraint violation grows rapidly (perhaps even exponentially) and thus destroys the accuracy of the simulation.

Finally there is the problem that these simulations deal with black holes, which contain spacetime singularities. A computer simulation cannot be continued past a time where a slice of constant time encounters a spacetime singularity. Thus either the simulations must only be run

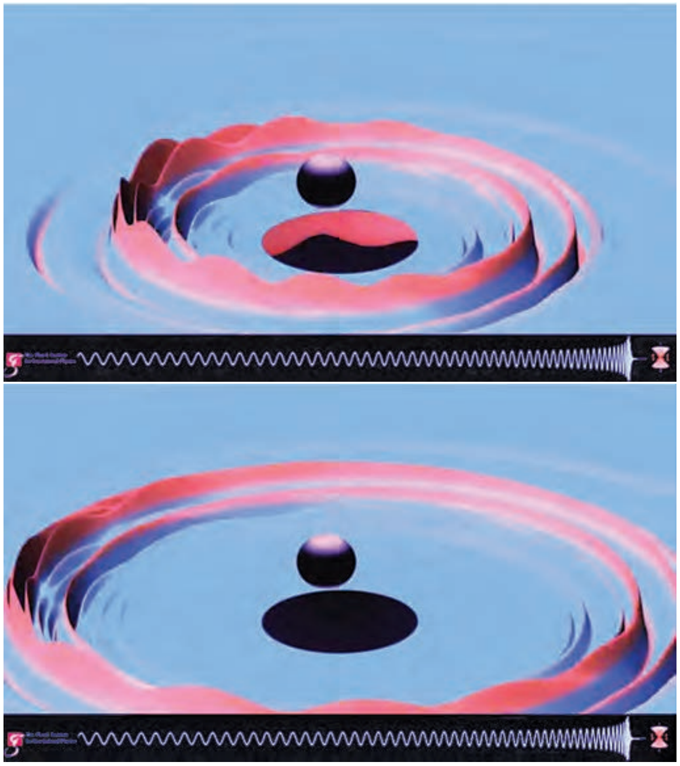

Figure 13. Numerical simulation of the ringdown after the merger of an unequal-mass, black hole binary. In the ringdown phase, perturbation theory provides an excellent approximation to the waveform.

for a short amount of time, or the time slices inside the black hole must somehow be "slowed down" so that they do not encounter the singularity. But then if the time slice advances slowly inside the black hole and rapidly outside it, this will lead to the slice being stretched in such a way as to lead to inaccuracies in the finite difference approximation.

Before 2005 these three difficulties were insurmountable, and none of the computer simulations of colliding black holes gave anything that could be used to compare with observations. Then suddenly in 2005 all of these problems were solved by Frans Pretorius, who produced the first fully successful binary black hole simulation. Then later that year the problem was solved again (using completely different methods!) by two other groups: one consisting of Campanelli, Lousto, Marronetti, and Zlochower and the other of Baker, Centrella, Choi, Koppitz, and van Meter. Though the methods are different, both sets of solutions can be thought of as consisting of the ingredients *hyperbolicity, constraint damping*, and *excision*, and we will treat each one in turn.

Hyperbolicity. Since one needs the equations to be strongly hyperbolic, one could perform the simulations in harmonic coordinates. However, one also needs the time coordinate to remain timelike, so instead Pretorius used generalized harmonic coordinates (as first suggested by Friedrich) where the coordinates satisfy a wave equation with a source. The other groups implemented hyperbolicity by using the BSSN equations (named for its inventors: Baumgarte, Shapiro, Shibata, and Nakamura). These equations decompose the spatial metric into a conformal factor and a metric of unit determinant and then evolve each of these quantities separately, adding appropriate amounts of the constraint equations to convert the spatial Ricci tensor into an elliptic operator.

Constraint damping. Because the constraints are zero in exact solutions to the theory, one has the freedom to add any multiples of the constraints to the right-hand side of the field equations without changing the class of solutions to the field equations. In particular, with clever choices of which multiples of the constraints go on the right-hand side, one can arrange that in these new versions of the field equations small violations of the constraints get smaller under evolution rather than growing. Carsten Gundlach showed how to do this for evolution using harmonic coordinates, and his method was implemented by Pretorius. The BSSN equations already have some rearrangement of the constraint and evolution equations. The particular choice of lapse and shift (Φ and X from eqns. (7–8)) used by the other groups (called 1+log slicing and Gamma driver shift) were found to have good constraint damping properties.

Excision. Because nothing can escape from a black hole, nothing that happens inside can have any influence on anything that happens outside. Thus in performing computer simulations of colliding black holes, one is allowed to simply excise the black hole interior from the computational grid and still obtain the answer to the question of what happens outside the black holes. By excising, one no longer has to worry about singularities or grid stretching. Excision was first proposed by Unruh and Thornburg, and first implemented by Seidel and Suen, and used in Pretorius' simulations. The other groups essentially achieve excision by other methods. They use a "moving puncture method" that involves a second asymptotically flat end inside each black hole, which is compactified to a single point that can move around the computational grid. The region between the puncture and the black hole event horizon undergoes enormous grid stretching, so that effectively only the exterior of the black hole is covered by the numerical grid.

Since 2005, many simulations of binary black hole mergers have been performed, for various black hole masses and spins. Some of the most efficient simulations are done by the SXS collaboration using spectral methods instead of finite difference methods. (SXS stands for "Simulating eXtreme Spacetimes" and the collaboration is based at Cornell, Caltech, and elsewhere.) Spectral methods use the grid values f_i to approximate the function $f(x)$ as an expansion in a particular basis of orthogonal functions. The expansion coefficients and the derivatives of the basis functions are then used to compute the derivatives of $f(x)$. Compared to finite difference methods, spectral methods can achieve a given accuracy of the derivatives with significantly fewer grid points.

Gravitational Wave Experiment

The experimental search for gravitational waves started in the 1960s through the construction of *resonant bar detectors*. These essentially consist of a large (meter-size) cylinder in a vacuum chamber that is isolated from vibrations. When a gravitational wave at the right frequency interacts with such a bar, it can excite the latter's resonant mode, producing a change in length that one can search for. In 1968, Joseph Weber announced that he had detected gravitational waves with one such resonant bar. The sensitivity of Weber's resonant bar to gravitational waves was not high enough for this to be possible, and other groups could not reproduce his experiment.

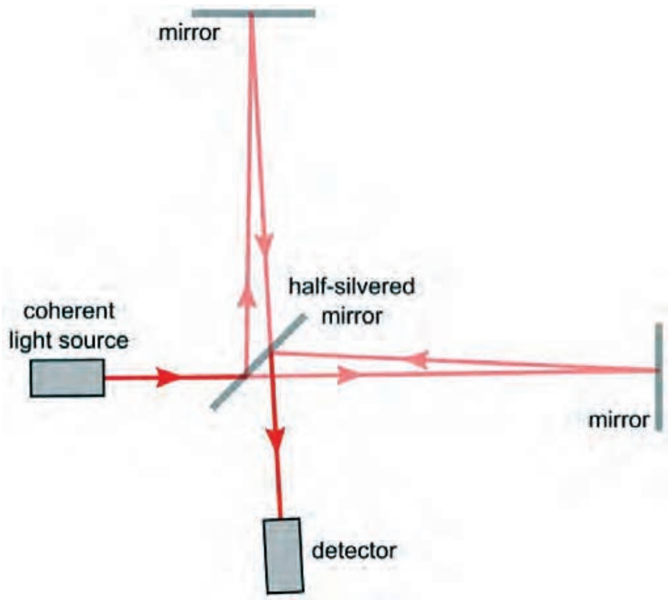

Figure 14. Schematic diagram of a Michelson interferometer, which is at the heart of the instrumental design used by aLIGO. In the diagram, a laser beam is split into two sub-beams that travel down orthogonal arms, bounce off mirrors, and then return to recombine.

In the late 1960s and early 1970s, the search for gravitational waves with laser interferometers began through the pioneering work of Rainer Weiss at MIT and Kip Thorne and Ronald Drever at Caltech, among many others. The basic idea behind interferometry is to split a laser beam into two sub-beams that travel down orthogonal arms, bounce off mirrors, and then return to recombine. If the light travel time is the same in each sub-beam, then the light recombines constructively, but if a gravitational wave goes through the detector, then the light travel time is not the same in each arm and interference occurs. Gravitational wave interferometers are devices that use this interference process to measure small changes in light travel time very accurately so as to learn about the gravitational waves that produced them, and thus, in turn, about the properties of the source of gravitational waves.

The initial Laser Interferometer Gravitational-Wave Observatory (iLIGO) was funded by the National Science

Figure 15. (from top to bottom) Ronald Drever, Kip Thorne, and Rainer Weiss pioneered the effort to detect gravitational waves with laser interferometers.

Foundation in the early 1990s and operations started in the early 2000s. There are actually two LIGO facilities (one in Hanford, Washington, and one in Livingston, Louisiana) in operation right now, with an Italian counterpart (Virgo) coming online soon, a Japanese counterpart (KAGRA) coming online by the end of the decade, and an Indian counterpart (LIGO-India) coming online in the 2020s. The reason for multiple detectors is to achieve redundancy and increase the confidence of a detection by observing the signal by independent detectors with uncorrelated noise. Although iLIGO was over four orders of magnitude more sensitive than Weber's original instrument in a wide frequency band, no gravitational waves were detected.

Figure 16. One of the two aLIGO facilities, this one in Livingston, Louisiana, where the interference pattern associated with a gravitational wave produced in the merger of two black holes was recorded within days of the first science run.

In the late 2000s, upgrades to convert iLIGO into advanced LIGO (aLIGO) commenced. These upgrades included an increase in the laser power to reduce quantum noise, larger and heavier mirrors to reduce thermal and radiation pressure noise, better suspension fibers for the mirrors to reduce suspension thermal noise, among many other improvements. aLIGO commenced science operations in 2015 with a sensitivity roughly 3–4 times greater than that of iLIGO's last science run.

Within days of the first science run, the aLIGO detectors recorded the interference pattern associated with a gravitational wave produced in the merger of two black holes 1.3 billion light years away. The signal was so loud (relative to the level of the noise) that the probability that the recorded event was a gravitational wave was much larger than 5σ, meaning that the probability of a false alarm was much smaller than 10^{-7}. There is no doubt that this event, recorded on September 14, 2015, as well as a second one, detected the day after Christmas of that same year, were the first direct detections of gravitational waves.

In order to understand how gravitational waves are detected, we must understand how the waves affect the motion of the parts of the interferometer. The mirrors are suspended from wires like a pendulum, but this means that for short time motion in the horizontal direction, the motion of each mirror can be treated as

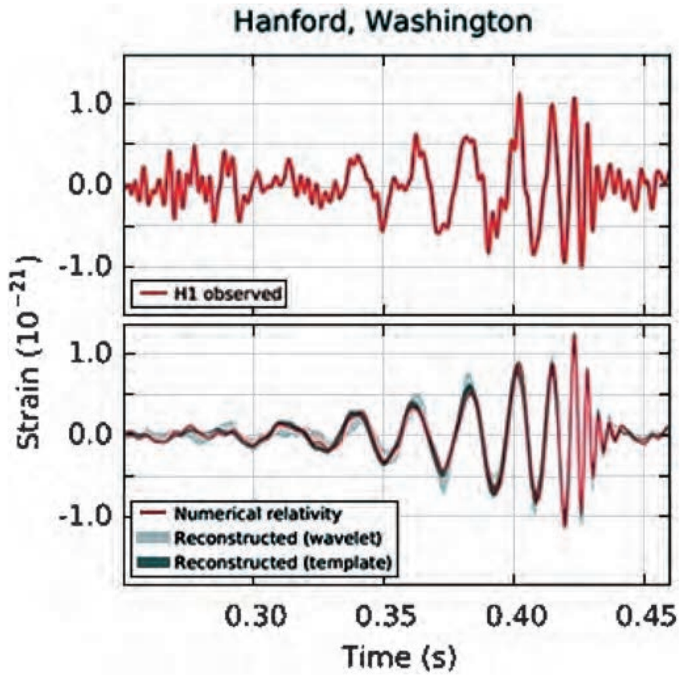

Figure 17. Top: Filtered GW strain as a function of time detected at the Hanford location of aLIGO. Bottom: Best fit reconstruction of the signal using a numerical relativity simulation (red), an analytical waveform template (gray), and a set of Morley wavelets. The latter two are shown as 90 percent confidence regions, while the simulation is a particular run with a choice of parameters within this the 90 percent confidence region.

a spacetime geodesic. But the interferometer measures distance between the mirrors, so what we want to know is how this distance changes under the influence of a gravitational wave. The answer to this question comes from the Jacobi equation: the relative acceleration of nearby geodesics is equal to the Riemann tensor times the separation of those geodesics.

Listen to the universe with gravity.

Thus if at any time we want to know the separation, we need to integrate the Jacobi equation twice with respect to time. However, the Riemann tensor is the second derivative of the TT gauge metric perturbation. Thus, by using this particular gauge we can say that LIGO directly measures the metric perturbation by using laser interferometry to keep track of the separation of its mirrors.

Astrophysics and Fundamental Physics

Up until now, we have created a picture of the universe from the information we have obtained from amazing telescopes, such as Chandra in the X-rays, Hubble in the optical, Spitzer in the infrared, WMAP in the microwave, and Arecibo in the radio frequencies. This information was provided by light that traveled from astrophysical sources to Earth. Every time humankind built a new telescope that gave us access to a new frequency range of the light spectrum, amazing discoveries were made. The discovery of accretion disk signatures of black holes using X-ray astronomy is a case in point. This expectation is especially true for gravitational wave detectors, which do not just open a new frequency range, but rather aim to *listen to the universe* in an entirely new way: with gravity instead of light.

This new type of astrophysics has an immense potential to truly revolutionize science because gravitational waves can provide very clean information about their sources. Unlike light, gravitational waves are very weakly coupled to matter, allowing gravitational waves to go right through the intermediate matter (which would absorb light) and provide a clean picture (or soundtrack) of astrophysical sources that until now had remained obscure. Of course, this is a double-edged sword because the detection of gravitational waves is extremely challenging, requiring the ability to measure distances that are as small as 10^{-3} times the size of a proton over a 4 km baseline.

The aLIGO detectors achieved just that, providing humanity with not only the first direct detection of gravitational waves, but also the first direct evidence of the existence of black hole binaries and their coalescence. As of the writing of this article, aLIGO had detected two events, both of which correspond to the coalescence of binary black hole systems in a quasi-circular orbit. Fitting the hybrid analytic and numerical models described in the sections "Approximation Methods" and "Mathematics and Numerics" to the data, the aLIGO collaboration found that the first event consisted of two black holes with masses

$$(m_1, m_2) \approx (36.2, 29.1)M_\odot,$$

where $M_\odot$ is the mass of our sun, colliding at roughly half the speed of light to produce a remnant black hole with mass

$$m_f \approx 62.3M_\odot$$

and dimensionless spin angular momentum

$$|\vec{S}|/m_f^2 \approx 0.68,$$

located 420 mega-parsecs away from Earth (roughly 1.3 billion times the distance light travels in one year). The second event consisted of lighter black holes, with masses

$$(m_1, m_2) \approx (14.2, 7.5)M_\odot$$

that collided to produce a remnant black hole with mass

$$m_f \approx 20.8M_\odot$$

and dimensionless spin angular momentum

$$|\vec{S}|/m_f^2 \approx 0.74,$$

located 440 mega-parsecs away from Earth. In both cases, the peak luminosity radiated was in the range of 10^{56} ergs/s with the systems effectively losing $3M_\odot$ and $1M_\odot$ respectively in less than 0.1 seconds. Thus, for a very brief moment, these events produced more energy than all of the stars in the observable universe put together.

Perhaps one of the most interesting inferences one can draw from such events is that black holes (or at the very least, objects that look and "smell" a lot like black holes) truly do form binaries and truly do merge in nature within an amount of time smaller than the age of the universe. Until now, we had inferred the existence of black holes by either observing how other stars orbit around supermassive ones at the center of galaxies or by observing enormous disks of gas orbit around stellar mass black holes and the X-rays emitted as some of that gas falls into the black hole. The aLIGO observations are the first direct observation of radiation produced by binary black holes themselves through the wave-like excitations of the curvature they generate when they collide. Not only did the aLIGO observation prove the existence of binary black holes, but even the first observation brought about a surprise: the existence and merger of black holes in a mass range that had never been observed before.

Figure 18. Nicolás Yunes and his team explore mathematically the extreme gravity of black holes and neutron stars, as well as the gravitational waves they emit when they inspiral into each other and collide. The goal of his research program is to construct analytic models that enable the extraction of the most astrophysics and theoretical physics information from future astrophysics and gravitational wave observations, thus allowing us to test Einstein's theory in the essentially unexplored extreme gravity regime.

The aLIGO observations have demonstrated that general relativity is not only highly accurate at describing gravitational phenomena in the solar system, in binary pulsar observations, and in cosmological observations, but also in the late inspiral, merger, and ringdown of black hole binaries. Gravity is truly described by Einstein's theory even in the most *extreme gravity* scenarios: when the gravitational interaction is strong, highly nonlinear, and highly dynamical. Such consistency with Einstein's theory has important consequences on theories that modify gravity in hopes of arriving at a quantum gravitational completion. Future gravitational wave observations will allow us to verify many other pillars of Einstein's theory, such as that the gravitational interaction is parity invariant, that gravitational waves propagate at the speed of light, and that it only possesses two transverse polarizations.

The detection of gravitational waves is not only a spectacular confirmation of Einstein's theory, but also the beginning of a new era in astrophysics. Gravitational waves will provide the *soundtrack* to the movie of our universe, a soundtrack we had so far been missing with telescopes. No doubt that they will be a rich source for new questions and inspiration in physics as well as mathematics. We wait anxiously for the unexpected beauty this music will provide.

Acknowledgments

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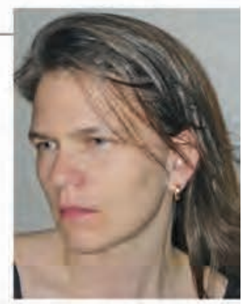

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NicolásYunes

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AWM–AMS Noether Lecture

The Association for Women in Mathematics (AWM) established the Emmy Noether Lectures in 1980 to honor women who have made fundamental and sustained contributions to the mathematical sciences. In April 2013 this one-hour expository lecture was renamed the AWM–AMS Noether Lecture. The first jointly sponsored lecture was held in January 2015 at the Joint Mathematics Meetings (JMM) in San Antonio, Texas. Emmy Noether was one of the great mathematicians of her time, someone who worked and struggled for what she loved and believed in. Her life and work remain a tremendous inspiration.

The mathematicians who have given the Noether Lectures in the recent past include: Lisa Jeffrey, Karen Smith, Wen-Ching Winnie Li, Georgia Benkart, Raman Parimala, and Barbara Keyfitz. Additional past Noether lecturers can be found at **https://sites.google.com/site/awmmath/programs/noether-lectures/noether-lecturers**.

The letter of nomination should include a one-page outline of the nominee's contribution to mathematics, giving four of her most important papers and other relevant information. Nominations must be submitted by October 15, 2017, and will be held active for three years.

The nomination procedure is described here: **https://www.sites.google.com/site/awmmath/programs/noether-lectures.**

If you have questions, call 703-934-0163 or email awm@awm-math.org.

ASSOCIATION FOR WOMEN IN MATHEMATICS

Post-Quantum Cryptography—A New Opportunity and Challenge for the Mathematics Community

Jintai Ding and Daniel Smith-Tone

Note: The opinions expressed here are not necessarily those of Notices.
Responses on the Notices *webpage are invited.*

Over the past three decades, the family of public-key cryptosystems, a fundamental breakthrough in modern cryptography in the late 1970s, has become an increasingly integral part of our communication networks. The Internet, as well as other communication systems, relies principally on the Diffie-Hellman key exchange, RSA encryption, and digital signatures using DSA, ECDSA, or related algorithms. The security of these cryptosystems depends on the difficulty of certain number-theoretic problems, such as integer factorization or the discrete log problem. In 1994 Peter Shor showed that quantum computers can solve each of these problems in polynomial time, thus rendering the security of all cryptosystems based on such assumptions impotent.

A large international community has emerged to address this issue in the hope that our public-key infrastructure may remain intact by utilizing new quantum-resistant primitives. In the academic world, this new science bears the moniker Post-Quantum Cryptography (PQC).

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In August 2015 the National Security Agency published a webpage announcing preliminary plans for transitioning to quantum-resistant algorithms (`www.iad.gov/iad/programs/iad-initiatives/cnsa-suite.cfm`). In December 2016 the National Institute of Standards and Technology (NIST) announced a call for proposals for quantum-resistant algorithms with a deadline of 30 November 2017 (`www.nist.gov/pqcrypto`). The effort to develop quantum-resistant technologies, and in particular post-quantum cryptosystems, is becoming a central research area in information security.

Current research in post-quantum cryptography is based on state-of-the-art computational techniques such as algorithms in algebraic geometry, coding theory, and lattice theory. The mathematics utilized in PQC is diverse and sophisticated, including representation theory, harmonic analysis, mathematical physics, algebraic number theory, lattice theory, and algebraic geometry. Even the Riemann hypothesis is often used to deal with critical problems in complexity

Even the Riemann hypothesis is often used to deal with critical problems in complexity analysis.

analysis. Yet this is a relatively new field, and many new challenging mathematical problems have arisen. Some of the major research avenues currently being probed include lattice reduction, algebraic attack complexity, differential symmetry, and quantum information theory.

The research required to develop and analyze a new quantum-resistant cryptographic standard for NIST brings a great opportunity for the mathematical community. We need to fully understand the mathematical structures behind those systems and refine the theory, which will enable us to design the best possible PQC algorithms for the next generation of security standards. The research in this area will serve as a great forum to introduce those critical mathematical questions to a broader mathematical audience to bring new stimulus to their theoretical development.

Cybersecurity is considered one of the most important aspects of our information technology-based society. In light of the threat that quantum computers pose to cryptosystems such as RSA and ECC, the development of post-quantum cryptography is expected to help build secure and efficient alternatives for the post-quantum computer world. The success of the NIST standards will not only have very significant applications in industry but also a broad impact on theoretical mathematics and computation. By now many mathematicians around the world have made fundamental contributions in this area. However, the broad mathematical community seems unaware of this unique opportunity to combine our expertise and skills to tackle some of the critical mathematical problems in post-quantum cryptography, where our work can have a profound impact on our society and also affect the development of mathematics itself.

EDITOR'S NOTE. Is a quantum computer actually feasible? See "The Quantum Computer Puzzle" by Gil Kalai in the May 2016 issue of the *Notices*.

ABOUT THE AUTHORS

Jintai Ding received the ZhongJia-Qing Mathematics Award from the Chinese Mathematical Society in 1990. He and his colleagues developed the Rainbow signature, the GUI HFEV-signature, the Simple Matrix encryption, and the LWE-based key exchange schemes.

Jintai Ding

Daniel Smith-Tone's interests include the development of algebraic, combinatorial, differential, and probabilistic techniques in symmetric and asymmetric cryptography. His current focus is post-quantum cryptography, to which he has contributed new tools in provable security and cryptanalysis.

Daniel Smith-Tone

Twenty Years Ago in the *Notices*

August 1997:

Review of *Noncommutative Geometry* by Alain Connes, reviewed by Vaughan Jones and Henri Moscovici.
This article discusses Alain Connes's visionary *1994 book Noncommutative Geometry.* Appearing in the same issue, `www.ams.org/notices/199707/jones.pdf`, "Noncommutative Geometry," by Andrew Lesniewski, emphasizes the physics aspects of the subject. Both articles aim to introduce non-experts to the main ideas of the subject, explaining what the word "noncommutative" means in this context, how Connes's revolutionary ideas are related to previous mathematical work, and how they connect to physics. Lesniewski wrote that Noncommutative Geometry is "one of the milestones of mathematics. It lays the foundations of a new branch of mathematics whose importance is difficult to overestimate. Its impact will be felt by generations of mathematicians to come, the way Riemann's Über die Hypothesen influenced the development of differential geometry."

FROM THE
AMS SECRETARY

ATTENTION ALL AMS MEMBERS

Voting Information for 2017 AMS Election

AMS members who have chosen to vote online will receive an email message on or shortly after August 21, 2017, from the AMS Election Coordinator, Survey & Ballot Systems.

The From Line will be “AMS Election Coordinator”, the Sender email address will be noreply@directvote.net, and the Subject Line will be “AMS 2017 Election—login information below”. If you use a spam filter you may want to use the above address or subject information to configure your spam filter to ensure this email will be delivered to you.

The body of the message will provide your unique voting login information and the address (URL) of the voting website.

AMS members who have chosen to vote by paper should expect to receive their ballot by the middle of September. Unique voting login information will be printed on the ballot, should you wish to vote online.

At midnight (US Eastern Time) on November 3, 2017, the website will stop accepting votes. Paper ballots received after this date will not be counted.

Additional information regarding the 2017 AMS Election is available on the AMS website: www.ams.org/election-info
or by contacting the AMS: election@ams.org, 800-321-4267 (US & Canada), 401-455-4033 (worldwide).

Thank you and . . . please remember to vote.

Carla D. Savage

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COMMUNICATION

The Global Math Project: Uplifting Mathematics for All

James Tanton and Brianna Donaldson

Communicated by Ben Braun

ABSTRACT. The Global Math Project aims to connect millions of students around the world through a shared experience of mathematics. For the past year a leadership team of seven math professionals, together with a worldwide network of ambassadors and partners, has been laying the groundwork for the inaugural Global Math Week, which will launch on 10.10.2017.

Here is a bold and audacious idea: let's generate a fundamental paradigm shift as to how the world perceives and enjoys mathematics. Can each and every person on this planet come to see mathematics as human, relevant, meaningful, creative, uplifting, and joyful? Can the play and wonder of mathematics transcend borders and truly unite communities?

Welcome to the Global Math Project

The vision just outlined is not without precedent. In 2013 the organization `code.org` set out to bring computer coding to students all across the globe. For one special week that year, millions of students took part in their Hour of Code program, each enjoying some activity—be it a relevant pencil and paper exercise or an advanced interactive online computing experience—that teaches an aspect of coding. The program has been going strong ever since then and has now reached over a quarter of a billion students.

James Tanton is the Mathematical Association of America's mathematician-at-large. His e-mail address is `tanton.math@gmail.com`.

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Why Not Do the Same for Math?

There is one substantial challenge, and it's a perception issue. For many cultures, the idea of signing up for an extracurricular hour of math, as opposed to programming, is decidedly unappealing.

On the other hand, students all across the globe are already engaged in mathematics four or five times a week each and every school week. We can reach millions of students by reaching out to just tens of thousands of teachers, homeschool leaders, math club and math circle leaders, and the like. So why not declare a special week of each year as Global Math Week and ask educators to share with their students one engaging and astonishingly thrilling piece of mathematics sometime that week? Let's have students and teachers share their reactions, thoughts, and ideas with comments, videos, or photos posted on social media. Let's foster a global conversation about joyous mathematics!

Let's foster a global conversation about joyous mathematics!

Enter the Global Math Project

For the past year a leadership team of seven math professionals has been laying the groundwork to turn the week starting 10.10.2017 into the inaugural Global Math Week (see box on page 715). We believe that the following ingredients are key to the success of Global Math Week 2017:

- a compelling topic,
- appealing and accessible resources for engagement,
- a global network of ambassadors committed to spreading the word, and
- partner organizations that support project activities through financial and in-kind donations.

Below we describe how these ingredients will combine to create an enthralling global experience of mathematics.

A Compelling Topic: Exploding Dots

Fundamental to the success of Global Math Week is presenting a mathematical experience that is directly relevant to the standard school content to show that even elementary school topics serve as portals to universes of wonder and delight. We want to show how math, as one youngster recently put it, is "continuous"[1] and keeps inviting further exploration. The mathematics topic should transcend language and the details of any particular curriculum while at the same time fostering an appreciation of fundamental math concepts. It should fit naturally into any classroom.

The team has identified several mathematical storylines that will serve well and have settled on presenting one in particular, Exploding Dots, as the topic for the inaugural experience:

> Here is a story that isn't true.
>
> When I was a child I invented a machine (not true) that was nothing more than a series of boxes that could hold dots. And these dots would, upon certain actions, explode. And with this machine, in this nontrue story, I realized I could explain true things! In one fell swoop I explained all the mathematics of arithmetic I learned in grade school (true), all of the polynomial algebra I was to learn in high school (true), elements of calculus and number theory (true)—and also begin to explore unanswered research questions intriguing mathematicians still to this day (also true)!
>
> Let me share this story with you. See how simple and elegant ideas connect to profound ideas in mathematics as a whole. See how these ideas will completely revolutionize your thinking of school arithmetic and algebra and beyond!

So begins the story of Exploding Dots, as developed in 2005 by Global Math Project founder James Tanton. Tanton drew inspiration from a "chip firing" model developed by German educationalist Arthur Engel in the 1970s to explain elementary probability to school students, as well as from mathematician James Propp's efforts to popularize Engel's work. Simple example configurations of Engel's model match the workings of an abacus and illustrate the mechanics of place value, but in all types of bases. Mathematicians have explored the ramifications of arithmetic in these fractional, negative, and irrational bases, and open questions remain [1]. Tanton turned these abacus models back to reconnect them with the K–12 curriculum, in particular moving beyond just place value and arithmetic of primary and middle school to the more advanced mathematics of high school algebra and precalculus, and elements of undergraduate work such as discovering the generating function of the Fibonacci numbers or exploring the 10-adic representation of negative one.

Exploding Dots is typically introduced by exploring a **1**←**2** machine, which consists of a row of boxes, extending as far to the left as one pleases. To operate this machine, one places a number of dots in the rightmost box, which the machine then redistributes according to the following rule: *Two dots in any one box are erased (they "explode"—kapow!) to be replaced with one dot located one box to their left.* For instance, placing six dots into a **1**←**2** machine yields four explosions, with a final distribution of dots that can be read as "1 1 0." See Figure 1.

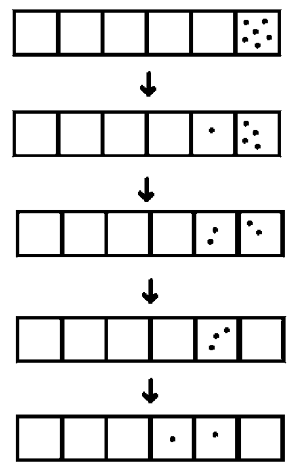


Figure 1: Placing six dots into a 1←2 machine yields four explosions, with a final distribution of dots that can be read as "1 1 0."

Of course, since one dot in a cell is deemed equivalent to two dots in the preceding cell, each cell is "worth" double the cell to its right. If we deem the rightmost cell as the units, then each cell of the machine corresponds to the powers of two. Thirteen, for instance, equals 8 + 4 + 1, and the base-2 representation of 13 is 1101. See Figure 2.

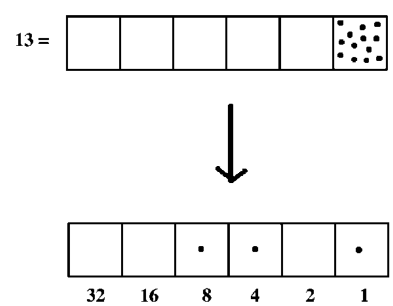


Figure 2: The 1←2 machine converts all numbers to their binary representations. Thirteen, for instance, equals 8 + 4 + 1, and the base-2 representation of 13 is 1101.

The **1**←**2** machine converts all numbers to their binary representations. In the same way, a **1**←**3** machine (three dots explode to make one dot to the left) gives the base-3

[1] *See video at* `https://www.youtube.com/watch?v=hB6bfw622fo`

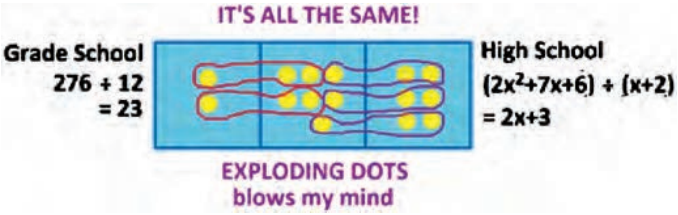


Figure 3: Exploding Dots can explain the mathematics of grade school arithmetic and high school polynomial algebra.

representation of a number and a **1**←**10** machine the base-10 representation. Taking it a step further, an abstract **1**←**x** machine gives the polynomials of high school algebra.

Exploding Dots is an extraordinary gateway to introduce the habits of mind for doing substantive mathematics—exploring, discovering, and explaining pattern and structure, and then utilizing one's newfound understanding for further exploration and discovery; developing perseverance in pursuing questions and not settling for half-formed explanations; working with both the abstract and the concrete translation of the abstract; and engaging in a joyful intellectual pursuit. Exploding Dots is both poetic and utilitarian. It is a genuine blend of beautiful mathematics worthy of exploration for its own sake, just as mathematics is often described by mathematicians, and the practical learning of concrete skills for implementation and application. Mathematics is both things, and Exploding Dots is a prime means to demonstrate both sides of this beautiful coin.

Exploding Dots is both poetic and utilitarian.

Tanton has delivered workshops and lectures on this topic to audiences all across the globe, and students, teachers, and parents alike consistently describe it as "mind blowing." In fact, the inspiration for Global Math Week came from project co-founder Jill Diniz's experience with introducing Exploding Dots to her teenaged son:

> … the next day he sent me a text during the school day which said, "Mom, I just showed Exploding Dots to Sammy and Hunter, and we were like, whoaaa, this blows my mind." Then later that evening he came to my room and wanted to talk about just how mind blowing Exploding Dots was, how it related even to what he was doing in AP calculus.

She adds:

> Soon thereafter, I sent a note to James and wanted to talk. I had recently become aware of the Hour of Code project and was inspired to apply this idea to Exploding Dots. We just had to get every kid in the country—in the world, even—doing Exploding Dots and doing it roughly at the same time, creating a shared, mind-blowing experience of mathematics that could serve to improve the everyday connection with math for millions of students.

A version of all the Exploding Dots content is currently available on the Web [1].

Appealing and Accessible Resources for Engagement

So, now we have our inaugural topic, but what will actually happen the week of 10.10.17?

Beginning in April, we opened registration for teachers, math club and math circle leaders, and other educators and math-outreach specialists who have committed to leading a one-hour experience of Exploding Dots during Global Math Week and to sharing that experience with the world in some way, most typically through social media. Also in April we started revealing our new Exploding Dots platform, so that educators can begin playing with the topic themselves and consult with our ever-growing list of ambassadors if guidance is needed.

During Global Math Week itself, our website will serve as a portal to multiple modalities of experiencing Exploding Dots, ranging from low-technology to technology-intensive alternatives. The low-technology experience will consist of downloadable pdfs with lesson plans for leading a discussion about Exploding Dots without any specialized classroom technology (Tanton typically uses only a whiteboard). The more technology-intensive options will use an appealing user interface presented as a collection of "islands" that each represent a particular Exploding Dots topic. Each island will contain three elements to experience: a short explanatory video, a teacher discussion guide, and an interactive Web applet. For those who wish to delve deeper, additional materials will be freely available on the Global Math Project website, created both by the Global Math Project team as well as by interested members of the mathematical community. These materials will support further exploration of place value, arithmetic algorithms, negative numbers, alternative bases, polynomials, formal infinite series, and more.

The entire storyline of Exploding Dots, of course, cannot be completed in just a single class period, but our hope is that teachers and students will be inspired to explore beyond the first few lessons and perhaps to incorporate aspects of the Exploding Dots lessons into their curriculum at other times during the year.

A Global Network of Ambassadors

A global network of volunteer ambassadors[2] will play a vital role in spreading the word about the Global Math Project and ensuring access for teachers around the globe by:

- posting about the Global Math Project on social media,
- assisting in forming partnerships with key teacher organizations around the world,
- facilitating translation of Global Math Week content

[2] `https://www.theglobalmathproject.org/ambassadors`

- hosting webinars to help train teachers on the Exploding Dots materials, and
- organizing public events in their home locations.

By the start of 2017, over 140 people representing more than forty countries had already signed on as Global Math Project Ambassadors. That number has since grown.

There is an infinite universe of wondrous mathematics to explore.

We have been in conversation with a number of international mathematics educator societies who want to help spread the word, and we have received photographs and videos from teachers and students all over the world who are already playing with Exploding Dots and eager to share.

Partner Organizations

Global Math Project Partner Organizations[3] make significant contributions to the underlying structure of the project, for example, through developing online interfaces and tools, translating materials, promoting Global Math Week to teachers and the public, hosting public events, and providing financial support. The project is hosted by the American Institute of Mathematics (AIM), one of the National Science Foundation-supported mathematical science research institutes, whose mission is to advance mathematics through collaborative problem solving.

Other founding partner organizations include:

- Great Minds, a nonprofit organization that offers content-rich curriculum and professional development
- Math Plus Academy, an after-school mathematics enrichment program focused on problem solving
- The National Museum of Mathematics, the nation's only museum focused on math and its many connections to the world around us
- Scolab, a Canadian educational technology company

Although we have yet to secure major funding, the project has generated much interest and significant in-kind services from partner organizations. We are honored to have these organizations publicly sharing their support for our efforts and welcome additional partner organizations.

How Can Mathematicians and Math Departments Get Involved?

There are multiple ways that individual mathematicians can become involved in the Global Math Project:

- introduce Exploding Dots to your own students and to K–12 students and teachers with whom you work, through outreach activities
- share information about the Global Math Project with K–12 colleagues and offer to help out when they introduce Exploding Dots to their students
- lead a public Global Math Week event for your community
- become an official Global Math Project Ambassador
- make a financial contribution to the project

Math departments might consider organizing training for local K–12 teachers who want to participate, or hosting a public event during Global Math Week.

What about Next Year?

Each year we plan to unveil a new Global Math Week topic with a wonderful, "mind-blowing" storyline deeply relevant to the school curriculum, while also keeping previous Global Math Week topics accessible in perpetuity. So Global Math Week 2018 will invite students and teachers and math professionals from all across the globe to try out a new second exciting topic or to experience Exploding Dots. And for 2019 a third topic will be added. And so on.

There is an infinite universe of wondrous mathematics to explore. Let's help communities of folks across the globe experience and share this joy with one another.

Founding Members of the Global Math Project:

- James Tanton, Mathematician-at-Large, Mathematical Association of America (MAA)
- Jill Diniz, Director of Mathematics Curriculum, Great Minds
- Cindy Lawrence, Executive Director, National Museum of Mathematics (MoMath)
- Brianna Donaldson, Director of Special Projects, American Institute of Mathematics (AIM)
- Derarca Lynch, mathematics instructor, New York University–Abu Dhabi
- Raj Shah, founder and CEO, Math Plus Academy
- Travis Sperry, Director of Information Technology, Math Plus Academy

Reference

[1] J. Tanton, Exploding Dots, Experience 9, gdaymath.com/courses/exploding-dots/.

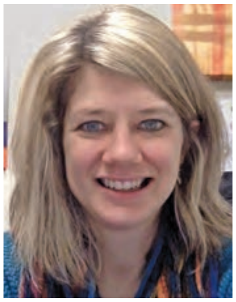
ABOUT THE AUTHORS


James Tanton

James Tanton believes that mathematics really is accessible to all and is committed to sharing the delight and the beauty of the subject through his books, online courses, and lectures. Currently the mathematician-at-large for the Mathematical Association of America, he conducts teacher and student workshops around the world.

[3] https://www.theglobalmathproject.org/partners

COMMUNICATION



Brianna Donaldson

Brianna Donaldson is director of special projects at the American Institute of Mathematics, where she works to broaden participation in mathematics and encourage collaboration through programs such as the Math Teachers' Circle Network, Research Experiences for Undergraduate Faculty, and the Global Math Project.

Photo Credit

Photo of James Tanton is courtesy of the Mathematical Association of America.

Photo of Brianna Donaldson is courtesy of Brianna Donaldson.

Figures 1–3 are courtesy of James Tanton.

Movie Review : "Gifted"

Gifted (2017) is a sweet movie about Mary, a mathematical prodigy, raised by her uncle. Her mother was apparently close to solving the Navier-Stokes million-dollar millennium problem before she committed suicide. Mary amazes her first-grade teacher by computing 57×135 in her head. Her ambitious grandmother takes her to MIT, where she is challenged to compute

$$\int_{-\infty}^{\infty} e^{-x^2/2\sigma^2}\,dx.$$

Later she attends a lecture on Ramanujan and partition functions by a professor played by mathematician Jordan Ellenberg.[1] I won't spoil the surprise ending.

—Frank Morgan

[1] *See the the interview of Ellenberg in this issue of* Notices *(page 779).*

Karen E. Smith Interview

Conducted by Laure Flapan

Communicated by Alexander Diaz-Lopez

Karen E. Smith is Keeler Professor of Mathematics at the University of Michigan. Recipient of the 2001 AMS Ruth Lyttle Satter Prize, Smith is interested in commutative algebra and algebraic geometry. She is a co-author of *An Invitation to Algebraic Geometry*. Her e-mail address is kesmith@umich.edu.

EDITOR'S NOTE. Karen E. Smith's article "Noether's Legacy: Rings in Geometry" appeared in *Notices*, January 2016, www.ams.org/notices/201601/rnoti-p7.pdf.

DOI: http://dx.doi.org/10.1090/noti1544

***Flapan**: When and how did you know you wanted to be a mathematician?*

Smith: That is an interesting question. I definitely enjoyed math from a young age. As early as middle school I played with different mathematical ideas on my own and read math books. For example, in seventh grade I devoured a book about the Fibonacci numbers, which I reread multiple times over the years (I wish I could remember the name!). However, I was perhaps in my fourth year of graduate school before I really began to seriously consider "mathematician" as a career option.

Growing up, I didn't know anyone with a PhD.

You see, I never really knew that mathematician was a career at all! My parents encouraged me to study engineering in college and were disappointed when I switched my major to math, fearing I would be unemployable. I switched because I loved my freshman calculus class out of Spivak's *Calculus* book, especially solving the problems for the final take-home exam. I guess I was stubborn and impractical enough to ignore their advice.

Growing up, I didn't know anyone with a PhD. Mentoring undergraduates was not something most Princeton professors did, at least not mentoring me. So, upon graduation, I landed a job as a high school math teacher. Continuing my education never occurred to me. For starters, I was eager to pay off my student loans, and I had no idea that "graduate student" was sort of a job itself. First-year high school teaching is extremely difficult, and I was in a miserable school district with little support. I soon resolved to do something else. By a stroke of luck, I bumped into one of my peers from college, who mentioned that he was getting paid to be a student in a math PhD program! This was an amazing revelation for me! I applied immediately.

Karen E. Smith (second from right) with current and former students Robert Walker (Ford Foundation Fellow), Sarah Mayes (assistant professor at the University of Toronto), and Will Traves (chair of the US Naval Academy math department).

I was thrilled to be a TA at Michigan, where I earned more to teach one class and study math than I earned teaching five high school classes! For me, grad school was a terrific job. I never envisioned myself actually writing a PhD; I simply enjoyed studying and teaching college students. It wasn't until I started getting attention for proving new results that I began to dream about being a professional mathematician.

Flapan: *Who encouraged or inspired you?*

Smith: My seventh-grade math teacher, Mr. Eckert, taught me modular arithmetic and gave me challenging problems to explore on my own. I think this is my earliest memory of "doing math" in the sense of playing, experimenting, conjecturing. Likewise, my twelfth-grade calculus teacher, Mr. Driscoll, offered an extra math class on number theory using Underwood Dudley's book. I loved that book as well! His take-home exam gave me my first taste of the satisfaction of solving a hard problem after suffering over it a week. These two teachers really nurtured my love for math.

In college, no one particularly encouraged me, and a few actively discouraged me. One exception was Charlie Fefferman, my freshman calculus teacher, who expressed surprise that I was an engineering student despite being "so good at math." This remark, in a brief but obviously influential conversation, was enough to make me switch majors. Other professors inspired me, especially Nick Katz. His homework sets were terrific, with a coherent set of exercises leading us to discover and develop nice chunks of mathematics on our own. I still remember one on p-adic numbers. I emulate Katz's teaching today in my own classes; ask my students about my "worksheets."

In graduate school, on the other hand, I did feel actively encouraged. Carolyn Dean, an assistant professor and the only female faculty member, took me out to lunch to chat several times my first year. Small things, like the fact that our department chair occasionally asked me how my classes were going, had a big impact. I was lucky to stumble into Mel Hochster's commutative algebra course. Mel was enthusiastic and encouraging and eventually became my thesis advisor. He has been a fantastic advisor and mentor ever since.

As a postdoc, I learned a tremendous amount of algebraic geometry from young mathematicians in Boston/Cambridge, especially my friend Sándor Kovács. He introduced me to János Kollár, who asked me on the spot, at the Santa Cruz algebraic geometry conference in 1995, if I could give a talk the next day. The conversations that followed that talk were critical to my research development.

As a faculty member, I have always been grateful to Bill Fulton, who still often encourages me by having seemingly tremendous faith in me.

But by far the most important encouragement came from my late husband, Juha Heinonen. His unflagging but breezy belief in me made a huge difference. Although he died ten years ago, I can still hear him say, "If not you, then who?"

Flapan: *How would you describe your research to a graduate student?*

Smith: I study commutative algebra, mostly motivated by problems in algebraic geometry. One of my favorite tools is the Frobenius or pth power map, which can be iterated, for example, to show that certain cohomology classes must be trivial on certain varieties. These methods can be used to prove theorems about varieties defined over the complex numbers by reduction to prime characteristic.

My favorite kinds of problems are those rich in interesting examples that connect different types of mathematics. For example, I have recently played with cluster algebras[1] (highly combinatorial objects defined by Sergey Fomin and Andrei Zelevinsky) by reducing to characteristic p to prove theorems about the structure of the varieties they define. This is joint work with my postdocs Angelica Benito, Greg Muller, and Jenna Rajchgot.

Flapan: *What theorem are you most proud of and what was the most important idea that led to this breakthrough?*

Smith: I am not sure I have a clear favorite among my theorems. I was excited to prove that the test ideal (a notion from characteristic p commutative algebra of importance in Hochster and Huneke's theory of tight closure) and the multiplier ideal (a notion from complex birational algebraic geometry) are essentially the same—that is, the multiplier ideal "reduces modulo p" to the test ideal for every sufficiently large prime p. This type of result spawned a great deal of research into the connections between these two fields, which continues today. I can't keep up with it all myself!

Another project that was especially fruitful was with Rob Lazarsfeld and Lawrence Ein: we found some applications of multiplier ideals—or more accurately, an asymptotic version of them—to some problems in commutative algebra, including a surprising comparison theorem for symbolic and ordinary powers of ideals in a regular ring. The third paper in that series, on an application to understanding valuation ideals, required resolution of singularities for an Abhyankar valuation.

Perhaps the theorem I am most pleased with at this moment is one with Michel Van den Bergh on the structure of the ring of differential operators on rings of invariants

[1] *See* "What is a cluster algebra?" *by Andrei Zelevinsky,* Notices, *December 2007,* www.ams.org/notices/200711/tx071101494p.pdf.

in characteristic p: we found some conditions on a ring in prime characteristic that guarantee its ring of differential operators is simple. The idea of "finite F-representation type," which we introduced in that paper, is arising again in a project on "noncommutative resolutions of singularities" right now with my postdocs Eleonore Faber and Greg Muller.

Rarely does anything understood deeply turn out to be useless.

Flapan: *Do you think your approach to or style of mathematics has changed with time? If so, how?*

Smith: Perhaps now I am less interested in solving every aspect of a problem and more interested in solving the big main cases while leaving some harder technical generalizations for others. I would rather find some new interesting phenomenon or surprising new connection, say, in polynomial rings and then move on to something completely different rather than spend a long time generalizing the result to arbitrary regular rings, say.

I have also come in and out of different interests—for a while I wanted nothing to do with prime characteristic, but I have since come back.

For sure, I am now a much better expositor of mathematics. Sometimes I cringe to read my earlier papers.

Flapan: *All mathematicians feel discouraged occasionally. How do you deal with discouragement?*

Smith: I take a break—the length depends on the magnitude of the discouragement—and eventually just get right back up. Life and math go on. It is important to make a habit of putting in the time. Eventually all those calculations—all the blood, sweat, and tears—pay off. I know that younger mathematicians often have a harder time believing that the payoff is coming, but after many disappointments I can assure you, it is. Rarely does anything understood deeply turn out to be useless, even though it may not serve the purpose you had hoped.

Flapan: *What is something people might be surprised to learn about you?*

Smith: I had many jobs before mathematician, including lifeguard, hotel maid, deli meat slicer, computer parts recycling factory worker, pizza delivery person, SAT prep course instructor, and high school teacher. Of course, I had a few more typical jobs as well, such as babysitter, math tutor, and camp counselor. I went to a fancy college, but I have more modest working class roots. I know how to hustle to make a buck!

Flapan: *What advice do you have for current graduate students in math?*

Smith: Start where you are at, and don't compare yourself to others. Work hard, get help, and stay on the path. Sometimes you will fail. That's OK. Enjoy what you are doing now, and don't forget to play, mathematically and otherwise. Do lots of calculations and examples, be curious, be solid on the basics.

Also, remember to take care of yourself. Take one day a week off work. Sleep well and exercise. Have a social life.

Find advice and mentoring from many different people at different places in their careers and even in different careers. Take it all in carefully, but much will be contradictory, so sort out what feels right and best for you.

You can soothe a lot of anxiety by helping others. So instead of looking around your graduate program and worrying about how many students are "better" than you, why not look around for someone you can help pull up?

Flapan: *If you could recommend one book or lecture to graduate students, what would it be?*

Smith: Shafarevich's *Basic Notions in Algebra* is one of my favorites. I also thought that Manjul Bhargava gave the best colloquium talk I've ever seen at the Seoul ICM in 2014. You can watch it online.[2]

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Laure Flapan

ABOUT THE INTERVIEWER

Laure Flapan just completed her PhD in algebraic geometry from the University of California, Los Angeles and is headed to a postdoc at Northeastern University in the fall of 2017. Her work is in algebraic geometry, particularly Hodge theory.

[2]https://www.youtube.com/watch?v=Vx-4MUKCMPg.

WHAT IS...

a CR Submanifold?

Phillip S. Harrington and Andrew Raich

Communicated by Cesar E. Silva

EDITOR'S NOTE: Check out the article by Raich in the April 2017 *Notices*.

A real hypersurface M of $\mathbb{C}^n \cong \mathbb{R}^{2n}$ has the following property: at every point $p \in M$, the tangent space T_pM has a $(2n-2)$-dimensional complex subspace. Whenever a submanifold M of $\mathbb{C}^n$ has the property that its tangent space T_pM admits a complex subspace whose dimension is independent of p, M is called a CR submanifold. Not all smooth submanifolds of $\mathbb{C}^n$ have this property. Consider the equator of the 2D sphere

$$S = \{(z, w) \in \mathbb{C}^2 : |(z, w)| = 1 \text{ and } \operatorname{Im} z = 0\}.$$

At $(\pm 1, 0)$, the tangent space $\{0\} \times \mathbb{C}$ is complex, but at $(0, e^{i\theta})$, the tangent space can be identified with the real span of $(1, 0)$ and $(0, ie^{i\theta})$, and this does not have a complex structure. In particular, it is not closed under multiplication by i. Hence, the real dimension of the largest complex subspace varies from 2 to 0. To motivate our definitions, we will first consider the boundary values of holomorphic functions of several complex variables.

Given a domain $\Omega \subset \mathbb{C}^n$, a continuously differentiable, or C^1, function $f : \Omega \to \mathbb{C}$ is said to be holomorphic if it satisfies the Cauchy–Riemann equations $\frac{\partial f}{\partial \bar{z}_j} = 0$ for all $1 \le j \le n$, where $\frac{\partial}{\partial \bar{z}_j} = \frac{1}{2}\frac{\partial}{\partial x_j} + \frac{i}{2}\frac{\partial}{\partial y_j}$. Holomorphic functions are the fundamental objects of study in complex analysis of one and several variables. For example, a function f is equal to a convergent power series in z_j for all $1 \le j \le n$ in a neighborhood of a point if and only if it is also holomorphic in a neighborhood of that point. Consequently, a standard technique in the analysis of real power series is to complexify them and study the corresponding holomorphic function.

We begin our discussion with the following classical boundary value problem. Suppose we are given a C^1 function $g : b\Omega \to \mathbb{C}$. Does there exist a function f in $C^1(\overline{\Omega})$ such that f is holomorphic in Ω and $f = g$ on $b\Omega$? The answer to this question highlights the differences between complex analysis in one and several variables.

When $n = 1$, we know that if such an f exists, then on Ω it must be given by the Cauchy Integral Formula

$$f(z) = \frac{1}{2\pi i}\int_{b\Omega} \frac{g(\zeta)}{\zeta - z} d\zeta.$$

Such an f will always be holomorphic, but it may not have g as a boundary value. For example, if Ω is the unit disc and $g(e^{i\theta}) = e^{-i\theta}$, then the Cauchy Integral Formula gives us $f(z) = 0$ on Ω. Nevertheless, the case $n = 1$ is completely understood. The Plemelj jump formula for the Cauchy Integral Formula implies that g is the boundary value of a holomorphic function f if and only if $\int_{b\Omega} g(\zeta)\zeta^m d\zeta = 0$ for all nonnegative integers m.

The cases $n \ge 2$ require further analysis. We focus on the $n = 2$ case for expositional clarity. Suppose ρ is a C^1 defining function for Ω (i.e., $\rho < 0$ on Ω, $\rho > 0$ outside Ω, and $\nabla \rho \ne 0$ on $b\Omega$). Then the vector field

$$\bar{L} = \frac{\partial \rho}{\partial \bar{z}_2}\frac{\partial}{\partial \bar{z}_1} - \frac{\partial \rho}{\partial \bar{z}_1}\frac{\partial}{\partial \bar{z}_2}$$

is a tangent vector to $b\Omega$ (since $\bar{L}\rho = 0$ on $b\Omega$), so $\bar{L}g$ is well-defined. If f is holomorphic in a neighborhood of $b\Omega$, then the Cauchy–Riemann equations would tell us that $\bar{L}f = 0$ on $b\Omega$, so g can be the boundary value

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of a holomorphic function only if $\bar{L}g = 0$ on $b\Omega$. Such functions are called CR functions. Once again, if g is the boundary value of a holomorphic function f, then f is given by an integral formula, in this case the Bochner–Martinelli Formula $f(z) = \int_{b\Omega} g(\zeta)B(\zeta, z)$ where

$$B(\zeta, z) = \frac{\left((\bar{\zeta}_2 - \bar{z}_2)d\bar{\zeta}_1 - (\bar{\zeta}_1 - \bar{z}_1)d\bar{\zeta}_2\right) \wedge d\zeta_1 \wedge d\zeta_2}{(2\pi i)^2 \, |\zeta - z|^4}.$$

In contrast to the Cauchy Integral Formula, the function f given by the Bochner–Martinelli Formula is not necessarily holomorphic (note that $B(\zeta, z)$ is not holomorphic in z). Fortunately, if g is a CR function and Ω is a bounded domain with C^1 boundary, then f is holomorphic and g is the boundary value of f. In contrast to the $n = 1$ case, there is no moment condition for g to satisfy. Instead, boundary values of holomorphic functions are characterized by the CR equation $\bar{L}g = 0$, just as holomorphic functions are characterized by the Cauchy–Riemann equations.

The CR structure reflects the ambient complex structure.

The complex structure on $\mathbb{C}^n$ can be identified with the decomposition of the complexified tangent space $\mathbb{C}T(\mathbb{C}^n)$ into Cauchy–Riemann derivatives of the form $\bar{L} = \sum_{j=1}^n a_j \frac{\partial}{\partial \bar{z}_j}$, denoted $T^{0,1}(\mathbb{C}^n)$, and their conjugates, denoted $T^{1,0}(\mathbb{C}^n)$. Consequently, the complexified tangent space has an orthogonal decomposition

$$\mathbb{C}T(\mathbb{C}^n) = T^{1,0}(\mathbb{C}^n) \oplus T^{0,1}(\mathbb{C}^n).$$

The CR structure on a real submanifold M of $\mathbb{C}^n$ is the subspace $T^{0,1}(M) \subset T^{0,1}(\mathbb{C}^n)$ given by all tangential vector fields. If $T^{1,0}(M)$ is the conjugate of $T^{0,1}(M)$, then the complex tangent space of M is given by $T^{1,0}(M) \oplus T^{0,1}(M)$. A CR submanifold then is simply a real submanifold M of $\mathbb{C}^n$ on which the dimension of $T^{0,1}(M)$ is constant. If $\dim_{\mathbb{R}} M = 2\dim_{\mathbb{C}} T^{0,1}(M) + 1$, then we say that M is of hypersurface type. The boundary of a domain with C^1 boundary will always be a CR submanifold of hypersurface type. A CR function on M is any function $f \in C^1(M)$ satisfying $\bar{L}f = 0$ whenever $\bar{L} \in T^{1,0}(M)$. One active area of research is the characterization of CR mappings between CR submanifolds.

We return to our motivating example in $\mathbb{C}^2$. Observe that the real and imaginary parts of $\bar{L}$ are linearly independent tangential vector fields. However, the tangent space of the boundary of a domain in $\mathbb{C}^2$ must have three real dimensions, so there must exist a third vector field T to complete the basis. For example, we can use

$$T = i \sum_{j=1}^{2} \left(\frac{\partial \rho}{\partial \bar{z}_j} \frac{\partial}{\partial z_j} - \frac{\partial \rho}{\partial z_j} \frac{\partial}{\partial \bar{z}_j} \right).$$

Notice that whenever a CR submanifold is of hypersurface type, there must always exist a unique (up to a choice of orientation) real tangential vector field that is orthogonal to the complex tangent space. The richness of CR manifolds lies in the interplay between the CR structure, which reflects the ambient complex structure, and this remaining direction, which acts like a totally real vector field.

The model example of a CR submanifold is the boundary M of the Siegel upper half space

$$\Omega = \{z \in \mathbb{C}^2 : \mathrm{Im} z_2 > |z_1|^2\}.$$

We choose $\bar{L} = \frac{\partial}{\partial \bar{z}_1} - 2iz_1 \frac{\partial}{\partial \bar{z}_2}$ to represent the CR equations and $T = \frac{\partial}{\partial z_2} + \frac{\partial}{\partial \bar{z}_2}$ to represent the totally real direction. In this setting, $\bar{L}$ is also known as the Lewy operator in honor of Lewy's result showing local nonsolvability of $\bar{L}$. This result stands in stark contrast to the real case where the Malgrange–Ehrenpreis Theorem tells us that any partial differential operator with real constant coefficients is locally solvable. Lewy showed that in order for $\bar{L}u = f$ to be locally solvable on M when f is a real function of $\mathrm{Re}\, z_2$, it must be the case that f is real-analytic. We note that the boundary of the Siegel upper half space also admits a group structure making it isomorphic to the Heisenberg group, but this useful tool is outside the scope of this article.

We can reformulate the notion of a CR manifold without complexification of the tangent bundle. If we write the coordinates of $\mathbb{C}^n$ by $(z_1, \dots, z_n)$ where $z_j = x_j + iy_j$, then the complex structure is denoted by J and acts on vector fields via

$$J\frac{\partial}{\partial x_j} = \frac{\partial}{\partial y_j} \quad \text{and} \quad J\frac{\partial}{\partial y_j} = -\frac{\partial}{\partial x_j},$$

where $j \in \{1, \dots, n\}$. The map J has two eigenvalues: i and $-i$. In the complexified tangent bundle, the eigenvectors corresponding to i are linear combinations of $\frac{\partial}{\partial z_j} = \frac{1}{2}(\frac{\partial}{\partial x_j} - i\frac{\partial}{\partial y_j})$, and the eigenvectors corresponding to $-i$ are linear combinations of $\frac{\partial}{\partial \bar{z}_j} = \frac{1}{2}(\frac{\partial}{\partial x_j} + i\frac{\partial}{\partial y_j})$. Even without complexifying the tangent bundle, we can see that J is analogous to multiplication by $\pm i$ since $J^2 = -I$, where I is the identity map. If $M \subset \mathbb{C}^n$ and $p \in M$, the tangent space at p is denoted $T_p(M)$, and the holomophic tangent space at p, $H_p(M)$, is defined by

$$H_p(M) = T_p(M) \cap J\{T_p(M)\}.$$

A smooth submanifold of $\mathbb{C}^n$ is an embedded CR manifold exactly when $\dim_{\mathbb{R}} H_p(M)$ is independent of p. This formulation of a CR manifold gives us a clean way to find many examples (and nonexamples). For example, all affine subspaces in $\mathbb{C}^n$ are CR submanifolds, while the manifold

$$M = \{(z_1, z_2) : x_2 = 0 \text{ and } y_2 = |z_1|^2\}$$

is not, since $\dim_{\mathbb{R}} H_{(0,p_2)}(M) = 2$, but $\dim_{\mathbb{R}} H_p(M) = 0$ if $p_1 \neq 0$. Returning to our initial example S, the equator of the unit sphere, one can check [Bog91, Example 1, p. 99] that $\dim_{\mathbb{R}} H_{(1,0,\dots,0)}(M) = 2n - 2$ and $\dim_{\mathbb{R}} H_{(0,1,0,\dots,0)}(M) = 2n - 4$, so that M is not a CR submanifold of $\mathbb{C}^n$. However, it turns out that the only bad points of M are $(\pm 1, 0, \dots, 0)$, and the manifold

$\tilde{M} = M \setminus \{(\pm 1, 0, \ldots, 0)\}$ is a (noncompact) CR submanifold of $\mathbb{C}^n$.

We have highlighted only the most basic aspects of the theory of CR manifolds; namely, we motivated the study of CR manifolds by considering boundary values of holomorphic functions, and we presented two formulations of the definition of CR manifolds to provide a wealth of examples. Problems on CR manifolds can be approached from many different directions, and we encourage the reader to seek out [Bog91] or [CS01] for a unified and in-depth discussion.

Problems on CR manifolds can be approached from many different directions.

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Phillip Harrington

ABOUT THE AUTHORS

Phil Harrington's area of research is partial differential equations in several complex variables, particularly the $\bar{\partial}$-Neumann problem. In his spare time, he enjoys hiking and reading.

Andrew Raich

Andy Raich's area of research is several complex variables and harmonic analysis, where he focuses on $\bar{\partial}$-problems, broadly construed. When he can find time, he enjoys running and biking in the beautiful hills around Fayetteville, AR.

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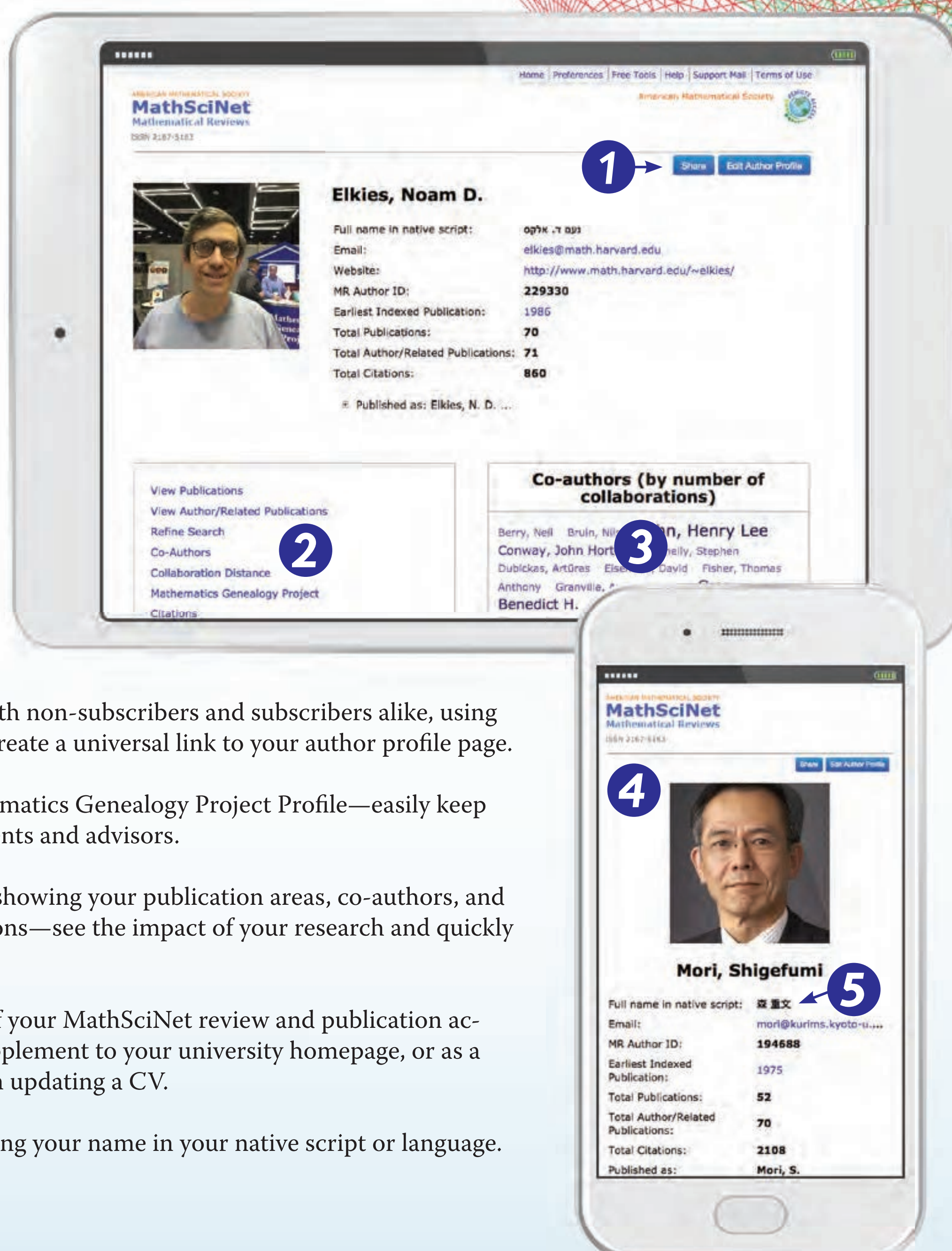

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Rohatgi, Ranjan, On the enumeration of Lozenge tilings of halved hexagons

Sadigov, Tural, Data assimilation and determining forms for weakly damped, dispersive systems

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Yang, Ping, Dynamic transition for Rayleigh-Bénard convection

Indiana University–Purdue University Indianapolis (4)

Department of Mathematical Sciences

Carichino, Lucia, Multiscale mathematical modeling of ocular blood flow and oxygenation and their relevance to glaucoma

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Purdue University (36)

Department of Mathematics

Backing, Thomas, Regularity of solutions and the free boundary for a class of Bernoulli-type parabolic free boundary problems with variable coefficients

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Cox, Britain, Supercuspidal representations arising from stable vectors

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University of Notre Dame (8)

Applied and Computational Mathematics and Statistics

Wu, Liang, High order fast iterative methods for steady state of hyperbolic partial differential equations

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Department of Statistics and Actuarial Science

Jiao, Feiran, High-dimensional inference of ordinal data with medical applications

KANSAS

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Department of Statistics

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Department of Biostatistics

Ardah, Husam, A new two-stage sampling design for sensitive questions through randomized response technique and direct questioning

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Zhu, Han, Bayesian sequential randomization designs for phase III clinical trials

Louisiana State University, Baton Rouge (12)

Department of Mathematics

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MARYLAND

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University of Maryland, Baltimore County (10)

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MASSACHUSETTS

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Boston University School of Public Health (5)

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Choi, Seung Hoan, Evaluation of statistical methods, modeling, and multiple testing in RNA-SEQ studies

Griffin, Paula Jean, Biological network models for inferring mechanism of action, characterizing cellular phenotypes, and predicting drug response

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Ly, Tue, Diophantine approximation in algebraic number fields and flows on homogeneous dynamics

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Biostatistics Department

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Perry, Alexander, Derived categories and birational geometry of Gushel-Makai varieties

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Tynan, Philip, Equivariant Weiss calculus and loop spaces of Stiefel manifolds

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Massachusetts Institute of Technology (26)

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MICHIGAN

Central Michigan University (3)

Department of Mathematics

Lazar, Drew, Scale and dimension reduction in symmetric spaces

Mohammad, Mutaz, Frame based method for investigating Gibbs phenomenon

Soller, Katherine, Normalizable and unitarizable matrices

Michigan State University (17)

Department of Mathematics

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Oakland University (4)

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NORTH CAROLINA

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Ou, Fang-Shu, Quantile regression models for interval-censored failure time data

Roy, Pourab, Non-parametric and semiparametric estimation in forward and backward recurrence time data

Rudra, Pratyaydipta, Statistical tools for general association testing and control of false discoveries in group testing

Stewart, Thomas, Statistical learning with missing data

Sun, Hengrui, Controlling multiplicity in confirmatory clinical trials

Wise, Alison, Making robust use of parental genotype data for finding effects of variants on the X-chromosome

Yang, Hojin, Learning methods in reproducing kernel Hilbert space based on high-dimensional features

Zhou, Xin, Machine learning techniques for optimal treatment regimes

Department of Mathematics

Brandon, Namdi, Novel integration in time methods via deferred correction formulations and space-time parallelization

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Mukherjee, Mayukh, Variational approaches to nonlinear Schrödinger and Klein-Gordon equations

Schuster, Michael, Rank reduction of conformal blocks

Sherman, Cass, Weight stretching in moduli of parabolic bundles and quiver representations

Tzou, Chung-Nan, Formulation of underwater plumes and velocity variations due to entertainment in stratified environments

Department of Statistics and Operation Research

Feng, Qing, Non-iterative joint and individual variation explained and automatic Toda transformation

Kimes, Patrick, New statistical learning approaches with applications to RNA-Seq data

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Zhai, Haojin, Principal component analysis in phylogenetic tree space

University of North Carolina at Charlotte (6)

Department of Mathematics and Statistics

Erturk, Huseyin, Limit theorems for random exponential sums and their applications to insurance and the random energy model

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Huang, Wei, Frame wavelets in high dimension

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NORTH DAKOTA

North Dakota State University, Fargo (7)

Department of Mathematics

Altmann, Hannah, Semidualizing DG modules over tensor products

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OHIO

Air Force Institute of Technology (2)

Department of Mathematics and Statistics

Knight, Emily, Modeling radiation effectiveness for inactivation of *bacillus* spores

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Bowling Green State University (5)

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Chen, Ying-Ju, Jackknife empirical likelihood and change point problems

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Li, Yi, Goodness-of-fit tests for Dirichlet distributions with applications

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Paler, Mary Elvi, On modern measures and tests of multivariate independence

Case Western Reserve University (7)

Department of Mathematics, Applied Mathematics and Statistics

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Department of Epidemiology and Biostatistics

Borsay Hall, Noemi, Genetics of metabolic syndrome in the women's resistance to infection, progression to active disease, host genetics and mycobaterium tuberculosis lineage

Chan, Philip Kit-Man, Mental health and sexual minorities in the Ohio Army National Guard

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Kent State University, Kent (4)

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Ohio State University, Columbus (12)

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Wang, Xiaomu, Robust Bayes in hierarchical modeling and empirical Bayes analysis in multivariate estimation

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Zaetz, Jiaqi, A Riemannian framework for shape analysis of annotated 3D objects

Ohio University, Athens (3)

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University of Cincinnati (11)

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Lopez, Marcos, Discrete approximations of metric spaces with controlled geometry

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University of Oklahoma (7)

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OREGON

Oregon State University (8)

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Costa, Timothy, Hybrid multiscale methods with applications to semiconductors, porous media and materials science

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Pennsylvania State University (26)

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Zelenberg, Aleksey, Rokhlin dimension for C^*-correspondences

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Christou, Eliana, A non-iterative method for fitting the single index quantile regression model with uncensored and censored data

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Wang, Yaqun, Inference of gene regulatory network based on gene expression dynamics in response to environmental signals

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Temple University (10)

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University of Pennsylvania (22)

Department of Applied Mathematics and Computational Science

Gu, Shi, Control theoretic analysis of human brain networks

Department of Biostatistics and Epidemiology

Gamerman, Victoria, Statistical methods for time-conditional survival probability and equally spaced count data

Kennedy, Edward H, Doubly robust causal inference with complex parameters

Kobie, Julie, Sparse simultaneous signal detection with applications in genomics

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Department of Mathematics

Astrand, Matti, Lifting problems and their independence of coefficient field

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Kjuchukova, Alexandra, On the classification of irregular dihedral branched covers of four-manifolds

Mo, Li-Ping, Hit polynomials have only real roots

Poh, Julius Wei Quan, Shape and other properties of 1324-avoiding permutations

Pun, Ying Anna, On decomposition of the product of Demazure atoms and Demazure characters

Sundstrom, James D., Lower bounds for generalized regulators

Tofts, Spencer, On the existence of solutions to the Muskat problem with surface tension

Wharton Department of Statistics

Fogarty, Colin, Modern optimization in observational studies

Johnson, Kory, Discrete methods in statistics: Feature selection and fairness-aware data mining

Peng, Peichao, Essays in problems in sequential decisions and large-scale randomized algorithms

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University of Pittsburgh (15)

Department of Biostatistics

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Ghebrehawariat, Kidane, Parametric inference on quantile residual life

Jiang, Yingda, Gene-based association testing of dichotomous traits using generalized functional linear mixed models for family data

Johnson, Geoffrey, Quality adjusted Q-learning and conditional structural mean models for optimizing dynamic treatment regimes

Wang, Tianxiu, Competing risks regression under random signs censoring using pseudo-values

Department of Mathematics

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Moraiti, Marina, Coupled groundwater-surface water flows: Effect small physical parameters and numerical methods

Tanase, Roxana, Parameter estimation of partial differential equations using stochastic methods

Department of Statistics

Chen, Xiaotian, Association analysis of successive events and diagnostic accuracy analysis for competing risk data

Gu, Hong, Statistical approaches in the RDOC paradigm for post-mortem brain tissue studies

Simsek, Burcin, Stochastic models with applications to imaging and neuroscience

Wei, Yafei, Estimation, model selection and resilience of power law distributions

Ye, Cong, Multiple change-point detection for piecewise stationary categorical time series

PUERTO RICO

University of Puerto Rico, Rio Piedras (4)

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Cui, Bo, Exponential rank and classification of AH-algebras using Morse theory

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Li, Ang, Bayesian calibration of p-values under multiple comparisons: Bounds and new approximations

Qin, Hu, Code raised from hypercube graph and completed graph

RHODE ISLAND

Brown University (10)

Department of Mathematics

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Newkirk, Edward, Billards with bombs

Ou, Yumeng, Multi-parameter commutators and new function spaces of bounded mean oscillation

Division of Applied Mathematics

Aghajani, Mohammadreza, Infinite-dimensional scaling limits of stochastic networks

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University of Rhode Island (2)

Department of Mathematics

Armstrong, Addie, Degree-limited defective 3-colorings of planar graphs

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SOUTH CAROLINA

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Finney, Michael, Estimating single gender classroom effects using propensity scores and matching

Grotheer, Rachel, Hyperspectral diffuse optical tomography using the reduced basis method and sparsity constraints

He, Qijun, Algebraic geometry arising from discrete models of gene regulatory networks

Hedetniemi, Jason, Problems in domination and graph products

Jiang, Chendi, Reliability analysis of load-sharing models

Leverenz, Jonathon, Network target coordination for multiparametric programming

Priyadarshani, Hewa Arachchige Anuradha, Bayesian minimum description length techniques for multiple change-point detection

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Medical University of South Carolina (6)

Department of Public Health Sciences

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University of South Carolina (11)

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Short, Taylor, Some extremal and structural problems in graph theory

Smith, Heather, Trees, partitions, and other combinatorial structures

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Department of Statistics

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Cipolli, William, Bayesian nonparametric approaches to multiple testing, density estimation and supervised learning

Wu, Haifeng, Frailty Probit models for clustered interval-censored failure time data

Yao, Bin, Semiparametric regression analysis of panel count data and interval censored failure time data

Zhou, Haiming, Bayesian semi- and nonparametric analysis for spatially correlated survival data

TENNESSEE

Middle Tennessee State University (3)

Department of Mathematical Sciences

Gaddy, Angeline, Identification of obstacles to transitioning to reform-oriented instruction among high school mathematics teachers

Gerstenschlager, Natasha, Identifying the supports needed by a sixth grade teacher implementing a reform-oriented, statistics unit

Liang, Xiao, Efficient numerical methods for nonlinear Schrödinger equations

University of Memphis (5)

Department of Mathematical Sciences

Dogan, Ali, On saturated graphs and combinatorial games

Fofana, Demba, On some Bayesian and empirical Bayes procedures for analyzing gene expression data

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Madahian, Behrouz, Statistical shrinkage methods for classification, prediction, and feature extraction using genomewide gene expression data and small sample sizes

Sokolov, Yury, Dynamics of discrete and continuous spatially distributed systems

University of Tennessee, Knoxville (13)

Department of Mathematics

Allen, Brian, Non-compact solutions of inverse mean curvature flow in hyperbolic space

Austin, Kyle, Geometry of scales

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TEXAS

Baylor University (12)

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University of Virginia (7)

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WASHINGTON

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University of Wisconsin, Milwaukee (11)

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University of Wyoming (4)

Department of Mathematics

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BOOK REVIEW

One Hundred Twenty-One Days

A Review by John McCleary

One Hundred Twenty-One Days
by Michèle Audin
Translated from French by Christiana Hills
Deep Vellum Publishing, Dallas, Texas, 2016,
Paperback, 200 pages, ISBN: 978-1-94-192032-9

How can we describe the effects of war on a community? There are statistics: Of the 195 students of the École Normale Supérieure who were mobilized in the First World War, at least 34 were confirmed dead, 15 disappeared, 21 were taken prisoner, 64 were wounded. Only 54 or 55 returned unharmed [1]. In his autobiography *Apprenticeship of a Mathematician*, André Weil recalled that of those who came back from World War I, "Very few who survived recovered an interest they used to have in [mathematics or science]." Richard Courant called the time away from ordinary research "a big hole." Some mathematicians served their countries during wartime, finding opportunities to develop mathematics in new areas. For the most part, however, the effect of the wars was loss—lost lives, lost work, a lost generation—an emptiness difficult to describe.

Michèle Audin's novel, describing the effect of the world wars on the French community of mathematicians, succeeds as a narrative of loss and the deep emotions attached to it. She has chosen an unusual style. The eleven chapters of the novel are each different in form, including a pastiche of a Kipling children's story, entries from diaries, news and journal clippings, an interview, the description of a photograph, even a list of numbers. Audin is well known as a mathematician. She is also a member of the *Oulipo*, a French writing group who embrace stylistic constraints in the pursuit of new modes of expression.

a narrative of loss and the deep emotions attached to it

The Oulipo stands for ***Ou****vroir de la* ***Li****ttérature* ***Po****tentielle*, or workshop on potential literature. It was founded in 1960 by François Le Lionnais (1901–1984), a polymath and well-known expositor of mathematics, and Raymond Queneau (1903–1976), a writer with an interest in mathematics. The main concerns of the group have been, in the words of mathematician and Oulipo member Jacques Roubaud, "the research, the discovery, and the invention of constraints for the composition of literary texts." Among other participants in the Oulipo have been the mathematician Claude Berge, computer scientist Paul Braffort, the painter Marcel Duchamp, and writers George Perec, Harry Mathews, and Italo Calvino. The best-known works of the Oulipo are Queneau's *Exercices de Style* and *Cent mille milliards de poèmes* (*One Hundred Thousand Million Poems*) and Perec's *La Disparition* (*The Disappearance*), a novel written without the letter *e*.

As an example of how mathematics and literature come together, consider the *sestina*, a poem of six stanzas followed by a three-line summary. The rhyming words of each stanza are the same, but in different orders. Furthermore, the last rhyme of a stanza becomes the first of the next.

The order of the rhymes of the second stanza determines a permutation of order six of the initial scheme and the subsequent rhyme schemes. The sestina was introduced in the twelfth century in France by troubadours. (The Oulipo would consider this a case of *anticipatory plagiarism* by the earlier writers [2].) Two features of troubadour poetry are found in Audin's novel: each chapter begins with the last words of the previous chapter, and the last chapter ends with the first paragraph of the first, making a cycle. Another feature of troubadour poetry may be described as a sort of mask. The poem has a surface meaning, but it is really about something else, known to the cognoscenti in the audience. Audin's novel thinly

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The author of the novel under review, Michèle Audin, counts mathematics, history, and literature as her primary interests. Her most recent novel is *La formule de Stokes* (Cassini, 2016, available only in French).

veils her rich historical work behind the characters she has invented.

The novel stretches across the twentieth century as seen through the lives of four mathematicians. The unifying character is Christian M., where M is followed by various permutations of the letters {o, r, t, s, a, u, f}. From these letters words emerge, for example, *sauf mort*, "except death"; *mot fraus*, "woman's word" (a combination of French and German); and *mor faust*, "more Faust." Christian's childhood opens the book with a chapter written in the manner of *The Elephant's Child,* a Just So Story of Kipling. Young Christian's constant questioning of the world leads to beatings until a teacher recognizes his talent for mathematics. M. leaves his home by the Saloum River in Africa for a school in France, where he also learns German. M. is injured in World War I, taking a bullet to the face that leaves him permanently disfigured. He is treated in a hospital, where we also meet Robert Gorenstein, a mobilized mathematician less gravely wounded. Gorenstein's story develops further in the third chapter, where we learn that after the war he murders three family members.

The second chapter is a selection from the diary of the nurse Marguerite Janvier, who becomes M.'s wife. Chapter III is a collection of clippings from newspapers and journals that we learn belonged to Marguerite. Bernadette, the daughter of Marguerite and Christian, is married to Pierre Meyer, a one-time student of mathematics in Strasbourg, who is interviewed in 2006 by a historian whom we take as Audin. The interview (Chapter IV) focuses on André Silberberg, a fellow student in Strasbourg who is Jewish and who has written a formidable thesis in class field theory. The presence of the Germans in Strasbourg in 1939 caused anxiety, especially when Heinrich Kürz came to lecture, met Silberberg, and then made disturbing comments in a café. We learn of Kürz's thoughts from his journals from Paris in 1942, where he is sent to enlist French mathematicians to write surveys for German journals. M. was the liaison to Kürz in Paris and later visited him in N., a German city with a famous university. The historian visits N. in current times and finds a photo from M.'s visit to Kürz. Chapter VI, "The Form of a City," is a fascinating account of impressions made by the photo and a map.

The thin veil between the novel and history is lifted.

The heart of the book is Chapter VII, which concerns Mireille, the niece of Gorenstein and beloved of Silberberg. *One Hundred Twenty-One Days* is the time from her acquaintance with André to her getting the news of his death. The time is liberation, but the dehumanizing effects of the war are depicted as Mireille seeks word of André. Though short, the chapter had a powerful effect on this reader.

The rest of the book delves deeper into the practice of the historian and consists of two notebooks, another collection of clippings, including the announcements of the deaths of Gorenstein and M., a list of numbers, and finally a return to "The Form of a City," this time Paris. The historian begins at the Cimetière Montmartre after the funeral of Pierre Meyer and continues through the streets of Paris. The stories we have read fill her thoughts, together with all the connections to history in the names of streets and places. Returning home with all these thoughts, she begins to write this novel.

The foundation of Audin's bold experiment in literature and history is the many contributions she has made to the history of twentieth-century French mathematics: *Fatou, Julia, Montel, le grand prix des sciences mathématiques de 1918, et après…* (2009), *Remembering Sofya Kovalevskaya* (2011), and *Une histoire de Jacques Feldbau* (2009). The thin veil between the novel and history is lifted in light of her work. For example, the topologist Jacques Feldbau (1914–45) published his papers during the war under the pseudonym Jacques Laboureur, and other Jewish mathematicians did the same to be able to publish under the wartime ban of Jewish authors. In the novel André Silberberg publishes a paper as André Danglars.

It was the history that connected Audin to the Oulipo: As she explained in an interview with *Publisher's Weekly*, she shared her unusual book on Kovalevskaya with Jacques Roubaud, who spoke of her work at a gathering of the group. She was invited to the next gathering and six months later she received a message from Oulipo's president inviting her to return. Eventually she was *co-opted*, as they call it; that is, she was made a member of the Oulipo.

There are two extra bits that follow the novel. The first is a "Supernumerary Chapter" that reveals literary sources and places that are cited or that shaped her choices in the writing. The second is a translator's note from Christiana Hills, who relates the problems of finding the right voices among so many forms of discourse. Translation of works written under constraints is a heroic task. Hills's translation is entirely worthy of the novel.

I have said too much about the novel and not enough about the initial question of the effects of war on the community of mathematicians. The book says a great deal about this and about the problems of history. The reader can accompany a historian in her search for the right story and discover the limitations under which historians labor. For its invention, for its emotion and depth, you should read this book.

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ABOUT THE REVIEWER

John McCleary is the author of a few books, including the forthcoming *Exercises in (Mathematical) Style* to be published by the MAA.

John McCleary

EDITOR'S NOTE. See Allyn Jackson's interview with author Michèle Audin in this issue of the *Notices* on page 761.

Michèle Audin, Mathematician and Writer

Interviewed by Allyn Jackson

In 2014, Michèle Audin retired from her position as professor of mathematics at the University of Strasbourg, in order to devote herself to writing. Her academic output includes about seventy-five research papers in global analysis, differential geometry, topology, and history. She has written several novels, including *121 Days*, which was translated into English by Christiana Hills in 2016 and is reviewed in this issue of the *Notices*. Her article "Differential Geometry, Strasbourg, 1953" appeared in the March 2008 issue of the *Notices*. Another piece by Audin, "Homage to Henri Cartan (1904–2008)," appeared in the May 2009 issue and includes a short sidebar about Cartan's little-known sister Hélène, who was also a mathematician and became a secondary school teacher.

Michèle Audin is the author of the novel *121 Days*, reviewed in this issue of the *Notices*.

Notices: *What was your inspiration in writing* 121 Days*?*

Audin: I have done a lot of work on the history of mathematicians living in the first half of twentieth century. I edited correspondence between André Weil and Henri Cartan. I have also written about the way the Jews were forbidden to publish in France during the German occupation. I found some correspondence between two mathematicians at the time of the occupation. One was French, a collaborationist, and the other one German, a member of the army. In their letters, they were very friendly and exchanged very pro-Nazi opinions. I hoped to publish this correspondence, but then I realized the family would never give permission. Even now, not everybody in France is willing to publicize the fact that he or she had relatives who, seventy-five years ago, collaborated with the Germans. This is one thing that led me to write the novel.

When you say, "So-and-so was French and became a German collaborator," or "this was a bad guy, and that was a good guy"—you are just making an accusation. That was quite the opposite of what I wanted to do. I wanted to have a different kind of freedom, to write something that was not academic research. I wanted to have something more—how to do I say this (very modestly!)?—something more universal. I wanted to write in a different way from a standard paper in history or mathematics and to reach different kinds of readers.

Of course, the main reason was that I wanted to write a novel! [Laughs]

Notices: *You are a member of the Oulipo. How did the Oulipo philosophy influence your writing of* 121 Days*?*

Audin: The idea was to use some constraints to build the text. It is a book mainly about mathematicians, so I wanted something using numbers. I made a plan of how to write the book using various constraints, mainly coming from poetry of the Middle Ages, like sestinas. The constraints dictated the order in which things would appear in the

Fiction writing is not very different from writing mathematics.

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book. I also tried to show how various materials are used by historians. There is a historian in the book, and he publishes a list of all the materials he used, like newspapers, diaries, testimonies, photographs, and so on.

There are numbers that appear in the book as numbers, but they also appear in the conception of the book. There are eleven chapters and eleven things that appear in all the chapters—a nurse, a dog, and so on—and they appear in a certain order but not always in the same form. There are eleven chapters with eleven things, which makes 121 days!

Notices: *Can you tell me about your transition from mathematics to writing?*

Audin: It was a very natural process. When I would write mathematics, I always tried to take care to write well. I am not the kind of mathematician who uses only fifty words of vocabulary! I just like to write, and I am happy to write about mathematics or mathematicians or anything else. Fiction writing is not very different from writing mathematics. It uses the same qualities, such as imagination and rigor.

Notices: *But when you sit down and write fiction, you get to make everything up, whereas when you write mathematics you are very constrained.*

Audin: That's not true. You are very constrained no matter what you write. It's hard work. It's not just sitting down and waiting for inspiration; I don't believe in that. You have to know what you want to say, and why, and how, and you have to organize how you say it. Of course, a mathematician is constrained to write things always in the same order: statement, proof, maybe one example and one conjecture, and that's it. A fiction writer has more freedom.

There is nothing objective, no truth in numbers.

Notices: *Your novel* La Formule de Stokes *appeared last year [in French only]. Can you tell me about it?*

Audin: There are many different forms of the Stokes formula—there was the Gauss formula at the beginning, then the Ostrogradski formula, Green's formula, the Green–Riemann formula, and so on. At the beginning of the twentieth century, under the influence of people like Élie Cartan, the formula became something very abstract and beautiful. The book tells the story of these different forms of the Stokes formula, but it is not written like a history of the formula. It's a series of short stories about the people working on this subject in the nineteenth and twentieth centuries and what happens around them, for example, the political context. And it is not written in a strict chronological order, but like a calendar, so that the first chapter is about events in January, the second about events in February, and so on.

The book is a novel, and the main character is the Stokes formula. The character appears in various contexts, in Russia, in England, in Germany, in France, in Italy. I used some constraints; for example, there is one and only one formula in each story. And they are all different!

Notices: *Your father, Maurice Audin, was a mathematician. He was killed by the French army in Algeria in 1957. You wrote a book about him,* Une Vie Brève (A Short Life)*. What is that book like?*

Audin: My father was twenty-five years old when he was killed, so this was a very short life. My problem is that, when people speak of him, they always mention the way he was killed, and that's it. I wanted to collect things about what his life had been, not his death. It's like a biography, but organized differently. It's the collection of everything I found about him in the familial memories and archives.

Notices: *Over all these many years, what do you feel now of the influence of your father?*

Audin: That's hard. I was 3 1/2 years old when he was killed. He taught me to read and write, and I was very happy to learn that when I was so young. The main influence is my mother, who was a teacher of mathematics.

Notices: *You turned down the Legion d'Honneur some years back. The reason was that then-president Nicolas Sarkozy never responded to a letter from your mother, in which she objected to France not doing enough to look into what happened to your father.*

Audin: They did nothing!

Notices: *Did you ever get any reply from Sarkozy?*

Audin: No. Under President Hollande, the archives have been opened. But I don't think there is anything in the archives, because this was something done secretly by the army. And it was sixty years ago.

Notices: *Are you working on something new now?*

Audin: I have a book that appeared in 2016, called *Mademoiselle Haas*. There were so many men in *121 Days* that I decided to write a book about women! *Mademoiselle Haas* is about women working in Paris in the 1930s. None of them are mathematicians—at that time there were very few women mathematicians. And I have another book that will appear in September this year, about the Paris Commune in 1871. It has nothing to do with mathematics, although there are some mathematicians in it.

Notices: *One chapter of* 121 Days *consists of a list of numbers or quantities and what they signify, such as "1 single bullet managed to remove one of M.'s eyes, his nose, and half of his jaw," and "-25, the temperature (in degrees Celsius) in Upper Silesia in January 1945 during the evacuation of Auschwitz." How did you put this chapter together?*

Audin: The thing I wanted to show is that numbers are exactly like words. Everybody knows that you can make words say whatever you want them to say. Numbers are the same. I wanted to say that there is nothing objective, no truth in numbers. There is a quotation of Simone de Beauvoir: "There are words as murderous as gas chambers." After the liberation of France, there was a trial of a journalist who was a collaborator. He wrote many things against Jews, including giving addresses where people were hiding. These were just words. But there are words that are murderous. It's just the same with numbers.

Photo Credit

Photo of Michèle Audin is courtesy of Michèle Audin.

Inside the AMS

AMS Congressional Fellow Announced

Margaret D. Callahan

Margaret D. Callahan has been awarded the 2017–2018 AMS Congressional Fellowship. Callahan is currently a visiting assistant professor at Emory University teaching linear algebra and a volunteer with Emory Math Circle, a free mathematics enrichment program for local middle and high school students. She received her PhD in applied mathematics from Case Western Reserve University.

Callahan is interested in STEM education and public health policy and has served in rural Kenya as a secondary school mathematics teacher with the US Peace Corps (USPC). She was elected a Math and Science Education Sector Representative to the Voluntary Advisory Council of the USPC working in support of corps volunteers.

The Congressional Fellowship program is administered by the American Association for the Advancement of Science (AAAS) and provides an opportunity for scientists and engineers to learn about federal policymaking while contributing their knowledge and analytical skills to the process. Fellows spend a year on the staff of a member of Congress or a congressional committee working as a special legislative assistant in legislative and policy areas requiring scientific and technical input. The fellowship program includes an orientation on congressional and executive branch operations and a year-long professional development program.

The fellowship is designed to provide a unique public policy learning experience to demonstrate the value of science-government interaction and to bring a technical background and external perspective to the decision-making process in Congress.

For more information on the AMS-AAAS Congressional Fellowship, go to `bit.ly/AMSCongressionalFellowship`.

—Anita Benjamin, AMS Washington Office

AMS-AAAS Mass Media Fellow Chosen

Benjamin Thompson

Benjamin Thompson of Boston University has been awarded the 2017 AMS-AAAS Mass Media Fellowship. He is a mathematics PhD student studying algebraic geometry. He will work this summer at Voice of America.

The AAAS Mass Media Science and Engineering Fellows program is organized by the American Association for the Advancement of Science (AAAS). This competitive program is designed to improve public understanding of science and technology by placing advanced undergraduate, graduate, and postgraduate science, mathematics, and engineering students in media outlets nationwide. The fellows work for ten weeks over the summer as reporters, researchers, and production assistants alongside media professionals to sharpen their communication skills and increase their understanding of the editorial process by which events and ideas become news.

In its forty-third year, this fellowship program has placed more than 670 fellows in media organizations nationwide as they research, write, and report today's headlines. The program is designed to report science-related issues in the media in easy-to-understand ways so as to improve public understanding and appreciation for science and technology.

For more information on the AAAS Mass Media Science and Engineering Fellows program, visit the website `www.aaas.org/mmfellowship`.

—Anita Benjamin, AMS Washington Office

Capitol Hill Exhibit Highlights Food and Water Security

Lea Jenkins (left) chats with attendees at the 2017 CNSF Exhibition and Reception.

The AMS sponsored an exhibit at the twenty-third annual Coalition for National Science Funding (CNSF) Exhibition and Reception on Capitol Hill held on May 16, 2017. Lea Jenkins, Clemson University, made a presentation entitled "Berry Smart: Mathematics for Food and Water Security," describing her team's work on minimizing water usage.

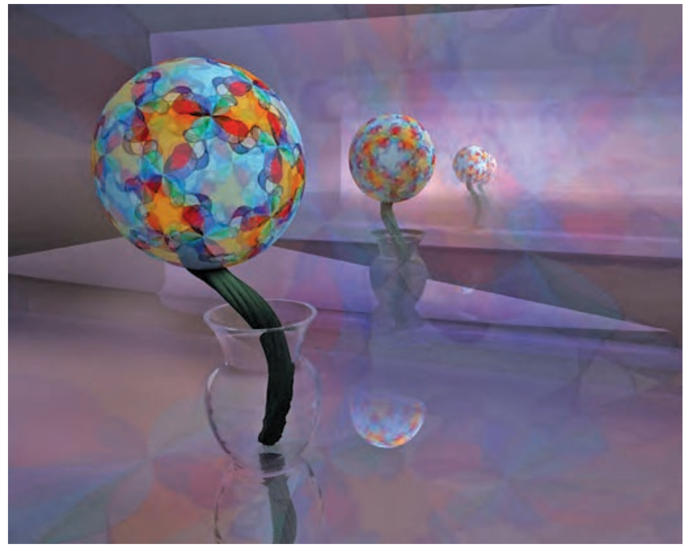
This team of researchers, sponsored by the American Institute of Mathematics and supported by the National Science Foundation, includes Lea Jenkins (Clemson University) and Kathleen Fowler Kavanagh (Clarkson University), as well as hydrologists, farmers, and other stakeholders. The team was interested in designing a plan that would minimize water usage for crops yet still make a profit for the farmers and also meet consumer demand. The mathematical models created incorporate data such as plant growth properties and water requirements of different crops to identify which crops to plant, the best time to plant the selected crops, and which areas to leave unplanted.

These models could apply broadly to farms of varying size. Next steps in the research will introduce more complexity and different farming scenarios into the problem, including simulating multifarm agricultural environments, evaluating the impact of changes in irrigation practices, and irrigation sources.

For more information on this research, see the AMS Mathematical Moments and listen to the podcast at `www.ams.org/samplings/mathmoments/mm128-farming-podcast`.

The Coalition for National Science Funding is an alliance of over 140 organizations united by a concern for the future vitality of the national science, mathematics, and engineering enterprise. The CNSF Exhibition is a well-attended annual event that features over thirty exhibits where researchers present their work and explain the critical importance of increased, sustained federal investments in basic scientific research.

—AMS Washington Office



"Icosahedral Lampflower," by Frank A. Farris, Santa Clara University, CA

From the AMS Public Awareness Office

New Works on Mathematical Imagery: See an album of selected works in the 2017 Mathematical Art Exhibition held at JMM 2017 and additional digital works by Frank A. Farris, Santa Clara University, California. `www.ams.org/mathimagery`

AMS for Students: Undergraduate and high school students and faculty in the mathematical sciences are invited to browse this page for regularly posted news and resources, including links to video collections, semester programs, graduate programs, competitions and awards, where to publish and present research, where to get free math help, and more. `www.ams.org/students`

Opportunities: This online resource allows organizations and institutions to submit calls for applications for fellowships, grants, and scholarships; nominations for prizes and awards; proposals for meetings and workshops; and information about contests and competitions. Calls may be designated by "audience": mathematical scientists/faculty, institutions and programs, postdocs/early-career mathematicians, graduate students, undergraduate students, and high school students and teachers. `www.ams.org/opportunities`

—Annette Emerson and Mike Breen
AMS Public Awareness Officers
paoffice@ams.org

Mathematics Opportunities

Listings for upcoming math opportunities to appear in Notices *may be submitted to* `notices@ams.org`.

The 2018–2019 Joan and Joseph Birman Fellowship for Women Scholars

The new Joan and Joseph Birman Fellowship for Women Scholars is a mid-career research fellowship specially designed to fit the unique needs of women. The fellowships are open only to women. This fellowship program, established in 2017, is made possible by a generous gift from Joan and Joseph Birman.

The fellowship seeks to address the paucity of women at the highest levels of research in mathematics by giving exceptionally talented women extra research support during their mid-career years.

The most likely awardee is a mid-career woman based at a US academic institution with a well-established research record in a core area of mathematics. The fellowship will be directed toward those for whom the award will make a real difference in the development of their research career. Candidates must have a carefully thought-through research plan for the fellowship period. Special circumstances (such as time taken off for care of children or other family members) may be taken into consideration in making the award.

The fellowship can be used to provide additional time for research of the awardee or opportunities to work with collaborators. This may include, but is not limited to, course buyouts, travel money, childcare support, or support to attend special research programs.

A complete application is required in order to be considered for the fellowship. Application instructions, deadlines, and the award amount can be found on the AMS website at `www.ams.org/programs/ams-fellowships/Birman-fellow`.

—AMS announcement

Call for Nominations for Adams Prize

The deadline for nominations for the 2017–2018 Adams Prize for achievements in the field of mathematics of astronomy and cosmology is **October 31, 2017**. See `www.maths.cam.ac.uk/applications-adams-prize-2017-18`.

—Cambridge University announcement

Call for Nominations for 2017 Abel Prize

The Norwegian Academy of Science and Letters awards the Abel Prize annually to recognize outstanding scientific work in the field of mathematics, including mathematical aspects of computer science, mathematical physics, probability, numerical analysis and scientific computing, statistics, and also applications of mathematics in the sciences. Nominations should be postmarked no later than **September 15, 2017**. See `www.abelprize.no/c53676/artikkel/vis.html?tid=53705`.

—Norwegian Academy of Science and Letters

Call for Nominations for AWM Falconer Lectureship

The Association for Women in Mathematics (AWM) and the Mathematical Association of America (MAA) annually present the Etta Z. Falconer Lecture at MathFest to honor women who have made distinguished contributions to the mathematical sciences or mathematics education. The deadline for nominations is **September 1, 2017**. See `https://sites.google.com/site/awmmath/programs/falconer-lectures`.

—From an AWM announcement

Call for Nominations for AWM Schafer Prize

The Association for Women in Mathematics (AWM) calls for nominations for the Alice T. Schafer Mathematics Prize to be awarded to an undergraduate woman for excellence in mathematics. The nominee must be an undergraduate when nominated. The deadline is **October 1, 2017**. See https://sites.google.com/site/awmmath/programs/schafer-prize.

—From an AWM announcement

Call for Nominations for Gerald Sacks Prize

The Association for Symbolic Logic invites nominations for the Gerald Sacks Prize for the most outstanding doctoral dissertation in mathematical logic. The deadline is **September 30, 2017**. See www.aslonline.org/info-prizes.html or www.aslonline.org/Sacks_nominations.html.

—From an ASL announcement

*Research Experiences for Undergraduates

The Research Experiences for Undergraduates (REU) program supports active research participation by undergraduate students in any of the areas funded by the National Science Foundation (NSF). Student research may be supported in two forms: REU sites and REU supplements. See www.nsf.gov/funding/pgm_summ.jsp?pims_id=5517. The deadline date for proposals from institutions wishing to host REU sites is **August 23, 2017**.

Deadline dates for REU supplements vary with the research program; contact the program director for more information. Students apply directly to the REU sites (not NSF) and should consult the directory of active REU sites at www.nsf.gov/crssprgm/reu/list_result.jsp?unitid=5044.

—From an NSF announcement

**The most up-to-date listing of NSF funding opportunities from the Division of Mathematical Sciences can be found online at:* www.nsf.gov/dms *and for the Directorate of Education and Human Resources at* www.nsf.gov/dir/index.jsp?org=ehr. *To receive periodic updates, subscribe to the DMSNEWS listserv by following the directions at* www.nsf.gov/mps/dms/about.jsp.

NSA Mathematical Sciences Grants Program

The National Security Agency's Mathematical Sciences Program (MSP) invites proposals from principal investigators to support Research Experiences for Undergraduates, conferences, and other special events that will take place during calendar years 2018 and 2019. Proposals should be submitted from **September 1, 2017**, through **October 16, 2017**. See www.nsa.gov/what-we-do/research/math-sciences-program or contact Charles Toll (chtoll@nsa.gov) or Barbara Johnson (bajohn1@nsa.gov).

Note. For budgetary reasons, the MSP regrets that we are not able to fund individual research grants (i.e. the Young Investigator Grant and the Standard Grant) this cycle.

—From an NSA announcement

News from MSRI

The Mathematical Sciences Research Institute (MSRI) invites applications for research professors, research members, and postdoctoral fellows in the following programs:

- Hamiltonian Systems, from Topology to Applications through Analysis (August 13–December 14, 2018)
- Derived Algebraic Geometry (January 22–May 24, 2019)
- Birational Geometry and Moduli Spaces (January 22–May 24, 2019).

Research professorships are intended for senior researchers who will be making key contributions to a program, including the mentoring of postdoctoral fellows, and who will be in residence for three or more months. Research memberships are intended for researchers who will be making contributions to a program and who will be in residence for one or more months. Postdoctoral fellowships are intended for recent PhDs. The deadlines are: research professorships, **October 1, 2017**; research memberships, **December 1, 2017**; postdoctoral fellowships, **December 1, 2017**. See www.msri.org/application.

—From an MSRI announcement

Mathematics People

Cormode and Samworth Awarded 2017 Adams Prize


Graham Cormode


Richard Samworth

Graham Cormode of the University of Warwick and Richard Samworth of the University of Cambridge have been awarded the 2017 Adams Prize for achievements in the field of statistical analysis of big data by the University of Cambridge. Both are faculty fellows of the Alan Turing Institute.

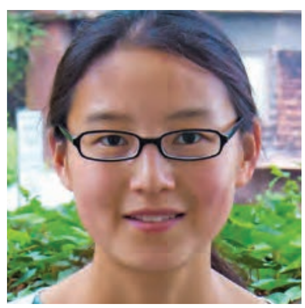
Cormode leads the University of Warwick's partnership with the Institute. His current research concerns verification of machine learning, privacy, data management, and big data analysis with applications to Internet scale data, vehicle data, telecommunications, and social data. His work has been used by organizations including Google, Netflix, and Twitter. Cormode tells the *Notices*: "Although fascinated by mathematics at school, I studied computer science at Cambridge, and have labeled myself a computer scientist since then. This award allows me to claim that the disciplinary boundaries between computer science and mathematics are much more permeable than people may believe. I am currently revisiting the foundations of the subject with my son, Adam, and newborn daughter, Anna." Samworth's main research interests are in developing methodology and theory for high-dimensional and nonparametric statistical inference. He is currently particularly interested in techniques for handling statistical challenges in big data that rely on perturbations of the data and aggregation. Samworth tells the *Notices*: "After spending much of my youth playing sport, I now enjoying giving visitors various challenges, including kneeling on a Swiss ball, and throwing juggling balls against a wall above a door and catching them behind one's back while walking through."

The Adams Prize is awarded annually by the Faculty of Mathematics at the University of Cambridge to a mathematician based in the United Kingdom for distinguished research in the mathematical sciences. The joint recipients will share a cash prize of 15,000 British pounds (approximately US$19,500).

—From a University of Cambridge announcement

2017 Rollo Davidson Prize Awarded


Jian Ding


Nike Sun

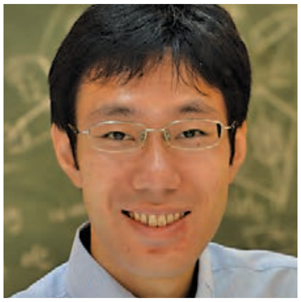
Jian Ding of the University of Chicago and Nike Sun of the University of California Berkeley have been awarded the 2017 Rollo Davidson Prize. Ding was honored for his achievements on mixing and cover times and on the random k-SAT conjecture. Sun was selected for her achievements in probability theory and, specifically, on the random k-SAT conjecture. The Rollo Davidson Trust was founded in 1975 and awards the annual prize to young mathematicians working in the field of probability.

— From a Davidson Trust announcement

Prizes of the Mathematical Society of Japan

The Mathematical Society of Japan (MSJ) has awarded several prizes for 2017.

The Spring Prize was awarded to Tomoyuki Abe of Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, for his outstanding contributions to the study of arithmetic D-module theory and Langlands correspondence. The Spring Prize and the Autumn Prize are the most prestigious prizes awarded by the MSJ to its members. The Spring Prize is awarded



Tomoyuki Abe

to those under the age of forty who have obtained outstanding mathematical results.

The 2017 Algebra Prize was awarded to Toshiyuki Katsura of Hosei University for work in algebraic geometry in positive characteristic; to Masanobu Kaneko of Kyushu University for research on quasimodular forms and multiple zeta values; and to Mitsuyasu Hashimoto of Okayama University for contributions to invariant theory and its applications to commutative ring theory.

The Outstanding Paper Prize for 2017 was awarded to Bo Berndtsson of the Chalmers University of Technology and László Lempert of Purdue University for their paper, "A Proof of the Ohsawa–Takegoshi Theorem with Sharp Estimates," *Journal of the Mathematical Society of Japan* **68** (2016), no. 4.

—From MSJ announcements

Huang Awarded CAIMS/Fields Industrial Mathematics Prize

Huaxiong Huang of York University has been awarded the CAIMS-Fields Industrial Mathematics Prize given by the Fields Institute and the Canadian Applied and Industrial Mathematics Society (CAIMS). According to the prize citation, he has more than seventy-five journal publications "that involve a surprisingly broad cross-section of applied mathematics, including partial differential equations, asymptotics, fluid mechanics, probability, stochastic processes, and scientific computing. His work impacts a broad sphere of influence to the study of applications ranging from industrial sectors such as banking, insurance, biomedicine, energy, and material science." He was the inaugural industrial coordinator at the Pacific Institute of Mathematical Sciences (PIMS). He played a critical role in the early years of the Industrial Problem-Solving Workshops and was also involved in the Graduate Industrial Mathematical Modeling Camps. The CAIMS-Fields annual Industrial Mathematics Prize is awarded to a researcher in recognition of exceptional research in any branch of industrial mathematics, interpreted broadly. The nominee's research should have been conducted primarily in Canada.

—From a CAIMS/Fields announcement

Joseph F. Traub Prize for Achievement in Information-Based Complexity

Thomas Kühn of the University of Leipzig and Winfried Sickel of the University of Jena have been named the recipients of the 2017 Joseph F. Traub Prize for Information-Based Complexity. The prize carries a cash award of US$3,000, to be divided between the recipients.

—Traub Prize Committee announcement

AWM Essay Contest Winners Announced

The Association for Women in Mathematics (AWM) has announced the winners of its 2017 essay contest, "Biographies of Contemporary Women in Mathematics." The grand prize was awarded to Karen Ge of Naperville North High School, Naperville, Illinois, for her essay, "The Limit Does Not Exist," about Elizabeth Moore of Naperville North High School. The essay also won first place in the high school category and will be published in the *AWM Newsletter*. First place in the undergraduate category was awarded to Yixuan He of Dartmouth College for the essay "Persisting through Barriers of Inequality: A Biography of Dr. Seema Nanda," about Seema Nanda of Dartmouth College. First prize in the middle school category was awarded to Asmi Kumar of Northwestern Middle School, Milton, Georgia, for the essay "Breaking Barriers—A Mathematical Journey" about Suzy Crowe, Career Technology Department Chair at Fulton County Schools.

—From an AWM announcement

Moody's Mega Math Challenge

The winners of the 2017 Mega Math Challenge for high school students have been announced. The topic for this year was "From Sea to Shining Sea: Looking Ahead with the National Park Service."

The Champion Team Prize of US$20,000 in scholarship money was awarded to a team from Adlai E. Stevenson High School in Lincolnshire, Illinois. The team members were Joshua Yoon, Haoyang Yu, Andrew Hwang, Deepak Moparthi, and Albert Cao. Their coach was Paul Kim.

The First Runner-Up Team Prize of US$15,000 in scholarship money was awarded to a team from Westford Academy in Westford, Massachusetts. The team members were Nihar Sheth, Harshal Sheth, Kartik Singh, and Adithya Vellal. Their coach was Lisa Gartner.

The Third Place Team Prize of US$10,000 in scholarship money was awarded to a team from Johns Creek High School in Alpharetta, Georgia. The team members were Daniel Bodea, Jamie Wang, Anshul Tusnial, Akhil Vaidya, and Alex Hammond. They were coached by Julie Meert.

Finalist Team Prizes of US$5,000 were awarded to three teams. The team from High Technology High School in Lincroft, New Jersey, consisted of Lori Zhang, Anjali Nambrath, Eric Jiang, Arvind Yalavarti, and Kevin Yan. They were coached by Ellen LeBlanc. The team from Montgomery Blair High School in Silver Spring, Maryland, consisted of James Vinson, Eshan Tewari, Siddharth Taneja, Andrew Komo, and Annie Zhao. They were coached by William Rose. The team from the North Carolina School of Science and Mathematics in Durham, North Carolina, consisted of Angela Deng, Evan Jiang, Miguel de los Reyes, Lucy Wu, and Dory Li. They were coached by Dan Teague.

The Mega Math Challenge invites teams of high school juniors and seniors to solve an open-ended, realistic, challenging modeling problem focused on real-world issues. The top five teams receive awards ranging from US$5,000 to US$20,000 in scholarship money. The competition is sponsored by the Moody's Foundation, a charitable foundation established by Moody's Corporation, and organized by the Society for Industrial and Applied Mathematics (SIAM).

—From a Moody's Foundation/SIAM announcement

NCTM Lifetime Achievement Awards

J. Michael Shaughnessy

Margaret J. Kenney

The National Council of Teachers of Mathematics (NCTM) has chosen two educators to receive Lifetime Achievement Awards for 2017. They are J. Michael Shaughnessy of Portland State University and the late Margaret J. Kenney of Boston College.

According to the prize citation, Shaughnessy's "infectious passion for the teaching and learning of mathematics has inspired mathematics students and teachers. With integrity, and a sense of humor, he has engaged us all in thinking about critically important ideas in mathematics education through his dedicated teaching, research publications, and talks and presentations." His work "is widely recognized for its contributions to students' understanding of chance and data as well as students' geometric thinking." He was a member of the NCTM board of directors and is a past president. His research has included work on how students think and learn about probability and statistics, and his writings on the subject have appeared in a number of books on mathematics and statistics education.

Kenney's prize citation reads in part: "She was an outstanding teacher, a strong leader for many professional organizations, a mentor for hundreds of classroom teachers, and an advocate for including discrete mathematics in the mathematics curriculum. The summer discrete mathematics institutes Peg facilitated were the highlight of professional development opportunities for hundreds of teachers who looked forward to working with her each year." She earned her PhD from Boston College and spent her career there. She assisted, instructed, or served as project coordinator in nearly fifty programs funded by the National Science Foundation. She was coauthor of *Navigating through Discrete Mathematics* in grades K–5 and grades 6–12. She lectured or presented in more than 440 institutes, seminars, and courses in Europe, Australia, Canada, and across the United States. A member of the boards of directors of both the Association of Teachers of Mathematics in Massachusetts and New England, she served as president of both associations. She was a charter member of the Massachusetts Hall of Fame for Mathematics Educators (inducted in 2004) and was recognized by the Council of Presidential Awardees for outstanding contributions to mathematics education. She passed away on July 5, 2016.

—From an NCTM announcement

Scott Awarded Jones Medal

The 2016 Jones Medal has been awarded to Alastair Scott for his contributions during a more than fifty-year career in statistics "through path-breaking research in survey sampling and biostatistics, and through service to the wider statistical profession in academia, government, and society." Scott died in May of this year.

The Jones medal was established in 2010 by the Royal Society Te Aparangi of New Zealand in honor of Sir Vaughan Jones, 1990 Fields Medalist. The medal is awarded biennially for lifetime achievement in pure or applied mathematics or statistics by a person with substantial connections to New Zealand.

—New Zealand Mathematics Research Institute

National Academy of Sciences Election

The National Academy of Sciences (NAS) has elected its new members and foreign associates for 2017. Following are the new members whose work involves the mathematical sciences.

- Nima Arkani-Hamed, Institute for Advanced Study
- Alexander Beilinson, University of Chicago
- Maury D. Bramson, University of Minnesota
- Ronald A. DeVore, Texas A&M University
- Noam D. Elkies, Harvard University

- Daniel A. Spielman, Yale University
- Madhu Sudan, Harvard University
- Don B. Zagier, Max Planck Institute for Mathematics
- Shigefumi Mori, Kyoto University, foreign associate

—From an NAS announcement

2017 Royal Society Elections

The Royal Society of London has elected its class of Fellows for 2017, including the following Fellows whose work involves the mathematical sciences.

- Mark Gross, Cambridge University
- Subhash Khot, New York University
- Lawrence Paulson, Cambridge University
- Gordon Slade, University of British Columbia

Elected as a Foreign Member was Whitfield Diffie, Stanford University.

—From a Royal Society announcement

Komaravolu S. Chandrasekharan (1920–2017)

K. S. Chandrasekharan, known for his work in number theory and summability, received, among other distinctions, the Padma Shri Award, one of the highest civilian honors of India. Born in the province now called Andhra Pradesh, he received his PhD at the University of Madras in 1946, under the direction of K. Ananda Rau (who had done his PhD with G. H. Hardy in Cambridge and had known Ramanujan). Chandrasekharan built up the Tata School of Mathematics and attracted to it many outstanding international researchers. In 1965, he took a position at the ETH in Zurich, where he remained until his retirement in 1988. He served as president of the International Mathematical Union from 1971 to 1974. Chandrasekharan was a man of great culture and wide knowledge, as can be seen in his review of the autobiography of Laurent Schwartz, which appeared in the October 1998 issue of the *Notices*.[1]

—Allyn Jackson

Photo Credits

The photo of Graham Cormode is courtesy of University of Warwick.
The photo of Richard Samworth is courtesy of Richard Samworth
The photo of Jian Ding is courtesy of Jian Ding.
The photo of Nike Sun is courtesy of Luisa Lee, Berkley Simons Institute.
The photo of Tomoyuki Abe is courtesy of Saneatsu Yogi.
The photo of J. Michael Shaughnessy is courtesy of J. Michael Shaughnessy.
The photo of Margaret Kenney is courtesy of Lee Pellegrini, Boston College Office of University Communications.
The photo of Tomoyuki Abe is courtesy of Saneatsu Yogi.

[1] www.ams.org/notices/199809/chandra.pdf

The Wide Influence of Leonard Eugene Dickson

Della Dumbaugh and Amy Shell-Gellasch

Communicated by Stephen Kennedy

ABSTRACT. Saunders Mac Lane has referred to "the wide influence" exerted by Leonard Dickson on the mathematical community through his 67 PhD students. This paper considers the careers of three of these students—A. Adrian Albert, Ko-Chuen Yang, and Mina Rees—in order to give shape to our understanding of this wide influence. Somewhat surprisingly, this influence extends to contemporary issues in academia.

Introduction

This paper raises the question: How do we, as a mathematical community, define and measure success? Leonard Dickson produced sixty-seven PhD students over a forty-year career and provides many examples of successful students. We explore the careers of just three of these students: A. Adrian Albert, Ko-Chuen Yang, and Mina Rees. Albert made important advances in our understanding of algebra and promoted collaboration essential to a flourishing research community. Yang returned to China with ideas and problems from the mathematical frontier and helped build the educational structures necessary to begin a research focus in his homeland. Rees played a fundamental role in creating the interface between government and academic research that has been crucial to the United States' preeminence in mathematics since World War II. And yet Albert is typically celebrated as Dickson's most noteworthy student. The lives of these three students combine with contemporary issues in hiring and diversity in education to suggest that the time is ripe to expand our understanding of success beyond traditional measures. It seems unlikely that Leonard Dickson had an intentional diversity agenda for his research program at the University of Chicago. Yet this contemporary theme of diversity adds a new dimension to our understanding of Dickson as a role model/mentor.

Leonard Dickson produced 67 PhD students over a forty-year career.

A. Adrian Albert (1905–1972)

When Albert arrived at Chicago in 1922, the theory of algebras was among Dickson's main research interests. As Irving Kaplansky observed, Dickson's "considerable" influence on Albert manifested itself in his 1927 master's thesis—where he determined all two-, three- and four-dimensional associative algebras over a nonmodular field—as well as in his 1928 dissertation "Algebras and their radicals and division algebras" [2, p. 246]. In his dissertation Albert proved that every central division algebra of dimension 16 is not necessarily cyclic but is always a crossed product. Albert's thesis placed him at the center of activity in the field of linear associative algebras. In particular, he, along with the German mathematicians Richard Brauer, Helmut Hasse, and Emmy Noether, sought to determine all central division algebras. In 1931 the German trio established the principal theorem that every central division algebra over an algebraic number field of finite degree is cyclic. One year later, Albert and Hasse published a joint work that gave the history

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of the theorem and described Albert's near miss. Although Albert would go on to make significant contributions to the theory of Riemann matrices and to introduce single-handedly the American school of nonassociative algebras, he maintained an interest in associative division algebras throughout his more than forty-year-long career. He wrote more than one hundred forty papers and eight books, was invited to deliver a plenary lecture at an International Mathematical Congress, and received the AMS Cole Prize in 1939.

Mac Lane referred to Albert as Leonard Dickson's best student

The scope of Albert's talents extended beyond the production and publication of mathematical results. He, like Dickson and E. H. Moore, made significant contributions to both the University of Chicago and the AMS. During Albert's tenure as a faculty member at the University of Chicago, he participated in a variety of committees, organized conferences, chaired the mathematics department, and served as dean of the Division of Physical Sciences. While chair he "skillfully" found support to maintain a steady flow of visitors and research instructors. Albert used his influence to persuade the university to make an apartment building available, affectionately known as "the compound," to house visitors. Kaplansky claims that the compound became the "birthplace of many a fine theorem" [2, pp. 251–2]. Albert realized that the infiltration of new ideas frequently encouraged a fresh perspective on mathematics.

Albert's career reflected a strong commitment to the mathematical community at large. He served the AMS in a variety of capacities: as a committee member, as an editor of the *Bulletin* and the *Transactions*, and, like Dickson and Moore, as president of the Society, in 1965–66. The concerns of American mathematicians in the middle two quarters of the twentieth century were, however, somewhat different from those in the early years when Moore and Dickson made their contributions, and Albert's service quite naturally addressed the changing needs of American mathematicians. In particular, Albert helped establish government research grants for mathematics comparable to those existing in other areas of science. He apparently found satisfaction in this nationally oriented work for "he was always pleased to use his influence in Washington to improve the status of mathematicians in general, and he was willing to do the same for individual mathematicians whom he considered 'worthy'" [4, p. 665]. This latter category included his students.


A. Adrian Albert served the AMS in a variety of capacities, including as president in 1965–1966.

Beyond his service to Chicago, the AMS, and the mathematical community at large, Albert exerted considerable influence in mathematics through his students. In his memorial article in *Scripta Mathematica*, I. N. Herstein observed, "Adrian was extremely good at working with students. This is attested by the thirty mathematicians who took their PhDs with him. In their number are many who are well known mathematicians today. His interest in his students—while they were students and forever afterwards—was known and appreciated by them." Daniel Zelinsky, in particular, described Albert as an advisor who treated his PhD students "almost like members of his family" [4, p. 665].

A. A. Albert's success clearly reflects the influence of Dickson. He pursued a vigorous research program that emphasized collaboration, helped launch the careers of numerous students, and served the profession and his institution in varied and important ways. Any advisor would consider a student like Albert an unqualified success. In fact, Saunders Mac Lane referred to Albert as Leonard Dickson's best student [3, p. 131]. But are there other ways of measuring influence and success? Would a career dedicated solely to bringing the next generation of researchers to maturity or striving to bridge the gap between academia and the larger world be worthy of this description?

Ko-Chuen Yang (1896–1973)

In addition to Albert, four other students completed their PhDs under Dickson's guidance in 1928. Yet we rarely hear of them. Dickson had recently turned his mathematical attention, in part, to Waring's Problem. Ko-Chuen Yang (克純 楊) earned his PhD that year with a dissertation on "Various Generalizations of Waring's Problem." This thesis not only represented the first of many dissertations that reflected Dickson's recent investigations in this area, but it also marked the first and only Chinese student to earn a PhD under Dickson.

Yang's journey to Dickson actually began as a small boy at the very beginning of the twentieth century, when China was still in the Qing Dynasty. In June 1900 the Boxer uprising spread to Beijing and, in particular, to the area where foreign diplomats lived and worked. On June 21, 1900, the Qing declared a war on all foreign nations with diplomatic ties to China. This Boxer Rebellion was suppressed in August by a coalition army of soldiers from eight countries (Russia, Britain, Germany, France, the United States, Italy, Japan, and Austria-Hungary). Consequently, in 1901 the Qing government was forced to sign the Boxer Protocol, which demanded that China pay an indemnity valued at about US$337 million at the time to the eight foreign governments over the course of thirty-nine years. About US$24–$25 million was paid to the United States.

This amount was not only deemed excessive by many American government officials, but it also exceeded the actual expense for losses incurred. President Theodore Roosevelt proposed to Congress that the United States return the indemnity funds to China with the stipulation that the money be used for Chinese students to study in the United States. The proposal was implemented in 1908 with about US$12 million returned to China in this manner. These students subsequently became known as Boxer Scholars. According to *The Cambridge History of China*, this sum "created a potent mechanism for support of Chinese higher education."

The Chinese government also used the Boxer Indemnity Funds to create a college preparatory school in 1911 to prepare students for study in the United States. This preparatory school, known as Tsing-hua School, ultimately grew into the National Tsing-hua University and, finally, Tsing-hua University in 1928. The initial department of mathematics at Tsing-hua University had four core faculty, three of them Boxer Scholars, including Ko-Chuen Yang. In this position, Yang would influence many Chinese mathematicians, including Hua Luo-geng (1910–1985), who would go on to become an important mathematician, leader, scholar, and teacher in China in the mid- to late-twentieth century.[1]

Ko-Chuen Yang left a lasting imprint on Chinese mathematics. His son, Franklin Yang, would go on to win a Nobel Prize in physics.

Ko-Chuen Yang's dissertation improved existing bounds for certain cases of Waring's Problem. The only manageable aspect of Waring's Problem is its statement. Waring's Problem concerns $g(k)$, the smallest integer such that any positive integer can be expressed as the sum of at most $g(k)$ nonnegative kth powers. The case for squares, $g(2) = 4$, has been known since Lagrange and was conjectured by Diophantus. Following Dickson, Yang extended known results using polynomials. In particular, he improved Edmond Maillet's 1896 result that showed every integer greater than 19271 is a sum of twelve pyramidal numbers. He also proved that every positive integer is a sum of at most nine pyramidal numbers.

While at Tsing-hua University, Yang introduced the young Hua Luo-geng to Waring's Problem. Inspired by Yang, Hua worked on Waring's Problem using summands of polynomial functions with odd power. Hua went on to study with G. H. Hardy at Cambridge, where he published more than ten papers, most of them related to Waring's Problem.

Hua was a visiting member at the Institute for Advanced Study in 1946–48 and then secured a position at the University of Illinois at Urbana-Champaign. He returned to China in March 1950, where he devoted his attention, in part, to educational reform, in particular to the organization of graduate-level education in mathematics. He helped establish the Mathematical Institute of the Academia Sinica and, in July 1952, was appointed its first director.

Hua Luo-geng emerged as an important mathematician, leader, scholar, and teacher in China in the mid- to late twentieth century.

Through it all, Hua emerged as an important mathematician, leader, scholar, and teacher in China in the mid-to late twentieth century. As the British number theorist Heini Halberstam put it, "If many Chinese mathematicians nowadays are making distinguished contributions at the frontiers of science and if mathematics in China enjoys high popularity in public esteem, that is due in large measure to the leadership Hua gave his country, as scholar and teacher, for 50 years."

Hua Luo-geng offers a compelling example of the influence a teacher can have, not just on one individual, but on an entire country. Although only a handful of mathematicians may recognize the name of Ko-Chuen Yang, he left a lasting imprint on Chinese mathematics, especially through his early influence on Hua Luo-geng.

Mina Rees (1902–1997)

In 1929, a year after Albert and Ko-Chuen Yang earned their PhDs, Mina Rees took a leave of absence from her position at Hunter College to pursue a doctorate at Chicago under Dickson. Rees had studied Dickson's celebrated *Algebras and Their Arithmetics* and had fallen in love with the topic. Dickson had evolved into a notably successful advisor for women pursuing PhDs in mathematics in the United States in the early decades of the twentieth century. Dickson's sixteen women PhD students between 1900 and 1940 meant that he advised 8 percent of all women PhDs in mathematics in the United States and 40 percent of those at Chicago.[2] Dickson's line of inquiry on division algebras was constructive, with an eye towards classification issues. This constructivist approach becomes unwieldly as the number of generators increases, so it was not generalizable. Since Rees had specifically asked to work in division algebras, Dickson assigned her the task of constructing an associative division algebra with four generators, the limit of what his method could realistically achieve, thus closing that line of research. This topic proved beneficial to both Dickson and Rees: it gave closure to Dickson's line of inquiry and provided Rees with a ready-made research topic.

Rees completed her PhD in December 1931 and returned to Hunter as an assistant professor. However, when Warren Weaver assumed his position as director of the wartime Applied Mathematics Panel (AMP) of the National Defense Research Committee in 1943, at the suggestion of Richard Courant he invited Rees to serve as a technical aide and then as his executive assistant. The AMP consisted of government-appointed mathematicians and

[1] *Halberstam describes Hua as "the leading mathematician of his time, and, with S. S. Chern, also a student of Yang, the most eminent mathematician of his generation" [1, p. 137].*

[2] *Data from Green and LaDuke,* Pioneering Women in Mathematics: The Pre-1940s PhDs, 2009.

engineers, including Courant, Marston Morse, and Oswald Veblen. The panel received priority problems from the military and assigned them to research groups at universities across the country. As Weaver's proxy, Rees traveled the country throughout the war to determine how to assign particular problems to the most appropriate research group. In the process, she became intimately acquainted with the state of mathematical and scientific research in the nation, its personalities, and its future. She gained unique understanding of the needs of researchers. The panel also oversaw contracts between the government and universities. These negotiations required tact and finesse, and Rees emerged as an effective bridge between research and academia on the one hand and the government and military on the other. The connections, skills, and insights she gained from her work on the AMP made Rees one of the most informed persons in the country on the pulse of academic scientific research.

With the end of hostilities in 1946, Rees once again tried to return to Hunter. But within a year the call came for her to head the Mathematical Sciences Division of the newly formed Office of Naval Research (ONR) and ultimately assume the role of deputy science director. While at ONR, Rees made funding decisions and set policy for mathematical research. As F. Joachim Weyl, son of Hermann Weyl, described it in *Science*, "ONR made [Rees] the architect of the first large-scale, comprehensively planned program of support for mathematical research; she pioneered its style, scale, and scope." Thus Rees's initiatives set the norms for funding research in the United States for the rest of the century.

Despite these valuable contributions to mathematics and the American mathematical community, Rees is more widely known for her influence on early advances and uses of computers. As just one example of her insight and influence, Rees emphasized the development of visual displays for computers. With output originally via ticker tape, the general opinion at the time was that the nation's needs for computers would be limited to fewer than a dozen machines in total. Rees clearly foresaw that multiple inputs and a more robust form of output and memory would prove essential and lead to the growth of computers.

A recommendation from Richard Courant landed Mina Rees on the Applied Mathematics Panel during World War II. Here Rees and Courant share a laugh at Courant's retirement party from NYU in 1965.

"Can we have excellence and equality or must we choose between them?"

With the founding of the National Science Foundation in 1950, the ONR's role in funding began to diminish (although the ONR supports a program of external research grants to this day), and Rees returned to Hunter in 1953 as professor and dean of the faculty. She aimed to create a graduate program at Hunter and the larger CUNY system that kept pace with an increasingly changing society. She became the first president of the Graduate School and University Center of the City University of New York. As such, her influence continued to shape academia in the United States, this time in the realm of graduate education. Rees posed this meaningful question in an essay that argued for equal access to higher education as a way to redress inequities in our society: "Can we have excellence and equality or must we choose between them?" This question guided much of her work and remains relevant to contemporary discussions in academia.

Rees reminding President and Lady Bird Johnson of the importance of science funding at the time of Rees's nomination to the National Science Board of the NSF, 1965.

As indications of her impact and influence, the Mathematical Association of America awarded Mina Rees the first Award for Distinguished Service to Mathematics in 1962 and the American Association of Science elected her its first female president in 1969.

Concluding Thoughts

George David Birkhoff described Leonard Dickson as "dogged," and his influence on the mathematical community supports that characterization. As Saunders Mac Lane put it, "One can contemplate with amazement the wide influence exerted by Dickson" [3, p. 133]. The careers of just three of his students exemplify this "wide influence." A. Adrian Albert, with his algebraic legacy and key leadership roles in the American mathematical community; Ko-Chuen Yang, with his work on establishing early links between Chinese and American mathematicians and his influence on one of the foremost Chinese mathematicians of the twentieth century; and Mina Rees, with her keen ability to build bridges between mathematicians at universities and the government, her wartime efforts, and her broad views of education.

Even more, these students, who earned their degrees in 1928 and 1931—one Jewish, one Chinese, and one female—show Dickson was willing to take a broad view of who could earn a doctorate in mathematics in this country at that time. In contemporary terms, Dickson modeled diversity, at least as a graduate advisor, long before diversity became a matter of concern, or even awareness, in academia. Long before his student Mina Rees gave voice to the thought, Dickson merged excellence and equality in graduate education in mathematics. That commitment was only a beginning. This analysis of one aspect of his career offers promising insight into a diverse group of graduate students who, in turn, led to diverse populations of faculty and researchers who, indeed, have had a wide influence.

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[4] D. Zelinsky, A. A. Albert, *Amer. Math. Monthly* **80** (1973), 661–665.

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Photo of Richard Courant and Mina Rees courtesy of the Graduate School and University Center Archives, CUNY.

Photo of President and Lady Bird Johnson with Mina Rees courtesy of the Graduate School and University Center Archives, CUNY.

For more on Mina Rees, see the article on "The World War II Origins of Mathematics Awareness," Michael Barany, in the April 2017 issue of *Notices.*

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Della Dumbaugh's research focuses on the history of mathematics, especially in the early twentieth century. Her co-authored book *Emil Artin and Beyond: Class Field Theory and L-Fuctions* appeared in 2015.

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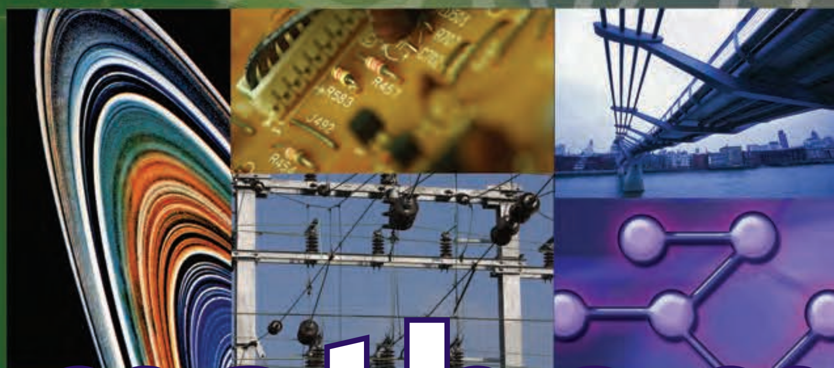

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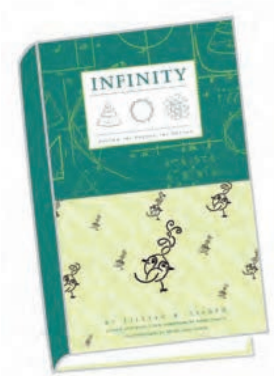
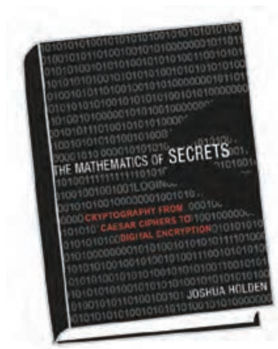


Infinity: Beyond the Beyond the Beyond, by Lillian R. Lieber, with illustrations by Hugh Gray Lieber (Paul Dry Books, November 2007).

In the May 2017 installment of the BookShelf, we noted the paucity of women authors of popular math books in the twentieth century—as compared to the fairly large number today—and asked readers to let us know of any popular math books by women published before around 1990. One reader kindly wrote in to let us know about Lillian Lieber (1886–1986), who wrote several outstanding books that attempt to explain modern mathematics to the general public. The books are deftly illustrated with whimsical drawings by her husband, Hugh Gray Lieber (1896–1961). Both Liebers were mathematicians—Lillian received a PhD and Hugh a master's degree in the subject—and both taught math at Long Island University. The book highlighted here was originally published in 1953 and reissued in abridged form in 2007. The abridgements were made by Barry Mazur of Harvard University, who in the book's foreword writes,"the *joy of thinking* the Liebers radiate is timeless." He goes on to say, "The Liebers sometimes appear to me to be discerning shoppers in the platonic fruit-stall of mathematics. Never content to just think a concept, they also have to test it, squeeze it, pinch it, sniff it, take a few bites, and muse about their own reactions to it before buying it. And then to thoroughly enjoy it." Paul Dry Books has also reissued two other Lieber classics, *The Education of T. C. Mits: What Modern Mathematics Means to You* (also with a foreword by Mazur) and *The Einstein Theory of Relativity: A Trip to the Fourth Dimension* (edited by David Derbes and Robert Jantzen, who also wrote the foreword). This latter book was praised by Einstein himself and later by his biographer Walter Isaacson, who called it "the clearest explanation of relativity available—and the most fun."



The Mathematics of Secrets: Cryptography from Caesar Ciphers to Digital Encryption, by Joshua Holden (Princeton University Press, February 2017).

Related to this month's Opinion column by Jintai Ding and Daniel Smith-Tone, who address the topic of post-quantum cryptography, is this new book by Joshua Holden, a mathematician at Rose-Hulman Institute of Technology. In the book's preface, Holden quotes Cambridge mathematician Ian Cassels, who was a cryptanalyst during World War II: "cryptography is a mixture of mathematics and muddle, and without the muddle the mathematics can be used against you." Holden decided that in his book he would set aside the muddle and concentrate on the mathematics. He also takes great care to keep the mathematics very simple—readers need background only up to the level of high school algebra to understand the exposition. The book is organized according to the historical development of cryptography, starting with Julius Caesar's use of ciphers, and throughout the book the historical background provides context and color to the story. But the emphasis is on the development of the underlying mathematical ideas. The book covers polyalphabetic substitution ciphers, connections between ciphers and computer encryption, ciphers involving exponentiation, and public-key ciphers. The book ends with a look to the future, including the effects quantum computers could have on cryptography. One section deals with post-quantum cryptography, including lattice-based cryptographic systems.

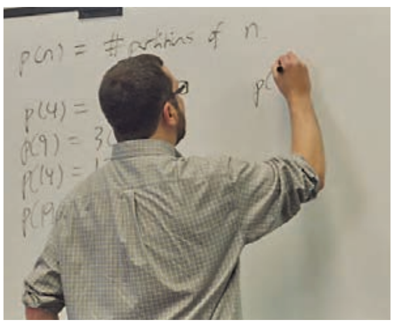
The BookShelf is prepared monthly by Allyn Jackson. Suggestions for the BookShelf can be sent to `notices-booklist@ams.org`.

We try to feature items of broad interest. Appearance of a book in the *Notices* BookShelf does not represent an endorsement by the *Notices* or by the AMS. For more, visit the AMS Reviews webpage `www.ams.org/news/math-in-the-media/reviews`.

Ellenberg in Movie *Gifted*

Allyn Jackson

EDITOR'S NOTE. See also Anna Haensch's AMS blog post on "Growing Up Gifted"[2] and Frank Morgan's short review in this issue of the *Notices* [p. 716].



Ellenberg lectures on Ramanujan and the partition function. From the movie trailer.[1]

The movie *Gifted*, released in April of this year, features a mathematical prodigy, Mary, as protagonist. In the movie University of Wisconsin's Jordan Ellenberg has a cameo role playing himself—that is, playing a mathematician. The movie trailer[1] on YouTube shows a split-second glimpse of Ellenberg at the whiteboard (Figure 1). Known for his conversational and eloquent popularizations, including the best-selling *How Not to be Wrong*, Ellenberg has become well known to the general public as a demystifier of math. He responded e-mail to a few questions from the *Notices* about his new acting gig.

Notices: *How did it come about that you were asked to act in* Gifted*?*

Ellenberg: It was a lucky series of coincidences! The producers ran across a piece[3] I wrote for the *Wall Street Journal* about child prodigies and set up a phone call with me and the director to talk about my own experience, which was both similar to and different from that of Mary, the character in the movie. Once we'd talked, they asked me if I could be a consultant to be on set during the big blackboard scene to check whether everything was on the level, and then, since they were filming a math professor scene on the same day of shooting, they figured they might as well use a real math professor!

Notices: *What part did you play, and how long did your scene last?*

Ellenberg: I played "Professor." So, as you can imagine, I don't have much of a backstory. I'm supposed to represent Mary's exposure to upper-level math. There's one other math professor character, who has a substantially bigger role and is a bit high-and-mighty towards Mary. I met the actor who played that role and, by way of small talk, told him, "So I guess you're the mean professor and I'm the nice professor!" He immediately grew very cold. It seemed he was already to some extent in character and was really a bit hurt that I called him "mean."

Notices: *What kind of directions did you get for the scene?*

Ellenberg: Minimal. In fact, I worked quite hard to learn the lines I was given, and when I got there, the director, Marc Webb, told me, "Don't worry about the lines; just talk about it the way you really would in class." So in one way, it was hardly acting at all; I was just being myself. But I had to do that little piece of exposition about thirty times in a row, and it had to be pretty much identical so they could cut from different takes. It's an interesting experience to try to "just be yourself" in exactly the same way again and again and again!

Notices: *Was it fun to do, or boring, or scary, or…?*

Ellenberg: Very fun. Boring at moments—there's a lot of sitting around and setting up! But it's pretty amazing to see how many people and how much work go into producing a minute or two of final product.

Notices: *How did it feel to see yourself on the big screen?*

Ellenberg: It's a very strange feeling. Imagine you were in the middle of watching a movie, and then suddenly it cut to footage of yourself giving a math talk! But I think for the audience it mostly plays as seamless. Your own voice sounds very strange to you. I accused the director of making my voice sound more hyperstimulated in post-production, and he said, "No, you just sound like that."

Photo Credit

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[1] https://www.youtube.com/watch?v=tIO1wBXGHUs *(fast-forward to 1:31)*

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MATHEMATICS CALENDAR

This section contains new announcements of worldwide meetings and conferences of interest to the mathematical public, including ad hoc, local, or regional meetings, and meetings and symposia devoted to specialized topics, as well as announcements of regularly scheduled meetings of national or international mathematical organizations. New announcements only are published in the print Mathematics Calendar featured in each *Notices* issue.

An announcement will be published in the *Notices* if it contains a call for papers and specifies the place, date, subject (when applicable). A second announcement will be published only if there are changes or necessary additional information. Asterisks (*) mark those announcements containing revised information.

In general, print announcements of meetings and conferences carry only the date, title and location of the event.

The complete listing of the Mathematics Calendar is available at: www.ams.org/meetings/calendar/mathcal

All submissions to the Mathematics Calendar should be done online via: www.ams.org/cgi-bin/mathcal/mathcal-submit.pl

Any questions or difficulties may be directed to mathcal@ams.org.

August 2017

7 – 11 **Eighth Montreal Industrial Problem Solving Workshop**
Location: *Université de Montréal, Montréal (Québec) H3T 1J4).*
URL: www.crm.umontreal.ca/probindustriels2017

21 – 25 **Gauge Theories, Monopoles, Moduli Spaces and Integrable Systems. A Conference honouring Jacques Hurtubise on his 60th birthday**
Location: *Université de Montréal Pavillon André-Aisenstadt 2920, Chemin de la tour, 5th floor Montréal (Québec) H3T 1J4 CANADA.*
URL: www.crm.umontreal.ca/2017/Hurtubise60/index_e.php

28 – September 1 **Combinatorics of Group Actions and its Applications**
Location: *Memorial University of Newfoundland, St. Johns, Canada.*
URL: www.mun.ca/aac/Workshops/NextWork/CGAA2017

September 2017

8 – 9 **The Prairie Analysis Seminar**
Location: *Kansas State University, Manhattan, Kansas.*
URL: www.math.ksu.edu/pas/2017

11 – 14 **Workshop: Risk Measurement and Regulatory Issues in Business**
Location: *Université de Montréal Pavillon André-Aisenstadt 2920, Chemin de la tour, 5th floor Montréal (Québec) H3T 1J4 CANADA.*
URL: www.crm.umontreal.ca/2017/Affaires17/index_e.php

October 2017

6 – 8 **Symposium on Biomathematics and Ecology: Education and Research (BEER)**
Location: *Illinois State University, Normal, IL, USA.*
URL: symposium.beer

15 – 15 **The Seventh Dr. George Bachman Memorial Conference.**
Location: *St. John's Univ. 8000 Utopia Parkway Jamaica, New York, 11439.*
URL:

November 2017

2 – 4 **Symplectic Geometry in Lyon – A conference in honor of Jean-Claude Sikorav**
Location: *Université de Lyon 1, France.*
URL: sikorav60.math.cnrs.fr

3 – 4 **2nd EAI International Conference on Computer Science and Engineering, November 3-4, 2017.**
Location: *Bangkok, Thailand.*
URL: compse-conf.org/2017/show/home

13 – 17 **First Belgium-Chile-Italy Conference in PDEs**
Location: *Université Libre de Bruxelles - Département de Mathématiques Campus de la Plaine, Batiment/Building NO Boulevard du Triomphe 1050 Bruxelles, Belgium.*
URL: pde.ulb.be

20 – 24 **Winter School: Categorification, representation theory and symplectic geometry**
Location: *University of Bonn, Bonn, Germany.*
URL: www.math.uni-bonn.de/people/dtubben/reptheory-school2017.html

27 – December 1 **Winter Workshop: Categorification, representation theory and symplectic geometry**
Location: *University of Bonn, Bonn, Germany.*
URL: www.math.uni-bonn.de/people/dtubben/reptheory-workshop2017.html

December 2017

5 – 7 **International Conference on Geometry and Mathematical Models in Complex Phenomena (ICGMMCP-2017)**
Location: *Calcutta Mathematical Society AE-374, Sector I, Salt Lake City Kolkata - 700064, West Bengal, India.*
URL: www.calmathsoc.org

18 – 21 **24th IEEE International Conference on High Performance Computing, Data, and Analytics**
Location: *Jaipur, India.*
URL: hipc.org

January 2018

9 – 11 **Fourth International Conference on Mathematics & Computing (ICMC) 2018**
Location: *Indian Institute of Technology (BHU), Varanasi, India.*
URL: iitbhu.ac.in/icmc2018/apm/index.html

29 – February 2 **Representation spaces, Teichmuller theory, and their relationship with 3-manifolds from the classical and quantum viewpoints**
Location: *CIRM, Marseille-Luminy, France.*
URL: scientific-events.weebly.com/1891.html

29 – February 9 **Winter School and Workshop "Riemann-Hilbert correspondences"**
Location: *Dipartimento di Matematica, Università di Padova, Italy.*
URL: events.math.unipd.it/rh2018

February 2018

26 – March 2 **Structure of 3-manifold Groups**
Location: *CIRM, Marseille-Luminy, France.*
URL: walsh-paoluzzi.weebly.com/conference.html

March 2018

19 – 23 **7th International Conference on High Performance Scientific Computing**
Location: *The Vietnam Institute for Advanced Study in Mathematics, Hanoi, Vietnam.*
URL: hpsc.iwr.uni-heidelberg.de/HPSCHanoi2018

June 2018

11 – 15 **3-Manifolds and Geometric Group Theory**
Location: *CIRM, Marseille-Luminy, France.*
URL: walsh-paoluzzi.weebly.com/school.html

July 2018

3 – 6 **14th Viennese Conference on Optimal Control and Dynamic Games**
Location: *Vienna University of Technology, Wiedner Hauptstrasse 8, 1040 Wien, Austria.*
URL: orcos.tuwien.ac.at/vc2018

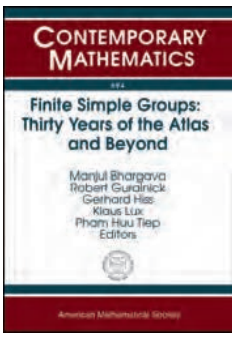
August 2018

20 – 24 **AIM Workshop: Additive combinatorics and its applications**
Location: *American Institute of Mathematics, San Jose, CA.*
URL: aimath.org/workshops/upcoming/addcombapp

New Publications Offered by the AMS

To subscribe to email notification of new AMS publications, please go to www.ams.org/bookstore-email.

Algebra and Algebraic Geometry



Finite Simple Groups: Thirty Years of the Atlas and Beyond

Manjul Bhargava, *Princeton University, NJ*, **Robert Guralnick**, *University of Southern California, Los Angeles, CA*, **Gerhard Hiss**, *RWTH Aachen University, Germany*, **Klaus Lux**, *University of Arizona, Tucson, AZ*, and **Pham Huu Tiep**, *University of Arizona, Tucson, AZ*, Editors

This volume contains the proceedings of the international conference Finite Simple Groups: Thirty Years of the Atlas and Beyond Celebrating the Atlases and Honoring John Conway, which was held from November 2–5, 2015, at Princeton University, Princeton, New Jersey.

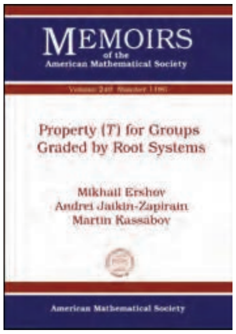
Classification of Finite Simple Groups, one of the most monumental accomplishments of modern mathematics, was announced in 1983 with the proof completed in 2004. Since then, it has opened up a new and powerful strategy to approach and resolve many previously inaccessible problems in group theory, number theory, combinatorics, coding theory, algebraic geometry, and other areas of mathematics. This strategy crucially utilizes various information about finite simple groups, part of which is catalogued in the *Atlas of Finite Groups* (John H. Conway et al.), and in *An Atlas of Brauer Characters* (Christoph Jansen et al.). It is impossible to overestimate the roles of the Atlases and the related computer algebra systems in the everyday life of researchers in many areas of contemporary mathematics.

The main objective of the conference was to discuss numerous applications of the Atlases and to explore recent developments and future directions of research, with focus on the interaction between computation and theory and applications to number theory and algebraic geometry. The papers in this volume are based on talks given at the conference. They present a comprehensive survey on current research in all of these fields.

Contents: **Y.-H. He** and **J. McKay**, Moonshine and the meaning of life; **S. P. Norton**, The monster is fabulous; **A. A. Ivanov**, Majorana representation of the monster group; **J.-P. Serre**, Letter to Donna Testerman; **T. Breuer**, **G. Malle**, and **E. A. O'Brien**, Reliability and reproducibility of Atlas information; **F. Lübeck**, Characters and Brauer trees of the covering group of ${}^2E_6(2)$; **R. A. Wilson**, Maximal subgroups of sporadic groups; **R. T. Curtis**, Construction of the Thompson chain of subgroups of the Conway group $\cdot$O and complete graphs on n letters; **N. Gill**, **N. I. Gillespie**, **C. E. Praeger**, and **J. Semeraro**, Conway's groupoid and its relatives; **M. Aschbacher**, The subgroup structure of finite groups; **K. Magaard**, Some remarks on maximal subgroups of finite classical groups; **J. F. Carlson**, Toward a classification of endotrivial modules; **G. Navarro**, Some remarks on global/local conjectures; **M. Geck**, Minuscule weights and Chevalley groups; **G. Nebe**, **R. Parker**, and **S. E. Rees**, A method for building permutation representations of finitely presented groups; **M. W. Liebeck**, Character ratios for finite groups of Lie type, and applications; **A. Shalev**, Conjugacy classes, growth and complexity; **R. Waldecker**, Permutation groups where non-trivial elements have few fixed points.

Contemporary Mathematics, Volume 694

August 2017, approximately 230 pages, Softcover, ISBN: 978-1-4704-3678-0, 2010 *Mathematics Subject Classification:* 01A70, 05Bxx, 17Bxx, 17D99, 20Bxx, 20Cxx, 20Dxx, 20Exx, 20Gxx, 20Pxx, **AMS members US$88.80**, List US$111, Order code CONM/694



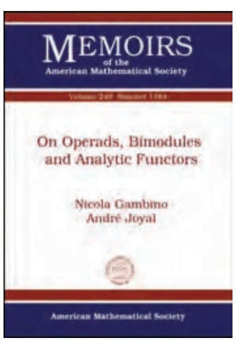
Property (T) for Groups Graded by Root Systems

Mikhail Ershov, *University of Virginia, Charlottesville, Virginia*, **Andrei Jaikin-Zapirain**, *Universidad Autónoma de Madrid, Spain, and Instituto de Ciencias Matemáticas, Madrid, Spain*, and **Martin Kassabov**, *Cornell University, Ithaca, New York, and University of Southampton, United Kingdom*

Contents: Introduction; Preliminaries; Generalized spectral criterion; Root systems; Property (T) for groups graded by root systems; Reductions of root systems; Steinberg groups over commutative rings; Twisted Steinberg groups; Application: Mother group with property (T); Estimating relative Kazhdan constants; Appendix A. Relative property (T) for $(\mathrm{St}_n(R) \ltimes R^n, R^n)$; Bibliography; Index.

Memoirs of the American Mathematical Society, Volume 249, Number 1186

August 2017, 135 pages, Softcover, ISBN: 978-1-4704-2604-0, 2010 *Mathematics Subject Classification:* 22D10, 17B22; 17B70, 20E42, **Individual member US$45**, List US$75, Institutional member US$60, Order code MEMO/249/1186



On Operads, Bimodules and Analytic Functors

Nicola Gambino, *University of Leeds, United Kingdom*, and **André Joyal**, *Université du Québec á Montrèal, Québec, Canada*

Contents: Introduction; Background; Monoidal distributors; Symmetric sequences; The bicategory of operad bimodules; Cartesian closure of operad bimodules; Appendix A. A compendium of bicategorical definitions; Appendix B. A technical proof; Bibliography.

Memoirs of the American Mathematical Society, Volume 249, Number 1184

August 2017, 110 pages, Softcover, ISBN: 978-1-4704-2576-0, 2010 *Mathematics Subject Classification:* 18D50; 55P48, 18D05, 18C15, **Individual member US$45**, List US$75, Institutional member US$60, Order code MEMO/249/1184

Advanced Modern Algebra

Third Edition, Parts 1 and 2

Joseph J. Rotman, *University of Illinois at Urbana-Champaign, IL*

This new edition, now in two parts, has been significantly reorganized and many sections have been rewritten. The first part, designed for a first year of graduate algebra, consists of two courses: Galois theory and Module theory. Topics covered in the first course are classical formulas for solutions of cubic and quartic equations, classical number theory, commutative algebra, groups, and Galois theory. Topics in the second course are Zorn's lemma, canonical forms, inner product spaces, categories and limits, tensor products, projective, injective, and flat modules, multilinear algebra, affine varieties, and Gröbner bases.

The second part presents many topics mentioned in the first part in greater depth and in more detail. The five chapters of the book are devoted to group theory, representation theory, homological algebra, categories, and commutative algebra, respectively. The book can be used as a text for a second abstract algebra graduate course, as a source of additional material to a first abstract algebra graduate course, or for self-study.

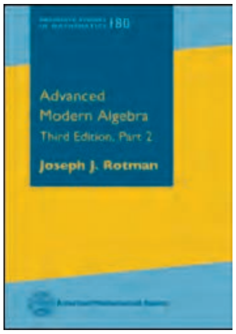
Contents: *Contents for Part 1: Course I:* Classical formulas; Classical number theory; Commutative rings; Groups; Galois theory; Appendix: Set theory; Appendix: Linear algebra; *Course II:* Modules; Zorn's lemma; Advanced linear algebra; Categories of modules; Multilinear algebra; Commutative algebra II; Appendix: Categorical limits; Appendix: Topological spaces; Bibliography; Special notation; Index; *Contents for Part 2:* More groups; Representation theory; Homology; More categories; Commutative rings III; Bibliography; Index.

Graduate Studies in Mathematics, Volume 165, Number 180

Part 1: October 2015, 706 pages, Hardcover, ISBN: 978-1-4704-1554-9, 2010 *Mathematics Subject Classification:* 12-01, 13-01, 14-01, 15-01, 16-01, 18-01, 20-01, Order code GSM/165

Part 2: October 2017, approximately 548 pages, Hardcover, ISBN: 978-1-4704-2311-7, 2010 *Mathematics Subject Classification:* 12-01, 13-01, 14-01, 15-01, 16-01, 18-01, 20-01, Order code GSM/180

Set: October 2017, approximately 1254 pages, Hardcover, ISBN: 978-1-4704-4174-6, 2010 *Mathematics Subject Classification:* 12-01, 13-01, 14-01, 15-01, 16-01, 18-01, 20-01, **AMS members US$139.20**, List US$174, Order code GSM/165/180



Advanced Modern Algebra

Third Edition, Part 2

Joseph J. Rotman, *University of Illinois at Urbana-Champaign, IL*

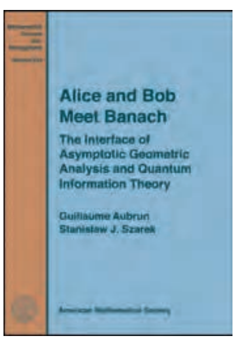
This book is the second part of the new edition of *Advanced Modern Algebra* (the first part published as Graduate Studies in Mathematics, Volume 165). Compared to the previous edition, the material has been significantly reorganized and many sections have been rewritten. The book presents many topics mentioned in the first part in greater depth and in more detail. The five chapters of the book are devoted to group theory, representation theory, homological algebra, categories, and commutative algebra, respectively. The book can be used as a text for a second abstract algebra graduate course, as a source of additional material to a first abstract algebra graduate course, or for self-study.

Contents: More groups; Representation theory; Homology; More categories; Commutative rings III; Bibliography; Index.

Graduate Studies in Mathematics, Volume 180

October 2017, approximately 548 pages, Hardcover, ISBN: 978-1-4704-2311-7, LC 2015019659, 2010 *Mathematics Subject Classification:* 12-01, 13-01, 14-01, 15-01, 16-01, 18-01, 20-01, **AMS members US$75.20**, List US$94, Order code GSM/180

Analysis



Alice and Bob Meet Banach

The Interface of Asymptotic Geometric Analysis and Quantum Information Theory

Guillaume Aubrun, *Université Claude Bernard Lyon 1, Villeurbanne, France*, and **Stanisław J. Szarek**, *Case Western Reserve University, Cleveland, OH*

This book builds a bridge between two scientific areas. The first area, Asymptotic Geometric Analysis (AGA), studies the geometry of Banach spaces through their subspaces or subsets of finite but large dimension. Geometric and probabilistic techniques, such as concentration of measure, play a fundamental role. The second area, Quantum Information Theory (QIT), provides the mathematical framework for manipulation of information in the quantum world, and for using quantum phenomena to transmit or store data. Both fields are given a detailed presentation, which includes a discussion of selected important results. One of the main goals of the book is to show how by combining these two areas, one can get deep recent results about the geometry of entanglement or superadditivity of quantum channel capacities.

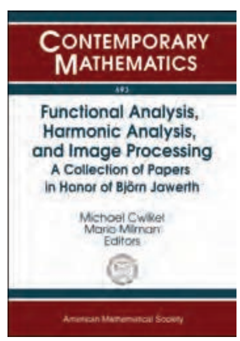
The book is aimed at multiple audiences connected through their interest in the interface of QIT and AGA: at quantum information researchers who want to learn AGA or apply its tools; at mathematicians interested in learning QIT, or at least the part of QIT that is relevant to functional analysis/convex geometry/random matrix theory and related areas; and at beginning researchers in either field. The book aims at making the relevant concepts and facts accessible to everyone from a casual reader to an expert looking for a reference.

This item will also be of interest to those working in applications.

Contents: *Alice and Bob: Mathematical Aspects of Quantum Information:* Notation and basic concepts; Elementary convex analysis; The mathematics of quantum information theory; Quantum mechanics for mathematicians; *Banach and His spaces: Asymptotic Geometric Analysis Miscellany:* More convexity; Metric entropy and concentration of measure in classical spaces; Gaussian processes and random matrices; Some tools from asymptotic geometric analysis; *The Meeting: AGA and QIT:* Entanglement of pure states in high dimensions; Geometry of the set of mixed states; Random quantum states; Bell inequalities and the Grothendieck-Tsirelson inequality; POVMs and the distillability problem; Gaussian measures and Gaussian variables; Classical groups and manifolds; Extreme maps between Lorentz cones and the S-lemma; Polarity and the Santaló point via duality of cones; Hints to exercises; Bibliography; Notation; Index.

Mathematical Surveys and Monographs, Volume 223

October 2017, approximately 413 pages, Hardcover, ISBN: 978-1-4704-3468-7, LC 2017010894, 2010 *Mathematics Subject Classification:* 46Bxx, 52Axx, 81Pxx, 46B07, 46B09, 52C17, 60B20, 81P40, **AMS members US$92.80**, List US$116, Order code SURV/223



Functional Analysis, Harmonic Analysis, and Image Processing

A Collection of Papers in Honor of Björn Jawerth

Michael Cwikel, *Technion-Israel Institute of Technology, Haifa, Israel*, and **Mario Milman**, *Instituto Argentino de Matematica, Buenos Aires, Argentina*, Editors

This volume is dedicated to the memory of Björn Jawerth. It contains original research contributions and surveys in several of the areas of mathematics to which Björn made important contributions. Those areas include harmonic analysis, image processing, and functional analysis, which are of course interrelated in many significant and productive ways.

Among the contributors are some of the world's leading experts in these areas. With its combination of research papers and surveys, this book may become an important reference and research tool.

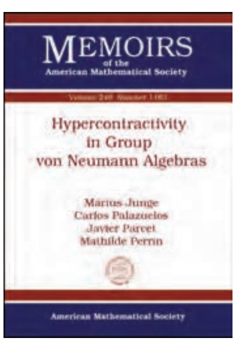
This book should be of interest to advanced graduate students and professional researchers in the areas of functional analysis, harmonic analysis, image processing, and approximation theory. It combines articles presenting new research with insightful surveys written by foremost experts.

This item will also be of interest to those working in applications.

Contents: M. Cwikel, **M. Frazier**, **L. M. Jawerth**, and **M. Milman**, Björn David Jawerth (1952–2013); **S. V. Astashkin** and **K. V. Lykov**, Jawerth–Milman extrapolation theory: Some recent developments with applications; **J. J. Benedetto** and **M. Dellatorre**, Uncertainty principles and weighted norm inequalities; **A. Bényi** and **R. H. Torres**, The discrete Calderón reproducing formula of Frazier and Jawerth; **H.-Q. Bui** and **T. Candy**, A characterisation of the Besov-Lipschitz and Triebel-Lizorkin spaces using Poisson like kernels; **C. Cabrelli**, **C. A. Mosquera**, and **V. Paternostro**, An approximation problem in multiplicatively invariant spaces; **G. Cleanthous**, **A. G. Georgiadis**, and **M. Nielsen**, Discrete decomposition of homogeneous mixed-norm Besov spaces; **H. G. Feichtinger** and **F. Voigtlaender**, From Frazier-Jawerth characterizations of Besov spaces to wavelets and decomposition spaces; **M. Frazier** and **S. Roudenko**, Traces and extensions of weighted Sobolev and potential spaces; **D. D. Haroske** and **L. Skrzypczak**, Compact embeddings of weighted smoothness spaces of Morrey type: An example; **L. M. Jawerth** and **D. A. Weitz**, Tracking the structural deformation of a sheared biopolymer network; **L. Lempert**, Extrapolation, a technique to estimate; **A. K. Lerner**, On a dual property of the maximal operator on weighted variable L^p spaces; **R. Rochberg**, Is the Dirichlet space a quotient of DA_n?; **W. Abu-Shammala**, **J.-L. Shiu**, and **A. Torchinsky**, Characterizations of the Hardy space $H^1(\mathbb{R})$ and $\mathrm{BMO}(\mathbb{R})$; **C. Tintarev**, Four proofs of cocompactness for Sobolev embeddings; **H. Triebel**, Tempered homogeneous function spaces, II; **V. K. Nguyen** and **W. Sickel**, Isotropic and dominating mixed Besov spaces: A comparison; **S. Voronin** and **I. Daubechies**, An iteratively reweighted least squares algorithm for sparse regularization.

Contemporary Mathematics, Volume 693

August 2017, 411 pages, Softcover, ISBN: 978-1-4704-2836-5, LC 2016055558, 2010 *Mathematics Subject Classification:* 42B20, 42B25, 42B35, 42C15, 46B70, 42C40, 42B37, 46E30, 46E35, **AMS members US$88.80**, List US$111, Order code CONM/693



Hypercontractivity in Group von Neumann Algebras

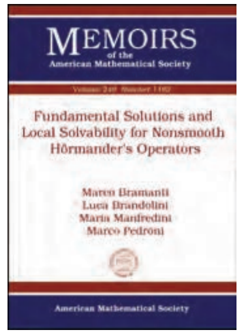
Marius Junge, *University of Illinois at Urbana-Champaign, Illinois*, **Carlos Palazuelos**, *Instituto de Ciencias Matemáticas, Madrid, Spain*, **Javier Parcet**, *Instituto de Ciencias Matemáticas, Madrid, Spain*, and **Mathilde Perrin**, *Instituto de Ciencias Matemáticas, Madrid, Spain*

Contents: The combinatorial method; Optimal time estimates; Poisson-like lengths; Appendix A. Logarithmic Sobolev inequalities; Appendix B. The word length in $\mathbb{Z}_n$; Appendix C. Numerical analysis; Appendix D. Technical inequalities; Bibliography.

Memoirs of the American Mathematical Society, Volume 249, Number 1183

August 2017, 83 pages, Softcover, ISBN: 978-1-4704-2565-4, 2010 *Mathematics Subject Classification:* 22D15, 43A22, 47D07, **Individual member US$45**, List US$75, Institutional member US$60, Order code MEMO/249/1183

Differential Equations



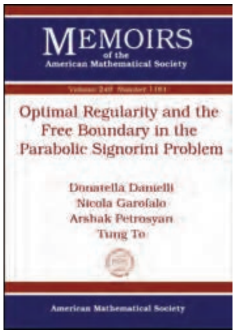
Fundamental Solutions and Local Solvability for Nonsmooth Hörmander's Operators

Marco Bramanti, *Politecnico di Milano, Italy*, **Luca Brandolini**, *Università di Bergamo, Dalmine, Italy*, **Maria Manfredini**, *Università di Bologna, Italy*, and **Marco Pedroni**, *Università di Bergamo, Dalmine, Italy*

Contents: Introduction; Some known results about nonsmooth Hörmander's vector fields; Geometric estimates; The parametrix method; Further regularity of the fundamental solution and local solvability of L; Appendix. Examples of nonsmooth Hörmander's operators satisfying assumptions A or B; Bibliography.

Memoirs of the American Mathematical Society, Volume 249, Number 1182

August 2017, 79 pages, Softcover, ISBN: 978-1-4704-2559-3, 2010 *Mathematics Subject Classification:* 35A08, 35A17, 35J20, **Individual member US$45**, List US$75, Institutional member US$60, Order code MEMO/249/1182



Optimal Regularity and the Free Boundary in the Parabolic Signorini Problem

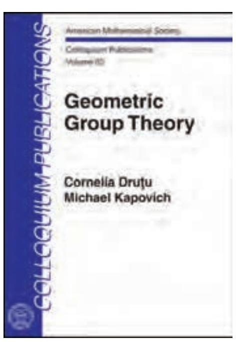
Donatella Danielli, *Purdue University, West Lafayette, Indiana*, **Nicola Garofalo**, *Università di Padova, Italy*, **Arshak Petrosyan**, *Purdue University, West Lafayette, Indiana*, and **Tung To**, *Purdue University, West Lafayette, Indiana*

Contents: Introduction; Notation and preliminaries; Known existence and regularity results; Classes of solutions; Estimates in Gaussian spaces; The generalized frequency function; Existence and homogeneity of blowups; Homogeneous global solutions; Optimal regularity of solutions; Classification of free boundary points; Free boundary: Regular set; Free boundary: Singular set; Weiss and Monneau type monotonicity formulas; Structure of the singular set; Appendix A. Estimates in Gaussian spaces: Proofs; Appendix B. Parabolic Whitney's extension theorem; Bibliography.

Memoirs of the American Mathematical Society, Volume 249, Number 1181

August 2017, 103 pages, Softcover, ISBN: 978-1-4704-2547-0, 2010 *Mathematics Subject Classification:* 35K35, 35K85, **Individual member US$45**, List US$75, Institutional member US$60, Order code MEMO/249/1181

Geometry and Topology



Geometric Group Theory

Cornelia Druţu, *Mathematical Institute, Oxford, United Kingdom*, and **Michael Kapovich**, *University of California, Davis, CA*

With an appendix by Bogdan Nica

The key idea in geometric group theory is to study infinite groups by endowing them with a metric and treating them as geometric spaces. This applies to many groups naturally appearing in topology, geometry, and algebra, such as fundamental groups of manifolds, groups of matrices with integer coefficients, etc. The primary focus of geometric group theory is to cover the foundations of geometric group theory, including coarse topology, ultralimits and asymptotic cones, hyperbolic groups, isoperimetric inequalities, growth of groups, amenability, Kazhdan's Property (T) and the Haagerup property, as well as their characterizations in terms of group actions on median spaces and spaces with walls.

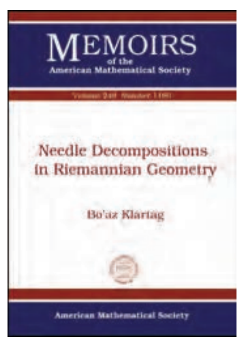
The book contains proofs of several fundamental results of geometric group theory, such as Gromov's theorem on groups of polynomial growth, Tits's alternative, Stallings's theorem on ends of groups, Dunwoody's accessibility theorem, the Mostow Rigidity Theorem, and quasiisometric rigidity theorems of Tukia and Schwartz. This is the first book in which geometric group theory is presented in a form accessible to advanced graduate students and young research mathematicians. It fills a big gap in the literature and will be used by researchers in geometric group theory and its applications.

This item will also be of interest to those working in algebra and algebraic geometry.

Contents: Geometry and topology; Metric spaces; Differential geometry; Hyperbolic space; Groups and their actions; Median spaces and spaces with measured walls; Finitely generated and finitely presented groups; Coarse geometry; Coarse topology; Ultralimits of metric spaces; Gromov-hyperbolic spaces and groups; Lattices in Lie groups; Solvable groups; Geometric aspects of solvable groups; The Tits alternative; Gromov's theorem; The Banach-Tarski paradox; Amenability and paradoxical decomposition; Ultralimits, fixed point properties, proper actions; Stallings's theorem and accessibility; Proof of Stallings's theorem using harmonic functions; Quasiconformal mappings; Groups quasiisometric to $\mathbb{H}^n$; Quasiisometries of nonuniform lattices in $\mathbb{H}^n$; A survey of quasiisometric rigidity; Appendix: Three theorems on linear groups; Bibliography; Index.

Colloquium Publications, Volume 63

November 2017, approximately 814 pages, Hardcover, ISBN: 978-1-4704-1104-6, LC 2017002521, 2010 *Mathematics Subject Classification:* 20F65, 20F67, 20F69, 20F05, 20F16, 20F18, 20F34, 20E08, 20E26, 57M07, **AMS members US$108**, List US$135, Order code COLL/63



Needle Decompositions in Riemannian Geometry

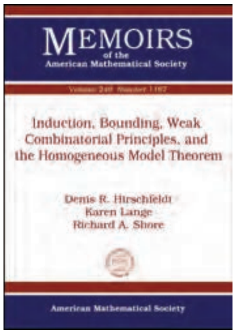
Bo'az Klartag, *Tel Aviv University, Israel*

Contents: Introduction; Regularity of geodesic foliations; Conditioning a measure with respect to a geodesic foliation; The Monge-Kantorovich problem; Some applications; Further research; Appendix: The Feldman-McCann proof of Lemma 2.4.1; Bibliography.

Memoirs of the American Mathematical Society, Volume 249, Number 1180

August 2017, 77 pages, Softcover, ISBN: 978-1-4704-2542-5, **Individual member US$45**, List US$75, Institutional member US$60, Order code MEMO/249/1180

Logic and Foundations



Induction, Bounding, Weak Combinatorial Principles, and the Homogeneous Model Theorem

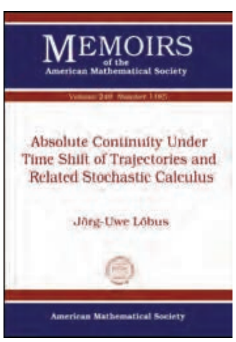
Denis R. Hirschfeldt, *University of Chicago, Illinois*, **Karen Lange**, *Wellesley College, Massachusetts*, and **Richard A. Shore**, *Cornell University, Ithaca, New York*

Contents: Introduction; Definitions; The atomic model theorem and related principles; Defining homogeneity; Closure conditions and model existence; Extension functions and model existence; The reverse mathematics of model existence theorems; Open questions; Appendix A. Approximating generics; Appendix B. Atomic trees; Appendix C. Saturated models; Bibliography.

Memoirs of the American Mathematical Society, Volume 249, Number 1187

August 2017, 101 pages, Softcover, ISBN: 978-1-4704-2657-6, 2010 *Mathematics Subject Classification:* 03B30; 03C07, 03C15, 03C50, 03C57, 03D45, 03F30, 03F35, **Individual member US$45**, List US$75, Institutional member US$60, Order code MEMO/249/1187

Probability and Statistics



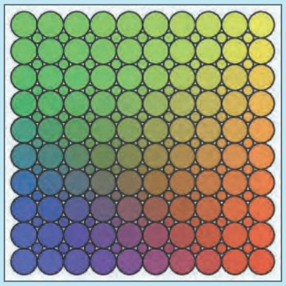
Absolute Continuity Under Time Shift of Trajectories and Related Stochastic Calculus

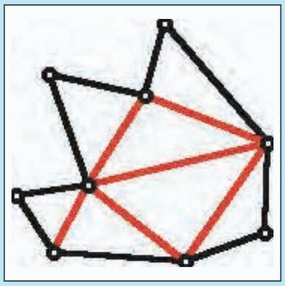
Jörg-Uwe Löbus, *Linköpings Universitet, Sweden*

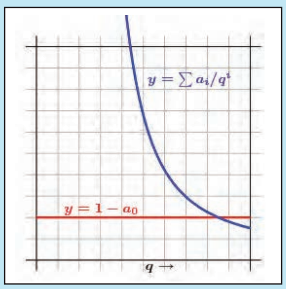
Contents: Introduction, Basic objects, and main result; Flows and logarithmic derivative relative to X under orthogonal projection; The density formula; Partial integration; Relative compactness of particle systems; Appendix A. Basic Malliavin calculus for Brownian motion with random initial data; References; Index.

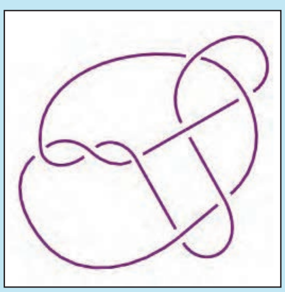
Memoirs of the American Mathematical Society, Volume 249, Number 1185

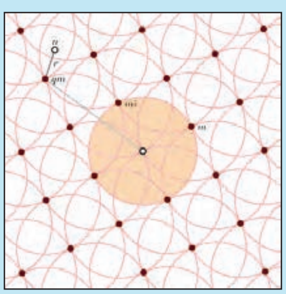
August 2017, 135 pages, Softcover, ISBN: 978-1-4704-2603-3, 2010 *Mathematics Subject Classification:* 60H07; 60J65, 60J75, **Individual member US$45**, List US$75, Institutional member US$60, Order code MEMO/249/1185

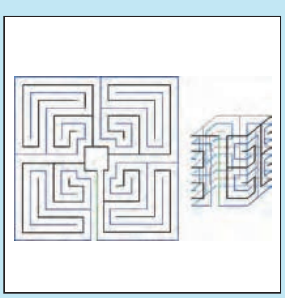





$y = \sum a_i/q^i$
$y = 1 - a_0$
$q \rightarrow$







MEETINGS & CONFERENCES OF THE AMS

AUGUST TABLE OF CONTENTS

The Meetings and Conferences section of the Notices gives information on all AMS meetings and conferences approved by press time for this issue. Please refer to the page numbers cited on this page for more detailed information on each event. Invited Speakers and Special Sessions are listed as soon as they are approved by the cognizant program committee; the codes listed are needed for electronic abstract submission. For some meetings the list may be incomplete. Information in this issue may be dated.

The most up-to-date meeting and conference information can be found online at: **www.ams.org/meetings/**.

Important Information About AMS Meetings: Potential organizers, speakers, and hosts should refer to page 75 in the January 2017 issue of the *Notices* for general information regarding participation in AMS meetings and conferences.

Abstracts: Speakers should submit abstracts on the easy-to-use interactive Web form. No knowledge of LaTeX is necessary to submit an electronic form, although those who use LaTeX may submit abstracts with such coding, and all math displays and similarily coded material (such as accent marks in text) must be typeset in LaTeX. Visit **www.ams.org/cgi-bin/abstracts/abstract.pl/**. Questions about abstracts may be sent to `abs-info@ams.org`. Close attention should be paid to specified deadlines in this issue. Unfortunately, late abstracts cannot be accommodated.

MEETINGS IN THIS ISSUE

See **www.ams.org/meetings/** *for the most up-to-date information on these conferences.*

ASSOCIATE SECRETARIES OF THE AMS

Central Section: Georgia Benkart, University of Wisconsin-Madison, Department of Mathematics, 480 Lincoln Drive, Madison, WI 53706-1388; e-mail: benkart@math.wisc.edu; telephone: 608-263-4283.

Eastern Section: Steven H. Weintraub, Department of Mathematics, Lehigh University, Bethlehem, PA 18015-3174; e-mail: steve.weintraub@lehigh.edu; telephone: 610-758-3717.

Southeastern Section: Brian D. Boe, Department of Mathematics, University of Georgia, 220 D W Brooks Drive, Athens, GA 30602-7403, e-mail: brian@math.uga.edu; telephone: 706-542-2547.

Western Section: Michel L. Lapidus, Department of Mathematics, University of California, Surge Bldg., Riverside, CA 92521-0135; e-mail: lapidus@math.ucr.edu; telephone: 951-827-5910.

Meetings & Conferences of the AMS

IMPORTANT INFORMATION REGARDING MEETINGS PROGRAMS: AMS Sectional Meeting programs do not appear in the print version of the *Notices*. However, comprehensive and continually updated meeting and program information with links to the abstract for each talk can be found on the AMS website. See `www.ams.org/meetings/`.

Final programs for Sectional Meetings will be archived on the AMS website accessible from the stated URL .

Denton, Texas

University of North Texas

September 9–10, 2017

Saturday – Sunday

Meeting #1131

Central Section
Associate secretary: Georgia Benkart
Announcement issue of *Notices*: June 2017
Program first available on AMS website: July 27, 2017
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 38, Issue 3

Deadlines

For organizers: Expired
For abstracts: July 18, 2017

The scientific information listed below may be dated. For the latest information, see `www.ams.org/amsmtgs/sectional.html`.

Invited Addresses

Mirela Çiperiani, University of Texas at Austin, *Title to be announced*.

Adrianna Gillman, Rice University, *Title to be announced*.

Kevin M Pilgrim, Department of Mathematics, Indiana University, Bloomington, IN, *Semigroups of branched mapping classes: dynamics and geometry*.

Special Sessions

If you are volunteering to speak in a Special Session, you should send your abstract as early as possible via the abstract submission form found at `http://www.ams.org/cgi-bin/abstracts/abstract.pl`.

Algebraic Combinatorics of Flag Varieties (Code: SS 11A), **Martha Precup**, Northwestern University, and **Edward Richmond**, Oklahoma State University.

Analysis and PDEs in Geometry (Code: SS 20A), **Stephen McKeown**, Princeton University.

Applicable and Computational Algebraic Geometry (Code: SS 17A), **Eric Hanson**, Texas Christian University, and **Frank Sottile**, Texas A&M University.

Banach Spaces and Applications (Code: SS 9A), **Pavlos Motakis**, Texas A&M University, and **Bönyamin Sari**, University of North Texas.

Combinatorial/Geometric/Probabilistic Methods in Group Theory (Code: SS 19A), **Rostislav Grigorchuk** and **Volodymyr Nekrashevych**, Texas A&M University, **Dmytro Savchuk**, University of South Florida, and **Zoran Sunic**, Texas A&M University.

Combinatorics and Representation Theory of Reflection Groups: Real and Complex (Code: SS 14A), **Elizabeth Drellich**, Swarthmore College, and **Drew Tomlin**, Hendrix College.

Commutative Algebra (Code: SS 10A), **Jonathan Montano**, University of Kansas, and **Alessio Sammartano**, Purdue University.

Differential Equation Modeling and Analysis for Complex Bio-systems (Code: SS 8A), **Pengcheng Xiao**, University of Evansville, and **Honghui Zhang**, Northwestern Polytechnical University.

Differential Geometry of Smooth and Discrete Surfaces in Euclidean and Lorentz Spaces (Code: SS 18A), **Barbara Shipman**, University of Texas at Arlington, and **Patrick Shipman**, Colorado State University.

Dynamics, Geometry and Number Theory (Code: SS 1A), **Lior Fishman** and **Mariusz Urbanski**, University of North Texas.

Fractal Geometry and Ergodic Theory (Code: SS 5A), **Mrinal Kanti Roychowdhury**, University of Texas Rio Grande Valley.

Generalizations of Graph Theory (Code: SS 22A), **Nathan Reff**, SUNY Brockport, and **Lucas Rusnak** and **Piyush Shroff**, Texas State University.

Geometric Combinatorics and Combinatorial Commutative Algebra (Code: SS 16A), **Anton Dochtermann** and **Suho Oh**, Texas State University.

Homological Methods in Commutative Algebra (Code: SS 15A), **Peder Thompson**, Texas Tech University, and **Ashley Wheeler**, University of Arkansas.

Integrable Systems and Applications (Code: SS 24A), **Baofeng Feng**, The University of Texas Rio Grande Valley, and **Akif Ibragimov** and **Magdalena Toda**, Texas Tech University.

Invariants of Links and 3-Manifolds (Code: SS 7A), **Mieczyslaw K. Dabkowski** and **Anh T. Tran**, The University of Texas at Dallas.

Lie Algebras, Superalgebras, and Applications (Code: SS 3A), **Charles H. Conley**, University of North Texas, **Dimitar Grantcharov**, University of Texas at Arlington, and **Natalia Rozhkovskaya**, Kansas State University.

Mathematical and Computational Biology (Code: SS 21A), **Rajeev K. Azad**, University of North Texas, and **Brandilyn Stigler**, Southern Methodist University.

Noncommutative and Homological Algebra (Code: SS 4A), **Anne Shepler**, University of North Texas, and **Sarah Witherspoon**, Texas A&M University.

Nonlocal PDEs in Fluid Dynamics (Code: SS 12A), **Changhui Tan**, Rice University, and **Xiaoqian Xu**, Carnegie Mellon University.

Numbers, Functions, Transcendence, and Geometry (Code: SS 6A), **William Cherry**, University of North Texas, **Mirela Çiperiani**, University of Texas Austin, **Matt Papanikolas**, Texas A&M University, and **Min Ru**, University of Houston.

Real-Analytic Automorphic Forms (Code: SS 2A), **Olav K Richter**, University of North Texas, and **Martin Westerholt-Raum**, Chalmers University of Technology.

Recent Progress on Hyperbolic Conservation Laws (Code: SS 23A), **Ilija Jegdic**, Texas Southern University, and **Katarina Jegdic**, University of Houston, Downtown.

Topics Related to the Interplay of Noncommutative Algebra and Geometry (Code: SS 13A), **Richard Chandler**, University of North Texas at Dallas, **Michaela Vancliff**, University of Texas at Arlington, and **Padmini Veerapen**, Tennessee Technological University.

Buffalo, New York

State University of New York at Buffalo

September 16–17, 2017

Saturday – Sunday

Meeting #1132

Eastern Section
Associate secretary: Steven H. Weintraub
Announcement issue of *Notices*: June 2017
Program first available on AMS website: August 3, 2017
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 38, Issue 3

Deadlines

For organizers: Expired
For abstracts: July 25, 2017

The scientific information listed below may be dated. For the latest information, see `www.ams.org/amsmtgs/sectional.html`.

Invited Addresses

Inwon Kim, University of California at Los Angeles, *Capillary drops on rough surfaces.*

Govind Menon, Brown University, *Building polyhedra by self-assembly.*

Bruce E Sagan, Michigan State University, *The protean chromatic polynomial.*

Special Sessions

If you are volunteering to speak in a Special Session, you should send your abstract as early as possible via the abstract submission form found at `http://www.ams.org/cgi-bin/abstracts/abstract.pl`.

Advanced Techniques in Graph Theory (Code: SS 9A), **Sogol Jahanbekam** and **Paul Wenger**, Rochester Institute of Technology.

Algebraic Topology (Code: SS 17A), **Claudia Miller**, Syracuse University, and **Inna Zakharevich**, Cornell University.

Automorphic Forms and L-functions (Code: SS 14A), **Mahdi Asgari**, Oklahoma State University, and **Joseph Hundley**, University at Buffalo-SUNY.

CR Geometry and Partial Differential Equations in Complex Analysis (Code: SS 5A), **Ming Xiao**, University of Illinois at Urbana-Champaign, and **Yuan Yuan**, Syracuse University.

Cohomology, Deformations, and Quantum Groups: A Session Dedicated to the Memory of Samuel D. Schack (Code: SS 6A), **Miodrag Iovanov**, University of Iowa, **Mihai D. Staic**, Bowling Green State University, and **Alin Stancu**, Columbus State University.

Geometric Group Theory (Code: SS 4A), **Joel Louwsma**, Niagara University, and **Johanna Mangahas**, University at Buffalo-SUNY.

High Order Numerical Methods for Hyperbolic PDEs and Applications (Code: SS 2A), **Jae-Hun Jung**, University at Buffalo-SUNY, **Fengyan Li**, Rensselaer Polytechnic Institute, and **Li Wang**, University at Buffalo-SUNY.

Infinite Groups and Geometric Structures: A Session in Honor of the Sixtieth Birthday of Andrew Nicas (Code: SS 7A), **Hans Boden**, McMaster University, and **David Rosenthal**, St. John's University.

Knots, 3-manifolds and their Invariants (Code: SS 15A), **William Menasco** and **Adam Sikora**, University at Buffalo-SUNY, and **Stephan Wehrli**, Syracuse University.

Nonlinear Dispersive Partial Differential Equations (Code: SS 18A), **Santosh Bhattrai**, Trocaire College, and **Sharad Silwal**, Jefferson College of Health Sciences.

Nonlinear Evolution Equations (Code: SS 16A), **Marius Beceanu**, SUNY Albany, and **Dan-Andrei Geba**, University of Rochester.

Nonlinear Partial Differential Equations Arising from Life Science (Code: SS 8A), **Junping Shi**, College of William and Mary, and **Xingfu Zou**, University of Western Ontario.

Nonlinear Wave Equations, Inverse Scattering and Applications. (Code: SS 1A), **Gino Biondini**, University at Buffalo-SUNY.

Polynomials in Enumerative, Algebraic, and Geometric Combinatorics (Code: SS 13A), **Robert Davis** and **Bruce Sagan**, Michigan State University.

Recent Advancements in Representation Theory (Code: SS 12A), **Yiqiang Li**, University at Buffalo-SUNY, and **Gufang Zhao**, University of Massachusetts.

Recent Progress in Geometric Analysis (Code: SS 11A), **Ovidiu Munteanu**, University of Connecticut, **Terrence Napier**, Lehigh University, and **Mohan Ramachandran**, University at Buffalo.

Structural and Chromatic Graph Theory (Code: SS 10A), **Hong-Jian Lai**, **Rong Luo**, and **Cun-Quan Zhang**, West Virginia University, and **Yue Zhao**, University of Central Florida.

p-adic Aspects of Arithmetic Geometry (Code: SS 3A), **Liang Xiao**, University of Connecticut, and **Hui June Zhu**, University at Buffalo-SUNY.

Orlando, Florida

University of Central Florida, Orlando

September 23–24, 2017

Saturday – Sunday

Meeting #1133

Southeastern Section
Associate secretary: Brian D. Boe
Announcement issue of *Notices*: June 2017
Program first available on AMS website: August 10, 2017
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 38, Issue 4

Deadlines

For organizers: Expired
For abstracts: August 1, 2017

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/sectional.html.

Invited Addresses

Christine Heitsch, Georgia Institute of Technology, *Strings, trees, and RNA folding.*

Jonathan Kujawa, University of Oklahoma, *Realizing the spectrum of tensor categories.*

Christopher D Sogge, Johns Hopkins University, *On the concentration of eigenfunctions.*

Special Sessions

If you are volunteering to speak in a Special Session, you should send your abstract as early as possible via the abstract submission form found at http://www.ams.org/cgi-bin/abstracts/abstract.pl.

Advances in Dirac Equations, Variational Inequalities, Sequence Spaces and Optimization (Code: SS 21A), **Ram N Mohapatra**, University of Central Florida, and **Turhan Koprubasi**, Kastamonu University (Turkey).

Algebraic Curves and their Applications (Code: SS 3A), **Lubjana Beshaj**, The University of Texas at Austin.

Applied Harmonic Analysis: Frames, Samplings and Applications (Code: SS 6A), **Dorin Dutkay**, **Deguang Han**, and **Qiyu Sun**, University of Central Florida.

Categorical Methods in Representation Theory (Code: SS 11A), **Brian Boe**, University of Georgia, **Jonathan Kujawa**, University of Oklahoma, and **Daniel K. Nakano**, University of Georgia.

Commutative Algebra: Interactions with Algebraic Geometry and Algebraic Topology (Code: SS 1A), **Joseph Brennan**, University of Central Florida, and **Alina Iacob** and **Saeed Nasseh**, Georgia Southern University.

Complex Analysis, Harmonic Analysis, and Approximation Theory (Code: SS 15A), **Alexander V Tovstolis**, University of Central Florida, and **John Paul Ward**, North Carolina A&T State University.

Differential Equations in Mathematical Biology (Code: SS 12A), **Andrew Nevai**, **Yuanwei Qi**, and **Zhisheng Shuai**, University of Central Florida.

Fractal Geometry, Dynamical Systems, and Their Applications (Code: SS 4A), **Mrinal Kanti Roychowdhury**, University of Texas Rio Grande Valley.

Global Harmonic Analysis and its Applications (Code: SS 10A), **Christopher Sogge** and **Yakun Xi**, Johns Hopkins University, and **Steve Zelditch**, Northwestern University.

Graph Connectivity and Edge Coloring (Code: SS 5A), **Colton Magnant**, Georgia Southern University.

Mathematics of Biomolecules: Discrete, Algebraic, and Topological (Code: SS 20A), **Natasha Jonoska**, University of South Florida, and **Christine Heitsch**, Georgia Institute of Technology.

Modern Statistical Methods for Structured Data (Code: SS 17A), **Marianna Pensky**, University of Central Florida.

Nonlinear Dispersive Equations (Code: SS 7A), **Benjamin Harrop-Griffiths**, New York University, **Jonas Lührmann**, Johns Hopkins University, and **Dana Mendelson**, University of Chicago.

Nonlinear Elliptic Partial Differential Equations (Code: SS 16A), **Luis E Silvestre**, University of Chicago, and **Eduardo V Teixeira**, University of Central Florida.

Operator Algebras and Related Topics (Code: SS 8A), **Zhe Liu**, University of Central Florida.

Progress in Fixed Point Theory and Its Applications (Code: SS 9A), **Clement Boateng Ampadu**, Boston, MA, and **Buthinah A. Bin Rehash** and **Afrah A. N. Abdou**, King Abdulaziz University, Saudi Arabia.

Recent Developments in Integral Geometry and Tomography (Code: SS 14A), **Alexander Katsevich**, **Alexander Tovbis**, and **Alexandru Tamasan**, University of Central Florida.

Stochastic Analysis and Applications (Code: SS 19A), **Hongwei Long**, Florida Atlantic University, and **Jiongmin Yong**, University of Central Florida.

Structural Graph Theory (Code: SS 2A), **Martin Rolek**, **Zixia Song**, and **Yue Zhao**, University of Central Florida.

Symplectic and Contact Topology and Dynamics (Code: SS 13A), **Basak Gürel**, University of Central Florida, and **Viktor Ginzburg**, University of California, Santa Cruz.

Trends in Applications of Functional Analysis in Computational and Applied Mathematics (Code: SS 18A), **M Zuhair Nashed**, University of Central Florida.

Riverside, California

University of California, Riverside

November 4–5, 2017

Saturday – Sunday

Meeting #1134

Western Section
Associate secretary: Michel L. Lapidus
Announcement issue of *Notices*: September 2017
Program first available on AMS website: September 21, 2017
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 38, Issue 4

Deadlines

For organizers: Expired
For abstracts: September 12, 2017

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/sectional.html.

Invited Addresses

Paul Balmer, University of California, Los Angeles, *An invitation to tensor-triangular geometry*.

Pavel Etingof, Massachusetts Institute of Technology, *Double affine hecke algebras and their applications*.

Monica Vazirani, University of California, Davis, *Combinatorics, categorification, and crystals*.

Special Sessions

If you are volunteering to speak in a Special Session, you should send your abstract as early as possible via the abstract submission form found at http://www.ams.org/cgi-bin/abstracts/abstract.pl.

Advances in Operator Algebras (Code: SS 13A), **Michael Hartglass**, UC Riverside, Santa Clara University, and **Chenxu Wen** and **Feng Xu**, University of California, Riverside.

Algebraic Geometry (Code: SS 9A), **Humberto Diaz**, **Jose Gonzalez**, and **Ziv Ran**, University of California, Riverside.

Algebraic and Combinatorial Structures in Knot Theory (Code: SS 3A), **Patricia Cahn**, Smith College, and **Sam Nelson**, Claremont McKenna College.

Analysis and Geometry of Fractals (Code: SS 6A), **Erin Pearse**, California Polytechnic State University, **Goran Radunovic**, University of California, Riverside, and **Tim Cobler**, Fullerton College, California.

Applied Category Theory (Code: SS 4A), **John Baez**, University of California, Riverside.

Characteristics of a Successful Mathematics Gateway Program (Code: SS 12A), **Sara Lapan**, University of California, Riverside, **Jeff Meyer**, California State University, San Bernardino, and **David Weisbart**, University of California, Riverside.

Combinatorial Aspects of the Polynomial Ring (Code: SS 1A), **Sami Assaf** and **Dominic Searles**, University of Southern California.

Combinatorial Representation Theory (Code: SS 5A), **Vyjayanthi Chari**, University of California, Riverside, and **Maria Monks Gillespie** and **Monica Vazirani**, University of California, Davis.

Conservation Laws, Nonlinear Waves and Applications (Code: SS 18A), **Geng Chen**, University of Kansas, **Tien Khai Nguyen**, North Carolina State University, and **Qingtian Zhang**, University of California, Davis.

Foundations of Quantum Theory (Code: SS 26A), **Jukka Virtanen**, University of California, Los Angeles, and **David Weisbart**, University of California, Riverside.

Generalized Geometry (Code: SS 16A), **Daniele Grandini**, Virginia State University, and **Yat-Sun Poon**, University of California, Riverside.

Geometric Analysis (Code: SS 24A), **Zhiqi Lu**, University of California, Irvine, **Jie Qing**, University of California, Santa Cruz, **Guofang Wei**, University of California, Santa Barbara, and **Qi Zhang**, University of California, Riverside.

Geometric Partial Differential Equations and their Applications (Code: SS 29A), **Po-Ning Chen**, University of California, Riverside, **Henri Roesch**, Duke University, and **Richard M. Schoen** and **Xiangwen Zhang**, University of California, Irvine.

Homotopy Theory (Code: SS 28A), **Jonathan Beardsley**, University of Washington.

Mathematical Fluid Mechanics (Code: SS 27A), **James P Kelliher** and **Lizheng Tao**, University of California, Riverside.

Model Theory (Code: SS 14A), **Artem Chernikov**, University of California, Los Angeles, and **Isaac Goldbring**, University of California, Irvine.

Non-Commutative Birational Geometry, Cluster Structures and Canonical Bases (Code: SS 19A), **Arkady Berenstein**, University of Oregon, Eugene, **Jacob Greenstein**, University of California, Riverside, and **Vladimir Retakh**, Rutgers University.

Nonlinear Elliptic Differential and Integral Equations (Code: SS 25A), **Mathew Gluck**, University of Oklahoma, and **John Villavert**, University of Texas, Rio Grande Valley.

Particle Methods and Nonlocal Partial Differential Equations (Code: SS 23A), **Katy Craig**, University of California, Santa Barbara, and **Franca Hoffman**, University of Cambridge.

Preparing Students for American Mathematical Competitions (Code: SS 7A), **Adam Glesser**, **Phillip Ramirez**, and **Bogdan D. Suceava**, California State University, Fullerton.

Random Matrices: Theory and Applications (Code: SS 20A), **Ioana Dumitriu**, University of Washington, and **Thomas Trogdon**, University of California, Irvine.

Random and Deterministic Dynamical Systems (Code: SS 15A), **Nicolai Haydn**, University of Southern California, Los Angeles.

Rational Cherednik Algebras and Categorification (Code: SS 8A), **Pavel Etingof**, Massachusetts Institute of Technology, and **Ivan Losev**, Northeastern University.

Research in Mathematics by Early Career Graduate Students (Code: SS 22A), **Michael Bishop**, **Stefaan Delcroix**, **Marat Markin**, **Khang Tran**, and **Oscar Vega**, California State University, Fresno.

Riemannian Manifolds of Non-Negative Sectional Curvature (Code: SS 21A), **Owen Dearricott**, University of Melbourne, and **Fernando Galaz-Garcia**, Karlsruhe Institute of Technology.

Ring Theory and Related Topics (Celebrating the 75th Birthday of Lance W. Small) (Code: SS 2A), **Jason Bell**, University of Waterloo, **Ellen Kirkman**, Wake Forest University, and **Susan Montgomery**, University of Southern California.

Several Complex Variables (Code: SS 10A), **Bingyuan Liu** and **Bun Wong**, University of California, Riverside.

Stochastic and Multi-scale Models in Mathematical Biology, Analysis and Simulations (Code: SS 17A), **Mark Alber**, University of California, Riverside, and **Bjorn Birnir**, University of California, Santa Barbara.

Tensor Categories: Bridging Algebra, Topology, and Physics (Code: SS 11A), **Paul Bruillard**, Pacific Northwest National Laboratory, **Julia Plavnik**, Texas A&M University, and **Henry Tucker**, University of California, San Diego.

San Diego, California

San Diego Convention Center and San Diego Marriott Hotel and Marina

January 10–13, 2018

Wednesday – Saturday

Meeting #1135

Joint Mathematics Meetings, including the 124th Annual Meeting of the AMS, 101st Annual Meeting of the Mathematical Association of America (MAA), annual meetings of the Association for Women in Mathematics (AWM) and the National Association of Mathematicians (NAM), and the winter meeting of the Association of Symbolic Logic (ASL), with sessions contributed by the Society for Industrial and Applied Mathematics (SIAM).

Associate secretary: Georgia Benkart
Announcement issue of *Notices*: October 2017
Program first available on AMS website: To be announced
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 39, Issue 1

Deadlines

For organizers: Expired
For abstracts: September 26, 2017

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/national.html.

Joint Invited Addresses

Gunnar Carlsson, Stanford University, *Title to be announced* (AMS-MAA Invited Address).

Moon Duchin, Tufts University, *Title to be announced* (MAA-AMS-SIAM Gerald and Judith Porter Public Lecture).

André Neves, University of Chicago, *Title to be announced* (AMS-MAA Invited Address).

AMS Invited Addresses

Federico Ardila, San Francisco State University, *Title to be announced.*

Ruth Charney, Brandeis University, *Title to be announced.*

Cynthia Dwork, Harvard University, *Title to be announced* (AMS Josiah Willard Gibbs Lecture).

Dana Randall, Georgia Institute of Technology, *Title to be announced.*

Edriss Titi, Texas A&M University, *Title to be announced.*

Avi Wigderson, Princeton University, *Title to be announced* (AMS Colloquium Lectures).

AMS Special Sessions

If you are volunteering to speak in a Special Session, you should send your abstract as early as possible via the abstract submission form found at http://jointmathematicsmeetings.org/meetings/abstracts/abstract.pl?type=jmm.

Some sessions are cosponsored with other organizations. These are noted within the parenthesis at the end of each listing, where applicable.

A Showcase of Number Theory at Liberal Arts Colleges (Code: SS 53A), **Adriana Salerno**, Bates College, and **Lola Thompson**, Oberlin College.

Accelerated Advances in Mathematical Fractional Programming (Code: SS 12A), **Ram Verma**, International Publications USA, and **Alexander Zaslavski**, Israel Institute of Technology.

Advances in Applications of Differential Equations to Disease Modeling (Code: SS 56A), **Libin Rong**, Oakland University, **Elissa Schwartz**, Washington State University, and **Naveen K. Vaidya**, University of Missouri - Kansas City.

Advances in Difference, Differential, and Dynamic Equations with Applications (Code: SS 20A), **Elvan Akin**, Missouri University S&T, and **John Davis**, Baylor University.

Advances in Operator Algebras (Code: SS 58A), **Marcel Bischoff**, Vanderbilt University, **Ian Charlesworth**, University of California, Los Angeles, **Brent Nelson**, University of California, Berkeley, and **Sarah Reznikoff**, Kansas State University.

Advances in Operator Theory, Operator Algebras, and Operator Semigroups (Code: SS 42A), **Asuman G. Aksoy**, Claremont McKenna College, **Zair Ibragimov**, California State University, Fullerton, **Marat Markin**, California State University, Fresno, and **Ilya Spitkovsky**, New York University, Abu Dhabi.

Algebraic, Analytic, and Geometric Aspects of Integrable Systems, Painlevé Equations, and Random Matrices (Code: SS 75A), **Vladimir Dragovic**, University of Texas at Dallas, **Anton Dzhamay**, University of Northern Colorado, and **Sevak Mkrtchyan**, University of Rochester.

Algebraic, Discrete, Topological and Stochastic Approaches to Modeling in Mathematical Biology (Code: SS 66A), **Olcay Akman**, Illinois State University, **Timothy D. Comar**, Benedictine University, **Daniel Hrozencik**, Chicago State University, and **Raina Robeva**, Sweet Briar College.

Alternative Proofs in Mathematical Practice (Code: SS 11A), **John W. Dawson, Jr.**, Pennsylvania State University, York.

Analysis of Fractional, Stochastic, and Hybrid Dynamic Systems (Code: SS 13A), **John R. Graef**, University of Tennessee at Chattanooga, **Gangaram S. Ladde**, University of South Florida, and **Aghalaya S. Vatsala**, University of Louisiana at Lafayette.

Analysis of Nonlinear Partial Differential Equations and Applications (Code: SS 85A), **Tarek M. Elgindi**, University of California, San Diego, and **Edriss S. Titi**, Texas A&M University and Weizmann Institute of Science.

Applied and Computational Combinatorics (Code: SS 55A), **Torin Greenwood**, Georgia Institute of Technology, and **Jay Pantone**, Dartmouth College.

Arithmetic Dynamics (Code: SS 41A), **Robert L. Benedetto**, Amherst College, **Benjamin Hutz**, Saint Louis University, **Jamie Juul**, Amherst College, and **Bianca Thompson**, Harvey Mudd College.

Beyond Planarity: Crossing Numbers of Graphs (a Mathematics Research Communities Session) (Code: SS 15A), **Axel Brandt**, Davidson College, **Garner Cochran**, University of South Carolina, and **Sarah Loeb**, University of Illinois, Urbana-Champaign.

Bifurcations of Difference Equations and Discrete Dynamical Systems (Code: SS 61A), **Arzu Bilgin** and **Toufik Khyat**, University of Rhode Island.

Boundaries for Groups and Spaces (Code: SS 7A), **Joseph Maher**, CUNY College of Staten Island, and **Genevieve Walsh**, Tufts University.

Combinatorial Commutative Algebra and Polytopes (Code: SS 1A), **Robert Davis**, Michigan State University, and **Liam Solus**, KTH Royal Institute of Technology.

Combinatorics and Geometry (Code: SS 70A), **Federico Ardila**, San Francisco State University, **Anastasia Chavez**, MSRI and University of California, Davis, and **Laura Escobar**, University of Illinois Urbana Champaign.

Commutative Algebra in All Characteristics (Code: SS 67A), **Neil Epstein**, George Mason University, **Karl Schwede**, University of Utah, and **Janet Vassilev**, University of New Mexico.

Computational Combinatorics and Number Theory (Code: SS 76A), **Jeremy F. Alm**, Illinois College, and **David Andrews** and **Rob Hochberg**, University of Dallas.

Connections in Discrete Mathematics: Graphs, Hypergraphs, and Designs (Code: SS 80A), **Amin Bahmanian**, Illinois State University, and **Theodore Molla**, University Illinois Urbana-Champaign.

Differential Geometry (Code: SS 28A), **Vincent B. Bonini** and **Joseph E. Borzellino**, Cal Poly San Luis Obispo, **Bogdan D. Suceava**, California State University, Fullerton, and **Guofang Wei**, University of California, Santa Barbara.

Diophantine Approximation and Analytic Number Theory in Honor of Jeffrey Vaaler (Code: SS 29A), **Shabnam Akhtari**, University of Oregon, **Lenny Fukshansky**, Claremont McKenna College, and **Clayton Petsche**, Oregon State University.

Discrete Dynamical Systems and Applications (Code: SS 51A), **E. Cabral Balreira**, **Saber Elaydi**, and **Eddy Kwessi**, Trinity University.

Discrete Neural Networking and Applications (Code: SS 6A), **Murat Adivar**, Fayetteville State University, **Michael A. Radin**, Rochester Institute of Technology, and **Youssef Raffoul**, University of Dayton.

Dynamical Algebraic Combinatorics (Code: SS 68A), **James Propp**, University of Massachusetts, Lowell, **Tom Roby**, University of Connecticut, **Jessica Striker**, North Dakota State University, and **Nathan Williams**, University of California Santa Barbara.

Dynamical Systems with Applications to Mathematical Biology (Code: SS 79A), **Guihong Fan**, Columbus State University, **Jing Li**, California State University Northridge, and **Chunhua Shan**, University of Toledo.

Dynamical Systems: Smooth, Symbolic, and Measurable (a Mathematics Research Communities Session) (Code: SS 16A), **Kathryn Lindsey**, Boston College, **Scott Schmieding**, Northwestern University, and **Kurt Vinhage**, University of Chicago.

Emergent Phenomena in Discrete Models (Code: SS 82A), **Dana Randall**, Georgia Institute of Technology, and **Andrea Richa**, Arizona State University.

Emerging Topics in Graphs and Matrices (Code: SS 60A), **Sudipta Mallik**, Northern Arizona University, **Keivan Hassani Monfared**, University of Calgary, and **Bryan Shader**, University of Wyoming.

Ergodic Theory and Dynamical Systems–to Celebrate the Work of Jane Hawkins (Code: SS 71A), **Julia Barnes**, Western Carolina University, **Rachel Bayless**, Agnes Scott College, **Emily Burkhead**, Duke University, and **Lorelei Koss**, Dickinson College.

Extremal Problems in Approximations and Geometric Function Theory (Code: SS 81A), **Ram Mohapatra**, University of Central Florida.

Financial Mathematics, Actuarial Sciences, and Related Fields (Code: SS 48A), **Albert Cohen**, Michigan State University, **Nguyet Nguyen**, Youngstown State University, **Oana Mocioalca**, Kent State University, and **Thomas Wakefield**, Youngstown State University.

Fractional Difference Operators and Their Application (Code: SS 59A), **Christopher S. Goodrich**, Creighton Preparatory School, and **Rajendra Dahal**, Coastal Carolina University.

Free Convexity and Free Analysis (Code: SS 21A), **J. William Helton**, University of California, San Diego, and **Igor Klep**, University of Auckland.

Geometric Analysis (Code: SS 86A), **Davi Maximo**, University of Pennsylvania, **Lu Wang**, University of Wisconsin-Madison, and **Xin Zhou**, University of California Santa Barbara.

Geometric Analysis and Geometric Flows (Code: SS 54A), **David Glickenstein**, University of Arizona, and **Brett Kotschwar**, Arizona State University.

History of Mathematics (Code: SS 50A), **Sloan Despeaux**, Western Carolina University, **Jemma Lorenat**, Pitzer College, **Clemency Montelle**, University of Canterbury, **Daniel Otero**, Xavier University, and **Adrian Rice**, Randolph-Macon College.

Homotopy Type Theory (a Mathematics Research Communities Session) (Code: SS 14A), **Simon Cho**, University of Michigan, **Liron Cohen**, Cornell University, and **Edward Morehouse**, Wesleyan University.

If You Build It They Will Come: Presentations by Scholars in the National Alliance for Doctoral Studies in the Mathematical Sciences (Code: SS 25A), **Edray Goins** and **David Goldberg**, Purdue University, and **Phil Kutzko**, University of Iowa.

Interactions of Inverse Problems, Signal Processing, and Imaging (Code: SS 36A), **M. Zuhair Nashed**, University of Central Florida, **Willi Freeden**, University of Kaiserslautern, and **Otmar Scherzer**, University of Vienna.

Markov Chains, Markov Processes and Applications (Code: SS 27A), **Alan Krinik** and **Randall J. Swift**, California State Polytechnic University.

Mathematical Analysis and Nonlinear Partial Differential Equations (Code: SS 33A), **Hongjie Dong**, Brown University, **Peiyong Wang**, Wayne State University, and **Jiuyi Zhu**, Louisiana State University.

Mathematical Fluid Mechanics: Analysis and Applications (Code: SS 38A), **Zachary Bradshaw** and **Aseel Farhat**, University of Virginia.

Mathematical Information in the Digital Age of Science (Code: SS 83A), **Patrick Ion**, University of Michigan, **Olaf Teschke**, zbMath Berlin, and **Stephen Watt**, University of Waterloo.

Mathematical Methods in Genomics (Code: SS 4A), **David Koslicki**, Oregon State University.

Mathematical Modeling and Analysis of Infectious Diseases (Code: SS 65A), **Kazuo Yamazaki**, University of Rochester.

Mathematical Modeling of Natural Resources (Code: SS 39A), **Shandelle M. Henson**, Andrews University, and **Natali Hritonenko**, Prairie View A&M University.

Mathematical Modeling, Analysis and Applications in Population Biology (Code: SS 47A), **Yu Jin**, University of Nebraska-Lincoln, and **Ying Zhou**, Lafayette College.

Mathematical Problems in Ocean Wave Modeling and Fluid Mechanics (Code: SS 49A), **Christopher W. Curtis**, San Diego State University, and **Katie Oliveras**, Seattle University.

Mathematical Relativity and Geometric Analysis (Code: SS 72A), **James Dilts** and **Michael Holst**, University of California, San Diego.

Mathematics Research from the SMALL Undergraduate Research Program (Code: SS 73A), **Colin Adams**, **Frank Morgan**, and **Cesar E. Silva**, Williams College.

Mathematics of Gravitational Wave Science (Code: SS 40A), **Andrew Gillette** and **Nikki Holtzer**, University of Arizona.

Mathematics of Quantum Computing and Topological Phases of Matter (Code: SS 26A), **Paul Bruillard**, Pacific Northwest National Laboratory, **David Meyer**, University of California San Diego, and **Julia Plavnik**, Texas A&M University.

Metric Geometry and Topology (Code: SS 77A), **Christine Escher**, Oregon State University, and **Catherine Searle**, Wichita State University.

Modeling in Differential Equations - High School, Two-Year College, Four-Year Institution (Code: SS 22A), **Corban Harwood**, George Fox University, **William Skerbitz**, Wayzata High School, **Brian Winkel**, SIMIODE, and **Dina Yagodich**, Frederick Community College.

Multi-scale Modeling with PDEs in Computational Science and Engineering:Algorithms, Simulations, Analysis, and Applications (Code: SS 37A), **Salim M. Haidar**, Grand Valley State University.

Network Science (Code: SS 31A), **David Burstein**, Swarthmore College, **Franklin Kenter**, United States Naval Academy, and **Feng Shi**, University of North Carolina at Chapel Hill.

New Trends in Celestial Mechanics (Code: SS 10A), **Richard Montgomery**, University of California Santa Cruz, and **Zhifu Xie**, University of Southern Mississippi.

Nilpotent and Solvable Geometry (Code: SS 32A), **Michael Jablonski**, University of Oklahoma, **Megan Kerr**, Wellesley College, and **Tracy Payne**, Idaho State University.

Noncommutative Algebras and Noncommutative Invariant Theory (Code: SS 24A), **Ellen Kirkman**, Wake Forest University, and **James Zhang**, University of Washington.

Nonlinear Evolution Equations of Quantum Physics and Their Topological Solutions (Code: SS 34A), **Stephen Gustafson**, University of British Columbia, **Israel Michael Sigal**, University of Toronto, and **Avy Soffer**, Rutgers University.

Novel Methods of Enhancing Success in Mathematics Classes (Code: SS 35A), **Ellina Grigorieva**, Texas Womans University, and **Natali Hritonenko**, Prairie View A&M University.

Open and Accessible Problems for Undergraduate Research (Code: SS 18A), **Michael Dorff**, Brigham Young University, **Allison Henrich**, Seattle University, and **Nicholas Scoville**, Ursinus College.

Operators on Function Spaces in One and Several Variables (Code: SS 45A), **Catherine Bénéteau**, University of South Florida, and **Matthew Fleeman** and **Constanze Liaw**, Baylor University.

Orthogonal Polynomials and Applications (Code: SS 17A), **Abey Lopez-Garcia**, University of South Alabama, and **Xiang-Sheng Wang**, University of Louisiana at Lafayette.

Orthogonal Polynomials, Quantum Probability, and Stochastic Analysis (Code: SS 8A), **Julius N. Esunge**, University of Mary Washington, and **Aurel I. Stan**, Ohio State University.

Quantum Link Invariants, Khovanov Homology, and Low-dimensional Manifolds (Code: SS 64A), **Diana Hubbard**, University of Michigan, and **Christine Ruey Shan Lee**, University of Texas at Austin.

Quaternions (Code: SS 23A), **Terrence Blackman**, Medgar Evers College, City University of New York, and **Johannes Familton** and **Chris McCarthy**, Borough of Manhattan Community College, City University of New York.

Recent Trends in Analysis of Numerical Methods of Partial Differential Equations (Code: SS 2A), **Sara Pollock**, Wright State University, and **Leo Rebholz**, Clemson University.

Research by Postdocs of the Alliance for Diversity in Mathematics (Code: SS 62A), **Aloysius Helminck**, University of Hawaii - Manoa, and **Michael Young**, Iowa State University.

Research from the Rocky Mountain-Great Plains Graduate Research Workshop in Combinatorics (Code: SS 69A), **Michael Ferrara**, University of Colorado Denver, **Leslie Hogben**, Iowa State University, **Paul Horn**, University of Denver, and **Tyrrell McAllister**, University of Wyoming.

Research in Mathematics by Early Career Graduate Students (Code: SS 46A), **Michael Bishop**, **Marat Markin**, **Khang Tran**, and **Oscar Vega**, California State University, Fresno.

Research in Mathematics by Undergraduates and Students in Post-Baccalaureate Programs (Code: SS 19A), **Tamas Forgacs**, CSU Fresno, **Darren A. Narayan**, Rochester Institute of Technology, and **Mark David Ward**, Purdue University (AMS-MAA-SIAM).

Set Theory, Logic and Ramsey Theory (Code: SS 5A), **Andrés Caicedo**, Mathematical Reviews, and **José Mijares**, University of Colorado, Denver (AMS-ASL).

Set-theoretic Topology (Dedicated to Jack Porter in Honor of 50 Years of Dedicated Research) (Code: SS 43A), **Nathan Carlson**, California Lutheran University, **Jila Niknejad**, University of Kansas, and **Lynne Yengulalp**, University of Dayton.

Special Functions and Combinatorics (in honor of Dennis Stanton's 65th birthday) (Code: SS 9A), **Susanna Fishel**, Arizona State University, **Mourad Ismail**, University of Central Florida, and **Vic Reiner**, University of Minnesota.

Spectral Theory, Disorder and Quantum Physics (Code: SS 57A), **Rajinder Mavi** and **Jeffery Schenker**, Michigan State University.

Stochastic Processes, Stochastic Optimization and Control, Numerics and Applications (Code: SS 78A), **Hongwei Mei**, University of Central Florida, **Zhixin Yang** and **Quan Yuan**, Ball State University, and **Guangliang Zhao**, GE Global Research.

Strengthening Infrastructures to Increase Capacity Around K-20 Mathematics (Code: SS 74A), **Brianna Donaldson**, American Institute of Mathematics, and **William Jaco** and **Michael Oehrtman**, Oklahoma State University.

Structure and Representations of Hopf Algebras: a session in honor of Susan Montgomery (Code: SS 30A), **Siu-Hung Ng**, Louisiana State University, and **Lance Small** and **Henry Tucker**, University of California, San Diego.

Theory, Practice, and Applications of Graph Clustering (Code: SS 63A), **David Gleich**, Purdue University, and **Jennifer Webster** and **Stephen J. Young**, Pacific Northwest National Laboratory.

Topological Data Analysis (Code: SS 84A), **Henry Adams**, Colorado State University, **Gunnar Carlsson**, Stanford University, and **Mikael Vejdemo-Johansson**, CUNY College of Staten Island.

Topological Graph Theory: Structure and Symmetry (Code: SS 3A), **Jonathan L. Gross**, Columbia University, and **Thomas W. Tucker**, Colgate University.

Visualization in Mathematics: Perspectives of Mathematicians and Mathematics Educators (Code: SS 52A), **Karen Allen Keene**, North Carolina State University, and **Mile Krajcevski**, University of South Florida.

Women in Symplectic and Contact Geometry and Topology (Code: SS 44A), **Bahar Acu**, Northwestern University, **Ziva Myer**, Duke University, and **Yu Pan**, Massachusetts Institute of Technology (AMS-AWM).

Columbus, Ohio

Ohio State University

March 17–18, 2018
Saturday – Sunday

Meeting #1136
Central Section
Associate secretary: Georgia Benkart
Announcement issue of *Notices*: December 2017
Program first available on AMS website: January 31, 2018
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 39, Issue 2

Deadlines
For organizers: August 15, 2017
For abstracts: January 22, 2018

The scientific information listed below may be dated. For the latest information, see `www.ams.org/amsmtgs/sectional.html`.

Invited Addresses

Aaron Brown, University of Chicago, *Title to be announced*.

Tullia Dymarz, University of Wisconsin-Madison, *Title to be announced*.

June Huh, Institute for Advanced Study, *Title to be announced*.

Special Sessions

If you are volunteering to speak in a Special Session, you should send your abstract as early as possible via the abstract submission form found at `http://www.ams.org/cgi-bin/abstracts/abstract.pl`.

Algebraic Combinatorics: Association Schemes, Finite Geometry, and Related Topics (Code: SS 15A), **Sung Y. Song**, Iowa State University, and **Bangteng Xu**, Eastern Kentucky University.

Algebraic Curves and Their Applications (Code: SS 17A), **Artur Elezi**, American University, **Monika Polak**, Maria Curie-Sklodowska University (Poland) and University of Information Science and Technology (Mac, and **Tony Shaska**, Oakland University.

Algebraic and Combinatorial Aspects of Tropical Geometry (Code: SS 11A), **Maria Angelica Cueto**, Ohio State University, **Yoav Len**, University of Waterloo, and **Martin Ulirsch**, University of Michigan.

Algebraic, Combinatorial, and Quantum Invariants of Knots and Manifolds (Code: SS 6A), **Cody Armond**, Ohio State University, Mansfield, **Micah Chrisman**, Monmouth University, and **Heather Dye**, McKendree University.

Coherent Structures in Interfacial Flows (Code: SS 14A), **Benjamin Akers** and **Jonah Reeger**, Air Force Institute of Technology.

Commutative and Combinatorial Algebra (Code: SS 18A), **Jennifer Biermann**, Hobart and William Smith Colleges, and **Kuei-Nuan Lin**, Penn State University, Greater Allegheny.

Convex Bodies in Algebraic Geometry and Representation Theory (Code: SS 20A), **Dave Anderson**, Ohio State University, and **Kiumars Kaveh**, University of Pittsburgh.

Differential Equations and Applications (Code: SS 8A), **King-Yeung Lam** and **Yuan Lou**, Ohio State University, and **Qiliang Wu**, Michigan State University.

Geometric Methods in Shape Analysis (Code: SS 10A), **Sebastian Kurtek** and **Tom Needham**, Ohio State University.

Graph Theory (Code: SS 5A), **John Maharry**, Ohio State University, **Yue Zhao**, University of Central Florida, and **Xiangqian Zhou**, Wright State University.

Homological Algebra (Code: SS 4A), **Ela Celikbas** and **Olgur Celikbas**, West Virginia University.

Multiplicative Ideal Theory and Factorization (in honor of Tom Lucas retirement) (Code: SS 7A), **Evan Houston**, University of North Carolina, Charlotte, and **Alan Loper**, Ohio State University.

Noncommutative Algebra and Noncommutative Algebraic Geometry (Code: SS 16A), **Jason Gaddis**, Miami University, and **Robert Won**, Wake Forest University.

Nonlinear Evolution Equations (Code: SS 9A), **John Holmes** and **Feride Tiglay**, Ohio State University.

Nonlinear Waves and Patterns (Code: SS 19A), **Anna Ghazaryan**, Miami University, **Stephane Lafortune**, College of Charleston, and **Vahagn Manukian** and **Alin Pogan**, Miami University.

Probability in Convexity and Convexity in Probability (Code: SS 2A), **Elizabeth Meckes**, **Mark Meckes**, and **Elisabeth Werner**, Case Western Reserve University.

Quantum Symmetries (Code: SS 3A), **David Penneys**, The Ohio State University, and **Julia Plavnik**, Texas A & M University.

Recent Advances in Approximation Theory and Operator Theory (Code: SS 1A), **Jan Lang** and **Paul Nevai**, The Ohio State University.

Recent Development of Nonlinear Geometric PDEs (Code: SS 12A), **Bo Guan**, Ohio State University, **Qun Li**, Wright State University, **Xiangwen Zhang**, University of California, Irvine, and **Fangyang Zheng**, Ohio State University.

Several Complex Variables (Code: SS 13A), **Liwei Chen**, **Kenneth Koenig**, and **Liz Vivas**, Ohio State University.

Portland, Oregon

Portland State University

April 14–15, 2018

Saturday – Sunday

Meeting #1137

Western Section
Associate secretary: Michel L. Lapidus
Announcement issue of *Notices*: January 2018
Program first available on AMS website: February 15, 2018
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 39, Issue 2

Deadlines

For organizers: September 14, 2017
For abstracts: February 6, 2018

The scientific information listed below may be dated. For the latest information, see `www.ams.org/amsmtgs/sectional.html`.

Invited Addresses

Sándor Kovács, University of Washington, Seattle, *Title to be announced*.

Elena Mantovan, California Institute of Technology, *Title to be announced*.

Dimitri Shlyakhtenko, University of California, Los Angeles, *Title to be announced*.

Special Sessions

If you are volunteering to speak in a Special Session, you should send your abstract as early as possible via the *abstract submission form found at* `http://www.ams.org/cgi-bin/abstracts/abstract.pl`.

Inverse Problems (Code: SS 2A), **Hanna Makaruk**, Los Alamos National Laboratory (LANL), and **Robert Owczarek**, University of New Mexico, Albuquerque & Los Alamos.

Pattern Formation in Crowds, Flocks, and Traffic (Code: SS 1A), **J. J. P. Veerman**, Portland State University, **Alethea Barbaro**, Case Western Reserve University, and **Bassam Bamieh**, UC Santa Barbara.

Nashville, Tennessee

Vanderbilt University

April 14–15, 2018

Saturday – Sunday

Meeting #1138

Southeastern Section
Associate secretary: Brian D. Boe
Announcement issue of *Notices*: January 2018
Program first available on AMS website: February 22, 2018
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 39, Issue 2

Deadlines

For organizers: September 14, 2017
For abstracts: February 13, 2018

The scientific information listed below may be dated. For the latest information, see `www.ams.org/amsmtgs/sectional.html`.

Invited Addresses

Andrea Bertozzi, University of California Los Angeles, *Title to be announced* (Erdős Memorial Lecture).

J. M. Landsberg, Texas A & M University, *Title to be announced.*

Jennifer Morse, University of Virginia, *Title to be announced.*

Kirsten Wickelgren, Georgia Institute of Technology, *Title to be announced.*

Special Sessions

If you are volunteering to speak in a Special Session, you should send your abstract as early as possible via the abstract submission form found at `http://www.ams.org/cgi-bin/abstracts/abstract.pl`.

Difference Equations and Applications (Code: SS 2A), **Michael A. Radin**, Rochester Institute of Technology, and **Youssef Raffoul**, University of Dayton, Ohio.

Quantization for Probability Distributions (Code: SS 1A), **Mrinal Kanti Roychowdhury**, University of Texas Rio Grande Valley.

Selected Topics in Graph Theory (Code: SS 3A), **Songling Shan**, Vanderbilt University, and **David Chris Stephens** and **Dong Ye**, Middle Tennessee State University.

Structural Graph Theory (Code: SS 4A), **Joshua Fallon**, Louisiana State University, and **Emily Marshall**, Arcadia University.

Boston, Massachusetts

Northeastern University

April 21–22, 2018

Saturday – Sunday

Meeting #1139

Eastern Section
Associate secretary: Steven H. Weintraub
Announcement issue of *Notices*: January 2018
Program first available on AMS website: March 1, 2018
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 39, Issue 2

Deadlines

For organizers: September 21, 2017
For abstracts: February 20, 2018

The scientific information listed below may be dated. For the latest information, see `www.ams.org/amsmtgs/sectional.html`.

Invited Addresses

Jian Ding, University of Chicago, *Title to be announced.*

Edward Frenkel, University of California, Berkeley, *Title to be announced* (Einstein Public Lecture in Mathematics).

Valentino Tosatti, Northwestern University, *Title to be announced.*

Maryna Viazovska, École Polytechnique Fédérale de Lausanne, *Title to be announced.*

Special Sessions

If you are volunteering to speak in a Special Session, you should send your abstract as early as possible via the abstract submission form found at `http://www.ams.org/cgi-bin/abstracts/abstract.pl`.

Algebraic and Extremal Graph Theory (Code: SS 13A), **Sebastian M. Cioaba**, University of Delaware, and **Michael Tait**, Carnegie Mellon University.

Analysis and Geometry in Non-smooth Spaces (Code: SS 5A), **Nageswari Shanmugalingam** and **Gareth Speight**, University of Cincinnati.

Arithmetic Dynamics (Code: SS 1A), **Jacqueline M. Anderson**, Bridgewater State University, **Robert Benedetto**, Amherst College, and **Joseph H. Silverman**, Brown University.

Arrangements of Hypersurfaces (Code: SS 2A), **Graham Denham**, University of Western Ontario, and **Alexander I. Suciu**, Northeastern University.

Ergodic Theory and Dynamics in Combinatorial Number Theory (Code: SS 7A), **Stanley Eigen**, Northeastern University, **Daniel Glasscock**, Ohio State University, and **Vidhu Prasad**, University of Massachusetts, Lowell.

Facets of Symplectic Geometry and Topology (Code: SS 3A), **Tara Holm**, Cornell University, **Jo Nelson**, Columbia University, and **Jonathan Weitsman**, Northeastern University.

Geometry of Moduli Spaces (Code: SS 10A), **Ana-Marie Castravet** and **Emanuele Macrí**, Northeastern University, **Benjamin Schmidt**, University of Texas, and **Xiaolei Zhao**, Northeastern University.

Homological Commutative Algebra (Code: SS 11A), **Sean Sather-Wagstaff**, Clemson University, and **Oana Veliche**, Northeastern University.

Hopf Algebras, Tensor Categories, and Homological Algebra (Code: SS 8A), **Cris Negron**, Massachusetts Institute of Technology, **Julia Plavnik**, Texas A&M, and **Sarah Witherspoon**, Texas A&M University.

New Developments in Inverse Problems and Imaging (Code: SS 9A), **Ru-Yu Lai**, University of Minnesota, and **Ting Zhou**, Northeastern University.

Polytopes and Discrete Geometry (Code: SS 6A), **Gabriel Cunningham**, University of Massachusetts, Boston, **Mark Mixer**, Wentworth Institute of Technology, and **Egon Schulte**, Northeastern University.

Singularities of Spaces and Maps (Code: SS 4A), **Terence Gaffney** and **David Massey**, Northeastern University.

The Gaussian Free Field and Random Geometry (Code: SS 12A), **Jian Ding**, University of Chicago, and **Vadim Gorin**, Massachusetts Institute of Technology.

Shanghai, People's Republic of China

Fudan University

June 11–14, 2018

Monday – Thursday

Meeting #1140

Associate secretary: Steven H. Weintraub
Announcement issue of *Notices*: April 2018
Program first available on AMS website: To be announced
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: To be announced

Deadlines

For organizers: To be announced
For abstracts: To be announced

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/internmtgs.html.

Invited Addresses

Yu-Hong Dai, Academy of Mathematics and System Sciences, *Title to be announced.*

Kenneth A. Ribet, University of California, Berkeley, *Title to be announced.*

Richard M. Schoen, University of California, Irvine, *Title to be announced.*

Sijue Wu, University of Michigan, *Title to be announced.*

Chenyang Xu, Peking University, *Title to be announced.*

Jiangong You, Nankai University, *Title to be announced.*

Call for Special Session Proposals

The Program Committee for the 2018 American Mathematical Society-Chinese Mathematical Society joint meeting invites proposals for special sessions to be held at this meeting.

A proposal should include:

* the title of the session,

* the names, affiliations, and email addresses of the organizers, with one organizer designated as the "contact person",

* a brief description of the topic of the session,

* a tentative list of people to be invited to speak in this session.

As one of the aims of this joint meeting is to increase cooperation between mathematicians in the US and China, each special session should have at least one organizer from each of the US and China.

Early submission of proposals is encouraged, and proposals will be approved on a rolling basis. The final deadline for special session proposals is **November 30, 2017**.

Proposals should be sent by email to Professor Steven H. Weintraub, AMS Associate Secretary, shw2@lehigh.edu.

Newark, Delaware

University of Delaware

September 29–30, 2018

Saturday – Sunday

Meeting #1141

Eastern Section
Associate secretary: Steven H. Weintraub
Announcement issue of *Notices*: June 2018
Program first available on AMS website: August 9, 2018
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 39, Issue 3

Deadlines

For organizers: February 28, 2018
For abstracts: July 31, 2018

The scientific information listed below may be dated. For the latest information, see `www.ams.org/amsmtgs/sectional.html`.

Invited Addresses

Leslie Greengard, New York University, *Title to be announced*.

Elisenda Grigsby, Boston College, *Title to be announced*.

Davesh Maulik, Massachusetts Institute of Technology, *Title to be announced*.

Fayetteville, Arkansas

University of Arkansas

October 6–7, 2018

Saturday – Sunday

Meeting #1142

Southeastern Section
Associate secretary: Brian D. Boe
Announcement issue of *Notices*: July 2018
Program first available on AMS website: August 16, 2018
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 39, Issue 3

Deadlines

For organizers: March 6, 2018
For abstracts: August 7, 2018

The scientific information listed below may be dated. For the latest information, see `www.ams.org/amsmtgs/sectional.html`.

Invited Addresses

Mihalis Dafermos, Princeton University, *Title to be announced*.

Jonathan Hauenstein, University of Notre Dame, *Title to be announced*.

Kathryn Mann, University of California Berkeley, *Title to be announced*.

Ann Arbor, Michigan

University of Michigan, Ann Arbor

October 20–21, 2018

Saturday – Sunday

Meeting #1143

Central Section
Associate secretary: Georgia Benkart
Announcement issue of *Notices*: July 2018
Program first available on AMS website: August 30, 2018
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 39, Issue 4

Deadlines

For organizers: March 20, 2018
For abstracts: August 21, 2018

The scientific information listed below may be dated. For the latest information, see `www.ams.org/amsmtgs/sectional.html`.

Invited Addresses

Elena Fuchs, University of Illinois Urbana-Champaign, *Title to be announced*.

Andrew Putman, University of Notre Dame, *Title to be announced*.

Charles Smart, University of Chicago, *Title to be announced*.

Special Sessions

If you are volunteering to speak in a Special Session, you should send your abstract as early as possible via the abstract submission form found at `http://www.ams.org/cgi-bin/abstracts/abstract.pl`.

Geometry of Submanifolds, in Honor of Bang-Yen Chens 75th Birthday (Code: SS 1A), **Alfonso Carriazo**, University of Sevilla, **Ivko Dimitric**, Penn State Fayette, **Yun Myung Oh**, Andrews University, **Bogdan D. Suceava**, California State University, Fullerton, **Joeri Van der Veken**, University of Leuven, and **Luc Vrancken**, Universite de Valenciennes.

San Francisco, California

San Francisco State University

October 27–28, 2018

Saturday – Sunday

Meeting #1144

Western Section
Associate secretary: Michel L. Lapidus
Announcement issue of *Notices*: July 2018
Program first available on AMS website: September 6, 2018
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: Volume 39, Issue 4

Deadlines

For organizers: March 27, 2018
For abstracts: August 28, 2018

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/sectional.html.

Invited Addresses

Srikanth B. Iyengar, University of Utah, *Title to be announced.*

Sarah Witherspoon, Texas A&M University, *Title to be announced.*

Abdul-Aziz Yakubu, Howard University, *Title to be announced.*

Baltimore, Maryland

Baltimore Convention Center, Hilton Baltimore, and Baltimore Marriott Inner Harbor Hotel

January 16–19, 2019

Wednesday – Saturday

Joint Mathematics Meetings, including the 125th Annual Meeting of the AMS, 102nd Annual Meeting of the Mathematical Association of America (MAA), annual meetings of the Association for Women in Mathematics (AWM)and the National Association of Mathematicians (NAM), and the winter meeting of the Association of Symbolic Logic (ASL), with sessions contributed by the Society for Industrial and Applied Mathematics (SIAM).

Associate secretary: Steven H. Weintraub
Announcement issue of *Notices*: October 2018
Program first available on AMS website: To be announced
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: To be announced

Deadlines

For organizers: April 2, 2018
For abstracts: To be announced

Auburn, Alabama

Auburn University

March 15–17, 2019

Friday – Sunday

Southeastern Section
Associate secretary: Brian D. Boe
Announcement issue of *Notices*: To be announced
Program first available on AMS website: To be announced
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: To be announced

Deadlines

For organizers: To be announced
For abstracts: To be announced

Honolulu, Hawaii

University of Hawaii at Manoa

March 22–24, 2019

Friday – Sunday

Central Section
Associate secretaries: Georgia Benkart and Michel L. Lapidus
Announcement issue of *Notices*: To be announced
Program first available on AMS website: To be announced
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: To be announced

Deadlines

For organizers: May 15, 2018
For abstracts: January 22, 2019

Invited Addresses

Barry Mazur, Harvard University, *Title to be announced* (Einstein Public Lecture in Mathematics).

Aaron Naber, Northwestern University, *Title to be announced.*

Deanna Needell, University of Colorado, Boulder, *Title to be announced.*

Katerine Stange, University of Colorado, Boulder, *Title to be announced.*

Andrew Suk, University of Illinois at Chicago, *Title to be announced.*

Call for Special Session Proposals

The AMS solicits proposals for Special Sessions at the 2019 Joint AMS Central and Western Sectional Meeting to be held Friday March 22 through Sunday March 24, 2019 at the University of Hawaii at Manoa, Honolulu, Hawaii. Each proposal must include:

1. the name, affiliation, and e-mail address of each organizer, with one organizer designated as the contact person for all communication about the session;
2. the title and a brief description (no longer than one or two paragraphs) of the topic of the proposed Special Session;
3. the primary two-digit MSC (Mathematics Subject Classification) number for the topic—see www.ams.org/mathscinet/msc/msc2010.html;
4. a sample list of the names of up to ten speakers and their institutions, whom the organizers plan to invite. (It is not necessary to have received confirmed commitments from these potential speakers.)

Organizers are strongly encouraged to consult the AMS Manual for Special Session Organizers at: www.ams.org/meetings/specialsessionmanual.html.

Proposals for Special Sessions should be sent by e-mail to AMS Associate Secretary, Michel Lapidus (lapidus@math.ucr.edu), by May 15, 2018. The contact organizer of the proposal will be notified whether their proposal has been accepted after the May 15, 2018 deadline for proposals has passed, but no later than June 15, 2018.

Special Sessions will be allotted between five and fifteen hours in which to schedule speakers. Additional instructions and the session's schedule will be sent to the contact organizer of the accepted sessions by July 1, 2018.

Denver, Colorado

Colorado Convention Center

January 15–18, 2020
Wednesday – Saturday
Joint Mathematics Meetings, including the 126th Annual Meeting of the AMS, 103rd Annual Meeting of the Mathematical Association of America (MAA), annual meetings of the Association for Women in Mathematics (AWM) and the National Association of Mathematicians (NAM), and the winter meeting of the Association of Symbolic Logic (ASL), with sessions contributed by the Society for Industrial and Applied Mathematics (SIAM)
Associate secretary: Michel L. Lapidus
Announcement issue of *Notices*: Ocrtober 2019
Program first available on AMS website: November 1, 2019
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: To be announced

Deadlines
For organizers: April 1, 2019
For abstracts: To be announced

Washington, District of Columbia

Walter E. Washington Convention Center

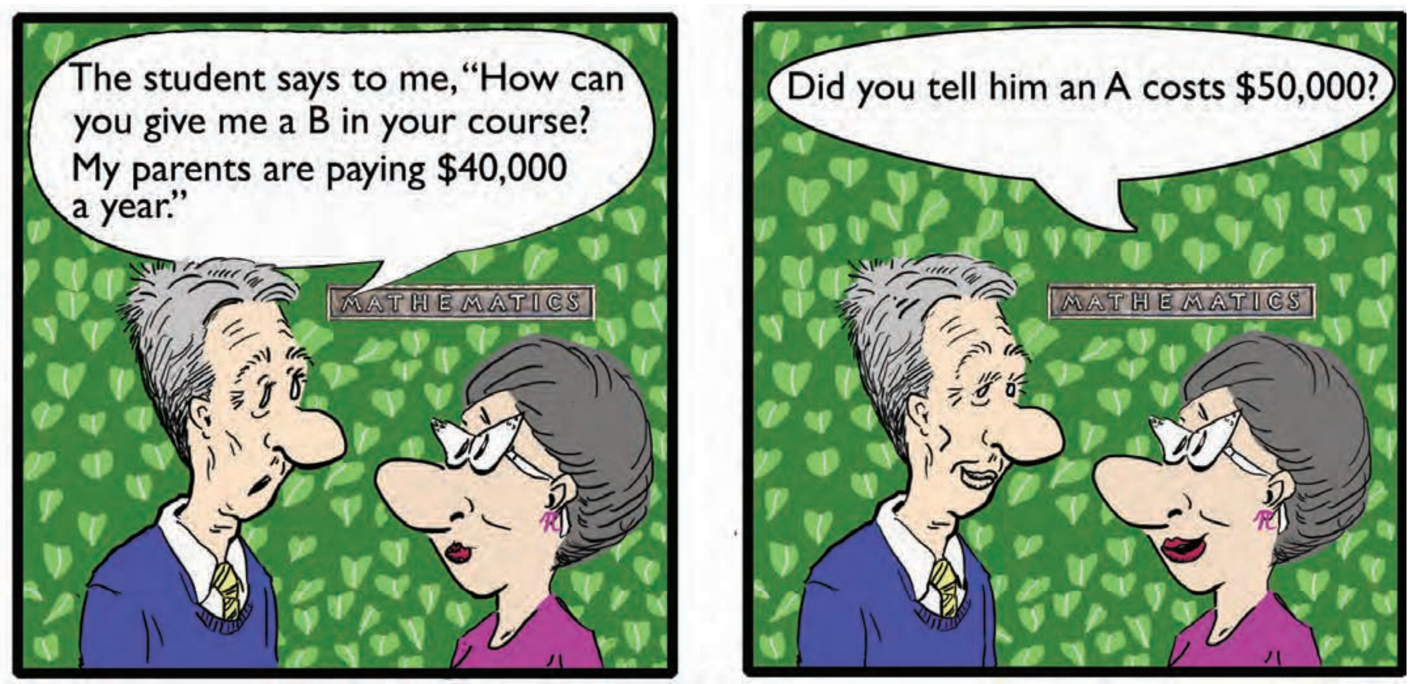
January 6–9, 2021
Wednesday – Saturday
Joint Mathematics Meetings, including the 127th Annual Meeting of the AMS, 104th Annual Meeting of the Mathematical Association of America (MAA), annual meetings of the Association for Women in Mathematics (AWM) and the National Association of Mathematicians (NAM), and the winter meeting of the Association of Symbolic Logic (ASL), with sessions contributed by the Society for Industrial and Applied Mathematics (SIAM).
Associate secretary: Brian D. Boe
Announcement issue of *Notices*: October 2020
Program first available on AMS website: November 1, 2020
Program issue of electronic *Notices*: To be announced
Issue of *Abstracts*: To be announced

Deadlines
For organizers: April 1, 2020
For abstracts: To be announced

"Think only about the problems that are a trillion dollars and up."

— *Advice given to D. J. Patil, Obama's deputy chief technology officer for data policy, according to an article, "Data for Good," by Tim Chartier in the April 2017* Math Horizons. *Other priorities included problems that affect either more than half the population or populations without recourse.*

Grade Inflation



Artwork by Sam White.

QUESTIONABLE MATHEMATICS

A freshman was bemoaning being the only one with a roommate. I said that was impossible, but the student didn't get it...

What crazy things happen to you? Readers are invited to submit original short amusing stories, math jokes, cartoons, and other material to: **noti-backpage@ams.org**.

American Mathematical Society
Distribution Center

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