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About the cover: Art by Bill Thurston (see page 1388)
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The Notices of the AMS: A Perspective

As my two terms as Editor of the Notices of the American Mathematical Society come to a close, I wish to reflect on the complementary roles of the Notices and the AMS in the professional lives of mathematicians.

Having served on numerous AMS committees and most recently as Editor of the Notices, I have sometimes been surprised and disturbed to hear mathematicians claim that our organization functions merely as a figurehead that benefits its members only marginally. Nothing could be further from the truth. The AMS publishes important books and journals; it organizes significant conferences; it awards fellowships and scholarships, thus ensuring a constant influx of new talent. By creating and maintaining MathSciNet, the AMS has, in addition, given a global audience access to current research. By actively promoting mathematics, both to the government and to the general public, it has promulgated the reality that mathematics is not only relevant but foundational.

As its journal of record, the Notices should surely reflect the diversity of the AMS, and indeed of the entire mathematical community. During my tenure as Editor, my staff and I consequently endeavored to broaden the scope of the journal well beyond expository articles about recent mathematical developments. Such pieces, written for a wide audience, are extremely valuable. But in this age of cultural (and academic) diversity, so are articles that take a more interdisciplinary approach. The last six years of the Notices have accordingly seen papers on mathematics and the arts, on mathematics and sports, on mathematical education at all levels, on the fast-changing world of mathematical publishing, and on mathematics and current events. Two new columns were developed, Doceamus and Scripta Manent, which allowed authors to express their opinions on education and publishing in a briefer and perhaps more forgiving arena than the feature articles would. Finally, considerable space was allotted to memorial articles in the belief that the Society’s journal of record should honor those who have contributed so notably to our field and to our very identities as mathematicians.

My tenure as Editor has not, of course, been without its controversies. We felt obligated, for example, to address the Elsevier boycott. We examined the alleged abuse of the impact factor. In both cases, we had to make hard decisions about who should write and who should not, and (with the help of attorneys) what legally could be printed and what could not. Controversy also surrounded our publication of one article detailing mathematical techniques to establish peace in the Middle East and of another one that mathematically analyzed the air crash of Malaysia Airlines Flight MH370. All of these pieces, and many more, have contributed to the lively and stimulating periodical that the Notices has become. Names have sometimes been named and fingers pointed, but always, I hope and believe, in a responsible way. Readers may well disagree with authors’ conclusions, may even at times be outraged by those conclusions, but the Notices should surely encourage both its writers and its readers to actively engage in the complex questions, the widely varied viewpoints, that characterize today’s world.

Our aim, in any case, was always to foster challenging but civilized discourse. As Editor, I learned that mathematicians speak in a multitude of voices, many if not all of which deserve to be heard. I learned as well that many in our community desire to express themselves on topics in which they are interested and informed but that would be inappropriate for the research journals. Yet mathematicians often have little experience with, and are uncomfortable with, expository argument. The parameters for such writing are different from those for research writing, and the rules can be unfamiliar and daunting. Part of my role as Editor, therefore, was to educate the writers on the conventions and to guide them towards the real joy in reaching out to and connecting with a broad and diverse audience.

Throughout it all, the AMS staff have been constant lifesavers. Sandy Frost and Rachel Rossi as managing editors, Allyn Jackson as deputy editor, and all the other amazingly talented people in Providence contributed years of editorial experience as well as the all-important institutional memory that we short-term editors lack. My assistant, David Collins, was an essential participant in all Notices activities. Playing a special role as contributing editor was Randi D. Ruden. Bill Casselman did a splendid job with the covers. Finally, the seventeen distinguished scholars who served as the Notices editorial board were my primary sounding board and source of inspiration for six years. I could not have done this job without the help of all these good people and also, of course, of the writers whose words remain alive in the pages of the Notices.

I look forward to Frank Morgan’s editorship. I say goodbye to mine with satisfaction, pride, and a little sadness.

—Steven G. Krantz
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The Mathematics Research Communities program helps early career mathematicians develop long-lasting cohorts for collaborative research projects in many areas of mathematics.
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**TOPICS FOR 2016**

**June 5–11, 2016**
**Lie Group Representations, Discretization, and Gelfand Pairs**
Organizers: Bradley Currey (Saint Louis University)
Gestur Olafsson (Louisiana State University)
Gail Ratcliff (East Carolina University)

**June 5–11, 2016**
**Character Varieties: Experiments and New Frontiers**
Organizers: Sean Lawton (George Mason University)
Christopher Manon (George Mason University)
Adam Sikora (State University of New York at Buffalo)

**June 12–18, 2016**
**Algebraic Statistics**
Organizers: Mathias Drton (University of Washington)
Elizabeth Gross (San Jose State University)
Serkan Hosten (San Francisco State University)
David Kahle (Baylor University)
Sonja Petrovic (Illinois Institute of Technology)

**June 19–25, 2016**
**Mathematics in Physiology and Medicine**
Organizers: Dan Beard (University of Michigan)
Brian Carlson (University of Michigan)
Adam Mahdi (University of Oxford)
Mette Olufsen (North Carolina State University)
Johnny Ottesen (Roskilde University)
We finish the year 2015 with an array of good mathematics: First there is a study of the Yates program at Illinois College. Then there is a report on the work of the 2014 Fields Medalists, including the first woman Fields Medalist! There is a presentation of the puzzling 120-cell. And finally there is the first part of a remembrance of the remarkable mathematician William (Bill) Thurston.

—Steven G. Krantz, Editor

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A burr puzzle is a collection of notched wooden sticks [2, page xi] that fit together to form a highly symmetric design, often based on one of the Platonic solids. The assembled puzzle may have zero, one, or more internal voids; it may also have multiple solutions. Ideally, no force is required. Of course, a puzzle may violate these rules in various ways and still be called a burr.

The best known, and certainly largest, family of burr puzzles comprises what are collectively called the 6-piece burrs [5]. Another well-known burr, the star burr, is more closely related to our work. Unlike the 6-piece burrs, the six sticks of the star burr are all identical, as shown in Figure 2A. The solution is unique, and, once solved, the star burr has no internal voids. The solved puzzle is a copy of the first stellation of the rhombic dodecahedron; see Figure 2B.

The goal of this paper is to describe Quintessence: a new family of burr puzzles based on the 120-cell, a regular four-dimensional polytope. The puzzles are built from collections of six kinds of sticks, shown in Figure 3; we call these ribs, as they are gently curving chains of distorted dodecahedra.

In the following sections we review regular polytopes in low dimensions, sketch a construction of the dodecahedron, and discuss the three-sphere,

Figure 1. The Dc30 Ring, one of the simpler puzzles in Quintessence.

Figure 2. The star burr.

Figure 3. The six rib types.
quaternions, and stereographic projection. Viewing the binary dodecahedral group as a subgroup of the quaternions, we construct and then investigate the combinatorics of the 120-cell, focusing on how it decomposes into spheres and rings of dodecahedra. Finally, we lay out our choice of ribs, as influenced by the cell-centered stereographic projection. We use this to give a basic combinatorial restriction on the possible burr puzzles in Quintessence. One of the completed puzzles, the Dc30 Ring, is shown in Figure 1. The connection between the star burr and Quintessence is left as a final exercise for the intrigued reader.

Polytopes

We refer to [16] for an in-depth discussion of polytopes.

Regular Polytopes

Suppose that $P$ is a $k$-dimensional polytope. An ascending chain of faces $Q_0 \subset Q_1 \subset \cdots \subset Q_{k-1} \subset Q_k = P$ is called a flag of $P$ if $Q_\ell$ has dimension $\ell$. See Figure 4 (top) for a picture of one of the forty-eight flags of the cube.

Let $\text{Sym}(P)$ be the group of rigid motions (and reflections) preserving $P$ setwise. We call elements of $\text{Sym}(P)$ the symmetries of $P$.

**Definition 1.** A polytope $P$ is regular if for any pair of its flags, $F$ and $G$, there is a symmetry $\phi \in \text{Sym}(P)$ with $\phi(F) = G$.

It follows that all facets of a regular polytope are congruent and are themselves regular.

Suppose $P$ is regular. Define $p = \text{center}(P)$ to be the average of the vertices of $P$. Since $\text{Sym}(P)$ permutes the vertices of $P$, it fixes $p$. Since $\text{Sym}(P)$ sends any flag to any other, the same is true of the vertices. So the vertices are all the same distance from $p$. Thus $p$ is a circumcenter: $P$ is circumscribed by the sphere $S_P$ centered at $p$ and running through the vertices of $P$. If we project $\partial P$ from $p$ outwards to $S_P$, we obtain a symmetrical spherical tiling $T_P$.

Conversely, when we are constructing an $n$-dimensional regular polytope $P$, our first move is to build a spherical tiling $T_P$ on $S^{n-1}$.

**Definition 2.** Suppose that $P$ is regular and $F = \{Q_i\}$ is a flag in $P$. Then the flag polytope $Q_F$ is the convex hull of the centers of the $Q_i$. The spherical flag polytope is the radial projection of $Q_F - p$ to $S_P$. See Figure 4 (bottom).

If $P$ is regular, then all of its spherical flag polytopes are congruent.

Constructions

There are four infinite families of regular polytopes; each family is associated with a topological operation. The regular polygons live within the unit disk in the plane and are associated to covering maps of the circle by itself. See Figure 5.

Next, there are three families of regular polytopes that exist in all dimensions. Each member of a family is obtained from the previous member by a geometric operation. The simplices are cones, the cubes are products (with an interval), and the cross-polytopes are suspensions, that is, a double-cone.

Figure 6 shows the first several members of each family. In dimension two these are the triangle, square, and diamond, respectively. The fifth
column shows the stereographic projections of the spherical tilings for the four-dimensional members of each family. These cannot be drawn in three-dimensional spaces so we instead radially project their boundaries to $S^3$ and then stereographically project to $\mathbb{R}^5$. This technique is explained in [10]. For the convenience of the reader, we repeat the definition of stereographic projection below.

The four families give almost all of the regular polytopes; see [8, p. 143] for proofs of the following.

**Lemma 3.** The simplex, cube, and cross-polytope are regular. The cube and the cross-polytope are dual; the simplex is self-dual. In dimensions three and higher these three polytopes are distinct. □

**Theorem 4.** There are exactly five regular polytopes not in one of the four families. These are, in dimension three, the dodecahedron and icosahedron (dual) and, in dimension four, the 24-cell (self-dual), and the 120-cell and 600-cell (dual). □

**Dodecahedron**

The dodecahedron exists for more subtle reasons than those for the existence of the polygons, simplices, cubes, or cross-polytopes. As such it has many constructions; the earliest seems to be Proposition 17 in Book 13 of Euclid’s *Elements* [7]. See [15] for one historical account of the five Platonic solids.

We sketch an indirect construction of the dodecahedron $D$ that has two advantages. The argument finds the symmetry group $\text{Sym}(D)$ along the way. It also generalizes to all other regular tessellations of the sphere, the Euclidean plane, and hyperbolic plane.

By continuity, for any angle $\theta \in (3\pi/5, 7\pi/5)$ there is a regular spherical pentagon $P \subset S^2$ with all angles equal to $\theta$. See Figure 7 (middle). Thus we may take $\theta$ equal to $2\pi/3$.

Adding a vertex at the center and at the midpoints of the edges, we divide $P$ into ten spherical flag triangles. These alternate between being right- and left-handed; all have internal angles $(\pi/2, \pi/3, \pi/5)$. See Figure 7 (middle). These three angles appear at the edge, vertex, and center of $P$. Let $T_R$ ($T_L$) be one of the right-handed (left-handed) spherical flag triangles. Note that there are rotations of $S^2$ matching the edges of $T_R$ and $T_L$ in pairs.

The celebrated Poincaré polygon theorem [6, Theorem 4.14] now implies that copies of $T_R$ and $T_L$ give a tiling $T$ of $S^2$, shown in Figure 7 (right). Poincaré’s theorem also implies that $\text{Sym}(T)$ is transitive on the triangles of $T$ and that any local symmetry extends to give an element of $\text{Sym}(T)$.

By Girard’s formula [4, Equation 2.11], the area of a spherical triangle with interior angles $A, B, C$ is $A + B + C - \pi$. Thus the area of $T_R$ is

$$\pi \cdot (1/2 + 1/3 + 1/5) - \pi = \pi/30.$$ 

Since the area of $S^2$ is $4\pi$, we deduce that the tiling $T$ contains 120 triangles.

**Definition 5.** We partition $T$ into copies of $P$ to obtain the tiling $T_D$; this has 12 pentagonal faces, $12 \cdot 5/2 = 30$ edges, and $12 \cdot 5/3 = 20$ vertices. We take the convex hull (in $\mathbb{R}^5$) of the vertices of $T_D$ (in $S^2$) to obtain $D$, the dodecahedron.

We end this section by examining the symmetries of $T$.

**Lemma 6.** The group $\text{Sym}(T)$ has order 120; the orientation-preserving subgroup $D = \text{Sym}^+(T)$ has order 60. The tiling $T$ is invariant under the antipodal map. □

**Corollary 7.** The group $D$ contains

- the identity,
- 12 face rotations through angle $2\pi/5$,
- 20 vertex rotations through angle $2\pi/3$,
- 12 face rotations through angle $4\pi/5$, and
- 15 edge rotations through angle $\pi$.

**Proof.** For any vertex $p$ of $T$ of degree $2d$ we obtain a cyclic subgroup $\mathbb{Z}/d\mathbb{Z}$ in $D$. By the second part of Lemma 6 the vertex $p$ and its antipode $q$ give rise to the same subgroup. Thus we may count elements of $D$ by always restricting to those rotations through an angle of $\pi$ or less. Counting the symmetries obtained this way gives 60; by the first part of Lemma 6 there are no others. □
Four-Space and Quaternions
In this section we recall the quaternions, the three-sphere, and stereographic projection. See also [4, Chapter 6], [14, Section 2.7], or [3, Part II]. The quaternions bridge the gap between the algebra of certain groups and the geometry of four-dimensional space. The three-sphere is the natural home of the spherical 120-cell.

Due to the physiology of the human eye, we only ever see two-dimensional images. The brain instinctively interprets some of these as representing three-dimensional objects but is not equipped to deal with higher dimensions. Hence we do not attempt to draw any native pictures of four-dimensional objects. Instead, we use stereographic projection to transport objects from the three-sphere into three-dimensional space, where they can be seen with human eyes [10].

The Quaternions
The real numbers \( \mathbb{R} \), being one-dimensional, can be augmented by adding \( i = \sqrt{-1} \) to obtain the two-dimensional complex numbers \( \mathbb{C} \). In very similar fashion Hamilton augmented \( \mathbb{C} \) to obtain the quaternions \( \mathbb{H} \). Let \( (1, i, j, k) \) be the usual orthonormal basis for \( \mathbb{R}^4 \). We take \( \mathbb{H} = \mathbb{R} \oplus \mathbb{I} \), where \( \mathbb{I} = \mathbb{R} \oplus j \mathbb{R} \oplus k \mathbb{R} \) is the subspace of purely imaginary quaternions. Following Hamilton we endow \( \mathbb{H} \) with the relations

\[
\begin{align*}
i^2 &= j^2 = k^2 = ijk = -1.
\end{align*}
\]

Since \( \mathbb{H} \) is identical to \( \mathbb{R}^4 \) as a real vector space, there is a copy of the three-sphere inside the quaternions, namely, \( S^3 = \{ q \in \mathbb{H} : |q| = 1 \} \) equipped with the induced metric. The function from \( S^3 \) to itself taking \( p \) to \( -p \) is called the antipodal map. When \( L \subset \mathbb{H} \) is a linear subspace of dimension one, two, or three, the intersection \( L \cap S^3 \) is a pair of antipodal points, a great circle, or a great sphere.

The Unit Quaternions
The points of the three-sphere, the unit quaternions, form a group under quaternionic multiplication. Again, we see how the group structure and geometry of \( S^3 \) are tightly intertwined, as follows.

\[
\begin{align*}
e^u \alpha &= \cos \alpha + u \cdot \sin \alpha.
\end{align*}
\]

Lemma 8. The left and right actions of \( S^3 \) on \( \mathbb{H} \) are via orientation-preserving isometries. The same holds for the three-sphere’s action on itself.

We can now parameterize great circles in \( S^3 \) through the identity. For any \( u \in S^2 \) define \( L_u = (1, u) \) to be the corresponding plane in \( \mathbb{H} \). The intersection \( L_u \cap S^3 \) is thus a great circle \( C_u \). We parameterize \( C_u \) by sending \( \alpha \in \mathbb{R} \) to the point

\[
\rho(q) = \frac{\sin(\alpha)}{1 + \cos(\alpha)} \cdot u
\]

with \( q = e^{u \alpha} \) as in Lemma 10. See Figure 9 for a cross-sectional view. Note that \( \rho \) sends the south pole to the origin, fixes the equatorial sphere \( S^2 \), pointwise, and sends the north pole to “infinity.” The one-parameter subgroup \( e^{u \alpha} \) is sent to the straight line in the direction of \( u \). Figure 10 shows the result of applying stereographic projection to various great circles connecting \( 1, i, j, k \) inside \( S^3 \).

Stereographic Projection
We define stereographic projection \( \rho : S^3 - \{ -1 \} \to \mathbb{I} \) by

\[
\rho(q) = \frac{\sin(\alpha)}{1 + \cos(\alpha)} \cdot u
\]

with \( q = e^{u \alpha} \) as in Lemma 10. See Figure 9 for a cross-sectional view. Note that \( \rho \) sends the south pole to the origin, fixes the equatorial sphere \( S^2 \), and sends the north pole to “infinity.” The one-parameter subgroup \( e^{u \alpha} \) is sent to the straight line in the direction of \( u \). Figure 10 shows the result of applying stereographic projection to various great circles connecting \( 1, i, j, k \) inside \( S^3 \).

Mapping to SO(3)
Recall that SO(3) is the group of three-by-three orthogonal matrices with determinant one. Taking \( (i, j, k) \) as a basis for \( \mathbb{I} \), we identify SO(3) with \( \text{Isom}_0^3(\mathbb{I}) \), the group of orientation-preserving isometries of \( \mathbb{I} \) fixing the origin.

Figure 8. Rotational symmetries of the dodecahedron.

Figure 9. Stereographic projection from \( S^3 - \{ -1 \} \) to \( \mathbb{I} \).
Thus we give a more explicit construction. We refer independently by Gauss, Rodrigues, Cayley, and Hamilton [12, p. 21].

**Lemma 11.** The map \( \psi_q \) is an element of \( \text{SO}(3) \). The induced map \( \psi : S^3 \to \text{SO}(3) \) is a group homomorphism. \( \square \)

We need an explicit form of \( \psi_q \), discovered independently by Gauss, Rodrigues, Cayley, and Hamilton [12, p. 21].

**Lemma 12.** For \( q = \pm e^{i\alpha} \) the isometry \( \psi_q \) is a rotation of \( \mathbb{I} \) about the direction \( u \) through angle \( 2\alpha \). Thus \( \psi_q : S^3 \to \text{SO}(3) \) is a double cover. \( \square \)

**Definition 13.** If \( G \subset \text{SO}(3) \) is a group, then we call \( G^* = \psi^{-1}(G) \) the binary group corresponding to \( G \).

### The 120-Cell

It is time to construct the 120-cell. We could use a continuity argument to build a spherical dodecahedron in \( S^3 \) with all dihedral angles equal to \( 2\pi/3 \). The Poincaré polyhedron theorem would then produce a tiling of \( S^3 \); regularity of the tile implies regularity of the tiling. Taking the convex hull of the vertices would give the 120-cell. However, computing the number of cells would require computing the volume of the spherical flag polytope, a highly nontrivial task. Also, it is crucial for us to see how the binary dodecahedral group \( D^* \) lies inside the symmetry group of the 120-cell. Thus we give a more explicit construction. We refer to [1, 12, 13] as very useful commentaries on the 120-cell.

**Voronoi Cells**

Suppose \( V \) is a finite set of points in a metric space \( X \). The Voronoi cell about a point \( q \in V \) is the set \( \text{Vor}(q) = \{ r \in S^3 \mid \text{for all } p \in V, d_X(q, r) \leq d_X(p, r) \} \).

Let \( D \subset \text{SO}(3) \) be the group of orientation-preserving symmetries of the dodecahedron \( D \), as listed in Corollary 7. Let \( D^* \subset S^3 \) be the corresponding binary dodecahedral group of 120\(^{\text{th}} \) elements. Let \( T_{120} \) be the tiling of the three-sphere by the cells \( \{ \text{Vor}(q) \mid q \in D^* \} \).

**Lemma 14.** The left action of \( D^* \) on \( T_{120} \) is transitive on the three-cells. The twisted action of \( D^* \) fixes \( \text{Vor}(1) \) setwise. \( \square \)

**Lemma 15.** Each cell \( \text{Vor}(q) \) is a regular spherical dodecahedron with dihedral angle \( 2\pi/3 \).

**Proof.** Figure 11 shows five points of \( D^* \): namely, the identity 1, a vertex rotation \( p \), and the three face rotations \( q, q', q'' \) about the faces immediately incident on the vertex. We also see three of the corresponding Voronoi cells, cut in half. Some delicate spherical trigonometry proves that \( \text{Vor}(1) \) meets only \( \text{Vor}(p) \) and its translates under the twisted action. Finally, the purple triangle in Figure 11 is equiangular, so \( \text{Vor}(q) \) (and thus \( \text{Vor}(1) \)) has the correct dihedral angle. \( \square \)

**Remark 16.** Applying the above construction to the cube does not give rise to a regular spherical cube; the vertex rotations are too close to the identity in \( S^3 \). The Voronoi cells are instead truncated cubes.

For the regular tetrahedron the vertex and face rotations are the same distance from the identity. Thus the Voronoi cells are regular spherical octahedra which tile the 24-cell.

**Definition 17.** The 120-Cell is the convex hull, taken in \( \mathbb{H} \), of the vertices of \( T_{120} \).
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Theorem 18. The 120-cell is a regular polytope.

Proof. We must show that the group $\text{Sym}(T_{120})$ acts transitively on the 14,400 spherical flag tetrahedra of $T_{120}$. Using the left action of $D^*$ we may move any such into Vor(1). Using the twisted action we can move any right-handed spherical flag tetrahedron inside Vor(1) to any other. Now, since $T$ is invariant under the antipodal map (Lemma 6) we deduce that $D^*$ is fixed setwise by quaternionic conjugation. Since this conjugation is the product of three reflections in $\mathbb{H}$, it is orientation reversing in $S^3$. □

See Figure 12 for a picture of the stereographic projection of the southern half of the one-skeleton of the spherical 120-cell.

Combinatorics of the 120-cell

With the 120-cell in hand, we turn to the combinatorics of the spherical tiling $T_{120}$.

Layers of Dodecahedra

The cells of $T_{120}$ divide into spherical layers, ordered by their distance from the identity element in $S^3$. Following our conventions, the identity lies at the south pole of $S^3$. Figure 13 displays the stereographic projections of the first five layers, expanding from the south pole out to the equatorial great sphere. The next four layers, nesting down to the north pole, are not shown. See Proposition 19 for more details.

Rings of Dodecahedra

Suppose that $q \in D^*$ is the lift of a face rotation $A \in D$ of angle $2\pi/5$. Let $R = \langle q \rangle < D^*$ be the resulting cyclic group of order ten. Note that $R$ has twelve right cosets in $D^*$. We call the cosets rings because each corresponding union of spherical dodecahedra forms a solid torus in $S^3$ (see Figure 14). We give the rings the following names: $R$ is the spinal ring, $R^{eq}$ is the equatorial ring (having all elements at distance $\pi/2$ from the south pole), $R^{in}_0$ to $R^{in}_4$ are the inner rings (each incident to the spine), and $R^{out}_0$ to $R^{out}_4$ are the outer rings (each incident to the equator).

Proposition 19. The rings meet the spherical layers of $T_{120}$ as follows.

<table>
<thead>
<tr>
<th>distance</th>
<th>rotation type</th>
<th># cells</th>
<th>spinal</th>
<th>equatorial</th>
<th>inner</th>
<th>outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0$</td>
<td>identity</td>
<td>$1$</td>
<td>$1$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\pi/5$</td>
<td>face</td>
<td>$12$</td>
<td>$2$</td>
<td>$0$</td>
<td>$2$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\pi/3$</td>
<td>vertex</td>
<td>$20$</td>
<td>$0$</td>
<td>$0$</td>
<td>$2$</td>
<td>$2$</td>
</tr>
<tr>
<td>$2\pi/5$</td>
<td>face</td>
<td>$12$</td>
<td>$2$</td>
<td>$0$</td>
<td>$0$</td>
<td>$2$</td>
</tr>
<tr>
<td>$\pi/2$</td>
<td>edge</td>
<td>$30$</td>
<td>$0$</td>
<td>$10$</td>
<td>$2$</td>
<td>$2$</td>
</tr>
<tr>
<td>$3\pi/5$</td>
<td>face</td>
<td>$12$</td>
<td>$2$</td>
<td>$0$</td>
<td>$0$</td>
<td>$2$</td>
</tr>
<tr>
<td>$2\pi/3$</td>
<td>vertex</td>
<td>$20$</td>
<td>$0$</td>
<td>$0$</td>
<td>$2$</td>
<td>$2$</td>
</tr>
<tr>
<td>$4\pi/5$</td>
<td>face</td>
<td>$12$</td>
<td>$2$</td>
<td>$0$</td>
<td>$2$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>identity</td>
<td>$1$</td>
<td>$1$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

The column titled “# cells” counts the number of cells in the named spherical layer. □

See also [11].

Remark 20. The Hopf fibration is the partition of $S^3$ into cosets of the one-parameter subgroup $\{\exp(\alpha \mathbf{i})\}$. After a rotation, we see that the cosets of $R$ give a combinatorial Hopf fibration: they divide the 120-cell into twelve rings of ten dodecahedra each. The centers of the rings lie on twelve great circles of the Hopf fibration. Note also that the quotient space of the Hopf fibration is homeomorphic to $S^2$. In similar fashion there is a kind of combinatorial map from the 120-cell to the dodecahedron, sending rings to faces.

Rings to Ribs

In this section we describe the ribs of Quintessence: a collection of physical pieces that combine in various ways to produce burr puzzles. The ribs are shown in Figure 2; they are constructed via stereographic projection as applied to (parts of) the rings of spherical dodecahedra.

Figure 12. The southern half of the one-skeleton of $T_{120}$, after cell-centered stereographic projection to $\mathbb{R}^3$. See also [13, color plate].

Figure 13. The five layers in the southern hemisphere, ordered by their spherical distance from the south pole. The colors of the cells follow the convention of Figure 8.
Following our notation above we have:

\[ \frac{d\rho}{d\alpha} = \frac{1}{1 + \cos(\alpha)} \cdot u. \]

Note that if \( e^u \) is near the south pole, then \( \alpha \) is close to zero and stereographic projection shrinks objects by a factor of approximately two. If \( e^u \) is near the equatorial sphere, then \( \alpha \) is close to \( \pi/2 \). In this case stereographic projection leaves sizes essentially unchanged. However, if \( e^u \) approaches the north pole, then \( \alpha \) approaches \( \pi \) and sizes blow up.

All of the calculations so far have been dimensionless. Now we wish to physically construct, say by 3D printing, our puzzle pieces. So we must choose a scale \( \lambda \), say in millimeters, corresponding to a unit distance in \( \mathbb{R}^3 \). Several issues influence the choice of \( \lambda \), but two are paramount. Large features are expensive; small features are fragile.

These two issues are in tension and lead to the general principle that features that are identical in \( S^3 \) should have sizes in reasonable ratio in \( \mathbb{R}^3 \) after projection. Here the features of the ribs are the dodecahedra. The principle tells us that we should not be using dodecahedra close to the north pole. On the other hand, sizes at the equator and at the south pole have an acceptable ratio of approximately two.

Accordingly, we remove from our rings any dodecahedra that lie strictly in the northern hemisphere, giving us the spine, the inner six ribs, and the outer six ribs. Experimentation shows that many interesting constructions require even shorter ribs; hence we also make the inner four ribs and the outer four ribs. These are the result of removing the two equatorial dodecahedra from the inner six and outer six. The equatorial ring can be printed as is, but again experimentation shows that more puzzles are possible if we break the equatorial ring into two ribs of five dodecahedra each. See Figure 3 as well as Figure 15.

With the spine and short ribs in hand, we can build, in \( \mathbb{R}^3 \), the stereographic projection of (almost) one-half of the 120-cell. We call the resulting puzzle the \( D_{c45} \) Meteor; its construction is shown in Figure 16. The spine and ribs are arranged according to the combinatorial Hopf fibration (Remark 20). Since all dodecahedra near the south pole are retained and all dodecahedra near the north pole are discarded, the result looks very much like Figure 12.

It is not at all obvious that the puzzle can be constructed in Euclidean space using physical objects. However, when printed in plastic the Meteor is possible to assemble. When complete it holds together with no other support. Apparently a small amount of flex in the ribs is necessary; we have not been able to solve a similar puzzle when printed in a steel/bronze composite (the \( D_{c30} \) Ring, shown in Figure 1).

It came as a surprise to us that there are numerous other burr puzzles using these ribs; most are not based on the combinatorial Hopf fibration [9]. However, there are significant combinatorial restrictions on the ribs that can be used in any burr puzzle. The following theorem is sharp, as shown by examples [9].

Theorem 21.

1. At most six inner ribs are used in any puzzle.
2. At most six outer ribs are used in any puzzle.
3. At most ten inner and outer ribs are used in any puzzle.

Proof. The stereographic projection map \( \rho \) is equivariant: \( \rho \) transports the twisted action on \( S^3 \) to the \( \text{SO}(3) \) action on \( \mathbb{R}^3 \). That is, \( \rho \) respects the \( S^2 \) symmetry about the south pole in \( S^3 \). Thus any two cells in a given layer (at fixed distance from the south pole) are congruent in \( \mathbb{R}^3 \). Also, any pair of cells in different layers are different due to the growth of \( d\rho/d\alpha \).

Figure 15. The coloring of the cells is by layer and is consistent with Figure 13. We obtain the inner four and outer four ribs by deleting the equatorial cells.
From the table in Proposition 19 we learn that each inner rib contains exactly two cells adjacent to the south pole. Next, column “# cells” tells us there are exactly twelve such. Part (21) follows. We prove part (21) by examining the layer at distance $2\pi/5$, and we prove part (21) using the layer at distance $\pi/3$. A color-coded guide is provided in Figures 13 and Figure 15.

Acknowledgments
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References
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Mathematical Modelling Workshop at School of Mathematics, University of Nairobi, Kenya, February 2015, Photo by Arthur Muchela
William P. Thurston, 1946–2012

David Gabai and Steve Kerckhoff, Coordinating Editors

William P. Thurston, a geometric visionary and one of the greatest mathematicians of the twentieth century, died on August 21, 2012, at the age of sixty-five. This obituary for Thurston contains reminiscences by some of his many colleagues and friends. What follows is the first part of the obituary; the second part will appear in the January 2016 issue of the Notices.

William Paul Thurston, known universally as Bill, was an extraordinary mathematician whose work and ideas revolutionized many fields of mathematics, including foliations, Teichmüller theory, automorphisms of surfaces, 3-manifold topology, contact structures, hyperbolic geometry, rational maps, circle packings, incompressible surfaces, and geometrization of 3-manifolds.

Bill's influence extended far beyond his incredible insights, theorems, and conjectures; he transformed the way people think about and view things. He shared openly his playful, ever curious, near magical and sometimes messy approach to mathematics. Indeed, in his MathOverflow profile he states, “Mathematics is a process of staring hard enough with enough perseverance at the fog of muddle and confusion to eventually break through to improved clarity. I'm happy when I can admit, at least to myself, that my thinking is muddled, and I try to overcome the embarrassment that I might reveal ignorance or confusion. Over the years, this has helped me develop clarity in some things, but I remain muddled in many others. I enjoy questions that seem honest, even when they admit or reveal confusion, in preference to questions that appear designed to project sophistication.”
His work was not only densely packed with wonderful ideas, it was immensely rich and deep. Studying an aspect of his work is often like opening a box to find two or more inside. Opening each of those reveals two or more boxes that often have little tunnels connecting to various other systems of boxes. With great effort one reaches an end, being simultaneously rewarded with both great illumination and the realization that one knows but a minuscule fraction of the whole. After a sufficient lapse of time, upon retracing the original trail, one catches further insights on topics that one once thought one completely understood.

In a similar manner, this article hardly does justice to the deep and complicated person that was Bill Thurston. It gives but a few facts and vignettes from various dimensions of his life and, at various spots, points readers to other resources where they might explore further.

Following this introduction are thirteen remembrances from mathematicians connected with different aspects of Thurston’s professional life. It is difficult not to be overcome by how Bill affected people and institutions in so many different and profound ways.

**Family**

Bill’s father, Paul Thurston, had a PhD in physics and worked at Bell Labs doing physics and engineering. He was an expert at building things and was bold, smart, imaginative, and energetic. Once he showed Bill how he could boil water with his bare hands. He took an ordinary basement vacuum pump and started it above the water so that the boiling point was just above the air temperature. Then he stuck his hands in the water and it started boiling!

Bill’s mother, Margaret (nee Martt), was an expert seamstress who could sew intricate patterns that would baffle Paul and Bill. In later years, Bill’s fascination with hyperbolic geometry inspired her to sew a hyperbolic hat-skirt, a seven-color torus, and a Klein quartic (genus-3 surface with a symmetry group of order 168) made from 24 heptagons that was designed by Bill and his sons, Nathaniel and Dylan. While at Ohio Wesleyan she wanted to be a math major but was told that women don’t major in mathematics.

Bill was named after his father, Paul, and his mother’s brother, William, who died in a hospital ship in the battle of Iwo Jima. He had an older brother, Bob, and sister, Jean, and a younger brother, George, who married Sarah, mathematician Hassler Whitney’s daughter. He married his college sweetheart, Rachel Findley, and they had children Nathaniel, Dylan, and Emily. He had children Jade and Liam from his second marriage with Julian Thurston.

**Childhood**

Bill had a congenital case of strabismus and could not focus on an object with both eyes, eliminating his depth perception. He had to work hard to reconstruct a three-dimensional image from two two-dimensional ones. Margaret worked with him for hours when he was two, looking at special books with colors. His love for patterns dates at least to this time. As a first-grader he made the decision “to practice visualization every day.” Asked how he saw in four or five dimensions he said it is the same as in three dimensions: reconstruct things from two-dimensional projections.

To stop sibling squabbling Paul would ask the kids math questions. While driving, Paul asked Bill (when he was five), “What is \(1 + 2 + \cdots + 100\)?” Bill said, “5,000.” Paul said, “Almost right.” Bill said, “Oh, I filled one square with 1, two squares for 2 and all the way up to 100, so that’s half of \(100 \times 100 = 10,000\), but I forgot that the middle squares are cut in two, so that’s 5,050!”

Paul was a scoutmaster, and Bill was very involved with the Scouts. They did all sorts of things with ropes, e.g., making bridges. Bill was expert at making fires in the pouring rain. The family loved camping and took many long trips. Music was a big part of their lives.

**New College, Florida**

Bill was a member of the charter class starting in 1964. According to alumnus and mathematician John Smillie, the founders of New College decided that it was much easier to maintain quality than to bring it up, so a tremendous effort was made to recruit one hundred of the brightest young people for the inaugural class. This included Bill’s future wife, Rachel Findley.

New College was a three-year program with classes eleven months of the year. There was tremendous freedom in how individual academic programs were structured and how students were
allowed to live. At various times Bill lived in a tent in adjacent woods or slept in academic buildings, playing hide and seek with the janitor. The library was minimal, and the college would buy whatever math books Bill wanted. Smillie said that nearly all the books he took out had Bill’s name in them.

In Bill’s words: “I guess I was disenchanted with how high school was and I wanted to go to a place where I’d have some more freedom to work in my own way.” New College gave him that and more. After the first year, half the faculty resigned and the library was on the brink of disaster. But Thurston says that he and many other students benefited from the turmoil. “It certainly taught us independence and how to think for ourselves.” According to Rachel, Bill could have left after two years for graduate school, but he really liked the independence the school offered and chose to stay.

Berkeley

Bill started Berkeley in 1967 in the thick of the Vietnam War. “Many of us were involved in student demonstrations and student strikes. We were sprayed with tear gas, whether or not we protested. We had friends who were killed, others who refused induction and were convicted as felons,....”

His concern about military activities continued throughout his life, particularly as it pertained to his professional life. In 1984 he declined an invitation to become the first Fairchild Professor at Princeton University because of the donor’s involvement in the business of military contracting.

Bill was a member of a committee that argued against mathematicians accepting military funding and that drafted five AMS resolutions related to this and related issues, each of which received majority votes from members of the AMS. (See also Epstein’s contribution.)

The early years in Berkeley also saw the expansion of his and Rachel’s family. Rachel said they had a baby (Nathaniel) in part to keep Bill from being drafted. She went into labor the night before his qualifying exam, which couldn’t be rescheduled. Although Bill passed, it was not a smooth process, as he gave answers that befuddled his examiners but provided hints at the remarkable originality of his thinking.

Thurston’s graduate career contained an extraordinary collection of mathematical results. He proved the striking theorem that the Godbillon-Vey invariant takes on uncountably many values. This invariant comes from a de Rham cohomology class that he relates to the helical wobble of the leaves of a foliation. His results show, among other things, that there exist uncountably many noncobordant codimension-one foliations of the 3-sphere. Bill’s (unpublished) thesis, written under the direction of Moe Hirsch, provided a precise description of a large class of $C^2$ foliations on 3-manifolds that are circle bundles. It also gave a counterexample to a result of S. P. Novikov that a certain partial order associated to a foliation has a maximum. But, beyond any single theorem, this period provided the foundation for a collection of ideas that would help answer many fundamental questions about foliations and would ultimately lead to Thurston’s revolutionary work on surfaces and 3-manifolds.

MIT and the Institute for Advanced Study

Bill was a member of the Institute for Advanced Study in 1972–73 and an assistant professor at MIT in 1973–74. There he continued his extraordinary work on foliations, for which he won the 1976 Veblen Prize (shared with James Simons). In particular, it was during this period that he and Milnor began their work on the kneading invariant of piecewise monotone maps of the interval. His interest in one-dimensional (real and complex) dynamics would stretch throughout his career, influencing his work on two- and three-dimensional manifolds. He would return to the topic once again during the final years of his life.

Princeton

He arrived at Princeton as a full professor in 1974 and remained for almost twenty years. There he did his revolutionary and foundational work on Teichmüller theory, automorphisms of surfaces, hyperbolic geometry, 3-manifolds, contact structures, and rational maps.

One of the most striking aspects of this period was how Thurston intertwined so many types of mathematics that had previously been viewed as disparate and utilized them in shockingly original ways. His classification of mapping classes of surfaces and foliations and would ultimately lead to Thurston’s revolutionary work on surfaces and 3-manifolds.

References

completely changed the landscape around the subject. The notes from his 1978 hyperbolic geometry course (in part written and edited by Bill Floyd and Steve Kerckhoff) were sent in installments (by regular mail) to over one thousand mathematicians. “The notes immediately circulated all over the world. It is probably the opinion of all the people working in low-dimensional topology that the ideas contained in these notes have been the most important and influential ideas ever written on the subject.”

The viewpoint represented by this work was encapsulated by his geometrization conjecture, which states that all closed, orientable 3-manifolds have a (classically known) decomposition into pieces, each of which has one of eight homogeneous metric geometries. Although this was a truly different way of viewing 3-manifolds, the conjecture subsumed many long-standing conjectures in the field, including the Poincaré Conjecture, the spherical space form problem, residual finiteness of their fundamental groups, and a classification of their universal covering spaces. He solved the conjecture for a large class of manifolds (Haken manifolds). His 1982 AMS Bulletin article, in which he described his view of 3-manifolds, included twenty-four problems. Although he did not view mathematics in terms of a list of problems to be solved, these received great attention and helped focus research in the field for the next three decades. See Otal ([7]) for an account of progress on these problems through 2013.

His Princeton years also included seminal contributions to the theory of rational maps of the 2-sphere, utilizing his ideas both from Kleinian groups and from the earlier work on surfaces. His interests in computing and group theory, both from a practical and theoretical point of view, led to his work (with Cannon, Epstein, and others) on automatic groups in Word Processing in Groups. The outpouring of ideas from this period was monumental and cannot be adequately captured in this space.

Bill was awarded the 1979 Waterman Prize “In recognition of his achievements in introducing revolutionary new geometrical methods in the theory of foliations, function theory and topology.”  In 1982 he won the Fields Medal and in 1983 was elected to the National Academy of Sciences.

Generally very generous with his time and ideas, Thurston had twenty-nine PhD students from his Princeton period, who, in turn, as of this writing have had 151 finishing students. In addition he influenced multitudes of visitors to both the university and the Institute for Advanced Study. He was a social center too, often bringing out his volleyball net for an impromptu game after tea in Fine Hall.

Beyond the extraordinary scope of his mathematical results, Bill was equally influential in the way he thought about and did mathematics. He thought deeply about the process of doing mathematics and methods for communicating it. His enthusiasm was infectious, and his truly unique point of view provided many new avenues for including it in people’s lives.

Computers
Bill was one of the first pure mathematicians to actively use computers in his research and was a strong proponent of all aspects of computing in the mathematical community. In the late 1970s he inspired Jeff Weeks to develop his SnapPea program to compute and visualize hyperbolic structures. This program and a later version, SnapPy (by Marc Culler and Nathan Dunfield), and the related Snap (Goodman, Hodgson, Neumann) are essential tools for anyone working in the area. Weeks himself discovered what is now known as the Weeks manifold with this program. (This manifold was independently discovered by Matveev-Fomenko and Józef Przytycki.)

According to Al Marden, Bill was the intellectual force behind the creation and activities of the Geometry Supercomputer Project and the Geometry Center, two NSF-funded programs centered at the University of Minnesota, with Marden as the founding director. Among many other things, these projects produced the wonderful videos Not Knot and Outside In. Not Knot is a computer-animated tour of hyperbolic space worlds that Bill discovered, portions of which have appeared in Grateful Dead concerts.8 Outside In is an award-winning video of Bill’s proof of sphere eversion, an amazing result first discovered by Steven Smale in 1957.

When a project by Gabai and Meyerhoff needed high-level computer expertise, they found it at the Geometry Center. This led to a computer-assisted proof of the log(3)/2-theorem with Nathaniel Thurston (Bill’s son), a brilliant apprentice at the Geometry Center who made full use of their computer resources. This result plays a crucial role in the proof of the Smale conjecture for hyperbolic 3-manifolds and the proof that the Weeks manifold

6A. Papadopoulos, MR1435975 (97m:57016) review of Three-Dimensional Geometry and Topology.
7www.nsf.gov/od/waterman/waterman_recipients.jsp
is the unique lowest-volume closed orientable hyperbolic 3-manifold.

Education
Bill was always interested in education. He and fellow New College students, including Rachel Findley, tutored disadvantaged students in math. At Berkeley he was part of a student committee that helped reform the TA program. He wrote, "I helped organize a program for our new teaching assistants, which involves discussion groups, and visiting of each others' classes. The group of TAs I observed seemed to me to retain much of the initial enthusiasm toward teaching which new TAs usually have, but older TAs frequently lose."  

Each year at the science day program at his kids' elementary school class (at a Princeton public school), he would teach a "thing or two." "It's really gratifying how open they are and how quickly they pick up things that seem to most adults far out and strange, the kinds of things that adults turn off as you're trying to explain it to them."  

At Princeton, with John Conway and Peter Doyle, he developed the innovative Geometry and the Imagination undergraduate course that was later given at the Geometry Center and UC Davis.

Thinking About and Doing Mathematics
Every student of mathematics needs to read Thurston's wide-ranging and well-thought-out essay “On proof and progress in mathematics". There he asks, How do mathematicians advance human understanding of mathematics? which has the subquestions: How do we understand and communicate mathematics? What motivates us to do it? What is a proof? He closes with some personal experiences from his work on foliations, hyperbolic geometry, and geometrization. In addition, he discusses how experts transmit new results to other experts and how he, at least, thinks about things. This is far different from the way outsiders, or even many advanced students, think working mathematicians function. 

Variants of ideas expressed in the BAMS article are given in other venues. He states, "Mathematics is an art of human understanding....Mathematics sings when we feel it in our whole brain....You only learn to sing by singing." "The most important thing about mathematics is how it resides in the human brain. Mathematics is not something we sense directly: it lives in our imagination and we sense it only indirectly. The choices of how it flows in our brains are not standard and automatic, and can be very sensitive to cues and context. Our minds depend on many interconnected special-purpose but powerful modules. We allocate everyday tasks to these various modules instinctively and subconsciously." Here are links to two other essays along related lines:

Building Things, Models, and Clothing Design
Bill enjoyed working with his hands and building things. He had a workshop in his Princeton home, and once, when guests came and there were not enough beds, he bought lumber and in an afternoon built a bunk bed. His mother, Margaret, was a master seamstress who sewed magnificent surfaces that he designed. He inspired Daina Taimina to crochet magnificent pieces and write the exquisite Euler Award-winning Crocheting Adventures with Hyperbolic Planes. With Kelly Delp he developed methods for building nearly smooth models by gluing Euclidean discs together. Characteristically, in just two days he built a workshop with a laminator, paper cutter, and riveter, and started constructing interesting models, eventually progressing to beautiful no-tape foam construction models that are marvels of engineering.

Fashion designer Dai Fujiwara contacted Thurston after reading about his eight geometries. Inspired by Bill, as well as by a multitude of geometric materials that Bill provided, including
a set of links whose 2-fold covers represented orbifolds of all eight geometries, Fujiwara and his team at Issey Miyake, Inc., designed and created an array of beautiful new women’s fashions that were presented at a March 2010 Issey Miyake fashion show.

Bill had expressed a connection between clothing design and manifold theory more than thirty-five years earlier. His 1974 ICM proceedings paper commences with “Given a large supply of some sort of fabric, what kinds of manifolds can be made from it, in a way that the patterns match up along the seams? This is a very general question, which has been studied by diverse means in differential topology and differential geometry.” Quoting a front-page *Wall Street Journal* piece: “Mr. Thurston compares this discovery [the eight geometries] to finding eight apparel outfits that can fit anybody in the world, just as he hopes to prove some day that the eight geometric categories fit every three-manifold imaginable.”

**MSRI, Berkeley, and Davis**

Bill moved to Berkeley in 1992, serving as director of MSRI from 1992 to 1997. He was on the faculty of UC Davis from 1996 to 2003. Carol Wood gives a detailed account of the MSRI years, pointing out that, during that period, MSRI introduced many innovative education and outreach initiatives that were revolutionary in their time but are standard for research institutes today. At Davis he published his long-awaited book, *Three-Dimensional Geometry and Topology* (edited by Silvio Levy), which grew out of a portion of his Princeton lectures and won the 2005 AMS Book Prize. He also wrote the influential monograph *Confoliations* with Yasha Eliashberg. At Davis he taught a wide array of courses, both for undergraduates and for graduate students. During his two-year postdoc at Davis, Ian Agol was both a co-teacher and a student in some of these classes. For family reasons, Bill was planning to return to Davis in the fall of 2012.

**Cornell**

Bill moved to Cornell in 2003. It was around this time that Grigori Perelman announced a proof of the geometrization conjecture. Although the techniques were primarily analytic and seemingly very different from his own work, Thurston felt that the proof was fully in keeping with the spirit of his vision, and he was genuinely pleased with its solution.15

In 2011 Bill was diagnosed with a melanoma, and in April he underwent surgery to remove a tumor, losing his right eye in the process.

Despite being under arduous medical treatments, he threw himself back into mathematics, attending conferences, inspiring young people, and proving fundamental results in the theory of rational maps that harkened back to his work with Milnor in the 1970s. He died on August 21, 2012, surrounded by his family.

In June 2014 a wide-ranging conference, What’s Next? The Mathematical Legacy of Bill Thurston, was held at Cornell. It was attended by his mother, brothers, and sister, Rachel and Julian, his children, and other family members, along with about three hundred mathematicians, including many students and recent PhDs. It was a true celebration of the tremendous future he left us.

**Thurston Resources**


2) Cornell tribute and remembrance page: [www.math.cornell.edu/News/2012-2013/thurston.html](www.math.cornell.edu/News/2012-2013/thurston.html)

3) New College obituary: [www.ncf.edu/william-thurston](www.ncf.edu/william-thurston)


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14 *WSJ*, March 18, 1983.

15 Perelman laudation at 2010 Clay Research Conference.
classes for deforming a plane field into an integrable one, i.e., tangent to a smooth foliation. It is this theorem that renewed my interest in foliation theory. In this year Gelfand and Fuks began to publish a series of articles on the cohomology of the Lie algebra of various vector fields. In a conference which took place in Mont-Aigual (near Montpellier) in 1969, I sketched the construction of a classifying space called $B\Gamma_q$ for $\Gamma_q$-structures, a notion I introduced in my thesis in 1958.

Here $\Gamma_q$ stands for the topological groupoid of germs of smooth local diffeomorphisms of $R^d$. A $\Gamma_q$-structure on a topological space $X$ can be defined by an open cover $\mathcal{U} = \{U_i\}_{i \in I}$ and a 1-cocycle over $\mathcal{U}$ with values in $\Gamma_q$; i.e., for each $i, j \in I$ a continuous map $\gamma_{ij}: U_i \cap U_j \to \Gamma_q$ is given such that

$$\gamma_{ij}(x) = \gamma_{ij}(x)\gamma_{jk}(x), \quad \forall x \in U_i \cap U_j \cap U_k.$$  

So $\gamma_{ij}$ is a continuous map $f_i: U_i \to R^d$ (identified with the subspace of units of $\Gamma_q$).

Two cocycles $\gamma_{ij}$ and $\gamma'_{ij}$ are equivalent if there exist continuous maps $\delta_i: U_i \to \Gamma_q$ such that $\gamma'_{ij}(x) = \delta_i(x)\gamma_{ij}(x)\delta_j(x)^{-1}$ for all $x \in U_i \cap U_j$. A $\Gamma_q$-structure on $X$ is an equivalence class of 1-cocycles after taking the limit over open covers of $X$. If $X$ is a smooth manifold and if the maps $f_i$ are submersions, then the 1-cocycle $\gamma_{ij}$ defines a smooth foliation of codimension $q$ on $X$. The construction above works as well if $\Gamma_q$ is replaced by any topological groupoid, for instance, the groupoid of germs of local analytic diffeomorphisms of $R^d$ or a Lie group $G$. The homotopy classes of $\Gamma_q$-structures on $X$ are in bijective correspondence with the homotopy classes of continuous maps from $X$ to the classifying space $B\Gamma_q$.

In 1971 Harold Rosenberg gave a course on foliation theory, and Thurston was among his students. Harold realized immediately that he was a brilliant student, and by the end of the course they wrote a paper together containing a lot of interesting geometric results. Meanwhile, in that year, Godbillon explained in a meeting at Oberwolfach the construction of the invariant GV of Godbillon and Vey, but at this time they did not know if it was trivial or not (but Roussarie, who was attending the meeting, almost immediately found a nontrivial example). When Lawson came back from this meeting he did not know the example of Roussarie; he explained the construction of the invariant to Bill (extract from an email): "I showed him the definition. The next day he knocked on my door, and said: 'The invariant is nontrivial.' The following day he knocked again, and this time said: 'The invariant can assume any real number.' WHAT????!!! Who is this fellow? I said to myself."

Very quickly after that, connections of the
Gelfand-Fuchs cohomology with the cohomology of various classifying spaces for foliations were understood theoretically and independently by many people.

Thurston got his PhD in Berkeley in early 1972. His thesis adviser was Moe Hirsch, and Blaine Lawson was the examiner. Bill submitted his thesis entitled “Foliations on 3-manifolds which are circle bundles” to Inventiones. The referee suggested that the author should give more explanations. As a consequence, Thurston, who was busy proving more theorems, decided not to publish it.

Meanwhile, John Mather became independently interested in discovering properties of classifying spaces for foliations. In 1971 he wrote several papers and preprints proving deep theorems on $B\Gamma$. His approach to foliation theory was not as geometric as Thurston’s, but nevertheless was very efficient.

When Rosenberg came back to Paris after his stay in Berkeley, he invited Bill to Paris. When he heard that we organized, at the last moment, the meeting in Les Plans-sur-Bex, Rosenberg brought Bill with him. Also participating in this meeting were A’Campo, Hector, Herman, Moussu, Siebenmann, Roger, Roussarie, Tischler, Vey, Wood, my student Banyaga from Rwanda, and many others.

Under the suggestion of Lawson, Milnor invited Bill (as his “assistant”) and me for the academic year 1972–73 to the IAS. Our two families were neighbors in the housing project of the institute. We organized a seminar which met once a week. Several people participated in it, and Bill gave several talks, always with new surprising results and ideas. In April 1973 I went back to Geneva.

On May 4, 1973, I wrote to William Browder a letter of recommendation for Bill for a position at Princeton University. In this letter I summarized the impressive list of results so far obtained by Thurston during this academic year: for instance, the deep connection between the homology of the group of diffeomorphisms of $R^n$ with support in compact sets and the homology of $B\Gamma_n$; the fact that any field of 2-planes on a manifold (in codimension $>1$) is homotopic to a smooth integrable one; an obstruction theory for deforming a field of $p$-planes on an $n$-manifold into a smooth integrable one (provided that $n-p>1$), as a consequence that a field of $p$-planes whose normal bundle is trivial can be deformed to a smooth integrable one; also that in contrast there is no obstruction to deform a field of $p$-planes into one tangent to a $C^0$-foliation, etc. As a conclusion I wrote: “I am very much impressed by the way he understands mathematics. He has a very direct and original way of looking at geometrical questions and an immediate understanding. He has sometimes difficulties to fill in the details of a proof, but after a while you realize the few words that he has written are just the essential ones.”

In a letter dated August 16, 1973, Thurston sent me, for publication in Comment. Math. Helv., the manuscript of his paper “The theory of foliations of dimension greater than one.” In the same letter, he sent me the preprint of a paper about volume-preserving diffeomorphisms of $T^n$ and said that he would send me a paper on the construction of foliations on 3-manifolds.

On October 10 he sent me a letter of six pages from Cambridge, Massachusetts, indicating the changes he made in his manuscript to take account of my remarks. In the last five pages he explained to me in detail the proof of his generalization of the Reeb stability theorem. In addition, he sent three pages of corrections of his manuscript for CMH.

On December 7, 1973, he sent me the corrected version of his manuscript. In a letter of seven pages, he explained his generalization of the classifying theorem to codimension one.

During the summer of 1976 a big symposium was organized by the University of Warwick. Thurston, Milnor, Vey, Mather, and Hirsch were among the participants. With our two boys, at that time very much interested in folk music, we drove from Switzerland to Warwick, where we stayed for two weeks. The enclosed picture shows a huge pile of straw built up by Bill and the youngsters. On the top were sitting my two boys and the older daughter of Milnor; on the side one can see Bill and many others. Moe Hirsch played a lot of folk music with my boys, and Vey beautifully sang traditional French songs.

From August 25 to September 4, 1976, a summer school organized by the CIME took place in Varenna in Italy. Thurston, Mather, and I gave expository courses on foliations. In addition, many participants gave talks, like Sergeraert; Banyaga spoke on his thesis concerning the group of symplectic diffeomorphisms of a compact symplectic manifold. This was a generalization of a nonpublished preprint of Thurston on the group of volume-preserving diffeomorphisms. Vaughn Jones, then a student in Geneva, was among the participants.

Thurston gave a beautiful course, but he did not write it up. At that time he was not interested anymore in foliations, but was planning to teach at Princeton a course on hyperbolic geometry.
Remembering Bill

In December 1970 I gave a lecture at UC Berkeley on my theorem that any foliation of a compact 3-manifold by circles is a Seifert fibration. After the lecture, Moe Hirsch, Bill’s PhD supervisor, introduced us, and Bill told me rather diffidently that he knew how to decompose $\mathbb{R}^3$ into round planar circles. He further explained that his circles did not form a foliation. Forty-three years later, I’m still wondering how this is possible.

I next heard from Bill when he wrote me a long letter (airmail; email did not yet exist) about foliations, classifying spaces, and Haefliger structures, with lots of hand-drawn diagrams and spectral sequences—quite a bit more than I was able to digest. Here’s one sentence to give you the flavor: You’ll see the point if you squint at this diagram. I worked for a long time on Bill’s letter, eventually coming up with a counterexample to one of the statements, thinking to myself with relief that now that I had found the error, I could stop struggling. However, by return post, Bill fixed the problem, at which point I had to reconcile myself to incomprehension.

In an interesting essay, “On proof and progress in mathematics,” Bill distinguishes between the way he contributed to foliation theory and the way he contributed to 3-manifold theory. The huge and daunting advances he made in foliation theory were off-putting, and students stopped going into the area, resulting in an unfortunate premature arrest in the development of the subject while it was still in its prime. (If someone writes a book incorporating Bill’s advances, it will take off again.) In contrast, Bill’s huge and daunting contributions to low-dimensional manifold theory were buttressed by substantial notes written by Bill and his students (not formally published but very widely circulated) and by notes by others. These fleshed out the infrastructure of the subject, easing the task of those who wished to push Bill’s work further. Later, there was also a beautiful book, Three-Dimensional Geometry and Topology, by Bill and Silvio Levy.

I knew Bill well during his marriage with Rachel Findley, and my remarks and reminiscences relate to that period, ending around 1993. I used to visit Princeton quite often, where I stayed in their large, untidy, warmly hospitable university-owned house, just a short walk from Fine Hall. Bill discovered or invented interesting mathematics all the time, in diverse situations, and there was never time to fully formalize and make public all or even a major part of what he thought about. As just one example, he developed probability distributions on the set of mazes made from a grid by marking certain edges as impenetrable walls, as found in children’s magazines, and was delighted by his computer program that churned out random mazes of a prescribed level of difficulty.

Talking mathematics to Bill was interesting, inspiring, and frustrating. I often wished that I had a tape recorder: while listening to him, I was sure I understood. But when I tried to reconstruct the conversation, I almost always found difficulties. After some work, I would focus on one particular point where I asked urgently for clarification. Instead of answering, he would say, “Maybe you would like this other proof better,” which he would then explain to me. And the process would repeat itself. On the other hand, reading, understanding, and helping to smooth the rough edges in Bill’s notes was an enthralling and rewarding task from which I learned an enormous amount, and I believe the same was true for his many other helpers.

The difficulties that people had in understanding Bill’s mathematics made him very alive to the problems of mathematical education. His views continue to be widely quoted. Even more striking than his writings were his experiments into a different way of teaching. Al Marden, the director of the Geometry Center in Minneapolis, had made it easy for me to visit frequently, so I arrived there in the summer of 1991, to find an atmosphere
of great intellectual ferment during a course entitled Geometry and the Imagination, given by Bill, John Conway, Peter Doyle, and Jane Gilman. The audience was a mixture of school children, undergraduates, school teachers, and college teachers of mathematics. Some of the material for this course is available online,\textsuperscript{18} where I strongly recommend any reader interested in mathematics or in mathematical education to spend time.

Some of the school children in the audience excitedly explained to me that Peter Doyle had just smeared the tires of his bicycle with mud, that enormous blank posters had been spread out on the floor of the Geometry Center, and that Peter had then cycled around the huge room while members of the audience were excluded. The first task of the audience, working in small groups, was to demolish the reasoning of Sherlock Holmes, quoted in The Adventure of the Priory School: “The more deeply sunk impression is, of course, the hind wheel, upon which the weight rests. You perceive several places where it has passed across and obliterated the more shallow mark of the front one. It was undoubtedly heading away from the school.” The audience’s second task was to correctly deduce from the mud-stained posters the direction of travel. Peter’s ingenious solution is explained in “Which way did the bicycle go?” \textsuperscript{19} by Stan Wagon and co-authors. Stan, from Macalester College, ‘round the corner from the Geometry Center, was a contributor to this course and was, I am told, in the audience at the time.

Bill arranged many courses like this, at many different levels. Quite a few good mathematicians currently in post at universities in the US and around the world were inspired by one or more of his courses.

I cannot omit mention of the two videos, \textit{Not Knot} and \textit{Outside In}, in which some of Bill’s ideas were concretely realized by Geometry Center staff. These winners of major worldwide prizes are still freely available for your enjoyment and amazement on YouTube. Each explains significant and accessible mathematics. (Each of the videos has an associated booklet to make deeper study more easily accessible.)

Bill was a pioneer in the use of computers as a tool in pure mathematics, an aspect of his strongly constructivist point of view. In fact, he wondered whether to study logic rather than topology for his PhD, but was dissuaded by Tarski, who told him that the logicians at Berkeley were not interested in intuitionism. Bill suggested to me the use of “hollow exist,”\textsuperscript{3} to denote the result of a nonconstructive existence proof (like Cantor’s proof of the existence of transcendental numbers). Bill wanted more than constructivism, something like “rapid constructivism,” with programs that complete in a reasonable amount of time. Jeff Weeks, one of Bill’s many talented students, developed SnapPea, a program that computes, if it exists, a complete hyperbolic structure on a simplicial 3-manifold. This program, based on Bill’s ideas, has been used in many significant projects. It can be used to give a quick proof that two simplicial 3-manifolds are not homeomorphic or that two complicated knots are not equivalent.

During the early 1980s, Bill decided that the Fine Hall pure mathematicians should be introduced to computing. The funding that he raised covered the purchase of a computer (very expensive at that time) but not the cost of employing a person. I remember Bill going in to Fine Hall over the weekend to himself lay all necessary cables. He also became the local UNIX expert and an intrepid systems programmer. When the very large UNIX editing program \textit{vi} didn’t behave correctly, he decided to debug the code. Unsurprisingly, this venture failed. On another occasion, a graduate student invented a process that continually spawned clones of itself until the machine was full. It was a science fiction scenario: if one of the clones was killed, one of the other clones would immediately construct a replacement. Bill was determined to find a humane method of getting rid of the clones that would not entail switching off the machine, and he eventually succeeded where most professional systems programmers would have failed. Computer-related activity of this kind took up a good deal of his time, time that the mathematical community might have preferred him to devote to writing up his mathematical discoveries, but Bill placed a high priority on converting his colleagues to the use of computers.

Bill and Rachel grew up during the Vietnam War and were strongly opposed to US military activities. Rachel was particularly active. In the early 1980s, as the usefulness of computers to pure mathematicians increased (partly because of the spread of computer typesetting by \LaTeX, the DOD (US Department of Defense) started to fund grants to pure mathematicians that were hard to refuse because alternative funding for computers was not readily available. Some of these grants dispensed with peer review and were funneled through the CIA. Mike Shub resigned from New York’s City University over the issue and started a campaign against the acceptance of military funds by academics, in which Bill became involved. Those

\textsuperscript{18}\url{http://www.geom.uiuc.edu/docs/education/institute91/handouts/handouts.html}

\textsuperscript{19}J. D. E. Kronhauser, D. J. Velleman, and Stan Wagon, MAA, 1996.
with access to the Notices of the AMS for 1987 and 1988 will find interesting correspondence on this issue, with many different points of view represented, including letters from Bill. Eventually, in 1988, the AMS passed a resolution calling for a greater effort to decrease the proportion of funding for mathematics research coming from the DoD. At the same time, the AMS declared skepticism about SDI, Reagan’s Star Wars program. Typically, Bill was not jubilant over the decision he had fought for and won, and was rather concerned at the dismay of applied mathematicians, who had a tradition of accepting military funds and who did not agree that this had a dangerous effect on the values of civil society.

During the period when I knew him well, Bill enjoyed life thoroughly. At conferences, and often at Fine Hall, he would organize and enthusiastically participate in games of volleyball. He had a great sense of humor. When my wife, staying with the Thurston’s, asked about their clothes dryer, he puzzled her briefly by replying that it was solar-powered. He earned a stiff reprimand from Princeton township officials for tapping a fine maple tree on the street outside his home for its syrup, which he did carefully, with the proper equipment. He was a passionately involved father, and I have vivid memories of him with his children. He was an excellent cook who would regularly produce both everyday meals and special treats, such as his unique peach ice cream. He loved games, picnics, socializing, and talking at a deeper level than chit chat. He was a very considerate friend. Bill was a person of exceptional warmth, whose presence, once experienced, will never be forgotten.

**Dennis P. Sullivan**

**A Decade of Thurston Stories**

**First Story**

In December of 1971 a dynamics seminar ended at Berkeley with the solution to a thorny problem in the plane which had a nice application in dynamics. The solution purported to move N distinct points to a second set of “epsilon near” N distinct points by a motion which kept the points distinct and moved while staying always “epsilon prime near.” The senior dynamicists in the front row were upbeat because the dynamics application up to then had only been possible in dimensions at least three, where this matching problem is obvious by general position, but now the dynamics theorem also worked in dimension two.

A heavily bearded, long-haired graduate student in the back of the room stood up and said he thought the algorithm of the proof didn’t work. He, Bill Thurston, went shyly to the blackboard and drew two configurations of about seven points each and started applying to these the method at the end of the lecture. Little paths started emerging and getting in the way of other emerging paths, which, to avoid collision, had to get longer and longer. The algorithm didn’t work at all for this quite involved diagrammatic reason. I had never seen such comprehension and such creative construction of a counterexample done so quickly. This combined with my awe at the sheer complexity of the geometry that emerged.

**Second Story**

A couple of days later, the grad students invited me (I was also heavily bearded with long hair) to paint math frescoes on the corridor wall separating their offices from the elevator foyer. While milling around before painting, that same graduate student came up to ask, “Do you think this is interesting to paint?” It was a complicated smooth one-dimensional object encircling three points in the plane. I asked, “What is it?” and was astonished to hear, “It is a simple closed curve.” I said, “You bet it’s interesting!”. So we proceeded to spend several hours painting this curve on the wall. It was a great learning and bonding experience. For such a curve to look good it has to be drawn in sections of short parallel slightly curved strands (like the flow boxes of a foliation) which are subsequently smoothly spliced together. When I asked how he got such curves, he said, “By successively applying to a given simple curve a pair of Dehn twists along intersecting curves.” The “wall curve painting,” two meters high and four meters wide (see AMS Notices cover “Cave Drawings”), dated and signed “DPS and Dennis P. Sullivan is professor of mathematics at SUNY Stony Brook and Einstein Chair, CUNY Graduate Center. His email address is dennis@math.sunysb.edu.
BT, December, 1971” lasted on that Berkeley wall with periodic restoration for almost four decades before finally being painted over a few years ago.

Third Story
That week in December 1971 I was visiting Berkeley from MIT to give a series of lectures on differential forms and the homotopy theory of manifolds. Since foliations and differential forms were appearing everywhere, I thought to use the one-forms that emerged in my story describing the lower central series of the fundamental group to construct foliations. Leaves of these foliations would cover graphs of maps of the manifold to the nilmanifolds associated to all the higher nilpotent quotients of the fundamental group. These would generalize Abel’s map to the torus associated with the first homology torus. Being uninitiated in Lie theory, I had asked all the differential geometers at MIT and Harvard about this possibility but couldn’t make myself understood. It was too vague, too algebraic. I presented the discussion in my first lecture at Berkeley, and to Bill privately, without much hope because of the weird algebra-geometry mixture. However, the next day Bill came up with a complete solution and a full explanation. For him it was elementary and really only involved actually understanding the basic geometric meaning of the Jacobi relation in the Elie Cartan $dd = 0$ dual form.

In between the times of the first two stories above I had spoken to old friend Moe Hirsch about Bill Thurston, who was working with Moe and was finishing in his fifth year after an apparently slow start. Moe or someone else told how Bill’s oral exam was a slight problem, because when asked for an example of the universal cover of a space Bill chose the surface of genus two and started drawing awkward octagons with many (eight) coming together at each vertex. This exposition quickly became an unconvincing mess on the blackboard. I think Bill was the only one in that exam room who had ever thought about such a nontrivial universal cover. Moe then said, “Lately, Bill has started solving thesis-level problems at the rate of about one every month.” Some years later, I heard from Bill that his first child, Nathaniel, didn’t like to sleep at night, so Bill was sleep-deprived, “walking the floor with Nathaniel” for about a year of grad school.

That week of math at Berkeley was life-changing for me. I was very grateful to be able to seriously appreciate the Mozart-like phenomenon I had been observing, and I had a new friend. Upon returning to MIT after the week in Berkeley, I related my news to the colleagues there, but I think my enthusiasm was too intense to be believed: “I have just met the best graduate student I have ever seen or ever expect to see.” It was arranged for Bill to give a talk at MIT, which evolved into a plan for him to come to MIT after going first to IAS in Princeton. It turned out that he did come to MIT, for just one year 1973–74. (That year I visited IHES, where I ultimately stayed for twenty-odd years, while Bill was invited back to Princeton, to the University.)

Fourth Story
IAS Princeton, 1972–73
When I visited the environs of Princeton from MIT in 1972–73, I had chances to interact more with Bill. One day, walking outside towards lunch at IAS, I asked Bill what a horocycle was. He said, “You stay here,” and he started walking away into the institute meadow. After some distance he turned and stood still, saying, “You are on the circumference of a circle with me as center.” Then he turned, walked much farther away, turned back, and said something which I couldn’t hear because of the distance. After shouting back and forth to the amusement of the members, we realized he was saying the same thing, “You are on the circumference of a circle with me as center.” Then he walked even farther away, just a small figure in the distance and certainly out of hearing, whereupon he turned, and started shouting presumably the same thing again. We got the idea what a horocycle was.

Atiyah asked some of us topologists if we knew if flat vector bundles had a classifying space (he had constructed some new characteristic classes for such). We knew it existed from Brown’s theorem but didn’t know how to construct it explicitly. The next day, Atiyah said he asked Thurston this question, who did it by what was then a shocking construction: take the Lie structure group of the vector bundle as an abstract group with the discrete topology and form its classifying space. Later, I heard about Thurston drawing Jack Milnor a picture proving any dynamical pattern for any unimodal map appears in the quadratic family $x \rightarrow x^2 + c$. Since I was studying dynamics, I planned to spend a semester with Bill at Princeton to learn about the celebrated Milnor-Thurston universality paper that resulted from this drawing.

Fifth Story
Princeton University, Fall 1976
I expected to learn about one-dimensional dynamics upon arriving in Princeton in September 1976, but Thurston had already developed a new theory of surface transformations. In the first few days, he expounded on this in a wonderful three-hour extemporaneous lecture at the institute. Luckily
for me, the main theorem about limiting foliations was intuitively clear because of the painstaking Berkeley wall curve painting described above. At the end of the stay that semester, Bill told me he believed the mapping torus of these carried hyperbolic metrics. When I asked why, he told me he couldn't explain it to me because I didn't understand enough differential geometry. A few weeks after I left Princeton, with more time to work without my distractions, Bill essentially understood the proof of the hyperbolic metric for appropriate Haken manifolds. The mapping torus case took two more years, as discussed below.

During the semester graduate course that Bill gave, the graduate students and I learned several key ideas:

1. The quasi-analogue of "hyperbolic geometry at infinity becomes conformal geometry on the sphere at infinity." (A notable memory here is the feeling that Bill conveyed about really being inside hyperbolic space rather than being outside and looking at a particular model. For me this made a psychological difference.)

2. We learned about the intrinsic geometry of convex surfaces outside the extreme points. (Bill came into class one day, and, for many minutes, he rolled a paper contraption he had made around and around on the lecturer's table without saying a word until we felt the flatness.)

3. We learned about the thick-thin decomposition of hyperbolic surfaces. (I remember how Bill drew a fifty-meter-long thin part winding all around the blackboard near the common room, and suddenly everything was clear, including geometric convergence to the points of the celebrated DM compactification of the space of Riemann surfaces.)

During that fall 1976 semester stay at Princeton, Bill and I discussed understanding the Poincaré conjecture by trying to prove a general theorem about all closed 3-manifolds, based on the idea that three is a relatively small dimension. We included in our little paper on “Canonical coordinates...Commentarii” the sufficient for Poincaré conjecture possibility that all closed 3-manifolds carried conformally flat coordinates. (However, an undergrad, Bill Goldman, who was often around that fall, disproved this a few years later.) We decided to try to spend an academic year together in the future.

In the next period, Bill developed limits of quasi-Fuchsian Kleinian groups and pursued the mapping torus hyperbolic structure in Princeton, while I pursued the Ahlfors limit set measure problem in Paris. After about a year, Bill had made substantial positive progress (e.g., closing the cusp), and I had made substantial negative progress (showing all known ergodic methods coupled with all known Kleinian group information were inadequate: there was too much potential nonlinearity). We met in the Swiss Alps at the Plan-sur-Bex conference and compared notes. His mapping torus program was positively finished but very complicated, while my negative information had revealed a rigidity result extending Mostow’s, which allowed a considerable simplification of Bill’s fibering proof. (See the Bourbaki report on Thurston’s work during the next year.)

Sixth Story
The Stonybrook Conference, Summer 1978

There was a big conference on Kleinian groups at Stonybrook, and Bill was in attendance but not as a speaker. Gromov and I got him to give a lengthy impromptu talk outside the schedule. It was a wonderful trip out into the end of a hyperbolic 3-manifold, combined with convex hulls, pleated surfaces, and ending laminations…. During the lecture, Gromov leaned over and said watching Bill made him feel like “this field hadn’t officially started yet.”

Seventh Story
Colorado, June 1980 to August 1981

Bill and I shared the Stanislaus Ulam Visiting Professorship at Boulder and ran two seminars: a big one drawing together all the threads for the full hyperbolic theorem and a smaller one on the dynamics of Kleinian groups and dynamics in general. All aspects of the hyperbolic proof passed in review with many grad students in attendance. One day in the other seminar, Bill was late. Dan Rudolph was very energetically explaining in just one hour a new, shorter version of an extremely complicated proof. The theorem promoted an orbit equivalence to a conjugacy between two ergodic measure-preserving transformations if the discrepancy of the orbit equivalence was controlled. The new proof was due to a subset of the triumvirate Katznelson, Ornstein, and Weiss and was notable because it could be explained in one hour, whereas the first proof took a minicourse to explain. Thurston at last came in and asked me to bring him up to speed, which I did. The lecture continued to the end with Bill wondering in loud whispers what the difficulty was and with me shushing him out of respect for the context. Finally, at the end, Bill said, just imagine a bi-infinite string of beads on a wire with finitely many missing spaces and (illustrated by full sweep of his extended arm) just slide them all to the left, say. Up to some standard bookkeeping this gave a new proof. Later that day an awe-struck Dan Rudolph said to me he never realized before then just how smart Bill Thurston really was.
Eighth Story
La Jolla and Paris, End of Summer 1981

The Colorado experience was very good, relaxing in the Thurston seminar with geometry (one day we worked out the eight geometries and another day we voted on terminology “manifolded” or “orbifold”) and writing several papers of my own. We worked out the eight geometries and another will see, the audience was formidable (Ahlfors, Bott, California and Paris, and the first day, awaking back and forth, so that by 8:00 a.m. his time, and he responded more fully. We took some discipline, but as viewers of the videos then goodbye to colleagues and back to bed. This came when presenting Bill's delicious argument. I noticed a phone on the desk by then, it was around 4:00 a.m. California time and 7:00 a.m. in Princeton. I called Bill's house, and he answered. I posed my questions. He gave quick responses, I took notes, and he said call back after he dropped the kids at school and got to his office. I gave my objections to his answers around 9:30 a.m. his time, and he responded more fully. We ended up with various alternate routes that all in covered every point. By 8:00 a.m. my time, I had a pair of lectures prepared. The first day went well: lecture, lunch/beach/swim, second lecture, dinner, then goodbye to colleagues and back to bed. This took some discipline, but as viewers of the videos will see, the audience was formidable (Ahlfors, Bott, Chern, Kirby, Siebenmann, Edwards, Rosenberg, Freedman, Yau, Maskit, Kra, Keen, Dodziuk,...).

Bill and I repeated this each day, perfecting the back and forth, so that by 8:00 a.m. California time each day, I had my two lectures prepared, and they were getting the job done. The climax came when presenting Bill’s delicious argument that controls the length of a geodesic representing the branching locus of a branched pleated surface by the dynamical rate of chaos or entropy created by the geodesic flow on the intrinsic surface. One knows that this is controlled by the area growth of the universal cover of the branched surface, which by negative curvature is controlled by the volume growth of the containing hyperbolic 3-space. QED. There was in addition Bill's beautiful example showing the estimate was qualitatively sharp. This splendid level of lecturing was too much for Harold Rosenberg, my astute friend from Paris, who was in the audience. He came to me afterwards and asked frustratingly, “Dennis, do you keep Thurston locked up in your office upstairs?” The lectures were taped by Michael Freedman, and I have kept my lips sealed until now. The taped Thurstons-Sullivan lectures are available online.²⁰

Ninth Story
Paris, Fall 1981

Bill visited me in Paris, and I bought a comfy sofa bed for my home office where he could sleep. He politely asked what would I have talked about had I not changed plans for the AMS lectures and, in particular, what had I been doing in detail in Colorado beyond the hyperbolic seminar. There were about six papers to tell him about. One of the most appealing ideas I had learned from him: namely, that the visual Hausdorff-dimensional measure of an appropriate set on the sphere at infinity, as viewed from a point inside, defines a positive eigenfunction for the hyperbolic 3-space Laplacian with eigenvalue \( f(2 − f) \). I started going through the ideas and statements. I made a statement, and he either immediately gave the proof or I gave the idea of my proof. We went through all the theorems in the six papers in one session, with either him or me giving the proof. There was one missing result: that the bottom eigenfunction when \( f > 1 \) would be represented by a normalized eigenfunction whose square integral norm was estimated by the volume of the convex core. Bill lay back for a moment on his sofa bed, his eyes closed, and immediately proved the missing theorem. He produced the estimate by diffusing geodesics transversally and averaging. Then we went out to walk through Paris from Port d’Orleans to Port de Cagnanourt. Of course, we spoke so much about mathematics that Paris was essentially forgotten, except maybe the simultaneous view of Notre Dame and the Conciergerie as we crossed over the Seine.

Tenth Story
Princeton-Manhattan, 1982–83

I began splitting time between IHES and the CUNY Grad Center, where I started a thirteen-year-long Einstein chair seminar on dynamics and quasi-conformal homeomorphisms (which changed then to quantum objects in topology), while Bill continued developing a cadre of young geometers to spread the beautiful ideas of negatively curved space. Bill delayed writing a definitive text on the hyperbolic proof in lieu of letting things develop along many opening avenues by his increasingly informed cadre of younger/older geometers. He wanted to avoid in hyperbolic geometry what had happened when his basic papers on foliations “tsunamied” the field in the early 1970s. Once,

²⁰www.math.sunysb.edu/Videos/Einstein
we planned to meet in Manhattan to discuss holomorphic dynamics in one variable and the analogy with hyperbolic geometry and Kleinian groups that I had been preoccupied with. We were not disciplined and began talking about other things at the apartment; we finally got around to our agenda about thirty minutes before Bill had to leave for his train back to Princeton. I sketched the general analogy: Poincaré limit set, domain of discontinuity, deformations, rigidity, classification, Ahlfors finiteness theorem, the work of Ahlfors-Bers,...to be compared with Julia set, Fatou set, deformations, rigidity, classification, non-wandering domain theorem, the work of Hubbard-Douady..., which he perfectly and quickly absorbed until he had to leave for the train. Two weeks later we heard about his reformulation of a holomorphic dynamical system as a fixed point on Teichmüller space, analogous to part of his hyperbolic theorem. There were many new results, including those of Curt McMullen some years later, and the subject of holomorphic dynamics was raised to another higher level.

Postscript

Bill and I met again at Milnor’s eightieth fest at Banff—Bill’s “Jackfest” lecture is pictured above—after essentially thirty years and picked up where we had left off. (I admired his checked green shirt the second time it appeared, and he presented it to me the next day.) We promised to try to attack together a remaining big hole in the Kleinian group/holomorphic dynamics dictionary: “the invariant line field conjecture.” It was a good idea, but unfortunately turned out to be impossible.
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The Notices solicited the following articles about the works of the four individuals to whom Fields Medals were awarded at the International Congress of Mathematicians in Seoul, South Korea, in August 2014. This was a historic occasion, as it marked the first time since the medal was established in 1936 that a woman was among the recipients. The International Mathematical Union also issued news releases describing the medalists’ work, and these appeared in the October 2014 issue of the Notices.

—Allyn Jackson
The Work of Artur Avila

Artur Avila was awarded the Fields Medal in 2014 for his deep contributions to dynamical systems and to the spectral theory of one-frequency Schrödinger operators. Many of his profound achievements—in one-dimensional dynamics, both real and complex, as well as in flat billiards and in the spectral theory of Schrödinger operators—are characterized by an intense use of the powerful ideas of renormalization. He has also made deep advances in the theory of conservative dynamical systems in any dimension and in the stable ergodicity of partially hyperbolic systems.

Artur Avila was born in Rio de Janeiro, Brazil, where he lived until he finished his PhD studies at the Instituto de Matemática Pura e Aplicada (IMPA) in 2001. Before starting his postdoc position in the Collège de France in Paris, Artur, with collaborators, obtained a complete description of typical dynamics of unimodal interval maps, i.e., smooth interval maps with a unique nonflat critical point. It was already known that the space of unimodal maps contains two disjoint regions where the dynamics is well understood. For maps in the regular region, there exists a unique attracting fixed point, and the trajectories of almost all initial conditions, in the Lebesgue measure sense, are asymptotic to this periodic point. The typical dynamical behavior is therefore periodic. For maps in the stochastic region the dynamics is chaotic but with a good statistical description: there exists an absolutely continuous invariant measure that controls the dynamics of a typical orbit in the sense that the time average of any physical observable is equal to the space average of the observable with respect to this measure. In particular, the typical behaviour of a typical orbit to any interval is equal to the measure of this interval. In the complement of these two regions there are maps where the dynamics can be completely described but there are other maps whose dynamics is pathological. These different dynamical behaviours were already present in the famous quadratic family

\[ x \in [0, 1] \mapsto q_n = \mu x (1 - x), \]

where the parameter \( \mu \) belongs to the interval (0, 4). The set of parameter values corresponding to regular maps is open and dense by a difficult result proved in [18] and [20]. On the other hand, the set of parameter values corresponding to stochastic maps has positive Lebesgue measure, as proved in [20], and the complement has measure zero [22] but positive Hausdorff dimension. The main result in [3, 9] is that, for typical one-dimensional families of unimodal maps, one does not see the third region; i.e., the set of parameter values corresponding to maps in the third region has Lebesgue measure zero. For a typical one-parameter family of unimodal maps we have a decomposition of the parameter space with the same properties as the quadratic family.

Another important result in his early career is the unexpected rigidity in the space of unimodal maps obtained in [10]. In this article it is shown that there is a large set \( R \) of unimodal maps such that any typical one-parameter family intersects \( R \) in a set of parameters of full Lebesgue measure in the complement of the regular parameters and any two maps in \( R \) that are topologically conjugate are in fact smoothly conjugate. In particular, the authors provide a combinatorial formula to calculate the multipliers of all periodic points for maps in \( R \).

More recently, in complex one-dimension dynamics, Avila and Lyubich described several fundamental properties on the geometry of the Julia set of Feigenbaum-type quadratic polynomials [6], [7], [2], [3], [4]. In particular, the existence of examples of such quadratic polynomials with Julia sets of positive Lebesgue measure is proven.

In most of these results, Avila uses as a fundamental tool the renormalization theory. This theory started with experimental discovery by the physicists Feigenbaum and Coullet-Tresser in the 1970s on the transition from simple to chaotic dynamics in families of unimodal maps. They formulated a conjecture that involves a nonlinear operator in the space of unimodal maps. The proof of the conjecture and some generalizations involve the work of several mathematicians such as Sullivan, McMullen, and Lyubich. Finally, Avila and Lyubich in [16] gave a very conceptual and much simpler proof of the general conjecture that holds also in the space of unimodal maps with higher criticality.

A second area of dynamical systems where Avila made fundamental contributions is the dynamics of interval exchange transformations, regular polygonal billiards, and ergodic properties of the geodesic Teichmüller flow in the moduli space of Abelian differentials on Riemann surfaces.

Given a partition \( I_1, \ldots, I_d \) of the interval \([0, 1]\) in \( d \geq 2 \) intervals and a permutation \( \sigma \) of \( \{1, \ldots, d\} \), we can define the mapping \( T: [0, 1] \to [0, 1] \) by

\[ T(x) = x - \sum_{j \in \sigma^{-1}(\sigma(j) + 1)} \lambda_j \]

if \( x \in I_i \), where \( \lambda_j \) is the length of the interval \( I_j \). This is what is called an interval exchange transformation, and it is completely characterized by the permutation \( \sigma \) and by the vector \((\lambda_1, \ldots, \lambda_d)\) that belongs to a simplex in \( \mathbb{R}^d \). The space of such maps is therefore finite dimensional. We say that a subset is typical if the complement has
zero Lebesgue measure. Veech proved that for any irreducible permutation the typical interval exchange transformation is uniquely ergodic. In 1980 Katok proved that no interval exchange transformation is mixing. Recall that a measure-preserving transformation $f: (X, \mu) \to (X, \mu)$ is mixing if

$$\lim_{n \to \infty} [\mu(f^{-n}(A) \cap B - \mu(A)\mu(B))] = 0$$

for any measurable sets $A$ and $B$, and it is weak mixing if

$$\lim_{N \to \infty} \frac{1}{N} \sum_{n=0}^{N} [\mu(f^{-n}(A) \cap B - \mu(A)\mu(B))] = 0.$$ 

The joint work of Avila and Forni [11] solved the main problem in the ergodic theory of interval exchange transformation: a typical interval exchange transformation is weakly mixing for any irreducible permutation that is not a rotation. This work is connected to a recent result of Avila and Delecroix proving that almost all regular polygonal billiards are weakly mixing. Again, one of the main tools for these results is a renormalization operator that consists of considering the first return map to a smaller interval and rescaling to the original size. It is called the Rauzy-Veech renormalization operator. Veech and Masur proved that it has an absolutely continuous invariant measure, and the ergodic properties of the operator give important information about the ergodic properties of a typical interval exchange transformation. The invariant measure is not finite, but in [25] Zorich defined an accelerated version of the renormalization operator, called the Rauzy-Veech-Zorich operator, that does have a finite absolutely continuous invariant measure. The new operator maps each interval exchange transformation into an iterate of the previous operator, the iterate depending on the interval exchange transformation. The dynamics of this new operator is closely related to the so-called Teichmuller geodesic flow that acts in the moduli space of Abelian differentials in compact Riemann surfaces of a given genus. Zorich experimentally discovered the existence of $d$ exponents that for a typical interval exchange transformation with $d$ intervals describes the deviation of the ergodic average from the mean and found that these exponents are given by the Lyapunov spectrum of the so-called Rauzy-Veech-Zorich cocycle over the renormalization operator. In [12] Avila and Viana proved the Kontsevich-Zorich conjecture stating that the Lyapunov spectrum of the Rauzy-Veech-Zorich cocycle is simple. Another important result in this area was obtained by Avila and collaborators establishing the exponential decay of correlation of the Teichmüller flow on strata of the moduli space of Abelian differentials that was conjectured by Veech.

The area of one-frequency Schrödinger operators was very active before the arrival of Avila. In particular, it was known that if one multiplies an analytic potential by a coupling constant generating a one-parameter family of operators, then for very small values of the coupling constant the spectrum of the operator is absolutely continuous, and for very large values the spectrum is pure point for typical values of the frequency. Not much was known for values of the coupling constant in between. However, it was known that to an operator corresponds a one-parameter family of $SL(2, \mathbb{R})$ cocycles, parmetrized by the energy, and it was known that the spectrum coincides with the bifurcation set of the dynamical object. These are the values of the parameter such that the cocycle is not uniformly hyperbolic. Probably inspired by the results in one-dimensional dynamics, Avila described three regions in this space of cocycles: UR (uniform hyperbolic), SpC (supercritical), and SbC (subcritical) and called the complement of these C (critical). The cocycles in SpC are not uniformly hyperbolic but have positive Lyapunov exponents and were already well understood. The part of the spectrum of the operator that lies in this region corresponds typically to the pure point spectrum. Avila proved that the part of the spectrum that lies in SbC corresponds to the absolutely continuous part of the spectral measure. Finally, he proved the existence of a stratification of the space into submanifolds of positive codimension and that the set of critical cocycles is a small subset, in the measure-theoretic sense, of these submanifolds [23]. As a consequence, Avila proved that a typical one-parameter family of cocycles does not contain critical cocycles at all. Also as a consequence of Avila’s construction, the spectrum of an operator corresponding to a typical potential, in a measure theoretical-sense (prevalence), decomposes into a finite number of disjoint open sets, and the spectral measure is absolutely continuous or pure point on a given open set if and only if the Lyapunov exponent is zero or positive in this region. This result justifies the intuition from physics that typically one is either in the conductor regime (absolutely continuous spectrum) or the insulator regime (pure point spectrum).

An intensely studied family of Schrödinger operators is the family of almost Mathieu operators, which is related to a celebrated physical phenomena, the quantum Hall effect. This family is not typical in the above sense because it has a critical cocycle where the coupling constant is equal to one. This is forced by a symmetry, the Aubry duality. Before the arrival of Avila in this area, much was known about this family. For example, for almost all frequencies and phases the spectrum is absolutely continuous in the subcritical region (coupling constant smaller than one) and pure point in the supercritical region. Also, the spectrum has positive Lebesgue measure in both regions. Still, some important questions remained open. Avila solved all the
remaining questions about the spectral measure of the almost Mathieu system: the spectrum is a Cantor set for critical values of the coupling constant for all irrational frequencies [14]; it has zero Lebesgue measure [24]; and for all irrational frequencies and almost all phases, the spectrum is continuous singular. To summarize, one can now say with Avila that the spectral measure is absolutely continuous precisely in the subcritical case and pure point precisely in the supercritical case.

In another area of dynamical systems, Avila proved that a $C^1$ volume-preserving diffeomorphism of a compact manifold can be approximated in the $C^1$ topology by a $C^\infty$ volume-preserving diffeomorphism [1]. This was an open question for more than thirty years, and Avila’s proof involves solving a partial differential equation with low regularity. The result is very relevant for the description of generic properties of conservative dynamical systems, because another fundamental tool, the closing lemma, is known only in the $C^1$ topology, and for good distortion estimates one needs higher regularity.

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Bjorn Poonen

The Work of Manjul Bhargava

Anyone solving equations over $\mathbb{Z}$ or $\mathbb{Q}$ soon recognizes the need to study the arithmetic of higher number fields and algebraic varieties. Manjul Bhargava has found new and improved ways to count many such objects by understanding the orbits of $G(\mathbb{Z})$ on $V(\mathbb{Z}) := \mathbb{Z}^n$ for various representations of algebraic groups $G = \text{GL}(V)$ over $\mathbb{Z}$. This has led to dramatic consequences in arithmetic geometry concerning the average behavior of elliptic curves and higher-genus curves over $\mathbb{Q}$.

Counting Number Fields

Consider the problem of estimating the number of isomorphism classes of degree $n$ number fields $k$ whose absolute discriminant $|D_k|$ satisfies $|D_k| \leq X$ as $X \to \infty$. The primitive element theorem guarantees that each such $k$ is obtained by adjoining a root of a degree $n$ irreducible polynomial over $\mathbb{Q}$. But there are many polynomials giving rise to each number field, and eliminating the redundancy is tricky.

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One can attempt to solve this and other arithmetic counting problems by following the outline below:

1. Identify a representation \( G \rightarrow \text{GL}(V) \) and local conditions (inequalities and congruence conditions) such that the nondegenerate \( G(\mathbb{Z}) \)-orbits in \( V(\mathbb{Z}) \) satisfying the local conditions parametrize the objects of interest.

2. Count the orbits satisfying the inequalities by counting lattice points inside a fundamental domain (a region in \( V(\mathbb{R}) \) consisting of one representative of each \( G(\mathbb{Z}) \)-orbit).

3. Sieve out the orbits that violate the congruence conditions.

Davenport and Heilbronn [19] successfully carried out this three-step approach to count degree 3 number fields of bounded discriminant (and they were preceded by Gauss, who studied the average behavior of class numbers of quadratic fields, possibly by a similar method). As will be explained, Bhargava has contributed significant ideas improving all three steps, enabling him to carry out this approach in much more complicated situations.

Consider Step 1. Davenport and Heilbronn used a bijection taking certain \( \text{GL}_2(\mathbb{Z}) \)-orbits in the space \( \text{Sym}^2 \mathbb{Z}^2 \) of degree 3 homogeneous forms over \( \mathbb{Z} \) to degree 3 number fields. For \( n \geq 4 \), however, the representation \( \text{Sym}^n \mathbb{Z}^2 \) of \( \text{GL}_2 \) does not yield a similar parametrization of degree \( n \) number fields. Instead, one studies prehomogeneous vector spaces, vector spaces \( V \) equipped with an algebraic group action for which geometrically there is a Zariski dense orbit. (The Zariski dense orbit condition is natural in hindsight, since any two degree \( n \) number fields become isomorphic when tensored with \( \mathbb{C} \).) Prehomogeneous vector spaces were classified in [27]. Wright and Yukie carried out a detailed study of their arithmetic over fields in [32]. In particular, they identified prehomogeneous spaces whose orbits over \( \mathbb{Q} \) gave rise to number fields of degrees 4 and 5, but they did not realize their goal of using these to count the fields.

Bhargava has gone through the list of prehomogeneous vector spaces to discover what their nondegenerate integral orbits correspond to, often with unexpected answers. For instance, whereas Wright and Yukie found a surjection taking nondegenerate \( \text{GL}_2(\mathbb{Q}) \times \text{GL}_3(\mathbb{Q}) \)-orbits in \( \mathbb{Q}^2 \otimes \text{Sym}^3 \mathbb{Q}^2 \) to degree 4 number fields, Bhargava discovered that nondegenerate \( \text{GL}_2(\mathbb{Z}) \times \text{GL}_3(\mathbb{Z}) \)-orbits in \( \mathbb{Z}^2 \otimes \text{Sym}^3 \mathbb{Z}^2 \) correspond to commutative rings of rank 4 over \( \mathbb{Z} \) equipped with a cubic resolvent ring (a notion he invented). There seems to be no recipe for predicting what extra arithmetic structure is rendered visible by considering integral orbits, but Bhargava has heuristics that have guided him to an answer in each case.

The extra structure can be a nuisance or a boon. It is a nuisance when counting degree 4 fields, for instance, because each field contains many orders (subrings that are free over \( \mathbb{Z} \) of the same rank as the field), and each order can have many cubic resolvent rings. But it is a boon if the extra structure itself is worth counting; for instance, one of the prehomogeneous spaces enabled Bhargava [2, Theorem 5] to prove the first nontrivial case of the Cohen-Martinet generalization [18] of the Cohen-Lenstra heuristics on the distribution of class groups.

In Step 2, heuristically the number of lattice points inside a fundamental domain \( f \) should be approximately the volume. If \( f \) has narrowing tentacles stretching to infinity, however, this heuristic can be hard to justify or even false! Bhargava’s brilliant solution was to average the counts over several fundamental domains (in fact, to integrate over a continuum of fundamental domains) [2], [4]. This effectively fattens the tentacles so that the volume heuristic can be justified farther out along the tentacle, out to the point beyond which the number of relevant lattice points is provably negligible.

Step 3 is necessary to sieve out unwanted objects. For instance, each number field \( k \) has a unique maximal order \( \mathcal{O}_k \), but the methods in Steps 1 and 2 lead more naturally to a count of all orders, so one must sieve out for each prime \( p \) the orders that fail to be maximal at \( p \). Ekedahl [22] proved a general sieve result: for instance, given relatively prime \( f, g \in \mathbb{Z}[x_1, \ldots, x_n] \), he computed the density of what remains of \( \mathbb{Z}^n \) after sieving out for each \( p \) the \( \mathcal{O} \in \mathbb{Z}^n \) satisfying \( f(\mathcal{O}) \equiv g(\mathcal{O}) \equiv 0 \pmod{p} \). But Bhargava’s applications require sieving out also \( \mathcal{O} \) satisfying congruences of the form \( h(\mathcal{O}) \equiv 0 \pmod{p^2} \) for a certain polynomial \( h \) and the existing results for the general problem of this kind rely on the abc conjecture [23], [24]. Bhargava circumvented this for the \( h \) arising in his application in a counterintuitive way: he mapped his problem to an Ekedahl-style counting problem in a higher-dimensional space. See [6] for the state of the art on this idea.

Ultimately, all these ideas enabled Bhargava to prove that for each \( n \leq 5 \), the number of isomorphism classes of degree \( n \) number fields \( k \) satisfying \( |D_k| \leq X \) is asymptotic to \( c_n X \) as \( X \to \infty \) for an explicit constant \( c_n \) [2], [4]. He was also led to formulate a precise conjecture for higher \( n \).

**Elliptic Curves**

If \( E \) is an elliptic curve \( y^2 = x^3 + Ax + B \) over \( \mathbb{Q} \), the set \( E(\mathbb{Q}) \) of rational points forms an abelian group that is finitely generated. The torsion subgroup of \( E(\mathbb{Q}) \) is well understood, but the rank as a function of \( (A, B) \) is so complicated that it is not even known whether it is computable in theory. Essentially the only known way to bound the rank is to observe that for any \( n \geq 2 \), the quotient
\(E(\mathbb{Q})/nE(\mathbb{Q})\) injects into a finite computable group \(\text{Sel}_n E\) the \(n\)-Selmer group. 

Birch and Swinnerton-Dyer showed that elliptic curves \(E\) equipped with a nonzero element of \(\text{Sel}_2 E\) are in bijection with nondegenerate \(\mathbb{Q}^\times \times \text{PGL}_2(\mathbb{Q})\)-orbits in \(\text{Sym}^2 \mathbb{Q}^2\) and proved that each orbit has an (almost) integral representative [15]. This representation is not a prehomogeneous space, but at least it is coregular, meaning that its ring of polynomial invariants is isomorphic to a polynomial ring. Using knowledge of the invariants, Bhargava and Shankar [10] succeeded in adapting the three-step approach to prove that the average size of \(\text{Sel}_2 E\) as \(E\) varies is 3 and hence the average rank of \(E(\mathbb{Q})\) is bounded! (See [25] for a summary of their proof.) Although de Jong [20] had proved analogous results over function fields by a similar approach of counting integral orbits and although Brumer [17] had proved that conjectures about elliptic curve \(L\)-functions would imply that the average rank over \(\mathbb{Q}\) was bounded, Bhargava and Shankar were the first to prove unconditionally that the average rank over \(\mathbb{Q}\) was bounded and also the first to obtain a precise value for the average of a Selmer group size over a global field.

In subsequent work, Bhargava and Shankar counted integral orbits in more complicated representations to show that for each \(n \leq 5\), the average of \(\#\text{Sel}_n E\) equals the sum of the divisors of \(n\). They proved also that the average remains unchanged if finitely many congruence conditions are imposed upon \(A\) and \(B\). This, combined with a theorem of Dokchitser and Dokchitser [21] relating Selmer groups to root numbers and Wong’s method [31, §9] for constructing a positive-density family of elliptic curves in which the root number is equidistributed, implies that the average rank of \(E(\mathbb{Q})\) is at most 0.885 [12, Theorem 3]. (Conjecturally the average is \(1/2\).)

Recent advances in the arithmetic of elliptic curves allow results on Selmer groups of an elliptic curve over \(\mathbb{Q}\) to be transferred to results about the rank and analytic rank (the order of vanishing at \(s = 1\) of the \(L\)-function of \(E\)). Specifically, in addition to the Dokchitser’s work mentioned above, there is work on the Iwasawa main conjecture for \(\text{GL}_2\) by Skinner and Urban [28] and by Wan [29]; work connecting \(p\)-adic \(L\)-functions to Heegner point heights by Bertolini, Darmon, and Prasanna [1] and by Brooks [16]; and work generalizing the Gross-Zagier formula by Yuan, Zhang, and Zhang [33]. Combining all of this with the work of Bhargava and Shankar, we now know that

- a positive fraction of elliptic curves over \(\mathbb{Q}\) have rank 0 and analytic rank 0 [11] and
- a positive fraction of elliptic curves over \(\mathbb{Q}\) have rank 1 and analytic rank 1 [13].

In particular, the Birch and Swinnerton-Dyer conjecture (that rank equals analytic rank) holds for a positive fraction of elliptic curves over \(\mathbb{Q}\)—in fact, more than 66 percent of them [14].

**Higher-Genus Curves**

Bhargava and Gross [7], using work of Wang [30], also found a coregular representation whose rational orbits parametrize 2-Selmer elements of Jacobians of hyperelliptic curves \(y^2 = f(x)\), where \(f\) is a polynomial of degree \(2g + 1\) over \(\mathbb{Q}\) for some fixed \(g\). They used this to prove that the average size of the 2-Selmer group of such Jacobians is 3, generalizing the result for elliptic curves. Combining this with Chabauty’s \(p\)-adic method, they could prove that many odd degree hyperelliptic curves have few rational points. Later, Stoll and the present author [26] were able to combine the Bhargava-Gross results with new ideas on the \(2\)-adic geometry of curves to show that as \(g \to \infty\), the fraction of these curves having no rational points at all (other than the one at infinity) tends to 1.

Bhargava also found a representation providing information on even degree hyperelliptic curves, enabling him to show that for all \(g \geq 0\), a positive fraction of curves \(y^2 = f(x)\) with \(\deg f = 2g + 2\) has no rational points (he showed that their \(2\)-coverings fail to have local points) and the fraction tends to 1 as \(g \to \infty\) [5]. Later, with Gross and Wang he showed that a positive fraction of these curves also has no points over any number field of odd degree despite having points over every completion of \(\mathbb{Q}\) [8].

Combining the results for odd and even degrees, we now know that most equations of the form \(y^2 = f(x)\) have no rational solutions.

**Final Words**

There are many other beautiful works of Bhargava we did not have space to discuss, such as a vast generalization [3] of Mahler’s theorem on series expansions for \(p\)-adic continuous functions and a preprint with Hanke [9] on Conway’s “290-conjecture” that a positive-definite quadratic form over \(\mathbb{Z}\) represents all nonnegative integers if and only if it represents all nonnegative integers up to 290. But it is the counting techniques that have had the greatest impact. Bhargava’s ideas will surely exert a strong influence on the future development of the subject.

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**References**

Jeremy Quastel

The Work of Martin Hairer

Martin Hairer of the University of Warwick was awarded a Fields Medal at the 2014 ICM in Seoul for his outstanding contributions to the theory of stochastic partial differential equations (SPDE). His most spectacular achievement has been his single-handed creation of the theory of regularity structures, which is a flexible analytic tool for giving sense to many ill-posed SPDEs. This breakthrough has opened up the entire field. Hairer is an Austrian who was raised in a mathematical family in Geneva, where he obtained a PhD in physics under Jean-Pierre Eckmann. But those who understand his work know that he is a mathematician in the best sense of the word: a quick study, patient, genial, and well rounded. His work ranges over many aspects of physically motivated problems in (stochastic) analysis. Here I will concentrate on explaining a few of his works in SPDE. First, some background.

Markov Processes

Markov processes are used widely in the sciences to model dynamical processes whose evolution is in some way random. They are defined through transition probabilities \( p(t,x,A) \) representing the probability for the state \( X_t \) at future time \( t+s \) to be in a set \( A \), given that at the present time \( t \), \( X_t = x \). If we had explicit transition probabilities and an initial measure \( \mu_0 \) in hand, we could in principle compute everything. However, they are usually presented to us only implicitly, the state evolving according to some sort of stochastic equation. Even in the case of stochastic ordinary differential equations, \( X_t \in \mathbb{R}^d, t \geq 0 \),

\[
X_t = b(X_t) + \sigma(X_t) \xi_t,
\]

where in the natural simplest cases \( \xi_t \) is Gaussian white noise, it is not obvious how to make sense of the equation. White noise means that averages of \( \xi_t \) over nice disjoint sets are uncorrelated, or, in other words, \( B_t = \int_0^t \xi_s ds \) is Brownian motion. One of the first things one learns is that with probability 1 it is nowhere differentiable; in fact, it just fails to be Hölder 1/2. From the equation, we expect the same of \( X_t \). A classical fact is that the Riemann-Stieltjes integral \( \int FdG \) is ill defined if the Hölder exponents of \( F \) and \( G \) sum to less than 1. Hence one cannot give unambiguous meaning for typical realizations of the noise to the stochastic integral which is the last term in the integrated version of (1),

\[
X_t = x + \int_0^t b(X_s) ds + \int_0^t \sigma(X_s) dB_s.
\]

However, the difference between various approximations turns out to have a probabilistically well-defined limit, and therefore the ambiguity can be understood as a modelling issue. This was worked out by Itô and others, the key concept being martingales. A downside is lack of continuity: If \( \xi_t \) are smooth approximations to the white noise, \( \int_0^t \sigma(X_s) \xi_t ds \) may not even converge to \( \int_0^t \sigma(X_s) \xi_t ds \). A modern point of view [8] due to Terry Lyons clarifies the approximation issue by noting that once one has made a choice of the simplest ambiguous quantity \( \mathbb{B}_t := \int_0^t B_s dB_s \), the rest is ordained. In particular, the solution map \( B_t \rightarrow X_t \) factors into a probabilistic step in which one enhances the Brownian motion \( B_t \) with an admissible choice of \( \mathbb{B}_t \), together with an explicit, deterministic, continuous map from the resulting rough path \((B_t, \mathbb{B}_t)\) to the solution \( X_t \).

Another important question about Markov processes concerns long time behavior. A nice situation is when the process is ergodic—there exists a unique invariant measure—and after a long time basically finds itself in the temporally stationary process started with the invariant measure.

In the finite-dimensional setting of (1), these problems can be studied through the operators

\[
L = \frac{1}{2} \sum_{i,j=1}^d a_{ij}(x) \frac{\partial^2}{\partial x_i \partial x_j} + \sum_{i=1}^d b_i(x) \frac{\partial}{\partial x_i}
\]

where \( a = \sigma \sigma^* \). The transition probabilities are the kernels of the semigroup \( e^{tL} \) and invariant measure solutions of \( L \mu = 0 \). If the variance matrix \( a \) is degenerate, the uniqueness follows from the Hörmander hypoellipticity theorem, probabilistic proofs of which can be obtained using the stochastic calculus of variations a.k.a. Malliavin calculus.

SPDE

However, many physically motivated problems are presented to us as stochastic partial differential equations, in particular, several equations for processes which arise as canonical representatives of huge fluctuation universality classes. Despite several decades of work, methods which could deal with these important examples proved elusive, and a general theory was not expected. Now \( d \) in (3) is replaced by a continuum \( \mathbb{R}^d \), and there exists no useful infinite-dimensional PDE theory to help us. Many of these equations are far more ill-posed than (1), where we were just marginally below the regularity at which things would have made classical sense. These singular SPDEs are relations between nonlinear functions of various derivatives of nowhere differentiable functions which are not even close to making classical sense. They seemed to contain some magical hidden meaning which could not be made precise.
Ergodicity of Navier-Stokes

An SPDE problem where the long time behavior is of obvious interest (e.g. in turbulence) is that of a randomly forced fluid. We have the incompressible Navier-Stokes equations which ask for a divergence-free vector field evolving according to

\[ \frac{\partial u}{\partial t} + (u \cdot \nabla)u + \nabla P = \nu \Delta u + F. \]

\( P \) is the pressure, and \( F \) is the external force. We assume \( F \) is acting in just a few long wavelength modes (i.e. someone is stirring it). Physically, the injected energy cascades down to smaller scales in the inertial range until it gets to a smallest scale, at which it is dissipated by the viscosity \( \nu \), which should be thought of as small. A natural question then is whether there is a unique invariant measure supported in this inertial range. One works in two dimensions (in \( d = 3 \) simply making sense of the unforced equation for more than a short time is already a millennium problem). Since the forcing is in only a few modes, the problem is highly hypoelliptic and becomes that of obtaining results that compare favorably to the Hörmander condition, but now in infinite dimensions. A key difficulty is lack of natural reference measures—it is just too easy to be singular in infinite dimensions—and a subsequent lack of good norms for the dynamics. The problem attracted the interest of several groups in the early 2000s [7], [17], [3]; with the finite-dimensional forcing it was finally solved by Hairer and Mattingly [10] with a condition allowing a forcing on only two Fourier modes for any \( \nu > 0 \)! An asymptotic Feller property is introduced which is sensitive to the regularization of the transition densities due to both probabilistic and dynamic mechanisms, and this in turn is verified through the nondegeneracy of the Malliavin covariance matrix. Naturally there are extremely interesting and important questions, such as the distribution of energy in these invariant measures, for which there are physical predictions which await mathematically rigorous work.

The KPZ Revolutions

In the mid-1980s, Kardar, Parisi and Zhang introduced the equation

\[ \partial_t h = \lambda (\partial_x h)^2 + \partial_x^2 h + \xi \]

to describe a randomly growing interface in \( d = 2 \), such as the boundary of a bacterial colony or a slowly burning front, idealized to be a height function \( h(t, x), t > 0, x \in \mathbb{R} \). The right-hand side identifies the three key mechanisms of relaxation \( (\partial_x^2 h) \), uncorrelated random forcing (space-time white noise \( \xi \)), and, most important, the nonlinear slope dependent drift or lateral growth \( (\partial_x h)^2 \).

If the asymmetry \( \lambda \) is set to 0, the equation becomes linear (in the noise) and readily integrated, yielding a continuous function-valued Markov process which has Brownian motion as invariant measure. A smooth initial function evolves for \( t > 0 \) to a locally Brownian version and in the long time limit after centering, to Brownian motion.

Amazingly, the nonlinear dynamics also preserves Brownian motion (modulo an absolute height shift), but the fluctuations are otherwise non-Gaussian and of nonstandard superdiffusive size \( t^{1/3} \) (compared to \( t^{1/4} \) when \( \lambda = 0 \)). At the physical level, this goes back to highly nonrigorous renormalization group computations on the stochastic Burgers equation satisfied by \( u = \partial_x h \).

In a breakthrough that surprised both the mathematics and physics communities, Johansson [15] (and [1] for a related model) succeeded in computing the free energy fluctuations of geometric last passage percolation and showing that normalized by \( t^{1/3} \) they converge to the Tracy-Widom law, which had arisen ten years earlier in the seemingly unrelated field of random matrices. These free energies satisfy discrete versions of the KPZ equation, and at the physical level one expects all such one-dimensional systems displaying the three basic mechanisms to have the same large time asymptotics, refined into asymptotic fluctuation classes depending only on initial data. This is the strong KPZ universality conjecture, and the poorly understood universal large time limit is known as the KPZ fixed point. There has been significant progress over the last fifteen years through the work of Spohn, Sasamoto, Tracy, Widom, le Doussal, Dotsenko, Borodin, Corwin, O’Connell, Seppäläinen, Ferrari, and others on a small number of exactly solvable models, including to some extent the KPZ equation itself, where a few exact one-point distributions have been computed. However, at this level KPZ is just one model within the huge universality class. The connection with random matrices and the origin of the exact solvability and its link to representation theory have been considerably clarified by the work of Borodin and coauthors, especially under the umbrella of Macdonald Processes [2].

However, the KPZ equation is also itself universal in the sense that it is expected to be the unique heteroclinic orbit connecting (by varying time \( t \) or equivalently \( \lambda \)) the Gaussian fixed point to the KPZ fixed point and consequently the universal fixed point of models with weakly tuned asymmetry or noise. This is the weak KPZ universality conjecture. In contrast to the strong conjecture, where at the present time we can rely only on fortuitous exact computations coupled with asymptotics, the weak conjecture is open to a general attack by mathematical analysis.

To attempt it, one needs an analytic theory of KPZ. But if \( h(t, x) \) in (5) is locally Brownian in \( x \), what could the nonlinear term \( (\partial_x h)^2 \) possibly mean? Of course, the problem of finding ways to multiply genuine Schwartz distributions is an old
one, and various idiosyncratic techniques existed, but here one has to find the definition imposed by the physics. It was far from clear how to accomplish this, and earlier attempts turned out not to be physical [4].

Actually, for the KPZ equation, there is a cheap way out. At a completely formal level,

\[ Z(t, x) = \exp h(t, x) \]

satisfies

\[ \partial_t Z = \partial^2_x Z + \xi Z. \]  

Due to the roughness of \( \xi \), there is really an infinite absolute height shift. But we are just looking at fluctuations, so a huge change of reference frame doesn’t matter. The multiplicative stochastic heat equation (7) was one of the few truly infinite-dimensional nonlinear SPDEs which could be handled by the Itô techniques. The resulting \( h := \log Z \) is known as the Hopf-Cole solution of KPZ, and it is now known to have the expected physical behavior arise in the weakly asymmetric/weak noise limits and is what the exact computations refer to, the remarkable fact being that the correlations, i.e. the noise averages \( E[Z(t, x_1) \cdots Z(t, x_n)] \), satisfy closed Bethe ansatz solvable delta-Bose gas equations.

This suggests that one way to prove the weak universality conjecture would be to show that the appropriate partition functions converge to (7). This was done first by Bertini and Giacomin for a model called asymmetric simple exclusion and then later for a few others. But only very special models can be handled in this manner; one is faced again with the problem that the Itô theory is not well set up for approximations, and it just begs the question of finding a more robust theory for nonlinear SPDE.

**Regularity Structures**

A natural approach to make sense of a singular SPDE is through regularization. For example, we could take smooth approximations \( \xi_\varepsilon \) to our noise \( \xi \). If we can somehow find a limit of the resulting solutions as the regularization is removed that doesn’t depend on the way we regularize, we can say it is the solution. But typically the solution map lacks continuity in the necessary topology, and convergence is false. However, it may converge after renormalization by some probabilistically well-defined but now divergent quantity. For KPZ (5), Hairer proved (so far only on the torus \( \mathbb{T} \)) that there is a diverging \( C_\varepsilon \) such that the solution \( h_\varepsilon(t, x) \) of

\[ \partial_t h_\varepsilon = \lambda [(\partial_x h_\varepsilon)^2 - C_\varepsilon] + \partial^2_x h_\varepsilon + \xi_\varepsilon \]

converges to the Hopf-Cole solution, in probability, locally uniformly as continuous functions. If the regularization of the noise were just in space, this could be done using the Hopf-Cole + Itô approach, but the key point is that the new method is general and robust. To give just one example, if the regularization of the noise is on a scale \( \varepsilon \) in space and \( \varepsilon^2 \) in time, the weak KPZ universality suggests that the classical solution to

\[ \partial_t \hat{h}_\varepsilon = \varepsilon (\partial_x \hat{h}_\varepsilon)^4 - C_\varepsilon + \partial^2_x \hat{h}_\varepsilon + \xi_\varepsilon \]

should converge to the Hopf-Cole solution of (5) with a highly nontrivial \( \lambda \), the exponent 4 miraculously becoming a 2 in the limit. Hairer’s method can be adapted to prove such things (see [13] for a review) as well as providing a good approximation theory for equations like (7) [14]. The interested reader is invited to write the equation for \( \hat{Z} = \log \hat{h} \) and try to understand why on Earth it would converge to (7).

Motivated by rough paths, the idea is to factor the solution map into a deterministic part and a probabilistic part. The deterministic part is provided by an abstract solution map which acts on an abstract version of the equation together with a lift of the noise. The probabilistic part, which has some degrees of freedom, is how you lift the noise to the abstract framework.

The main new tool to construct the abstract solution map is the notion of regularity structures. This is a vector space tailor-made for the equation, with sufficient information to provide a local description of the solution at each point at various levels of regularity. It contains polynomials in the time and space variables, like a classical Taylor expansion. But our solution is going to be built out of various functionals of the noise which are too rough to represent using only these. So it should also contain symbols representing the input noise and enough rules for multiplication and versions of the heat operator and differentiation so that we can represent our equation there. One also needs a group of transformations from the description at one point to another point, and it is here that a highly nontrivial algebraic structure arises. Next one builds a space of functions \( D \) taking values in the regularity structure that generalizes the classical Hölder spaces and on which there are analogues of the Schauder estimates for the heat operator. These allow one to obtain the solution there as a fixed point.

Finally, a reconstruction operator pastes together the expansions at different points so that the abstract solution is taken as a genuine Schwartz distribution, which (one hopes!) is the solution to the original equation.

It is indeed the solution for the naïve lift of the regularized noise. But as we remove the regularization, things do not converge. Fortunately, a renormalization group acts on the space of lifts of the noise/multiplication rules, and by a careful choice one can find a sequence which does converge as one removes the regularization. These renormalizations are realized as concrete
renormalizations of the equations satisfied by the reconstruction; in the case of KPZ we get (8), and the Hopf-Cole limit can be thought of as at best satisfying

\begin{equation}
\partial_t \Phi = \lambda [(\partial_x \lambda)^2 - \infty] + \Delta \Phi + \xi.
\end{equation}

In this way, the problem is reduced to finding the correct renormalization, usually by educated guesswork, and then proving convergence of the corresponding finite collection of multilinear transformations of the noise.

If the smooth approximating noises are Gaussian, we are in a situation of Wiener chaoses, and there are well-known criteria for convergence based on $L^2$ norms. While these are completely explicit, they are generally complicated convolutions of singular kernels, and convergence depends on a careful counting of singularities in integrals over a resulting graph. This is highly reminiscent of earlier calculations in quantum field theory, and Feynman-like diagrams are used to keep track of the cumbersome computations.

**Dynamic $\Phi^4_3$**

The $\Phi^4_3$ model is supposed to be the Gibbs probability measure on Schwartz distributions $\Phi$ on $\mathbb{R}^d$, or the torus $\mathbb{T}^d$ or some subset, where the probability of $\Phi$ is proportional to $e^{-H(\Phi)}$ where $H(\Phi) = \int [\frac{1}{2} |\nabla \Phi|^2 + \frac{\lambda}{2} \Phi^2 - \frac{1}{4} \Phi^4]$. It is a universal model for phase coexistence in near-critical phenomena, closely related to SPDE and similarly ill-posed in $d \geq 2$, since the regularity of the Gaussian field obtained by setting $\lambda = 0$ is insufficient to define $\int \Phi^4$. So we take some regularization and try to find a nontrivial (i.e. non-Gaussian) limit as it is removed, perhaps after some renormalization. The problem was well studied, the main result being that it is nontrivial in $d \leq 3$. An outstanding issue was whether the limits resulting from different regularizations in the difficult $d = 3$ case were really the same. Similar to the SPDE problems, what was missing was an intrinsic characterization of the limit.

It was suggested that by analogy with the Ising model, where information about the static model had been obtained from the Glauber dynamics, one might approach this through a study of the stochastic dynamics (“stochastic quantization”) with $\Phi^4_3$ as invariant measure:

\begin{equation}
\partial_t \Phi = \Delta \Phi + \lambda \Phi^3 - C \Phi + \xi.
\end{equation}

It is expected to be a universal model for such dynamical models near criticality in a limit similar to the weak limits for KPZ.

But (11) just opened a new can of worms; for twenty years nobody could even make sense of it in $d = 3$ until Hairer constructed the appropriate regularity structure, in which the solution exists as an abstract model to which lifts of appropriate renormalized solutions of regularized versions of (11) converge.

Since Hairer’s first well-posedness results, several proofs have appeared for KPZ [9] and dynamic $\Phi^4_3$ [16], [5]. However these appear to be far more closely tied to the particular regularization as well as the specifics of the equation. One of the key points of the regularity structures is that they do give an intrinsic characterization of solutions for a large class of equations like (5) or (11) as the solution in the appropriate $D$ with the lift of the rough noise. The condition is that the equation should be subcritical, meaning that as you zoom in, the nonlinearity vanishes. In addition, regularity structures provide a precise description of the solution, level by level of (ir)regularity.

**References**


**Anton Zorich**

**The Work of Maryam Mirzakhani**

On August 13, 2014 (the opening day of ICM at Seoul), Maryam Mirzakhani received the Fields Medal “for her outstanding contributions to the dynamics and geometry of Riemann surfaces and their moduli spaces,” becoming the first woman to win the Fields Medal. We outline several directions of Mirzakhani’s research, which ranges from geometry of hyperbolic surfaces to dynamics in moduli spaces passing through applications of symplectic topology to algebraic geometry of moduli spaces. More scientific details can be found in the presentation of C. McMullen for the ICM [McM] and in a very accessible article [W] of A. Wright. For a more personal biographical note we recommend the paper of E. Klarreich [Kl].

**Moduli Spaces**

We are used to the fact that geometric objects might form continuous families with a rich topology. For example, the family of all straight lines in the plane passing through the origin forms a circle; the family of all complex lines passing through the origin forms the complex projective space \( \mathbb{CP}^1 \).

One can consider continuous families of certain geometric structures on a fixed manifold. For example, the family of all possible complex structures on a smooth compact surface \( S \) of genus \( g \) forms the moduli space \( \mathcal{M}_g \) of complex dimension \( 3g - 3 \). By the uniformization theorem complex structures on a smooth surface are in natural bijection with hyperbolic metrics of constant curvature, so the moduli space \( \mathcal{M}_g \) can also be seen as the family of nonsingular metrics of a fixed negative curvature on the surface \( S \).

During the last several decades various moduli spaces became very common in mathematics and theoretical physics. When working on extremely naive objects, such as graphs or interval exchange transformations, one might run into questions related to moduli spaces.

Theoretical physics continually develops its opinion on the nature of the relevant space which we inhabit. Strings give way to d-branes, and moduli spaces of Riemann surfaces give way to moduli spaces of Calabi-Yau manifolds.

While the geometry of the world most of us inhabit is not yet clear, what is clear is that Maryam Mirzakhani has spent many years in the worlds of hyperbolic and flat surfaces.

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**The Hyperbolic World**

**Weil-Petersson Volumes**

Consider a smooth surface \( S \) of genus \( g \) with \( n \) holes (where \( n = 0 \) is not excluded). A closed curve \( \alpha \) on \( S \) is called simple if it does not have self-intersections. Speaking about simple closed curves on a surface \( S \) we always tacitly assume that they are not contractible either to a point or to one of the boundary components (if there are any).

Suppose now that the surface \( S \) is endowed with a metric of constant curvature \(-1\). By convention, we always assume that the boundary components of the resulting hyperbolic surface \( X \) are realized by geodesics \( \beta_i \) in the hyperbolic metric, where \( i = 1, \ldots, n \). The hyperbolic lengths of the geodesic boundary components \( \beta_i \) are denoted by \( b_i(X) \) or by \( L_i(X) = |\beta_i|_X \). By convention, the zero value \( L_i = b_i = 0 \) corresponds to a cusp of the hyperbolic metric.

Fixing the hyperbolic lengths \( b_i \) of all boundary components and varying the hyperbolic metric, we get a continuous family of hyperbolic metrics on \( S \). The real \((6g - 6 + 2n)\)-dimensional space of all such metrics is called the moduli space \( \mathcal{M}_{g,n}(b_1, \ldots, b_n) \) of bordered hyperbolic surfaces. By the work of W. Goldman and S. Wolpert it carries a natural closed 2-form \( \omega_{WP} \) called the Weil-Petersson symplectic form.

The wedge power \( \omega^n \) of a symplectic form on a manifold \( M^{2n} \) defines a volume form. The volume of the moduli space \( \mathcal{M}_{g,n}(b_1, \ldots, b_n) \) with respect to the volume form \( \omega_{WP}^{3g-3+n} \) is called the Weil-Petersson volume of the moduli space \( \mathcal{M}_{g,n}(b_1, \ldots, b_n) \). To give an account of Mirzakhani’s work on Weil-Petersson volumes, we start with the mysterious identity of G. McShane.

**Theorem** (McShane). Let \( f(x) = (1 + e^x)^{-1} \) and let \( X \) be a hyperbolic torus with a cusp. Then

\[
\sum_{\gamma} f(\ell_\gamma(X)) = \frac{1}{2},
\]

where the sum is taken over all simple closed geodesics \( \gamma \) on \( X \), and \( \ell_\gamma(X) \) is the length of the geodesic \( \gamma \).

This identity is in some sense a miracle: though the length spectrum of simple closed geodesics is different for different hyperbolic tori with a cusp, the sum above is identically \( 1/2 \) for any \( X \in \mathcal{M}_{1,1}(0) \). Ten years after the work of McShane, Mirzakhani discovered a remarkable generalization of McShane’s identity to hyperbolic surfaces of any genus with any number of boundary components.

Let us discuss why such identities are relevant to the Weil-Petersson volumes of the moduli spaces. Integrating the right-hand side of McShane’s identity over the moduli space \( \mathcal{M}_{1,1}(0) \) with respect to the Weil-Petersson form, one obviously gets

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\[ \frac{1}{2} \text{Vol } M_{1,1}(0). \] What is not tautology is that the integral of the sum on the left-hand side admits a geometric interpretation as the integral of \( f \) over the natural cover \( M(1)_{1,1}(0) \) of the initial moduli space \( M_{1,1}(0) \). This cover is already much simpler than the original moduli space: it admits global coordinates in which the integral of \( f \) can be easily computed.

Mirzakhani's more general identity does not immediately yield the volume. However, cutting the initial surface by simple closed geodesics involved in her identity and developing the idea of averaging over all possible hyperbolic surfaces, Mirzakhani gets a recursive relation for the volume \( V_{g,n}(L_1, \ldots, L_n) := \text{Vol } M_{g,n}(L) \) in terms of analogous volumes of simpler moduli spaces. These relations allow Mirzakhani to prove the following statement and to compute the volumes explicitly.

**Theorem** ([M2]). The volume \( V_{g,n}(L_1, \ldots, L_n) \) is a polynomial in \( L_1^2, \ldots, L_n^2 \); namely, we have
\[
V_{g,n}(L) = \sum_{|\alpha| \leq 3g-3+n} C_\alpha \cdot L^{2n},
\]
where \( C_\alpha > 0 \) lies in \( \mathbb{N}^{6g-6+2n-2|\alpha|} \cdot \mathbb{Q} \).

Simple recursive formulae for volumes in genera 0, 1, 2 were found earlier by P. Zograf. Very precise asymptotics of volumes for large genera were recently proved by M. Mirzakhani and P. Zograf [MZg] (up to a multiplicative constant conjecturally equal to \( \frac{1}{2\pi} \) which still resists a rigorous evaluation).

**Counting Simple Closed Geodesics**

Consider a hyperbolic surface \( X \) of finite area. In this section there are no boundary components, but we still allow the hyperbolic metric of constant curvature \(-1\) to have cusps. We denote the corresponding moduli space by \( \mathcal{M}_{g,n} \). It is known that the growth rate of the number of closed geodesics of length at most \( L \) on any such surface \( X \) has the rate \( e^{\frac{L}{2}}/L \) when the bound \( L \) grows.

It is not surprising that most long closed geodesics have self-intersections. A quantitative estimate of “most” is much more subtle: M. Rees and I. Rivin showed that the number \( s_X(L) \) of *simple* closed geodesics of length at most \( L \) grows polynomially in \( L \).

In counting geodesics, one can count separately those simple closed geodesics which separate \( X \) into two connected components and those which do not. More generally, two simple closed curves on a topological surface \( S \) have the same *topological type* if one curve can be transformed to another by a homeomorphism of \( S \). For any surface of a fixed genus \( g \) with a fixed number \( n \) of punctures the number of different topological types of simple closed curves is finite. M. Mirzakhani counted simple closed hyperbolic geodesics by type.

**Theorem** ([M3]). For any hyperbolic surface \( X \in \mathcal{M}_{g,n} \) the number \( s_X(L, \text{type}) \) of simple closed geodesics on \( X \) of length at most \( L \) and of a fixed topological type has exact polynomial asymptotics:
\[
\lim_{L \to +\infty} s_X(L, \text{type}) \frac{L^d}{\text{Vol } B^g_{11}(X)} = c(\text{type}) \cdot \text{Vol } B^g_{11}(X),
\]
where \( d = 6g - 6 + 2n = \dim \mathcal{M}_{g,n} \).

For geometers we add that the quantity \( \text{Vol } B^g_{11}(X) \) is the normalized volume of the “unit ball” in the space of *measured laminations* \( \mathcal{ML}_{g,n} \) where the “unit ball” is defined in terms of the hyperbolic metric on \( X \) and its volume is computed in terms of the Thurston measure on \( \mathcal{ML}_{g,n} \).

Note that the asymptotic proportion of simple closed geodesics of fixed type is the same for all hyperbolic surfaces \( X \in \mathcal{M}_{g,n} \):
\[
\lim_{L \to +\infty} \frac{s_X(L, \text{type}_1)}{s_X(L, \text{type}_2)} = \frac{c(\text{type}_1)}{c(\text{type}_2)}.
\]

For example, Mirzakhani shows that nonseparating simple closed geodesics on any hyperbolic surface of genus two are six times more frequent than the separating ones.

The proof of the theorem combines methods from two domains. On the one hand, technology elaborated by Mirzakhani in [M2] allows one to compute averages over \( \mathcal{M}_{g,n} \) of all kinds of counting functions of simple closed geodesics (and not only Weil-Petersson volumes). To prove asymptotic formulae for *individual* hyperbolic surfaces, Mirzakhani elegantly relates the counting problems to the Thurston measure on the space of measured laminations \( \mathcal{ML}_{g,n} \) and deduces the desired results from the ergodicity of the action of the mapping class group on \( \mathcal{ML}_{g,n} \) with respect to the Thurston measure, a result proved by H. Masur.

**The Symplectic World**

**Witten's Conjecture**

Complex projective space \( \mathbb{CP}^n \) mentioned in the introduction carries the natural *tautological line bundle*; its fiber over a “point” \([L] \in \mathbb{CP}^n\) is the line \( L \) considered as a vector space. Any complex line bundle \( \xi \) over a compact manifold \( M \) can be induced from the tautological bundle by an appropriate map \( f_\xi : M \to \mathbb{CP}^n \) (for a sufficiently large \( n \) depending on \( M \)). The second cohomology of the complex projective space \( H^2(\mathbb{CP}^n; \mathbb{Z}) \cong \mathbb{Z} \) has a distinguished generator \( c_1 \). The induced element \( f_\xi^* c_1 \in H^2(M; \mathbb{Z}) \) is called the *first Chern class* of the line bundle \( \xi \).

There is a natural bijective correspondence between hyperbolic metrics of constant negative curvature with \( n \) cusps and complex structures endowed with \( n \) distinct marked points \( x_1, \ldots, x_n \) on a closed smooth surface of genus \( g \). In this section we use this latter interpretation of the moduli space \( \mathcal{M}_{g,n} \).
Consider the (co)tangent space $L(C, x_i)$ to the Riemann surface $C$ at the marked point $x_i$. Varying $(C, x_1, \ldots, x_n)$ in $\mathcal{M}_{g,n}$ we get a family of complex lines $L(C, x_i)$ parameterized by the points of $\mathcal{M}_{g,n}$. This family forms a line bundle $L$ over the moduli space $\mathcal{M}_{g,n}$. This tautological line bundle $L$ extends to the natural Deligne-Mumford compactification $\mathcal{M}_{g,n}$ of the initial moduli space. The space $\mathcal{M}_{g,n}$ is a nice compact complex orbifold, so for any $i = 1, \ldots, n$ one can define the first Chern class $\psi_i := c_1(L_i)$. Recall that cohomology has a ring structure, so taking a product of $k$ cohomology classes of dimension 2 (as the first Chern class) we can integrate the resulting cohomology class over a compact complex manifold of complex dimension $k$. In particular, for any partition $d_1 + \cdots + d_n = 3g - 3 + n$ of $\dim_c \mathcal{M}_{g,n} = 3g - 3 + n$ into the sum of nonnegative integers, one can integrate the product $\psi_1^{d_1} \cdots \psi_n^{d_n}$ over the orbifold $\mathcal{M}_{g,n}$. By convention, the intersection number (or the "correlator" in a physical context) is defined as

$$\langle \tau_{d_1} \cdots \tau_{d_n} \rangle := \int_{\mathcal{M}_{g,n}} \psi_1^{d_1} \cdots \psi_n^{d_n}. \tag{13}$$

As always, when there are plenty of rational numbers indexed by partitions or such, it is useful to wrap them into a single generating function. The resulting generating function is really famous. For physicists it is a partition function in two-dimensional quantum gravity. In mathematical terms, E. Witten conjectured in 1991 a certain recursive formula for the numbers (13) and interpreted this recursion in the form of KdV differential equations satisfied by the generating function. The conjecture caused an explosion of interest in the mathematical community: a single formula interlaced quantum gravity, algebraic geometry, enumerative geometry, combinatorics, topology, and integrable systems.

The first proof of Witten’s conjecture is due to M. Kontsevich, who used metric ribbon graphs as a "combinatorial model" of the moduli space to express the intersection numbers (13) as a sum over 3-valent ribbon graphs. Maryam Mirzakhani suggested in [M1] an alternative proof. She ingeniously applied techniques of symplectic geometry to moduli spaces of bordered Riemann surfaces $\mathcal{M}_{g,n}(L_1, \ldots, L_n)$ discussed in the previous section. Namely, Mirzakhani recognized the intersection numbers (13) in the coefficients $C_\alpha$ from formula (12) for the Weil-Petersson volumes $V_{g,n}(L)$ (up to a routine normalization factor). This allowed Mirzakhani to reduce the recurrence relations for the intersection numbers contained in Witten’s formula to recurrence relations for the volumes $V_{g,n}(L)$ discussed above and thus prove Witten’s conjecture. (Yet other proofs are due to A. Okounkov and R. Pandharipande, who used the Gromov-Witten theory of $\mathbb{P}^1$ and to M. Kazarian and S. Lando, who used the ELSV-formula.)

To construct a flat metric on a surface of genus different from one, we have to allow isolated conical singularities. We consider only those flat metrics which mimic a flat metric on a torus: namely, parallel transport of any tangent vector along any closed curve avoiding singularities is required to bring the vector to itself. A surface endowed with this kind of flat metric is called a translation surface. Since parallel transport along a small loop around any conical singularity brings the vector to itself, the cone angle at any singularity on a translation surface is an integer multiple of $2\pi$.

Similar to what one finds in the case of the torus, all translation surfaces can be obtained by the following construction. Consider a collection of vectors $\vec{v}_1, \ldots, \vec{v}_n$ in $\mathbb{R}^2$ and arrange these vectors into a broken line. Construct another broken line starting at the same point as the first one, arranging the same vectors in the order $\vec{v}_{\pi(1)}, \ldots, \vec{v}_{\pi(n)}$, where $\pi$ is some permutation of $n$ elements. By construction the two broken lines share the same endpoints; suppose that they bound a polygon as in Figure 1. Identifying the pairs of sides corresponding to the same vectors $\vec{v}_j$, $j = 1, \ldots, n$, by parallel translations, we obtain a closed topological surface.

It is convenient to consider the vertical direction as part of the structure. Under this convention, the structure of a translation surface is equivalent to the structure of a pair (Riemann surface $C$, holomorphic 1-form $\omega$ on it). As a complex coordinate on $C$ one can use the coordinate $z$ in the complex plane $\mathbb{C}$ where the polygon $\Pi$ lives, the holomorphic 1-form $\omega$ is the form $dz$ in these coordinates, $\omega$ has zeroes exactly at the conical singularities, and the order of zero at a singularity with the cone angle $2\pi(d_1 + 1)$ is $d_1$.

The polygon in our construction depends continuously on the vectors $\vec{v}_j$. This means that the topology of the resulting translation surface (its genus $g$, the number and the types of the resulting conical singularities) do not change under small deformations of the vectors $\vec{v}_j$. Fixing a collection of cone angles $2\pi(d_1 + 1), \ldots, 2\pi(d_m + 1)$
with integer $d_i$ for $i = 1, \ldots, n$, we get a family $H(d_1, \ldots, d_m)$ of translation surfaces. The vectors $v_1, \ldots, v_n$ can be viewed as complex coordinates in this family, called period coordinates. These coordinates define an orbifold structure and a natural volume element on every $H(d_1, \ldots, d_m)$.

Readers preferring algebro-geometric language may view any such family as a stratum in the moduli space $H_{g_0}$ of pairs (Riemann surface $C$, holomorphic 1-form $\omega$ on $C$), where the stratum is specified by the degrees $d_1, \ldots, d_m$ of the zeroes of $\omega$.

Each stratum admits a natural action of the group $\text{GL}(2, \mathbb{R})$. A linear transformation $g \in \text{GL}(2, \mathbb{R})$ of the ambient $\mathbb{R}^2 \cong C$ maps the polygon $\Pi$ to a polygon $g\Pi$. Identifying pairs of parallel sides of $g\Pi$ by translations, we get a translation surface $g \cdot S$.

The subgroup $\text{SL}(2, \mathbb{R}) \subset \text{GL}(2, \mathbb{R})$ preserves the flat area. This implies that the action of $\text{SL}(2, \mathbb{R})$ preserves the real hypersurface $H_1(d_1, \ldots, d_m)$ of translation surfaces of unit area. The latter codimension one subspace can be compared to the unit sphere (or rather to the unit hyperboloid) in the ambient stratum $H(d_1, \ldots, d_m)$. The action of the group $\text{SL}(2, \mathbb{R})$ preserves the naturally induced volume element on our “unit hyperboloid.” The flow induced by the action of the diagonal subgroup is called the Teichmüller geodesic flow.

**Theorem** (H. Masur, W. A. Veech). For any $(d_1, \ldots, d_m)$, the stratum $H_1(d_1, \ldots, d_m)$ has finite volume. The Teichmüller geodesic flow is ergodic on every connected component of every stratum.

Here “ergodic” means that any measurable subset invariant under the action of the group has necessarily measure zero or full measure. The ergodic theorem says that in such situations the orbit of almost every point homogeneously fills the ambient connected component. Namely, for almost all starting data the “time” average of an integrable function $f$ over the corresponding trajectory coincides with the “space” average, that is, with the integral of $f$ over the ambient connected component of $H_1(d_1, \ldots, d_m)$.

We state the ergodic theorem for almost all starting data, because even for extremely nice and smooth maps (like a map homogeneously winding}

![Figure 2](image-url)
model introduced by physicists P. and T. Ehrenfest more than a century ago. We study the billiard in the plane filled periodically with the identical rectangular obstacles as in Figure 2. A trajectory might go far away, then return relatively close back to the starting point, then make other long trips. The diffusion rate \( \nu \) describes the average rate \( T^\nu \) with which the trajectory expands in the plane on a long range of time \( T \gg 1 \). More formally,

\[
\nu := \lim_{T \to \infty} \frac{\log(\text{diameter of trajectory of length } T)}{\log T}.
\]

For the random walk in the plane or for a billiard with periodic circular obstacles, the diffusion rate is known to be \( 1/2 \): the most distant point of a piece of trajectory corresponding to segment of time \( [0, T] \) would be located roughly at a distance \( \sqrt{T} \). It was recently discovered in [DHL] that for the windtree model as in Figure 2 the diffusion rate is \( 2/3 \).

Suppose now that we want to find the diffusion rate for a generalized windtree model with periodic scatterers of the shape of a more complicated rational polygon. Replace the periodic billiard with an associated compact flat surface. Touch it with the Magic Wand of Eskin-Mirzakhani-Mohammadi and find its \( \text{SL}(2, \mathbb{R}) \)-orbit closure in the space of flat surfaces. Run the geodesic flow to compute the mean monodromy (Lyapunov exponents) of the appropriate block of the complex Hodge bundle, and we get the answer.

To be honest, in full generality, this strategy is a new dream (though in some situations it already works; see [DZ]). We do not yet have a classification of \( \text{SL}(2, \mathbb{R}) \)-invariant orbifolds except in genus two. This presents a new challenge, which might be full of mysteries and marvels, as indicated by recent results of M. Mirzakhani and A. Wright, who have found a \( \text{GL}(2, \mathbb{R}) \)-invariant suborbifold of completely enigmatic origin in the family \( \mathcal{H}(6) \).

A billiard in a polygon is just an elegant way to describe a certain class of dynamical systems; the same kind of dynamical systems appear in solid-state physics, in conductivity theory, in the theory of surface foliations, and the Magic Wand is extremely useful for the related problems in these areas (see [Zor] for details on applications of the Magic Wand). It also opens a new way to study moduli spaces.

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References


Book Review

Creating Symmetry: The Artful Mathematics of Wallpaper Patterns
Reviewed by James S. Walker

This new book by Frank A. Farris, professor of mathematics at Santa Clara University, is a comprehensive introduction to the mathematics of symmetry. Symmetry has long provided a connection between mathematics and the visual arts. This book distinguishes itself from other treatments of the subject (e.g., [9], [5], and [1]) by its detailed descriptions of exactly how one creates new artistic designs. It doesn’t just analyze existing patterns but provides mathematical formulas that allow you to create your own designs, exhibiting a wide variety of different types of symmetries, including not only wallpaper patterns (patterns with two independent plane translational symmetries) but several other designs as well. It is filled with many beautiful images. The publisher also deserves commendation for printing the book on photo-quality glossy paper, with high-resolution color images, and at a modest price. Farris writes in a style that invites the reader to participate in the artistic process. In fact, I was so intrigued by his approach that I tried my hand at creating my own designs, some of which are shown in this review. I believe many readers will also become involved in this way.

The book provides a unified development of fundamental ideas from group theory, Fourier series, complex variables, linear algebra, and geometry. It shows how all of these ideas can be brought to bear in understanding and creating symmetric planar designs. It is most suitable for one of three audiences: (1) undergraduate mathematics majors studying it as a "capstone" experience or an Independent Study. This audience might benefit from having an actively involved instructor to guide their study, someone to help them over typographical errors and one incorrect mathematical argument that I will describe later. (2) Mathematics professors looking for ideas to supplement one or more of their courses in any of the fields mentioned above or who are looking for ideas for undergraduate research projects. (3) People who the author refers to as "brave mathematical adventurers," who are studying this material on their own.

Rather than try to summarize all of the manifold topics dealt with in the book, I will concentrate on three topics that are representative of the overall content. These topics are (1) color maps of complex functions, (2) creating rosette images, and (3) creating symmetric wallpaper patterns.

Color Maps of Complex Functions
At the very end of the twentieth century, Farris [3] played a principal role in developing the use of color maps to sketch graphs of functions, \( f : \mathbb{C} \to \mathbb{C} \).
The idea is to use a color wheel, a well-known tool in the visual arts. An example of a color wheel is shown at the top left of Figure 1. This color wheel is used to mark locations in the complex plane. For each value of w, the value of C(w) is a unique color (at least in principle). For example, on the top left of Figure 1, the values of w that are near i are colored greenish-yellow, while values near −1 have a light blue tint. As values approach zero they turn black, and beyond a certain radius they are all colored white. By composing a function f(z) with C, we get a function C(f(z)) that gives a color portrait of f(z). For instance, on the top right of Figure 1, a color map for w = z² is shown. Notice how the colors near w = 0 cycle twice through the rainbow as we move once around w = 0. The connection to winding numbers is thereby made visually evident. Also, contour lines meet at right angles away from w = 0, just as they do for w = z. This illustrates conformality of w = z² away from the origin.

The preceding color plots were created by me. The ones created by Farris are similar—although he marks points near zero as white and exceedingly large values as black—and are shown in his book and at the webpage [3]. There is software now that produces color plots with great ease. At the bottom of Figure 1, we show a color plot of the function w = 3(z + 1)(z − i)²(z − 1 + i)³. This plot was produced with the free SageMath system [6], [7]. I needed just two commands:

\[
3*(z+1)^2*(z-1+i)^3 \\
\text{complex_plot(f, (-2, 2), (-2, 2))}
\]

The plot that SageMath produced clearly marks the location of the zeros at −1, i, and 1 − i and their multiplicities of 1, 2, and 3, respectively. All of that information is encoded in the number of times the colors of the rainbow are cycled through in the neighborhood of each zero. There are several nice examples of color plots at the website [2], including plots of branching in Riemann surfaces.

Creating Rosette Images

The first truly artistic images in the book occur when Farris creates rosette images. Instead of using a color wheel for the color map C, Farris decides to use “The World as my Color Wheel.” In other words, he uses the color map C for any of a series of color photographs that he has taken over the years. I will now outline his method for creating the rosette image shown on the left of Figure 2.

Farris uses the following basic fact (Theorem 4, p. 42):

If, in the [convergent] sum

\[
f(z) = \sum a_{nm}z^nz^m,
\]

we have \(a_{nm} = 0\) unless \(n \equiv m \pmod{p}\),

then \(f\) is invariant under rotation through an angle of \(2\pi/p\). In other words, \(f\) is a rosette function with \(p\)-fold symmetry.

Here we see rotational symmetry of these functions \(f\) corresponding to number-theoretic symmetry for their coefficients. Of course, \(\mathbb{Z}_p\) is isomorphic to the rotational group about the origin of \(\mathbb{C}\) generated by \(e^{2\pi i/p}\), as Farris points out. Farris then shows that additional symmetries can be created by invoking further symmetries on the coefficients \(a_{nm}\). For example, for the functions \(f(z) = \sum a_{nm}z^nz^m\) to have mirror symmetry \(\sigma_x\) about the x-axis, Farris symmetrizes using group averaging based on the symmetry group generated by \(\sigma_x\). The group average function \((f(z) + f(\sigma_x z))/2\) is guaranteed to have the required mirror symmetry. The power series for \(f\) then leads to the following requirement—or “recipe,” as Farris calls it—that the coefficients for \(f\) should satisfy \(a_{nm} = a_{mn}\) (since they do so for the symmetrized group average function). He has then prepared the way for stating what function \(f\) he used to create the rosette image shown in Figure 2. It is a function having the form

\[
f(z) = z^n\bar{z}^a + z^b\bar{z}^c + a(z^d\bar{z}^e + z^f\bar{z}^g) + b(z^h\bar{z}^i + z^j\bar{z}^k)
\]

for any complex constants \(a\) and \(b\). Farris does not tell us the specific values of \(a\) and \(b\) he chose, as his aim (quite rightly) is to teach us how to create our own designs, not reproduce his. By construction, such a function \(f(z)\) will be
invariant under 5-fold rotations about the origin and have mirror symmetry about the x-axis. The color mapped display, \( C(f(z)) \), then inherits all symmetries enjoyed by \( f(z) \). Farris is careful to point out that group operations then force both \( f(z) \) and its display \( C(f(z)) \) to have many more symmetries than the ones singled out in the initial design. He discusses how the symmetry group for the rosette is the dihedral group \( D_5 \), and he contrasts that group with the cyclic group \( C_5 \), isomorphic to the integer powers of \( e^{i2\pi/5} \), which is a normal subgroup of \( D_5 \). As we can see by comparing the color map image of the rhododendron with the rosette image, none of the symmetry of the rosette comes from the color map; it all comes from the construction of symmetry enjoyed by the function \( f \). For reasons of space, I will not show any more of the color map images \( C \), only the designs \( C \circ f \).

I found the rosette display that Farris has created to be just gorgeous! The method outlined above is typical of his approach throughout the book, introducing mathematical ideas from complex analysis, Fourier analysis, group theory, and geometry in the concrete setting of creating visually stunning symmetric designs.

**Creating Wallpaper Patterns**

As lovely as the rosette figures are, they are just a prelude to the topic he devotes the most space to: creating color images with wallpaper symmetries. The methods he used for rosettes are now deepened and extended to handle these designs, which have infinite symmetry groups. As an example of his techniques, I shall outline his method for constructing functions possessing 4-fold rotational symmetry about the origin along with translational symmetries of period 1 along the x and y axes (square lattice symmetry), while also including additional symmetries if desired. After that, I will show some additional examples of designs for other wallpaper groups that he discusses.

To create functions with square lattice symmetry and 4-fold rotational symmetry, Farris proceeds as follows. First, he uses as a basis the set of complex exponentials \( \{ E_{n,m}(z) = e^{2\pi i(nx+my)} \} \) for all \( n \) and \( m \) in \( \mathbb{Z} \) and \( z = x + iy \in \mathbb{C} \). Any finite (or convergent) sum \( \sum a_{n,m}E_{n,m}(z) \) is guaranteed to have the required translational symmetry. To obtain the rotational symmetry, he again employs group averaging. In this case, the group comprises the rotations generated by \( \omega_4 = e^{2\pi i/4} \). The group average \( W_{n,m} \) of \( E_{n,m} \) is defined by \( W_{n,m}(z) = \frac{1}{4} \sum_{k=0}^{3} E_{n,m}(\omega_4^k z) \). Farris refers to all of these group averages, \( \{ W_{n,m}(z) \} \), as wave packets. Any finite, or convergent, linear combination \( f(z) = \sum a_{n,m}W_{n,m}(z) \) is guaranteed to have both square lattice symmetry and 4-fold rotational symmetry about the origin. By choosing various coefficients \( a_{n,m} \) and composing with various color maps \( C \), we obtain an infinite variety of designs, all with the same symmetry group. Farris uses the notation of crystallography to refer to this symmetry group; it is \( p4 \). I like the fact that he uses crystallographic notation. Although it has weaknesses, which Farris points out, it makes his book more accessible to a wider audience.

To add additional symmetry, as with the rosette construction, we enforce symmetries on the coefficients \( a_{n,m} \) corresponding to the symmetry we desire for the functions \( f \). For example, to obtain mirror symmetry about the line \( y = x \) we require that the coefficients satisfy \( a_{n,m} = a_{m,n} \). In Figure 3, I show an image I constructed using this recipe. Notice that there are additional symmetries in this image other than the ones intentionally created, such as mirror symmetries about the x and y axes. Farris is careful to show that these symmetries all arise from the group properties of the symmetry group, \( p4m \), for this design. He also provides a helpful fundamental cell diagram that gives a concise geometric picture of all the symmetries of the design. He does this for each of the symmetry groups he discusses.

I cannot adequately convey the joy I felt when this image popped onto my computer after about a week of preparation of the computer code [8]. All of the mathematics actually works and creates, in my opinion, a lovely image. This is praise for Farris; I was only following his detailed descriptions of what to do. I strongly encourage you to get his book and try his methods for yourself.

By way of comparison with the image I created, I show in Figure 4 a design by Farris that exhibits 4-fold symmetry as well as glide reflection symmetry along the line \( y = x - 1/2 \). This image was created by a different recipe involving the coefficients \( a_{n,m} \). What’s the recipe? Well, I encourage you to read...
the book to find out. Farris is again careful to point out that the symmetry group operations create multiple glide reflection axes in addition to $y = x - 1/2$. These glide reflection axes are not hard to spot, as they pass through barbell shaped figures within the image. Farris says that “undulatig changes in direction and the mixture of mirror rigidity with free waviness make p4g one of my favorite pattern types.” This made sense to me, as it explains why the image appeared to vibrate when I looked for the location of the unit cell.

For another example that seems to vibrate, Figure 5 shows an image I created with 6-fold rotational symmetry and mirror symmetry, a p6m design. By similar methods to those outlined above for 4-fold symmetry, Farris creates designs with either 3-fold or 6-fold rotational symmetry. An interesting feature of the 6-fold case is that there will be centers of 3-fold rotational symmetry within unit cells. For example, in Figure 5 we can see these centers by locating points where three propeller-like arms extend outwards in a 3-fold symmetric pattern. This phenomenon is even clearer in the p6m design created by Farris, shown in Figure 6. Farris points out these 3-fold rotational centers and gives a concise explanation, via group operations again, for their existence in the 6-fold rotationally symmetric design. Another symmetry that is forced upon the design is the horizontal glide reflection axis that one can see below the row of flower-like hexagons in Figure 5 and between the rows of carrot-colored hexagon objects in Figure 6. As Farris demonstrates, there are multiple glide reflection axes in addition to the horizontal one.

I have highlighted here just a few of the many intriguing mathematical topics Farris covers in his book. For more details, go through the link to the book’s website at [4].

A Near Masterpiece
While the book is a near masterpiece, it does have quite a lot of typos. These pesky errors could lead readers to question the book’s validity, which would be a shame, because the book is mathematically sound. There is unfortunately one exception to this soundness: The proof of convergence of Fourier series for continuously differentiable periodic functions is incorrect. It is correctable, but probably not by students. Fortunately, this material is in an optional section and is not used in the rest of the book. Farris told me he plans to post errata on his website [4].

The book neither includes nor provides links to computer code. Some readers might consider this a weakness. I do not. I agree with Farris...
that there are ample resources (software such as SageMath, Maple, Mathematica, or Matlab and programming languages such as C++) and help for image graphing on the Internet. Farris explains carefully what to do with this software, i.e., the mathematics needed. In the not-too-distant future it is unlikely that any of those computer programs will exist in anything like their present form. But the mathematics described in this book surely will remain vital for centuries to come.

This book thoroughly engaged me with its application of fundamental and important mathematics to produce striking artistic designs. It is a major contribution that aids in our understanding of symmetry, art, and how mathematics unifies them. I recommend it most highly.

References
[2] L. CRONE, webpage on complex variable color plots: w.american.edu/cas/mathstat/lcrone/ComplexPlot.html
Search for an Executive Director for the American Mathematical Society

Position
The Trustees of the American Mathematical Society seek candidates for the position of Executive Director of the Society to replace Dr. Donald McClure, who plans to retire in the summer of 2016. This position offers the appropriate candidate the opportunity to have a strong positive influence on all activities of the Society, as well as the responsibility of overseeing a large, complex, and diverse spectrum of people, publications, and budgets. The desired starting date is July 1, 2016.

Duties and terms of appointment
The American Mathematical Society, with headquarters in Providence, RI, is the oldest scientific organization of mathematicians in the U.S. The Society’s activities are mainly directed toward the promotion and dissemination of mathematical research and scholarship, broadly defined; the improvement of mathematical education at all levels; increasing the appreciation and awareness by the general public of the role of mathematics in our society; and advancing the professional status of mathematicians. These aims are pursued mainly through an active program of publications, meetings, and conferences. The Society is a major publisher of mathematical books and journals, including MathSciNet, an organizer of numerous meetings and conferences each year, and a leading provider of electronic information in the mathematical sciences. The Society maintains a Washington office for purposes of advocacy and to improve interaction with federal agencies.

The Executive Director is the principal executive officer of the Society and is responsible for the execution and administration of the policies of the Society as approved by the Board of Trustees and by the Council. The Executive Director is a full-time employee of the Society appointed by the Trustees and is responsible for the operation of the Society’s offices in Providence and Pawtucket, RI; Ann Arbor, MI; and Washington, DC. The Executive Director is an ex-officio member of the policy committees of the Society and is often called upon to represent the Society in its dealings with other scientific and scholarly bodies.

The Society employs a staff of about 200 in the four offices. The directors of the various divisions report directly to the Executive Director. A major part of the Society’s budget is related to publications. Almost all operations (including the printing) of the publications program are done in-house. Information about the operations and finances of the Society can be found in its Annual Reports, available at www.ams.org/annual-reports.

The Executive Director serves at the pleasure of the Trustees. The terms of appointment, salary, and benefits will be consistent with the nature and responsibilities of the position and will be determined by mutual agreement between the Trustees and the prospective appointee.

Qualifications
Candidates for the office of Executive Director should have a Ph.D. (or equivalent) in mathematics, published research beyond the Ph.D., and significant administrative experience. The position calls for interaction with the staff, membership, and patrons of the Society as well as leaders of other scientific societies and publishing houses; thus leadership, communication skills, and diplomacy are prime requisites.

Applications
A search committee chaired by Robert Bryant (bryant@math.duke.edu) and Ruth Charney (charney@brandeis.edu) has been formed to seek and review applications. All communication with the committee will be held in confidence. Suggestions of suitable candidates are most welcome. Applicants can submit a CV and letter of interest to:

Executive Director Search Committee
c/o Carla D. Savage
Secretary, American Mathematical Society
Department of Computer Science
North Carolina State University
Raleigh, NC 27695-8206
ed-search@ams.org

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Frank Morgan Appointed Notices Editor-in-Chief

Elaine Kehoe

In 2000 Morgan et al. proved that the standard double soap bubble is more efficient than any other possibility, such as the bubble inside a bubble pictured here.

Frank Morgan of Williams College will begin a three-year term as editor in chief of the Notices starting with the January 2016 issue. He succeeds Steven G. Krantz of Washington University in St. Louis, who has been editor since 2010.

Frank Morgan attended the Massachusetts Institute of Technology and Princeton University, from which he received his PhD under Fred Almgren in minimal surfaces. In 2000, working with colleagues and students, he proved the Double Bubble Conjecture, which states that the standard double soap bubble—a little sphere and a big sphere, with the surface between them—is the least-area way to enclose and separate two given volumes of air.

Morgan has taught for ten years at MIT and now for twenty-eight at Williams, where he founded the SMALL undergraduate research project. Last fall he taught developmental algebra at Berkshire Community College. He has served on the AMS Council, and as AMS vice president he did an eight-week Asian speaking tour and founded the AMS Graduate Student Blog.

Morgan has published two hundred papers and six books, including Geometric Measure Theory, Calculus, and The Math Chat Book, based on his live call-in TV show and newspaper column. He has given over eight hundred talks at venues ranging from high schools to research seminars. He has a busy website at math.williams.edu/morgan.

But what qualifications does Morgan have to be an editor? Well, he was editor of the Raub Junior High School yearbook, Warrior.

Morgan loves the Notices and its potential. “I feel very close to the wide audience of Notices readers and promise with their help to make it as interesting as possible,” he says.

Elaine Kehoe is a Notices contributing writer. Her email address is elainekehoe@cox.net.

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“...I hope that they’ll like the new Graduate Student section and entertaining Back Page along with the latest math, participate in the new Commentary feature at the Notices homepage, submit all kinds of interesting articles, and enjoy Notices with friends.” He invites wide-ranging suggestions for articles, authors, innovations, consultants, and editors, including self-nominations, at fmorgan@williams.edu.
From the AMS Secretary


I am pleased to report that 2014 was again a successful year for the AMS. The Society remains financially healthy, very active in supporting the mathematics community, and flexible in addressing professional and public advocacy issues, thanks to the efforts of its members and dedicated staff. Several notable events and transitions occurred in 2014.

- The Joint Mathematics Meetings (JMM) in Baltimore maintained the very high level of participation of the previous two JMMs. The total registration of 6,448 was 26 percent greater than that of the 2003 JMM in Baltimore and essentially equal to the 2013 attendance in San Diego.

- Edward Dunne became Executive Editor of Mathematical Reviews (MR) in August, succeeding Graeme Fairweather who completed six years of service upon retirement in the summer. Ed moved to MR from his previous position as Senior Editor in the Editorial Division of the AMS.

- T. Christine Stevens joined the AMS in August as Associate Executive Director (AED) of Meetings and Professional Services. She succeeded Ellen Maycock who started a period of phased retirement after nine years as AED. Chris is widely known for her service to the mathematics community, notably her role in the building and the leadership of MAA’s Project NExT.

Current Issues

An issue affecting the AMS in its role as a scholarly publisher is the steady growth of research literature in the mathematical sciences. A society publisher such as the AMS has its incentives perfectly aligned with the community members and with research libraries. During the period 2000 through 2009, the number of new research articles published annually in journals covered by Mathematical Reviews increased by 37 percent, a compounded annual growth rate of 3.6 percent. To accommodate the growth in the volume of research literature, the AMS should be publishing more—and the Committee on Publications reached the same conclusion in its 2014 review of the primary research journals. An unanticipated issue affecting the mathematics community and the AMS stemmed from the summer 2013 revelations about the National Security Agency (NSA) by Edward Snowden. The controversies affected mathematics more than many other disciplines because of the major role that mathematics has in the NSA. During much of 2014, the Notices of the AMS provided a forum for presentation and discussion of disparate opinions in seven articles, an Opinion piece, and Letters to the Editor.

The Society made substantial progress on strategic planning for (1) membership, professional programs, and activities of the Washington office, (2) journal and book publishing, and (3) MathSciNet®. The last section of this report highlights some findings from a survey of the mathematics community designed to help guide the formulation of strategic initiatives.

Highlights of 2014 Activities

The Society’s major activities rely on the contributions of dedicated volunteers and staff as well as the philanthropy of many individuals. We are grateful for their contributions.

Serving the Community

Mathematicians continue to attend meetings and conferences in person—to learn, advance their careers, meet colleagues, and recognize recipients of AMS prizes and awards. While AMS staff handle the complicated logistics, AMS secretaries and organizers of special sessions and panels manage the scientific programs of AMS meetings. Special thanks go to AMS Secretary Carla Savage and Associate Secretaries Georgia Benkart, Brian D. Boe, Michel L. Lapidus, and Steven H. Weintraub and the many organizers, speakers, and panelists who contribute their time, leadership, and expertise.

James H. Simons, Chairman, Simons Foundation, gave the Einstein Public Lecture, “Mathematics, Common Sense, and Good Luck” at the sectional meeting at San Francisco State University in October. About 300 people filled the room to hear him talk about his career in mathematics, finance, and philanthropy. Some of the audience members were recipients of AMS-Simons Travel Grants, supported by the AMS and the Simons Foundation, and they came up and spoke with him afterward. It was nice to see the philanthropist and his beneficiaries connect in person and so warmly.

Photograph by Lisa Sze.

James Simons with recipients of AMS-Simons Travel Grants, after his 2014 Einstein Lecture
The Mathematics Research Communities (MRC) program continues to be highly successful. The 2014 MRC summer conferences at the Snowbird Resort in Utah drew 120 early-career mathematicians. These conferences, funded by the National Science Foundation, are part of this AMS program that also includes special sessions at JMMs, ongoing support from conference organizers, and a continuation of the connections and collaborations funded substantially by endowment income. Through 2014, a total of 769 participants have taken part in the MRC program.

“I feel very lucky to have had the opportunity as a young researcher to participate in this MRC program. It is a great way to network, think about new research problems not entirely connected to your dissertation topic, and spend a week in a beautiful setting with people who are passionate about math. I would highly recommend the conference to anyone.”

—2014 MRC participant

Each year, approximately 300 graduate students receive travel support from the AMS to attend meetings. About 100 students attended JMM in Baltimore with support. They were treated to a brunch where they could meet other students and members of the AMS leadership. The student travel grants are supported by one generous anonymous donor.

Members and the broader mathematical community also look to the AMS to provide crucial services—employment services, career information, and other opportunities to advance and get involved.

MathJobs.org and the Employment Center at the JMM remain valued by both employers and job seekers, especially for academic employment. By the end of 2014 MathJobs was serving over 8000 job applicants and 650 employers, including some international employers who began accepting job applications through the system in July 2014.

The AMS also gathers data on the profession in annual surveys regarding faculty recruitment, hiring and salaries, course enrollments, degrees awarded, and the demographics of new PhD recipients along with their employment status. The survey reports are vital for the mathematical sciences community in gaining support for programs, in understanding how one’s department compares to peers, and in providing reliable information about employment patterns and higher education in mathematics, applied mathematics, and statistics.

Support of summer math camps for talented pre-college students continues to grow. The Epsilon endowment fund continues to be broadly supported by AMS member-donors. In 2014, the summer camps receiving Epsilon Fund grants hosted over 1,200 students. It is a great program in which a modest amount of funding contributes to the support of a very large number of individual beneficiaries.

AMS Publishing

Mathematical Reviews (MR) completed its 75th year of publishing comprehensive coverage of new research in the mathematical sciences. Over 126,000 items were added to the MR database, including more than 91,000 reviews. The growth in the mathematics literature presents a significant challenge to MathSciNet® in its mission of (1) covering all new research contributions in mathematics and, at the same time, (2) continuing to improve the capabilities of MathSciNet® for discovery of new research results; for example, the addition of fifteen new Reference List journals in 2014 improves the research-discovery capabilities of MathSciNet®. The strategic planning for MathSciNet® is addressing the challenge.

The Publishing Division under the leadership of Associate Executive Director Robert Harington continues to make major strides in broadening the availability of AMS eBooks. In 2014, the Society launched availability of backfile collections for Memoirs of the AMS and for the Mathematical Surveys and Monographs series. In all, 220 volumes of Memoirs were released, spanning the years 1950 to 2012, and 169 volumes of Surveys were released, spanning the years 1943 to 2010. The newly digitized volumes all meet the highest quality standards. The release of other electronic book series continues in 2015.

In 2014, the book program published 74 new titles, of which we are very proud. Two AMS books published in 2014 received noteworthy awards: Hilbert’s Fifth Problem and Related Topics by Terence Tao received a prestigious American Publishers Award for Professional and Scholarly Excellence (PROSE Award) for the best book published in mathematics in 2014. Really Big Numbers, by Richard E. Schwartz, the Society’s first book for children (“of all ages”), received an...
A behind-the-scenes, high-priority mission of the AMS is to continue the advancement of technology for the electronic distribution of mathematical content. The AMS partners with about twenty other organizations in the development of MathJax™. The AMS and the Society for Industrial and Applied Mathematics (SIAM) are the two leading partners for the MathJax™ Consortium. MathJax™ has had a revolutionary impact in enabling the high quality web rendering of MathML and mathematics authored in \( \text{M\textsc{i}X} \), in all standard browsers. In 2014, the key developers of MathJax™ received funding from the Sloan Foundation to develop capabilities using MathJax™ for embedding semantic markup of mathematical content and for developing capabilities of handicap accessibility of mathematics on the web, such as text-to-speech processing. This is just one part of the technology development being done by the Publishing Technology Group in the Computer Services Division and by the Publishing Division.

There were major developments for publishing of the AMS research journals as well in 2014. I believe that a professional society such as the AMS has incentives that are perfectly aligned with the communities that our publications serve—the libraries who are our customers and the mathematical scientists who are both our authors and our consumers. We can deliver the highest quality publications at the lowest possible cost. The logical implication for the AMS is that we should strive to publish more of the high-quality research content that is being created.

In 2014, the AMS launched two new open access research journals, Proceedings of the AMS, Series B and Transactions of the AMS, Series B, companion journals to the primary AMS journals Proceedings and Transactions. The new journals offer the open access option for authors who wish to publish their work in the “gold” open-access model. We also made substantial increases in the pages published annually in the primary subscription journals Proceedings, Transactions, Mathematics of Computation, and Memoirs.

Advocacy, Partnerships for Mathematics and Science, and Public Awareness

The AMS Public Awareness Office and the Washington, DC Office, as well as many in the profession, are key in promoting awareness of news and information about mathematics and mathematicians—to our own community as well as to scientists in other fields, students, decision-makers, the media, and the broader public.

The Washington Office leads or oversees a number of activities in advocacy for the mathematical sciences and public policy in support of science. These activities include an annual Congressional Briefing, leadership of the Coalition for National Science Funding (CNSF), staff liaison for the AMS policy committees on Education and Science Policy, recruitment and selection of the AMS Congressional Fellow and the AMS Mass Media Fellow, and a variety of advocacy initiatives.

CNSF is an alliance of over 140 professional societies, research institutes, higher education institutions, and businesses that works to increase the national investment in the National Science Foundation’s research and education programs. The coalition organizes a reception and exhibition each year for members of congress and congressional staffers. Over 280 attendees came to the May 2014 event on Capitol Hill, where Robert Ghrist (University of Pennsylvania) represented the AMS and presented his work on “Topological Sensor Networks.”

For several years, the Committee on Science Policy has combined its annual spring meeting in Washington with “visits to the hill.” In March 2014, committee members visited the offices of twenty-nine senators and representatives to have conversations about the state of science funding and to ask for support of budget increases proposed for NSF in FY2015. Such visits are important; at the time of the visits, the NSF was being subjected to unprecedented scrutiny by the House Committee on Science, Space, and Technology.

The Public Awareness Office (PAO) provides leadership and support for activities that communicate with the general public and with select constituencies about the importance of mathematics. In 2014, the AMS worked to motivate mathematical scientists to become more proactive in communicating with the public. At JMM 2014, a forum on The Public Face of Mathematics was organized jointly by the committees on Education and Science Policy. Moderated by Arthur Benjamin, the panelists included Keith Devlin (Stanford University), Jerry McNerney (US House of Representatives), Cathy O’Neil (Johnson Research Labs), Tom Siegfried (Freelance Science Journalist), and Steven Strogatz (Cornell University). The forum motivated more members of the mathematical sciences community to take initiatives in representing mathematics to the general public and to key audiences of leaders in discussions of public policy.

Strategic Planning

At the May 2013 meeting of the Executive Committee and Board of Trustees, the ECBT approved of the President appointing a committee to oversee the strategic planning for the AMS. President Vogan appointed a Strategic Planning Oversight Committee (referred to as SPOCK) including Ralph Cohen (EC member), Mark Green (BT Chair), Donald McClure (Executive Director), Emily Riley (CFO), Carla...
The activities were then ordered by the proportion of responses categorizing that objective as “among the most important.”

The four top-ranked activities were:
1. Support and encourage young mathematicians and individuals pursuing undergraduate/graduate degrees in mathematics.
2. Increase advocacy efforts on key issues, such as support for basic research.
3. Promote awareness and appreciation of the importance of mathematics among the public.
4. Create programs to promote and foster diversity in the mathematics profession.

—Donald McClure
Executive Director
Professor Stewart’s Casebook of Mathematical Mysteries

Reviewed by Sam Vandervelde

The publication of Professor Stewart’s Cabinet of Mathematical Curiosities in 2008 established Ian Stewart as a master of an unusual genre of mathematical exposition: one that juxtaposes old puzzles and open problems, that sets whimsical anecdotes and light humor cheek to jowl with forays into recent research. The reader is likely to discover why $\pi$ is equal to 3 in the Arctic, and also that the shortest opaque fence for a unit circle is believed to equal $\pi + 2$, all in the same sitting. The author stoutly maintains that such a book is properly categorized as a miscellany, and thus is not bound by any particular logical ordering of material, which in turn is not constrained by anything beyond the author’s taste. Fortunately, his taste proves to be excellent—not only in the opinion of this reviewer, but also in the eyes of the general public, who bought copies of the original book in droves.

With the wildly successful Cabinet seemingly unable to accommodate all the pearls in the good Professor’s files, a sequel followed a scant year later. Professor Stewart’s Hoard of Mathematical Treasures employed the same formula, experimenting with the addition of a pirate theme to enliven some of the posers. With this compilation the author was content to rest for a while, but as he writes in the introduction to his latest collection, “They say that three is a good number for a trilogy.” And so after a five-year hiatus a third (and final?) volume has arrived, Professor Stewart’s Casebook of Mathematical Mysteries.

The variety of subject matter, range of sophistication, and abundance of illustrations in this latest installment help to ensure that it will appeal to as wide a readership as ever, from budding middle school math kids to professionals who unfailingly attend MathFest each summer. (In fact, my fifth grader just stumbled upon the review copy of Casebook on my desk and has been deeply absorbed for the past fifteen minutes and counting, pausing only to relay a joke or inform me of the smallest integer that can be written as a sum of two cubes in six different ways.) Granted, Stewart does not hesitate to dress up a number of classic conundrums, such as in The Scandal of the Stolen Sovereign, which lays out the familiar puzzle of three diners, a bill that has been reduced from thirty to twenty-five (choose your favorite monetary unit), and a troublesome tip. In other instances favorite chestnuts are presented with no adornment, as is the case for the Jigsaw Paradox in which the same set of pieces are assembled in two configurations to yield regions with purportedly different areas.

However, every reader will find more than enough novel and genuinely delightful mathematical nuggets to make a perusal, if not a careful read, of Casebook highly worthwhile. This reviewer was introduced for the first time to the operator theory method of deducing the series for $e^x$, which involves the observation that $\int e^x = e^x$, hence $(1 - \int) e^x = 0$, leading to $e^x = (1 - \int)^{-1}0$. One now expands $(1 - \int)^{-1}$ as a geometric series, takes successive antiderivatives of 0, sums the results, and the familiar series for $e^x$ appears almost as if

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by magic. At the risk of appearing to be poorly read, this reviewer will also confess to being previously ignorant of the fact that there exists a set of three distinct planar regions having precisely the same boundary, not being aware of the latest research explaining why the bubbles in Guinness beer drift downward, and having missed the recent revelation that a single shape (with markings) has been found that tiles a plane but cannot tile it periodically.

There are plenty of tidbits that are accessible to virtually everyone, such as the observation that beginning with the arithmetic identity
\[
123789^2 + 561945^2 + 642864^2 = 242868^2 + 761943^2 + 323787^2,
\]
one can successively remove the leftmost digits of all six numbers, yielding a sequence of equalities all of which are valid, concluding with the true statement that \(9^2 + 5^2 + 4^2 = 8^2 + 3^2 + 7^2\). In fact, successively removing rightmost digits instead also yields a sequence of equalities, which seems almost too much to ask. However, Stewart does not shy away from more advanced topics, such as an overview of the startling fact that quadratic residues modulo a prime can be used to design efficient sound diffusers for ceilings of concert halls. In another essay he presents the concept of a random harmonic series (in which the sign of each term is chosen randomly) and goes on to survey several quite remarkable characteristics of the resulting probability distribution.

The playful manner in which the Professor presents his mathematical mysteries belies the extreme care with which each is written. From the introduction to the previous volume, we read “Hoard is supposed to be fun, not work.” By extension the same may be said of Casebook. Indeed, perusing its pages is quite pleasurable, but this is due to the great deal of work expended by the author on our behalf, evident throughout in the clarity of thought, the expansive vocabulary, and the attention to selection and ordering of the various items that Stewart chooses to include. So in the end there is method to the miscellany after all, in the form of optimizing the material to engage and delight as wide an audience as possible. And if the success of Cabinet is any indication, Professor Stewart has quite a knack for this sort of optimization.

Approximately one in every four of the essays penned by Ian Stewart in Casebook is framed as a memoir of Dr. John Watsup, who embarks upon a series of mathematical adventures while in the company of a certain Hemlock Soames located at 222B Baker Street, across the street from the more well-known pair. (The author assures us at the outset that his concept for this latest compilation of mathematical morsels predates the airing of the BBC series Sherlock, which also modernizes this legendary sleuth, albeit in a rather different manner.) Readers familiar with the works of Sir Arthur Conan Doyle will at once recognize any number of allusions, from Professor Moriarty to “The Hound of the Basketballs.” The style is also unmistakable; consider this excerpt from “The Affair of the Above-Average Driver,” found on page 169.

The detective sighed. “A common misconception, Watsup.”

“Miscon—what’s wrong with it?”

“Just about everything, Watsup. Suppose one hundred people are assessed on a score ranging from zero to ten. If 99 of them score ten and the other scores zero, what is the average?”

“Uh…990/100…which is 9.9, Soames.”

“And how many are above average?”

“Uh…ninety-nine of them.”

“As I said, a misconception.”

I was not so readily diverted. “But the excess is small, Soames, and the data are not typical.”

“I exaggerated the effect to demonstrate its existence, Watsup. Any data that are skewed—asymmetric—are likely to behave in a similar manner. For example, suppose that most drivers are reasonably competent, a significant minority is appallingly bad, and a very tiny number is excellent. Which drivers are above average in such circumstances?”

“Well…the bad ones bring the average down, and the excellent ones don’t compensate…My word! The competent and excellent drivers are all above average!”

This reviewer, who spent countless hours as a child devouring the exploits of Sherlock Holmes, has mixed feelings regarding the use of these beloved characters and distinctive prose to relate matters that at times felt mundane in comparison to the tales on which they are based. However, there is no denying that Stewart is quite adept at emulating Doyle’s style; the reader will be immediately transported to a world in which penetrating deductions based on the barest of clues are related in a casual manner. For example, suppose that most drivers are reasonably competent, a significant minority is appallingly bad, and a very tiny number is excellent. Which drivers are above average in such circumstances?”

Regardless of how the reader feels about this device for bundling math, Stewart brings to the fore an aspect of recounting mathematics that is easily overlooked when assembling problem collections and that is typically expunged from academic journals: Mathematical investigation.
unfolds chronologically, with compelling reasons for adopting certain avenues of inquiry, and hence is a narrative. Therefore, it is fitting that mathematics be presented in a narrative format. Of course, the acumen displayed by Detective Soames coupled with Dr. Watsup’s admiring enthusiasm serve to draw the reader into the story and therefore into the mathematics as well.

To play devil’s advocate for a moment, one could forward the same criticism of Soames and Watsup that has been leveled at the class of textbook word problems reading something like the following. “Charlie is thinking of a right triangle. He tells Deborah that its perimeter is fifty-six and its area is eighty-four. What is the hypotenuse of Charlie’s triangle?” The criticism is that packaging mathematics in a social wrapping provides a false motivation for problem-solving. Worse yet, it potentially confuses abstract exercises with real world modeling, a distinct and important field in its own right. Mathematics should be intrinsically compelling; if a topic comes across as uninteresting, the fault lies with its explanation, or in a mismatch on some level between topic and audience. Any number of beloved compilations of mathematical essays rest on the premise that their subject material (and sparkling presentation) is sufficiently arresting to capture and hold the reader’s attention—Ross Honsberger springs immediately to mind, for instance.

This review certainly does not intend to settle the debate. But few would deny that mathematics is as much a social as an individual endeavor, or overlook the efficacy of interpersonal communication as a vehicle for motivating and advancing mathematics. And if my fifth grader is any indication, Stewart’s approach to incorporating these principles into his latest miscellany is just as powerful as ever.

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(Ref. 1516/024(576)/2)

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Please send the completed application form and/or full curriculum vitae, together with copies of qualification documents, a publication list and/or abstracts of selected published papers, and names, addresses and fax numbers/e-mail addresses of three referees to whom the applicants’ consent has been given for their providing references (unless otherwise specified), to the Personnel Office by post or by fax to (852) 3942 0947.

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Mathematics in the Yates Program at Illinois College

Jeremy F. Alm and Andrew B. Jones

Illinois College is a small liberal arts college in Jacksonville, Illinois. We serve just under one thousand undergraduate students, more than half of whom are first generation or low income. We are a test-optional institution with an average ACT mathematics subscore of 22. The ACT benchmarks indicate that 45 percent of our students should not expect to have a successful outcome (C or better) in their first mathematics course at Illinois College. We also enroll a number of students from underresourced high schools that are unable to provide either the breadth or depth of mathematics instruction to prepare students for the rigor of the college classroom. Many of our students begin their first year of college having completed only three years of mathematics in high school, often ending their coursework with Algebra II.

To address the underpreparedness of our entering students, Illinois College instituted the Yates Summer Bridge Program for first-generation college students. For two weeks prior to the start of classes, eighteen first-year first-generation students participate in a living/learning community, the purpose of which is to introduce participants to the academic rigor and expectations of Illinois College. We focus primarily on mathematics and writing instruction, as we know that deficits in these areas are the primary academic obstacles to success.

Students enrolled in the Yates Program have two hours of mathematics instruction and one hour of mathematics lab every day of the program, for approximately twenty-five total hours of engagement with mathematics. Yates Fellows also generate several drafts of their first college writing assignment during their writing course and participate in a variety of service and team-building activities designed to connect them to one another, to their faculty leaders, and to the institution at large. The crux of the program, however, is the academic preparation and success strategy intervention that will lay the foundation for their success as college students.

While summer bridge programs are increasingly common, our approach to academic skill development—particularly as it relates to mathematics instruction—is successful, based on professional practice, and easily replicable. Below, we discuss the details of this approach to mathematics in the Yates Program (and, more generally, in college algebra courses), why this unconventional approach is necessary, and give a priori reasons to believe it should be more successful than the standard approach.\footnote{The a priori case that students are better off learning better mathematics is clear enough. The a posteriori case that student learning in the classroom is actually improved is more complicated (but anecdotal evidence and our observations certainly support it). In particular, small sample sizes are a major issue. We are currently working on constructing a multiyear study over several cohorts to measure the practical effectiveness of the approach described here.}

1
Pathology

In “A revolution in mathematics? What really happened a century ago and why it matters today,” Quinn [1] details the profound changes that took place in roughly 1890–1930, through which mathematics took its modern form, characterized by precision, rigor, and free use of proof by contradiction. The importance and utility of modern definitions would be difficult to overstate; a good definition is a tool that is designed to be used. Yet, despite the profound successes of mathematics in the twentieth century, the school mathematics curriculum in the United States has not adopted and integrated the changes that made this success possible. As has been thoroughly and depressingly documented by Hung-Hsi Wu, one rarely finds in the school curriculum (especially K–8) a definition from which one would be able to make deductions or prove things. A particularly glaring omission is the lack of definition of a fraction.2,3 Since students are not told what a fraction is, only what it is like (like a piece of pizza, etc.), when asked to reason about fractions they are forced to rely on rote mechanics.

If we want students to be able to actually use fractions, then core experience points a way: use a precise definition that looks obscure at first but that can be internalized by working with it and that is far more effective once it is learned. [1]

It may be that these curricular problems have consequences for faculty as well; the dislike of teaching courses such as college algebra among mathematics faculty is nearly universal. A reason frequently given is that such courses are too “low-level.” This reason seems to be inadequate to explain the depth and ubiquity of the hatred; it might be that it is the lack of adherence to the standards of the discipline that is the problem. (The first author’s cursory survey of college algebra textbooks found that most suffered from the insufficiencies of the high school textbooks described by Wu in [2].) After all, Wu [4] says, “There is no trivial mathematics, only trivial mathematical exposition.” The thrust of our work in remedial mathematics at Illinois College is to give rational arithmetic, leading up through elementary algebra, a nontrivial exposition for our students.

Mathematics at Illinois College

In the Yates Program, we begin with Wu’s definition of a fraction as a certain kind of point on the number line. (See [5], [6].) Addition of fractions is defined geometrically using concatenation of line segments, and we prove that the usual addition formula

\[ \frac{a}{b} + \frac{c}{d} = \frac{ad + bc}{bd} \]

is correct. We proceed quickly—after all, we have only two weeks—through fraction arithmetic, decimals, percentages, and linear equations in a single unknown. We pay careful attention throughout to the fact that everything we do is in service to the goal of achieving facility with algebra. A point on which Wu is quite persuasive (see [3]) is that if fractions were taught in a way that was both rich and consistent with modern practice, then fraction arithmetic would provide a smooth path to algebra. We testify that this claim bears out in actual practice. Many Yates students take the first author’s college algebra course in the fall semester, of which the first three weeks are more or less a repeat of the Yates Program, and these students (along with other college algebra students) who are willing to change their thinking are able to make sense of the more abstract manipulations (algebra) in virtue of the fact that we had made coherent the concrete (arithmetic). The initial investment in establishing a solid grounding in rational arithmetic pays dividends, though it does require an investment of time; one might say that while the standard college algebra course moves at constant velocity, the course described here moves at constant acceleration.

One of the best illustrations available to the students of the power of definition-as-tool is the definition of percentages:

**Definition.** Let \( N \) be a fraction. Then \( N \) percent is defined to be the (complex) fraction \( \frac{N}{100} \).

Many people reason with percentages using intuitive notions, but intuition is not that hard to foil, as, for instance, with the following question:

What percent of \( \frac{7}{2} \) percent is 19 percent?4

This question strikes most people as confusing, but it lends itself perfectly well to literal translation using the definitions of percentage and of fraction multiplication:5

Let \( N \) be the unknown fraction. Then

\[ \frac{N}{100} \times \frac{7}{2} = \frac{19}{100} \]

| 2 | One finds mention of this omission in much of Wu’s writing on education; a good place to start is [7]. |
| 3 | While this column was under review, an editor pointed out that over forty states have now adopted curricula that include proper definitions of “fraction.” This is an encouraging sign, yet for the next ten years we will still have to deal with the fact that so many of the college students in our classes have learned algebra with foundation in arithmetic that was shaky at best. |
| 4 | Questions such as this—those that expose the dysfunctionality of the methods most students learn in high school—are essential for helping the students change their point of view. If given only “standard” questions, students may be able to get along by leaning on their old crutches. Wu’s materials are full of such stultifying questions. |
| 5 | Wu’s definition [5], [6] of fraction multiplication, although slightly complicated, is nonetheless intuitive and is clearly modeled on the common use of “of”, as in, “Give me 2/3 of that submarine sandwich.” |
Quinn and Wu both argue for the need for updates to the K–12 curriculum to take advantage of the high functionality of the modern methodology in mathematics. Here we have presented some evidence that college students in high school-level courses can benefit as well, especially those who are disadvantaged and at the greatest risk for attrition. A side benefit may be that faculty would find such courses less arduous—even enjoyable—to teach. The first author enjoys teaching college algebra, as he enjoys mathematical research; both efforts are part of a common project to produce mathematics that is correct, coherent, and beautiful, and to help others do the same.

References
The YMSC invites applications for the above positions in the full spectrum of mathematical sciences: ranging from pure mathematics, applied PDE, computational mathematics to statistics. The current annual salary range is between 0.15-1.0 million RMB. Salary will be determined by applicants’ qualification. Strong promise/track record in research and teaching are required. Completed applications must be electronically submitted, and must contain curriculum vitae, research statement, teaching statement, selected reprints and/or preprints, three reference letters on academic research and one reference letter on teaching (Reference letters must be handwritten by referees), sent electronically to msc-recruitment@math.tsinghua.edu.cn.

The review process starts in December 2015, and closes by April 30, 2016. Applicants are encouraged to submit their applications before December 31, 2015.

Positions: post-doctorate fellowship

Yau Mathematical Sciences Center (YMSC) will hire a substantial statistics, number of post-doctorate fellows in the full spectrum of mathematical sciences. New and recent PhDs are encouraged for this position.

A typical appointment for post-doctorate fellowship of YMSC is for two-years, renewable for the third years. Salary and compensation package are determined by qualification, accomplishment, and experience. YMSC offers very competitive packages.

Completed applications must contain curriculum vitae, research, statement, teaching statement, selected reprints and/or preprints, three reference letters with referee’s signature, sent electronically to msc-recruitment@math.tsinghua.edu.cn.

The review process starts in December 2015, and closes by April 30, 2016. Applicants are encouraged to submit their applications before December 31, 2015.

Tsinghua Sanya International Mathematics Forum (TSIMF)

Call for Proposal

We invite proposals to organize workshops, conferences, research-in-team and other academic activities at the Tsinghua Sanya International Mathematics Forum (TSIMF).

TSIMF is an international conference center for mathematics. It is located in Sanya, a scenic city by the beach with excellent air quality. The facilities of TSIMF are built on a 140-acre land surrounded by pristine environment at Phoenix Hill of Phoenix Township. The total square footage of all the facilities is over 28,000 square meter that includes state-of-the-art conference facilities (over 9,000 square meter) to hold two international workshops simultaneously, a large library, a guesthouse (over 10,000 square meter) and the associated catering facilities, a large swimming pool, two tennis courts and other recreational facilities.

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For information about TSIMF and proposal submission, please visit: http://ymsc.tsinghua.edu.cn/sanya or write to Ms. Yanyu Fang yyfang@math.tsinghua.edu.cn.
The Closing of IMA and MBI
Nilima Nigam

Editor’s Note: The Division of Mathematical Sciences (DMS) of the National Science Foundation (NSF) has a program that supports eight major mathematics institutes in the United States. Included among these are the Institute for Mathematics and its Applications (IMA) at the University of Minnesota and the Mathematical Biosciences Institute (MBI) at Ohio State University. In January of this year, news circulated that the DMS planned to ramp down significantly its funding of IMA and MBI. This issue of the Notices features two articles on this topic. The first, an opinion piece by Nilima Nigam, professor of mathematics at Simon Fraser University, is below.

Another unusual feature of the mathematical sciences is the mathematical sciences institutes. These are our community’s large projects, our telescopes peering into the future and our microscopes focusing intently on the deepest fundamental problems, our laboratories experimenting with new configurations of people and ideas and a significant vehicle for cultural change in the mathematical sciences. The Committee of Visitors endorses the great value of the institutes, is happy with the way that they are managed, while recommending a few improvements, largely to adjust certain artifacts of the history of the program.... [3]

Introduction
Since the beginning of 2015, the international community of mathematical scientists has been trying to absorb the impact of two recommendations from the Division of Mathematical Sciences (DMS) at the National Science Foundation (NSF): a call to end funding to the Institute for Mathematics and its Applications (IMA) and a call to end funding to the Mathematical Biosciences Institute (MBI) unless half its budget is funded through a different directorate within the NSF. As I write this, these recommendations have not been made official by the NSF, and the foundation therefore is not allowed to publicly comment on the recommendation. In this note I seek to explain why I think the MBI and IMA are successful in their central missions and worthy of our continued support. These are my own views and opinions.

At this juncture what is visible to the broader scientific community is the dismantling of a communal infrastructure of great importance, which includes vital training programs and an entire mode of scientific interaction aimed at promoting the reach of the mathematical sciences in other areas of scientific inquiry.

We recognize this is a time of unique challenges in terms of government funding of fundamental scientific and mathematical research and that the NSF has had to respond to severe budgetary pressures. These pressures are unfortunately present and evident in many countries. It is inevitable that the math institutes would also, in turn, be asked to share in the pain. Responsible decision making in an already strained fiscal environment may involve choices which are difficult but should strive to minimize the cumulative negative impact.

In my personal view the current DMS recommendations concerning the MBI and IMA give the appearance of difficult choices courageously made which unfortunately seem to discount the central and ongoing importance of these two institutes to many mathematical scientists at all stages of their careers. These institutes have played a profound role in identifying interdisciplinary applications of many mathematical subdisciplines and supporting research groups that work in them. We have gone from a period when the mathematical sciences were isolated to an era where the centrality of mathematics in interdisciplinary endeavors is widely
Weinberger contains a truly well-articulated where mathematics can play a central role. We need
The quote above remains pertinent today. The December 2015
inclusive and intellectually stimulating environment
research disciplines. We need to provide an in-
scientists from other areas and identify problems
have a forum where our community can meet
requires a sustained effort on many levels. We
missed connections and insights remains high.
lead to interesting mathematical questions, which
parallel, new developments in other disciplines
parallel, new developments in other disciplines
lead to new areas of research. This cycle seems rather inefficient.
application area. This cycle seems rather inefficient.
application area. This cycle seems rather inefficient.
were being recommended for defunding.

Like many others, I have been the beneficiary of the rich intellectual environment and mathe-
generosity of the US-based mathematical sciences community, especially through the insti-
tute programs. I am deeply indebted to the National Science Foundation and the US-based
mathematical community for their truly generous support of my academic training and of others
like me. I do not know and cannot speculate what factors led to the NSF recommendations.

The Beneficiaries
...the mathematical sciences have encountered a growth in the number of mathematicians, the number of results, and the number of publications. Unfortunately, much of this growth has been centrifugal...Many of the questions which have led to the development of whole fields, and consequently the connections of these fields with the rest of mathematics and with other sciences, have been lost in the teacher-to-student chain. The historical linkage between mathematics and the sciences, which had been of such great mutual benefit in the past, is in need of nurture. [2]

The First Annual Report of the IMA by Hans Weinberger [2] contains a truly well-articulated and prescient vision of the needs of mathematical scientists embarking on interdisciplinary work. The quote above remains pertinent today. The mathematical sciences are vital and ever-growing at a pace which renders it difficult for any individual to keep abreast of all major developments. In parallel, new developments in other disciplines lead to interesting mathematical questions, which first need to be properly formulated. The risk for missed connections and insights remains high.

Developing and nurturing connections between the mathematical sciences and other disciplines requires a sustained effort on many levels. We need to train young mathematicians. We need to have a forum where our community can meet scientists from other areas and identify problems where mathematics can play a central role. We need to provide opportunities for sustaining nascent research disciplines. We need to provide an inclusive and intellectually stimulating environment for scholars seeking to develop a new area of application of mathematics. At its best, such work requires considerable intellectual risk taking, but enriches the application area immeasurably. It will produce novel mathematical insights, which in turn should be a source of continual regeneration [2] in our discipline. Supporting such endeavors is, and should continue to be, a priority.

It is in this setting that both the IMA and the MBI play a central role as shared large infrastructure. The IMA was founded in 1982 to spawn new areas of mathematical research through contact with the physical, engineering, and social sciences. The MBI was founded in 2001 to foster the development of new mathematical areas motivated by questions in the biosciences. The IMA and MBI programs include training initiatives aimed at students (undergraduate and graduate) and post-doctoral fellows (PDFs). They host well-attended workshops on newer topics as well as thematic annual programs. Hundreds of mathematical scientists access their programs each year, many for the first time. For many, these institutes provide a valuable regional hub for long-term training and research initiatives. The mentoring and networking initiatives have helped many younger researchers from diverse backgrounds. Certainly these visitors and trainees benefit from these institutes.

What about the mathematical sciences as a whole? As I describe below, both institutes have been very successful in sparking new research on mathematical questions motivated by applications. Our discipline as a whole is richer for their presence. Equally, thanks to the programming at these institutes, the impacts and development of new mathematical ideas in the application areas have been tremendous.

While the principle of seeking funding from receptor disciplines is reasonable, in practice this neglects the push-and-pull nature of research in applied mathematics. As new interdisciplinary fields develop and begin to have impact in the receptor area, the research rightly gets pulled into that field, and the insights developed by mathematicians become part of the mainstream practice. Young biologists now are increasingly trained to use quantitative tools. The more common the adoption of these tools, the less urgent it seems that we need to support new mathematical sciences research in these areas. I have heard it said: “But why do we need to support mathematics in robotics? Isn’t that field sorted out?” However, if there is not a counterbalancing pull from the mathematical sciences side, over time a problem emerges. New insights in the mathematical sciences are not adopted in the receptor field, and, conversely, mathematicians lose contact with the newest developments in the application area. This cycle seems rather inefficient. Efforts to sustain interdisciplinary connections are vital. Fields such as mathematical biology are
very much aware of this danger. Supporting the core mission—to sustain mathematical sciences research which is motivated by applications and to maintain contact with the applications areas—is integral to the health of our discipline.

The New Generation

I come from an ecology background and there was [sic] many incredibly helpful hands-on session [sic] on mathematical models that can be applied to ecology. Learning such methods was extremely beneficial for the development of my PhD. In addition, I found the talks inspiring and I am considering a few of the speakers as potential post-docs advisors. —MBI participant

When I was a graduate student, I was having difficulty finding a project to pursue, and I was having doubts about whether to continue with my graduate education. A research mentor sent me to the IMA to attend my first applied mathematics conference, a 2001 meeting on Ideal Data Representation. …This visit ultimately led to my first paper. Indeed, I owe my career as a researcher to this trip to the IMA. —Joel Tropp, Caltech

The training of future generations of mathematical scientists—undergraduates, graduate, and postdoctoral fellows—is an integral part of the IMA and MBI. Attracting students to research in mathematics takes effort. Both institutes have novel and highly successful Research Experience for Undergraduates (REU) programs. Their public lecture series are an integral part of the intellectual culture in their communities. Both institutes also set a high priority for the participation of graduate students in various programs. The impact of visits to these institutes can be profound on a fledgling career. A quick look at the editorial boards of the major journals in applied, computational, and industrial mathematics, as well as mathematical biology, shows that alumni from the IMA and MBI PDF programs are represented there in impressive numbers.

The IMA postdoctoral program was established in 1982. Since then, 296 PDFs have spent formative years at the IMA, immersed in the annual programs. This is a hugely successful program, providing young researchers with novel opportunities, intellectual support, and protected time to pursue ambitious research projects at the very forefront of applied mathematics. The program prioritizes fresh PhDs, for whom the IMA experience provides excellent training and career-related mentoring. While receiving support for collaboration with the visitors at the myriad IMA workshops as well as with faculty across many departments at the University of Minnesota, the PDFs learn to interact with a broad range of scientists. Perhaps less visibly, the advantage of interacting with each other and forming lasting research networks is an invaluable benefit for the PDFs. Postdocs from the IMA go on to successful careers in academe and industry and include thirteen Sloan Research Fellows and six NSF CAREER Award recipients. Alumni of the program hold positions in top-notch research departments and in the R&D (research and development) groups of major technology firms.

The pioneering IMA industrial PDF program was established in 1988 and has since supported sixty-five industrial PDFs. The PDFs spend half of their two-year IMA stint working on an industrial research project at the company site with a mentor from the industrial R&D group. This enables them to work on long-term projects of interest to the company and learn vital industry-relevant skills. The IMA provides critical support at all stages—identifying companies, matching the PDFs with local (IMA) and industrial mentors, ensuring the research project is well defined, and helping with knowledge transfer and intellectual property issues. Specific and often time-sensitive issues arise with industrial collaborations, and the IMA has accumulated a wealth of experience in dealing with these. The program is open to international scholars and serves as an important mechanism for the US to attract the best talent.

The MBI has hosted eighty-one PDFs since its inception. Each PDF has two mentors: one from the biological sciences and one from mathematics. The duration of these PDFs is three years, which is the usual length of time needed to establish collaborations and embark on an independent research program in mathematical biology. Like the IMA, the MBI puts a high priority on nurturing first-time PDFs.

In both institutions, NSF funding supports part of the PDF program. At the IMA it helps support one year of the PDF’s stay. The remaining time is supported through other sources, including other departments at the University of Minnesota and industrial partnerships. At the MBI, some PDFs are supported through NSF funding for the duration of their stay; others are co-sponsored with biosciences researchers. Between these institutes represent a large number of available opportunities for first-time PDF researchers who are in a vulnerable phase of their careers. The cessation of NSF funding will have a crippling effect on these PDF programs.

What will be lost with the defunding of these institutes? It can be argued that PDFs can be absorbed into individual departments. What will be lost is the opportunities they have access to: annual programs, scientists from other disciplines, visitors, mentorships, industrial interactions, and each other. Individual supervisors can seek to recreate
some, but surely not all, aspects of this milieu. Similarly, one can envisage each component—graduate workshops, REU programs, outreach activities—surviving in numerous institutions. What is lost is the synergy and interplay between them. One can replant ten trees, but that does not regenerate an ecosystem.

**The Growth of Knowledge**

Each yearly program is devoted to studying the possible interactions of mathematics with a specific area of science. Scientists with common interests are invited to be in residence for sufficiently long periods of time to allow interest in the nontrivial problems which arise to grow and familiarity to develop. … —First IMA Annual Report

This paper, and some of our recent work on which it draws, has its origins in a remarkable IMA workshop on gait patterns and symmetry held in June 1998, which brought together biologists, engineers, and mathematicians. … Workshop discussions in which we all took part also inspired the creation of RHex, a six-legged robot…. [4]

The reach and influence of the mathematical sciences is vast. Many scientific and engineering disciplines use mathematical ideas and tools; in fact, it is possible that we as mathematicians have not even fully appreciated the extent of the “unreasonable effectiveness” of our own discipline. The crystallization of some of the most exciting and promising research areas emerges from the interaction and cross-fertilization of different disciplines with the mathematical sciences. This does not happen in a vacuum. One needs an environment hospitable to both the application-area experts as well as the mathematical scientists. Scientists and mathematicians need a forum to interact and develop a common vocabulary. In the early stages it is not even clear which subdisciplines of mathematics will be most helpful. One needs a few nucleation sites: scholars who have the opportunity to interact with a large number of experts in more specialized areas, so they can begin to aggregate existing knowledge and help generate new ideas.

The long-term programs of the IMA and MBI have played a vital role in interdisciplinary exploration involving mathematics. This model of workshops and tutorials addressing different aspects of the overarching theme allows for both flexibility and depth. A large number of visitors specializing in different aspects of the new area gather for workshops. A smaller number of PDFs and long-term visitors stay in residence, participate in all the activities, develop a shared vocabulary, and obtain a bird’s-eye view of the field. This is vital: connections between different topics do not emerge unless someone is present to see them. It is particularly important that PDFs have a long-term affiliation with reduced teaching responsibility in this setting; they are embarking on research in newly emerging areas, where even the specification of a core mathematical question will take time. This particular feature of applications-driven research also distinguishes the IMA and MBI programs from those which bring together different mathematical communities. In the latter setting, a great deal of shared knowledge already exists.

As an example, the vibrant area of mathematical materials science has deep links to the IMA. In the 1990s this was a relatively new field; many important research directions were formulated and explored during the IMA annual programs and workshops in the 1990s. This is a field which is now both established and mature (the SIAM Activity Group on Mathematical Aspects of Materials Science (SIAG/MS) was established in 2008), but the influence of the IMA is clearly seen: most of the leaders in this area have been visitors or PDFs of the IMA.

As another example, in 1998 the IMA held a workshop on animal locomotion. As Holmes, Full, Koditsche, and Guckenheimer describe in their 2006 paper [4], workshop discussions led to an extensive collaboration, which included the creation of hexapod robots (a project funded for many years by DARPA) and to NSF-funded work on the neural and muscular control feedback loops that govern legged locomotion. This has been a productive interaction which continues to influence developments in the fields of neuromechanics, robotics, and sensorimotor control, as well as in the mathematical study of dynamical systems.

Surely thirty years ago no one would have predicted that tools from algebraic topology would become important for sensor networks, actuators, and robotics. The IMA has, over the years, hosted programs on networks. There have been workshops on dynamical systems and actuators. Perhaps it was at one of these events that researchers identified the potential for using local-to-global principles from algebraic topology? I do not know for sure. What is certain is the huge impact of the 2013-2014 IMA Theme Year on applications of algebraic topology. This program brought together a truly wide array of mathematicians and scientists and included a workshop on topological systems in communication and sensing. A research network of over two hundred mathematicians was created, and their activities continue to be supported by the IMA. I can claim to have personally benefitted: as a young graduate student I made a bet with a fellow student who asserted algebraic topology would never be “sullied by relevance in the real world” during his lifetime. He is still alive, and now I am owed US$5.
The biological and biomedical sciences include problems of staggering complexity and scope which require a truly multidisciplinary approach. For instance: What is the role of stochasticity in biological systems? Does it serve a necessary purpose? To understand these questions, the 2011–2012 MBI Emphasis Year on Stochastics in Biological Systems brought together probabilists, algebraic geometers, engineers, epidemiologists, systems biologists, and other biological scientists. Open questions of mutual interest were identified and carefully formulated. On the biomedical side, consider the study of cancer. Oncology is by no means a new field, and the central importance of a vast range of mathematical ideas is clear: from the study of changes in the genome to modelling the effects of ablation therapy. It is also known that cancers interact with their environment in a complex manner at many scales, ranging from the level of genes and proteins to the level of entire populations. There is a range of therapies which target specific interactions. Is there a mathematical framework which can account for these disparate phenomena? Can it be used to generate predictions about the efficacy of new treatments? These are truly big questions, which are being studied during the 2014–2015 MBI Emphasis Year in Cancer and Its Environment. The role of the MBI is central.

The Relationships

Macalester has partnered with the IMA in running an applied mathematics REU for the past six years. ...The program involved scientists, engineers and mathematicians of all stripes: university researchers, liberal arts professors, post-doctoral fellows, graduate and undergraduate students. Everyone got something out of participating in this focused research community, not just the undergraduates. This broad impact was by design, and credit for that revolutionary approach goes to the IMA.

—Andrew Beveridge, Macalaster

While a graduate student, I received funding to travel to the IMA and participate in the workshop “Fostering Mathematical Entrepreneurship.” Even though I felt confident I would be able to secure a post doc position when I finished my PhD, I was interested in work outside academia, and so naturally the above IMA program was very appealing....The workshop was a hugely important experience for me, a pivotal part of my graduate and professional career.

—Zachary Gelbaum, Spacetime Capital Management & Research, LLC

Consider first the numbers. The IMA hosts around 1,200 visitors each year, of which 50 percent are first-time visitors. These numbers include graduate students (24 percent) and nonmathematicians (32 percent). Nearly 50 percent of the visitors apply themselves (i.e., are not selected by the organizers). MBI, the younger (and smaller) of the two institutes, has hosted over 9,200 visitors since 2002. If you had to design a method for efficiently mixing a population of mathematicians and scientists, ensuring serendipitous interactions, you would be hard pressed to find a more successful model than these institutes.

The role of the IMA and the MBI in creating new research communities at the interface of mathematics and other disciplines has already been discussed. Relationships with R&D groups in industry are, if anything, even more challenging to initiate. Almost surely, mathematicians seeking to build links with companies on their own will find the process time consuming and frustrating. The IMA has dedicated significant efforts to nurturing these activities and relationships through a range of programs and seminars. The graduate student problem-solving workshops have already been mentioned, as has the industrial PDF program. Colleagues from the eleven IMA corporate partners provide mentorship and valuable career advice to young mathematicians at the IMA. This model of fostering relationships between industry and the academy through PDFs has proven very successful, and the IMA model has inspired similar initiatives. The NSF GOALI (Grant Opportunities for Academic Liaison with Industry) program comes to mind, as does the MITACS industrial internship program in Canada (a national research organization that manages and funds research and training programs for undergraduate, graduate students, and post-doctoral fellows in partnership with universities, industry, and government in Canada). The learning curve for any individual researcher attempting such activities is high, and the barriers to success are formidable. I spent time at MITACS as these programs were being developed and often looked to the IMA programs for guidance. The IMA is the place I recommend that students visit if they are contemplating careers in industry: they will receive excellent mentoring, ideas of career paths, opportunities to network with mathematicians in companies. The suite of IMA industrial programs is unique in North America in terms of scope and active involvement by industrial partners.

Individuals can seek to recreate these relationships, but it is hard to achieve the same scale. The loss of both institutes in the Midwest will have a critical effect on many colleagues: for many students, the geographical proximity of these institutes is an important factor in their ability to attend conferences. Interactions and collaborations made possible through the IMA and MBI will now have yet another barrier. The DMS will have essentially dismantled the only sustained forum for the training of industrial PDFs in the mathematical sciences.
The International Influence

In the crucial field of understanding the basics of biology in strict (i.e. mathematical) terms the US is so much in advance of us (the rest). This will lead not only to fundamental breakthroughs, comparable to those of physics a century ago but also to new medical technologies. To a great extent this seems to be the consequence of a conscious and concerted effort from the leadership of the National Science Foundation. Wish we could have something similar in Europe.

—MBI participant

Of the many modes of scholarly research supported by the NSF, a highly efficient mechanism in terms of international impact has been through the institutes. The leadership role and importance of the IMA and the MBI cannot be emphasized enough. Globally, we collectively learn and benefit from their expertise on how to enhance links between the mathematical sciences and applications.

As a concrete example, in 2008 the International Commission on Mathematical Instruction (ICMI) and the International Council for Industrial and Applied Mathematics commissioned a joint study called the Educational Interfaces between Mathematics and Industry. During this study, I learned about the challenges colleagues around the world experienced while trying to train students to develop mathematical skills which they could use in industry. I was struck by how many institutions around the world had adopted variants of the successful IMA graduate student mathematics-industry training camp model, often explicitly crediting the format. The Canada-based Pacific Institute for the Mathematical Sciences now runs this event in collaboration with the IMA. The IMA industrial postdoctoral program was discussed as one of the more successful initiatives which institutions in other countries would like to adopt. The major hurdle we all identified—establishing links and long-term relationships with industrial partners—is one that the IMA has successfully surmounted.

As another example, the MBI runs a very successful summer graduate program to train young researchers in new topics at the interface of mathematics and the life sciences. These are in new topics, and most graduate programs do not offer courses in these. The format is nimble and effective, and MBI has accumulated a wealth of experience in running these programs well. Other countries would like to adopt similar initiatives and look to the MBI model. In 2012 the Center for Applied Mathematics in Biosciences and Medicine (in Canada) began to partner with MBI on this program. Many of us internationally recognize the importance of the life sciences in our times; we admire the innovative educational and research initiatives pioneered and supported at the MBI.

A Final Word

The institutes constitute major infrastructure in the mathematical sciences, akin to the large telescopes and particle accelerators in physics. What role do these institutes play in the research and training landscape? What is their broader impact? Do these roles need updating? What is being done well, and what needs to change? In my view, the community should have an opportunity for consultation on long-range plans and strategic investments in such infrastructure, especially if something with enormous impact is being phased out.

Both the IMA and MBI have a sustained track record in their respective missions and offer much-needed intellectual opportunities to a truly large number of mathematical scientists. They have a suite of programs which together generate a vibrant environment, much greater than the sum of the individual workshops. They have significantly contributed to a culture of change in our discipline, providing opportunities to researchers from diverse backgrounds and interests.

These institutes are important to a large number of mathematical scientists. Many were taken aback by the NSF recommendations and have sought venues to express their support of the IMA and the MBI. An open letter to the NSF indicating the importance of the IMA has been signed by over 3,400 mathematical scientists worldwide [5], including colleagues from universities, industry, and government labs. The signatories include SIAM Fellows and Fellows of the AMS. Many mathematical scientists at the beginning of their careers have also signed on; they recognize that the loss of these institutes will disproportionately impact them. This was a strong and constructive signal from members of the community about the critical importance of these resources.

The potential defunding of these institutes represents a large blow to the mathematical sciences at large and in particular to the development of novel applications of mathematics. I hope that the IMA and the MBI are able to continue their stellar work.

References

Revel in a 100 Years of Mathematics

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DMS Mathematical Sciences Research Institutes Update

Michael Vogelius and Henry Warchall

The National Science Foundation (NSF) Division of Mathematical Sciences (DMS) supports a portfolio of distinguished investments in Mathematical Sciences Research Institutes. These institutes are important components of the US mathematical sciences infrastructure. The institutes serve as national resources for advancing research, increasing the impact of the mathematical sciences, engaging with scientific opportunities in other fields, enabling the mathematical sciences to respond to national needs, and expanding the US talent base engaged in mathematical and statistical research. Recently the NSF has decided to ramp down funding of two of the mathematics institutes. This update provides some information about this portfolio of unique DMS investments and places it in the context of the entire DMS awards portfolio.

Background

DMS provides major support for eight national research institutes:
- American Institute of Mathematics (AIM) in San Jose, California (DMS support for workshops and the "structured quartet research ensembles" program begun in 2001).
- Institute for Advanced Study (IAS) in Princeton, New Jersey (DMS support for postdoctoral and midcareer visitors, begun in 1997).
- Institute for Computational and Experimental Research in Mathematics (ICERM) in Providence, Rhode Island, begun in 2009.
- Institute for Mathematics and its Applications (IMA) in Minneapolis, Minnesota, begun in 1981.
- Institute for Pure and Applied Mathematics (IPAM) in Los Angeles, California, begun in 1998.
- Mathematical Biosciences Institute (MBI) in Columbus, Ohio, begun in 2001.
- Mathematical Sciences Research Institute (MSRI) in Berkeley, California, begun in 1981.

In addition, DMS contributes support to the National Institute for Mathematical and Biological Synthesis (NIMBioS) in Knoxville, Tennessee, and also provides funding to four international institutes to support participation of US-based researchers in their activities:
- Banff International Research Station (BIRS) (Canada).
- Mathematisches Forschungsinstitut Oberwolfach (MFO) (Germany).
- Institute des Hautes Études Scientifiques (IHÉS) (France).
- Fields Institute (Canada).

DMS support for the two oldest institutes, IMA and MSRI, dates back to the early 1980s. These two institutes were funded continuously by DMS for the next decade, undergoing periodic merit review but without facing competition from other applicants. By the 1990s, however, NSF policy had evolved to require that long-running programs be exposed to open competition. The first program solicitation for DMS institute proposals was issued in 1997. As a result of that competition, the award establishing support for IPAM was granted, while support for IMA and MSRI was continued.
In 1999 the National Research Council released a report [1] that underscored the importance of research institutes in mathematics and made recommendations for the evolution of DMS-supported institutes. In 2001, as a result of a subsequent open competition, DMS established institute support for AIM, MBI, and SAMSI. Following a subsequent open competition, ICERM was established in 2009. During this expansion of the portfolio of DMS institutes, support for existing DMS institute investments was maintained.

The result of the open DMS institute competitions in the past two decades has been to create a suite of mathematical sciences research institutes of substantial breadth in terms of both program style and emphasis area. The institutes play a unique role among DMS investments as convening bodies that catalyze mathematical sciences research through programs that attract leading players to assemble and exchange ideas. They are unmatched in their ability to host programs of substantial duration, international scale, and prestige. The institutes provide venues and logistical support for these gatherings, but more importantly, institute directors and advisory boards work tirelessly to develop top-quality programming that pushes the cutting edge of research opportunities. Institute activities significantly help shape the progress of research in the mathematical sciences.

In view of the distinguished role that the institutes play on a national scale in advancing research in the mathematical sciences, DMS supervision of the institute awards in recent years has evolved from management of individual institute awards to management of the suite of awards as a portfolio. DMS oversees and makes recommendations regarding the portfolio through the efforts of a management team. For their part, the institute directors meet regularly to collaborate, to coordinate plans for programming, and to keep DMS apprised of issues of common concern or interest.

The Mathematical Sciences Research Institutes in the Context of DMS Investments

The mission of the Division of Mathematical Sciences is to support research at the frontiers of discovery in mathematical sciences and to support training of the next generation of mathematical sciences researchers. DMS is responsible for programs with a total 2015 budget of over US$225 million available for research investments. These programs support activities that expand the knowledge base of the mathematical sciences through research awards to individual investigators and small groups, workforce training grants, and the portfolio of national mathematical sciences research institutes. DMS invests in discovery in mathematics and statistics; promotes interdisciplinary connections across all fields of science, engineering, and technology; and cultivates a diverse and capable community of researchers, students, and professionals. These top investment priorities—discovery, connections, and community—are essential components of the innovation engine that drives the nation’s economy in the twenty-first century.

Meeting this mission requires constant effort on the part of DMS staff to identify the most effective ways to invest the resources furnished by US taxpayers. The Division establishes investment priorities that support the development of the mathematical sciences and at the same time increase the amount of resources available to the mathematical sciences community. Because there are continuously emerging new and important opportunities for DMS investments, and because the growth of the DMS budget is frequently tied to new opportunities, the Division engages in continual rebalancing of its investment portfolio.

Consequently, members of the DMS scientific staff make difficult choices every day. Many activities compete for funding: supporting established individuals, supporting junior investigators, investing in diversity, building infrastructure for research (such as institutes, stand-alone conferences, and research groups), and training future generations of mathematical scientists. Many topical areas compete as well; there are choices between long-term versus short-term goals and between activities of immediate relevance to national initiatives versus investments in the development of basic knowledge. The Division wishes to support all of these, and the job of the DMS scientific staff is to find the right balance.

Not only is the Division’s scientific staff continually making choices among proposals for activities that are before them, they are also trying to anticipate the future, foster growth, and nurture creativity. Funding opportunities come and go; even within the DMS disciplinary research programs, which may seem like a constant feature of the divisional investment portfolio, the individuals and the topics supported undergo dramatic changes over the years. For all these reasons, the Division is not able to indefinitely support any person, area, facility, or program, even if there could be good reasons to do so.

Decisions concerning portfolio balance remain for the most part invisible to the mathematical sciences community overall, unless the decisions concern larger DMS investments. Such visible recent decisions concerning larger investments include the VIGRE, RNMS, EXTEREMS-QED, and MCTP programs that have been discontinued, as well as the decisions this article hopes to put in context, namely, to make awards that ramp down funding for two of the mathematical sciences research institutes, IMA and MBI.
The DMS Awards Portfolio
In more detail, the DMS awards portfolio has three major components: (1) the unsolicited Individual Investigator awards (IIA) (73.5 percent), (2) the Mathematical Sciences Research Institute awards (13.7 percent), and (3) Workforce/Infrastructure awards (W/IA) (12.8 percent). The percentages in parentheses are the approximate percentages of the total US$218 million available for DMS research investments in 2014. The Individual Investigator component is managed by eight different disciplinary programs: Algebra and Number Theory, Analysis, Computational Mathematics, Statistics, etc. The awards of this component typically support single investigators, but are also given to small groups of investigators. In addition to support for research projects, this component also provides almost US$6 million in support of conferences each year. It is the oldest and probably best-known component of the DMS portfolio.

The Workforce/Infrastructure component is perhaps the least known; it provides funding for dedicated activities to help train the next generation(s) of mathematical scientists and also for activities that support the growth of the mathematical sciences community as a whole. Programs include the Mathematical Sciences Postdoctoral Research Fellows (MSPRF) program, the Research Training Group (RTG) program, the Enriched Doctoral Training (EDT) program, the Research Experiences for Undergraduates (REU) program, and the NSF-CBMS Regional Research Conferences in the Mathematical Sciences program.

It is well known that the DMS budget was significantly cut in 2013 in connection with the government-wide sequestration. Moreover, even though the budget has seen partial restorations in 2014 and 2015, it has still not recovered to the absolute dollar amount of 2012. Since 2012, funding for the IIA program has stayed largely constant, though there has been significantly reduced spending on Focused Research Groups (FRGs), from seven awards in 2012 to four awards in 2014. In combination with a higher number of proposals and the inflationary increased costs of individual awards, the essentially level IIA budget has resulted in a significantly lower funding success rate in this program. To mention numbers: in the last fiscal year (2014) DMS received 2,313 proposals for IIA (not counting proposals for conference funding) and made 620 awards, for a funding success rate of 26.8 percent. The success rate prior to 2012 was commonly in the low thirties. The W/IA program has shrunk considerably, with a significantly lower number of RTG awards. In the two-year period 2011–2012 DMS made 14 RTG awards, whereas the number in the two-year period 2013–2014 was 10. These circumstances mean that DMS currently has to decline many IIA and W/IA proposals of extremely high value and potential impact. Funding for the institutes program has stayed constant these last three years, although it has seen a significant expansion since its beginning with two institutes more than thirty years ago.

The Mathematical Sciences Research Institutes Review Process
The DMS institutes program has significantly more flexibility in terms of duration of continued funding than the centers programs funded by other NSF divisions. Since the institutes do not concentrate on a single research topic but are intended to reinvent themselves year after year by developing new programs with changing organizers and participants, they are not subject to the (ten-year) sunset provision that centers are. A DMS institute grant is of five years’ duration; any existing institute may submit a proposal for a renewal and could in principle continue to receive DMS funding indefinitely. Every ten years, the competition is open to proposals for “new” institutes—this situation is traditionally referred to as a competitive renewal situation. However, it is important to point out that the evaluation criteria used in competitive and noncompetitive renewal situations are the same. The possibility for continued funding of DMS institutes without automatic sunset places additional responsibility on the Division to monitor and constantly evaluate the performance of its institutes. Through regular review of its institute portfolio, DMS aims to ensure that all the supported institutes continue to be highly successful and of high impact to a large community.

The Division recently completed a lengthy and careful review of five of the DMS-supported institutes in response to proposals for noncompetitive renewal. As a result of this review, it was decided to give requested five-year renewal awards to ICRM, IPAM, and MSRI, to give a three-year phase-out award to MBI, and to give a two-year phase-out award to IMA.

The fact that the recent renewal process was noncompetitive meant that there was no possibility to submit proposals for entirely new ventures, and it also meant that the five institutes were not seen as competing against each other for a more limited number of slots. The review process is conscientious and deliberate, with several instances of input from the mathematical community. The review started with a joint panel that evaluated all five proposals and “graded” them individually as any panel does (but made no comparisons). This panel also made recommendations on whether or not to arrange a site visit to further assess each application. While there were significant differences in the “grades” assigned, all five institutes were recommended for site visits, which then took place in the fall of 2014. Each site visit team typically consisted of four external “visitors” and four DMS...
scientific staff members. The external visitors were responsible for furnishing a site visit report that was submitted to DMS immediately after the completion of each visit. These reports outlined the strengths and weaknesses of each institute as perceived by the external visitors; these reports made suggestions for changes; and, finally, each report made a recommendation to DMS concerning the continued funding of the particular institute. It should be pointed out that, unlike the “anonymous” panel that reviewed all the institute proposals, the members of the site visit teams are of course known to the institutes, and their names appear on the site visit reports.

Upon completion of the site visits, the information gathered—i.e., the panel reviews, the site visit reports, the impressions of the NSF program directors who had participated in the site visits, as well as information from the institute annual reports—was discussed extensively by the DMS Institute Management Team (a group of six program directors) and by the group of all DMS program directors. The Institute Management Team made a recommendation to the full group of program directors that was discussed and adopted at a meeting on December 3, 2014. This recommendation was to make the requested five-year awards, held to the current budget levels, to three of the institutes: namely, ICERM at Brown University, IPAM at UCLA, and MSRI in Berkeley. The same recommendation was to make a two-year phase-out award to the IMA at the University of Minnesota. At the end of those two years IMA will no longer receive DMS core funding. The fifth institute under review was MBI at Ohio State University. This is a mathematical biology institute, and as a result of the most recent review (but also following earlier reviews) it has become the strongly held belief of DMS that, after twelve years of “incubation” entirely supported by DMS, there is a need to broaden the reach of this potentially very important activity in such a way that units or agencies that provide funding for the biology community (for instance, the NSF Directorate for Biological Sciences or the National Institutes of Health) would be willing to serve as equal funding partners. While the feasibility of such joint arrangements is being investigated, it was decided to give MBI a three-year phase-out award. Should joint funding not prove feasible, the DMS core support of MBI will expire at the end of these three years.

The Future of the DMS Institutes Program
The Division of Mathematical Sciences is extremely supportive of its Mathematical Sciences Research Institutes program and views it as a strong, continuing component of its awards portfolio. DMS finds the institutes to be very important for numerous reasons: (1) their concentration periods, which help focus the attention of some

of the best mathematical minds on problems of particular importance and timeliness; (2) their ability to reach a much wider community of US mathematicians than those reached by the DMS through its Individual Investigator program; (3) their significant contribution to workforce development; and (4) their capability for outreach to the general public. DMS is firmly committed to continued support of these important national resources. On the other hand, the DMS budget situation does not allow for continued relative growth of the institutes program similar to that seen in the past. The funding decisions recently taken should be seen as an expression of the DMS’s desire to keep the institutes program dynamic and vibrant and able to respond to potential future demands for new activities within its current financial scope. In this context it may be relevant to note that there will be a call for (competitive) submission of proposals for Mathematical Sciences Research Institutes with a due date in early 2019.

References
Applications are invited for a full-time position as an Associate Editor of Mathematical Reviews/MathSciNet, to commence as early as possible in late spring/early summer 2016. The Mathematical Reviews (MR) division of the American Mathematical Society (AMS) is located in Ann Arbor, Michigan, in a beautiful, historic building close to the campus of the University of Michigan. The editors are employees of the AMS; they also enjoy certain privileges at the university. At present, the AMS employs approximately seventy-eight people at Mathematical Reviews, including sixteen mathematical editors. MR’s mission is to develop and maintain the MR Database, from which MathSciNet is produced.

An Associate Editor is responsible for broad areas of the mathematical sciences. Editors select articles and books for coverage, classify these items, determine the type of coverage, assign selected items for review to reviewers, and edit the reviews on their return.

The successful applicant will have mathematical breadth with an interest in current developments, and will be willing to learn new topics in pure and applied mathematics. In particular, we are looking for an applicant with expertise in algebraic geometry, or related areas of mathematics, such as commutative rings and algebras or group theory. The ability to write well in English is essential. The applicant should normally have several years of relevant academic (or equivalent) experience beyond the Ph.D. Evidence of written scholarship in mathematics is expected. The twelve-month salary will be commensurate with the experience that the applicant brings to the position. Applications (including a curriculum vitae; bibliography; and the names, addresses, phone numbers, and email addresses of at least three references) should be sent to:

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The review of the applications will begin on February 15, 2016 and will continue until the position is filled.

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Hans Schneider, the James Joseph Sylvester Professor Emeritus of Mathematics at the University of Wisconsin-Madison, died on Tuesday, October 28, 2014. He was eighty-seven. In the field of linear algebra he was one of the most influential mathematicians of the twentieth century.

Hans was born in Vienna, Austria, on January 27, 1927, as the only child of two dentists, Hugo and Isabella (Saphir) Schneider. The family fled the Nazi occupation in March of 1938, traveling through Czechoslovakia and Poland before the eleven-year-old Hans gained admission to a Quaker boarding school in Holland. Hans was reunited with his family in Edinburgh in 1939 just three weeks before the outbreak of war. In 1952 he obtained a PhD from Edinburgh University under A. C. Aitken. He was an assistant lecturer at Queen’s University in Belfast before emigrating in 1959 to the USA with an assistant professorship at the University of Wisconsin—Madison. He was the department chair from 1966 to 1968. He held visiting positions at several universities, including the Technion in Israel, the Technical University of Munich, and the University of Birmingham (UK).

Hans took over as editor-in-chief of the journal *Linear Algebra and its Applications* in 1972 and remained as one of the editors in chief until 2012. This commercial journal afforded him the opportunity to redress the neglect of the field of linear algebra in the mathematical community. The field is now flourishing, with several journals devoted to it and its applications.

In 1987, Hans, with some colleagues, established the International Matrix Group, which was incorporated three years later as the International Linear Algebra Society (ILAS). In order to give the society permanence, a formal structure with annual elections was established. He served as its first president from 1990 to 1996. The society is now a substantial community with about four hundred members from more than twenty countries, publishing two journals, *IMAGE* and *The Electronic Journal of Linear Algebra*. In 1993 when Hans retired from the University of Wisconsin—Madison, ILAS established the Hans Schneider Prize in Linear Algebra.

Hans is the author of more than one hundred sixty papers on a wide range of topics in linear algebra and matrix theory, including two papers published in 2014. His favorite topic was the many ramifications and generalizations of the Perron—Frobenius theory of nonnegative matrices. He had seventeen PhD students and about eighty collaborators. He is survived by his wife, Miriam (Wieck), three children, and six grandchildren.

Portions excerpted from “Last Words” and “A Personal History”, available at [www.math/wisc.edu/~hans](http://www.math/wisc.edu/~hans).

Richard A. Brualdi

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Departments Coordinate Job Offer Deadlines

For the past sixteen years, the American Mathematical Society has led the effort to gain broad endorsement for the following proposal:

That mathematics departments and institutes agree not to require a response prior to a certain date (usually early in February of a given year) to an offer of a postdoctoral position that begins in the fall of that year.

This proposal is linked to an agreement made by the National Science Foundation (NSF) that the recipients of the NSF Mathematical Sciences Postdoctoral Fellowships would be notified of their awards, at the latest, by the end of January.

This agreement ensures that our young colleagues entering the postdoctoral job market have as much information as possible about their options before making a decision. It also allows departmental hiring committees adequate time to review application files and make informed decisions. From our perspective, this agreement has worked well and has made the process more orderly.

There have been very few negative comments. Last year, one hundred seventy-one mathematics and applied mathematics departments and four mathematics institutes endorsed the agreement.

Therefore we propose that mathematics departments again collectively enter into the same agreement for the upcoming cycle of recruiting, with the deadline set for Monday, February 1, 2016. The NSF’s Division of Mathematical Sciences has already agreed that it will complete its review of applications by January 22, 2016 at the latest, and that all applicants will be notified electronically at that time.

The American Mathematical Society facilitated the process by sending an email message to all doctoral-granting mathematics and applied mathematics departments and mathematics institutes. The list of departments and institutes endorsing this agreement was widely announced on the AMS website beginning November 1, 2015, and will be updated weekly until mid-January.

We ask that you view this year’s formal agreement at [www.ams.org/employment/postdoc-offers.html](http://www.ams.org/employment/postdoc-offers.html) along with this year’s list of adhering departments.

**Important:** To streamline this year’s process for all involved, we ask that you notify T. Christine Stevens at the AMS (tcs@ams.org) if and only if:

1. your department is not listed and you would like to be listed as part of the agreement or
2. your department is listed and you would like to withdraw from the agreement and be removed from the list.

Please feel free to email us with questions and concerns.

Thank you for consideration of the proposal.

—Donald McClure  
AMS Executive Director

—T. Christine Stevens  
AMS Associate Executive Director
Inside the AMS

Project NExT Fellows Chosen

Six mathematicians have been selected as AMS Project NExT fellows for 2015. Their names, affiliations, and areas of research are: Thomas Bellsky, University of Maine, dynamical systems and PDEs; Vindya Bhat, New York University, discrete mathematics; Houssein El Turkey, University of New Haven, representation theory; Marie Jameson, University of Tennessee, number theory; Anisah Nu’Man, Trinity College, geometric group theory; Alexander Zupan, University of Nebraska—Lincoln, geometry and topology.

Project NExT (New Experiences in Teaching) is a professional development program for new and recent PhDs in the mathematical sciences (including pure and applied mathematics, statistics, operations research, and mathematics education). It addresses all aspects of an academic career: improving the teaching and learning of mathematics, engaging in research and scholarship, and participating in professional activities. It also provides the participants with a network of peers and mentors as they assume these responsibilities. The AMS provides funding for a number of the fellowships.

—From an MAA announcement

Deaths of AMS Members

Susana F. L. R. de Foglio, of Brazil, died on September 21, 2013. Born on June 6, 1924, she was a member of the Society for 42 years.

Cecil E. Duncan, of Palo Alto, California, died on July 27, 2012. Born on October 21, 1921, he was a member of the Society for 60 years.

Guydo R. Lehner, of College Park, Maryland, died on May 8, 2014. Born on April 14, 1928, he was a member of the Society for 61 years.

John A. Pfaltzgraff, of Chapel Hill, North Carolina, died on October 12, 2014. Born on November 1, 1936, he was a member of the Society for 53 years.

Walter V. Philipp, of Champaign, Illinois, died on July 19, 2006. Born on December 14, 1936, he was a member of the Society for 42 years.

T. K. Puttaswamy, of Muncie, Indiana, died on April 26, 2013. Born on January 17, 1932, he was a member of the Society for 43 years.

Donald W. Robinson, of Albuquerque, New Mexico, died on November 10, 2014. Born on February 29, 1928, he was a member of the Society for 58 years.

William W. Rowell, of Johnson City, Tennessee, died on December 4, 2014. Born on November 28, 1955, he was a member of the Society for 30 years.

Yibao Xu, of Plainsboro, New Jersey, died on November 7, 2013. Born on December 10, 1965, he was a member of the Society for 14 years.

From the AMS Public Awareness Office


AMS Grad Student Blog. Thanks to Tyler Clark for his three and a half years of service as editor-in-chief of the AMS Grad Student Blog, and welcome to Matthew Simonson as the new editor-in-chief. Simonson, at Northeastern University, invites graduate students in the mathematical sciences to serve on the blog’s editorial board. See blogs.ams.org/mathgradblog/about/.

New Works on Mathematical Imagery. See stunning colorful symmetry images by Frank Farris and line images by Hamid Naderi Yeganeh at www.ams.org/mathimagery.

—Annette Emerson and Mike Breen
AMS Public Awareness Officers
paoffice@ams.org
AMS-AAAS Mass Media Summer Fellowships

The AMS provides support each year for a graduate student in the mathematical sciences to participate in the American Association for the Advancement of Science (AAAS) Mass Media Science and Engineering Fellows Program. This summer fellowship program pairs graduate students with major media outlets nationwide, where they will research, write, and report on science news and use their skills to bring technical subjects to the general public.

The principal goal of the program is to increase the public's understanding of science and technology by strengthening the connection between scientists and journalists to improve coverage of science-related issues in the media. Past AMS-sponsored fellows have held positions at National Public Radio, Scientific American, Voice of America, The Oregonian, the Chicago Tribune, and the Milwaukee Journal Sentinel.

Fellows receive a weekly stipend of US$500, plus travel expenses, to work for ten weeks during the summer as reporters, researchers, and production assistants in newsrooms across the country. They observe and participate in the process by which events and ideas become news, improve their ability to communicate about complex technical subjects in a manner understandable to the public, and increase their understanding of editorial decision making and of how information is effectively disseminated. Each fellow attends an orientation and evaluation session in Washington, DC, and begins the internship in mid-June. Fellows submit interim and final reports to AAAS. A wrap-up session is held at the end of the summer.

Mathematical sciences faculty are urged to make their graduate students aware of this program. The deadline to apply for fellowships for the summer of 2016 is January 15, 2016. Further information about the fellowship program and application procedures is available online at [www.ams.org/programs/ams-fellowships/media-fellow/massmediafellow](http://www.ams.org/programs/ams-fellowships/media-fellow/massmediafellow) and through the AMS Washington Office, 1527 Eighteenth Street, NW, Washington, DC 20036; telephone: 202-588-1100; email: amsc@ams.org.

—AMS Washington Office

*NSF Program in Computational and Data-Enabled Science and Engineering in Mathematical and Statistical Sciences

The Program in Computational and Data-Enabled Science and Engineering in Mathematical and Statistical Sciences (CDS&E-MSS) of the National Science Foundation (NSF) accepts proposals that confront and embrace the host of mathematical and statistical challenges presented to the scientific and engineering communities by the ever-expanding role of computational modeling and simulation on the one hand and the explosion in production of digital and observational data on the other. The goal of the program is to promote the creation and development of the next generation of mathematical and statistical theories and tools that will be essential for addressing such issues. To this end, the program supports fundamental research...
Mathematics Opportunities

in mathematics and statistics whose primary emphasis will be on meeting the aforementioned computational and data-related challenges. The research supported by the CDS& E-MSS program aims to advance mathematics or statistics in a significant way and addresses computational or big-data challenges. Proposals should include a principal investigator or co-principal investigator who is a researcher in the mathematical or statistical sciences in an area supported by the NSF Division of Mathematical Sciences (DMS). The program encourages submission of proposals that include multidisciplinary collaborations or the training of mathematicians and statisticians in CDS&E. The window for submission of full proposals is November 25–December 9, 2015. See www.nsf.gov/funding/pgm_summ.jsp?pims_id=504687&org=DMS&from=home.

—NSF announcement

NDSEG Fellowships

As a means of increasing the number of US citizens trained in disciplines of military importance in science and engineering, the Department of Defense (DoD) awards National Defense Science and Engineering Graduate (NDSEG) Fellowships each year to individuals who have demonstrated ability and special aptitude for advanced training in science and engineering. The fellowships are awarded for a period of three years for study and research leading to doctoral degrees in any of fifteen scientific disciplines.

The NDSEG Fellowship Program is open only to applicants who are citizens or nationals of the United States. NDSEG Fellowships are intended for students at or near the beginning of their graduate studies in science or engineering. Applicants must have received or be on track to receive their bachelor’s degree by fall of 2016. Fellows selected in spring 2016 must begin their fellowship tenures in fall 2016. Fellowships are tenable only at US institutions of higher education offering doctoral degrees in the scientific and engineering disciplines specified. Fellows will receive full tuition and a total of US$102,000 in stipend funds over the course of the thirty-six-month tenure, prorated monthly based on a twelve-month academic year. Applications are encouraged from women, persons with disabilities, and minorities, including members of ethnic minority groups such as African American, American Indian and Alaska Native, Asian, Native Hawaiian and other Pacific Islander, Hispanic, or Latino.

Complete applications must be submitted electronically by December 18, 2015. Application forms are available online at ndseg.asee.org/apply_online. For further information, see ndseg.asee.org/

—From an NDSEG announcement
Oertel-Jäger Receives von Kaven Award

Tobias H. Oertel-Jäger of the Technical University of Dresden is the recipient of the 2015 von Kaven Award presented by the Deutsche Forschungsgemeinschaft (DFG, German Science Foundation) for his work in dynamical systems, a field that, according to the prize citation, “ranges from theoretical work to applications in biology and physics. A dynamical system is a concept in mathematics that describes a certain class of models of time-dependent processes, which in synopsis raise very basic issues and are as important when describing many natural and technological processes. Tobias Oertel-Jäger’s fundamental research work is part of the discipline called ergodic theory.”

Oertel-Jäger received his doctorate from the University of Erlangen-Nuremberg in 2005. He was granted a DFG research fellowship for postdoctoral study at the Collège de France in Paris from 2006 to 2009. In 2009 he became head of the Emmy Noether independent junior research group at the Technical University of Dresden, in which he researches topological and geometric aspects and probability theory in dynamical processes.

The von Kaven Award carries a cash prize of 10,000 euros (approximately US$11,000) and was presented in September 2015 at the annual meeting of the German Mathematical Society (DMV) in Hamburg. The von Kaven Award is presented each year to an outstanding mathematician based in the European Union. The von Kaven Foundation was established in December 2004 by its benefactor, Herbert von Kaven, of Detmold, Germany, and the DFG’s Executive Board.

—From a DFG announcement

Freitas Awarded Rubio de Francia Prize

Nuno Freitas of the University of Barcelona has been awarded the 2014 Rubio de Francia Prize of the Royal Spanish Mathematical Society (RSME) “for his contributions to number theory, which improve our understanding of Fermat’s equation on real quadratic bodies, those obtained by adding to the rational numbers the square root of a positive integer.” His work with Le Hung and Siksek showing that any elliptic curve on a real quadratic field is modular allowed the proof of Fermat’s Last Theorem by Wiles and represents an important step in demonstrating the modularity conjecture.

The prize honors the memory of J. L. Rubio de Francia (1949–1988), an internationally renowned Spanish analyst. It is awarded annually to a young mathematician from Spain or residing in Spain, and it is the highest distinction given by the RSME. The prize carries a monetary award of 3,000 euros (approximately US$3,300). The prize jury consisted of Jesús Bastero Eleizalde (chair), Ingrid Daubechies, Timothy Gowers, Subhash Khot, Marco A. López Cerdá, Alvaro Pelayo, and Claire Voisin.

—From a Royal Spanish Mathematical Society announcement

2015 Davidson Fellows Selected

Four high school students whose projects involved the mathematical sciences have been named 2015 Davidson Fellows. Noah Golowich, seventeen, of Lexington, Massachusetts, was awarded a top prize of a scholarship worth US$50,000 for his project “Resolving a Conjecture on De-
degree of Regularity, with Some Novel Structural Results.”

Dhaivat Pandya, seventeen, of Appleton, Wisconsin, also received a US$50,000 scholarship for his project “Algorithms for Minimum Cost Linear Network Coding Design for Networks with General Connections.” Scholarships worth US$25,000 were awarded to Peter Tian, eighteen, of Hilliard, Ohio, for his project “Extremal Functions of Forbidden Multidimensional Matrices,” and to Sreya Vemuri, sixteen, of Carmel, Indiana, for her project “Effect of Time-Dependent Gain and Loss in a PT-Symmetric Lattice.”

The Davidson Fellows program, a project of the Davidson Institute for Talent Development, awards scholarships to students eighteen years of age or younger who have created significant projects that have the potential to benefit society in the fields of science, technology, mathematics, literature, music, and philosophy.

—From a Davidson Fellows announcement

Prizes of the Canadian Mathematical Society

The Canadian Mathematical Society (CMS) will award several prizes at its winter meeting in Montreal in December 2015.

Mark Mac Lean of the University of British Columbia has been named the recipient of the Adrian Pouliot Award “for his excellence in teaching and contributions to mathematics education in Canada, particularly Aboriginal education.” He has worked with the Pacific Institute for the Mathematical Sciences (PIMS) on several Aboriginal mathematics education projects, including workshops for teachers. He has served as academic director for Jump Start, a program that supports international and First Nations students at the University of British Columbia since 2011. The Pouliot Award recognizes individuals or teams of individuals who have made significant and sustained contributions to mathematics education in Canada.

Philippe Gille of the Université Claude Bernard has been honored with the G. de B. Robinson Award “for his excellence in teaching and contributions to mathematics education in Canada, particularly Aboriginal education.” He has worked with the Pacific Institute for the Mathematical Sciences (PIMS) on several Aboriginal mathematics education projects, including workshops for teachers. He has served as academic director for Jump Start, a program that supports international and First Nations students at the University of British Columbia since 2011. The Pouliot Award recognizes individuals or teams of individuals who have made significant and sustained contributions to mathematics education in Canada.

Alejandro Adem of the University of British Columbia has been awarded the Jeffery-Williams Prize. According to the prize citation, Adem is “one of the world’s leading experts in group cohomology and the geometry of group actions” who “is fascinated by the deep mathematics and beauty associated to symmetry groups, which manifest themselves both in nature and across a variety of scientific disciplines.” He is managing editor of the Memoirs and the Transactions of the American Mathematical Society and is an AMS Fellow. The prize recognizes mathematicians who have made outstanding contributions to mathematical research.

The CMS Doctoral Prize has for the first time been awarded to two recipients. Yuval Filmus of the University of Toronto was honored for research predominately focused on extremal combinatorics, and Hector H. Pasten Vasquez of Queen’s University was honored for his work in number theory and logic. The award recognizes outstanding performance by a doctoral student who graduated from a Canadian university in the preceding year.

—From CMS announcements

Floudas and Grossmann Awarded Carathéodory Prize

Christodoulos A. Floudas of Texas A&M University and Ignacio E. Grossmann of Carnegie Mellon University have been awarded the Constantin Carathéodory Prize of the International Society of Global Optimization for fundamental contributions to theory, algorithms, and applications of global optimization. Floudas was honored for work in mathematical modeling and optimization of complex systems. Grossmann was recognized for his work in developing novel mathematical programming models and techniques for a variety of problems in process systems engineering. The prize carries a cash award of US$2,000.

—From an International Society of Global Optimization announcement

Scheinkman Awarded CME-MSRI Prize

José Scheinkman of Columbia University has been awarded the 2014 CME-MSRI Prize in Innovative Quantitative Applications of the CME Group and the Mathematical Sciences Research Institute (MSRI). The annual CME Group-MSRI Prize is awarded to an individual or a group to recognize originality and innovation in the use of mathematical, statistical, or computational methods for the study of the behavior of markets and, more broadly, of economics.

—From a CME-MSRI announcement

NDSEG Fellowships Awarded

Nine young mathematicians have been awarded National Defense Science and Engineering Graduate (NDSEG) Fellowships by the Department of Defense (DoD) for 2015. The fellowships are sponsored by the United States Army, Navy, and Air Force. As a means of increasing the number of US citizens trained in disciplines of military importance in science and engineering, DoD awards fellowships to...
individuals who have demonstrated ability and special aptitude for advanced training in science and engineering. Following are the names of the fellows in mathematics, their institutions, and the offices that awarded the fellowships: ZACHARY BOYD, University of California Los Angeles, Office of Naval Research (ONR); NICHOLAS DERR, Harvard University, Air Force Office of Scientific Research (AFOSR); VICTORIA GERSHUNY, University of Arizona, Army Research Office (ARO); MAYA MATHUR, Harvard University, ONR; BRADLEY NELSON, Stanford University, AFOSR; ROBERT RAVIER, Duke University, AFOSR; BEN SOUTHWORTH, University of Colorado, Boulder, ARO; ROBERT TUNNEY, University of California Berkeley, ARO; LEIGHTON WILSON, University of Michigan, Ann Arbor, AFOSR.

—From an NDSEG announcement

Royal Society of Canada Elections

The Royal Society of Canada has elected eighty-seven new Fellows, among whom are three who work in the mathematical sciences. They are CHRISTIAN GENEST of McGill University; MARK LEWIS of the University of Alberta; and CATHERINE SULEM of the University of Toronto.

—From a Royal Society announcement

B. H. Neumann Awards Given

The Australian Mathematics Trust has honored three mathematics teachers with B. H. Neumann Awards for service to the mathematics profession. The honorees are KUMUDINI DHARMADASA, NORMAN DO, and DANIEL MATHEWS. The awards honor Bernhard H. Neumann, who supported mathematics and mathematics teaching at all levels in Australia.

—From an Australian Mathematics Trust announcement

David Hestenes Honored

The Sixth Conference on Applied Geometric Algebras in Computer Science and Engineering (AGACSE 2015, Barcelona, Spain) was dedicated to DAVID HESTENES of Arizona State University “in recognition for his masterly leadership.” This was highlighted by issuing a second edition of his landmark 1966 book Space-Time Algebra (fifty years later, but it is as fresh now as it was then!). Hestenes was present during the whole week, and the standing ovation after his keynote lecture was a very moving moment for all participants. The inaugural David Hestenes Prize was awarded to LEI HUANG of the Academy of Science, Beijing, P.R. China, for “the best work submitted to the AGACSE 2015 Conference by a young researcher.” The conference was preceded, for the first time, by a two-day summer school to better prepare beginners for the conference and was attended by two-thirds of the participants. The next conference will be in Campinas, Brazil, in 2018.

—Sebastià Xambó-Descamps, Chair
AGACSE 2015 Organizing Committee

Alphonse Buccino (1931–2015)

ALPHONSE (AL) BUCCINO died July 6, 2015, at the age of eighty-four. Born in New York City to parents who were Italian immigrants, he had to drop out of high school to support his family after the death of his mother. He was drafted to serve in Korea and reached the rank of captain. After his war service, he enrolled at the University of Chicago, where he earned his PhD in 1967 under the direction of Irving Kaplansky. He was a member of the faculty at Roosevelt University and DePaul University before taking a position at the National Science Foundation in 1970. Known for his support of research and education, Buccino became the dean of the University of Georgia’s College of Education. In the early 1990s, he spent a year as an advisor in the White House Office of Science and Technology. Buccino had been an AMS member since 1960.

—Allyn Jackson
About the Cover

Art by Bill Thurston

The December cover image accompanies the memorial article about Bill Thurston coordinated by David Gabai and Steve Kerckhoff. It reproduces a drawing made by Thurston that was included as a color insert in the book *The Eightfold Way: The Beauty of Klein’s Quartic Curve,* published by the Mathematical Sciences Research Institute (MSRI) in Berkeley and Cambridge University Press in 1999. The immediate motive for the book was the unveiling at MSRI of a sculpture by Helaman Ferguson inspired by the algebraic curve discovered by Felix Klein containing $\text{PSL}_2(\mathbb{Z}/7)$ as an automorphism group. This curve is a quotient of the Poincaré half plane by an arithmetic subgroup of $\text{PSL}_2(\mathbb{R})$, and the drawing illustrates how that works.

The editor of the book was Silvio Levy. He writes to us: "Bill Thurston was always looking for ways to visualize and explain geometric facts. While the standard gluing construction easily describes the topology of a closed surface of arbitrary genus, Bill wanted to visualize the geometry of particular examples as well. He was intrigued by Hurwitz’s 1893 theorem, which (in Bill’s preferred geometric language) specifies the maximum number of possible self-isometries a closed hyperbolic surface of a certain genus can have. Around 1990 he became aware of work of Felix Klein from the 1870s, exhibiting a compact Riemann surface that exemplifies Hurwitz’s theorem in genus 3; it has 168 automorphisms, or 336 symmetries if we allow orientation reversal. Known as the Klein Quartic, this surface has the remarkable projective equation $x^3y + y^3z + z^3x = 0$.

"In 1992, as director of MSRI, Bill was in a position to commission a sculpture (paid for with private donations) from the sculptor Helaman Ferguson, and it was decided that it should illustrate the Klein Quartic. The base was to be a heptagonal tiling of the Poincaré disc, made in serpentine; I prepared a paper collage of the tiling with a few hundred heptagons, to serve as a model for the stone cutting. The upper portion, an elegant rendition in white marble of a genus-three surface with tetrahedral symmetry, showed ‘the same’ tiling by heptagons on the wrapped-up surface, but some of the edges were raised to represent the ‘eightfold way’ that leads from any vertex of the tiling back to itself after a polygonal trip along the edges, alternating lefts and rights.

"At the sculpture’s unveiling in November 1993, Thurston lectured briefly on the mathematics behind it; the event handout included the drawing on this *Notices* cover, which he made to indicate both the symmetries and the eightfold way—but also the right way to pronounce the abbreviation MSRI. (He disliked the thitherto prevalent nickname for the Institute. He was successful in supplanting it but not with his proposal of ‘Emissary’, which became instead the name of MSRI’s newsletter; what caught on for the Institute was, simply enough, Em-Ess-Are-L.)

"A few years later, *The Eightfold Way* was published in the MSRI Publications series. The texts of the articles in it (but not the insert with the cover image) are available at [library.msri.org/books/Book35/contents.html](http://library.msri.org/books/Book35/contents.html)

They deal with the Klein Quartic from several points of view (complex-analytic, algebraic, geometric) and with the sculpture itself."

Silvio Levy got his PhD at Princeton in 1985 under Thurston and collaborated with him as a programmer, illustrator, and editor until the late 1990s. We thank him for suggesting the cover image to represent Thurston’s art, and we thank both Cambridge University Press and the Mathematical Sciences Research Institute for allowing us to reproduce it.

—Bill Casselman
Graphics Editor
notices-covers@ams.org

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Reference and Book List

The Reference section is intended to provide readers with frequently sought information in an easily accessible format. New information is printed as it becomes available and is referenced after its first printing.

Contacting the Notices
The preferred method for contacting the Notices is e-mail.

The editor-in-chief, Steven G. Krantz, should be contacted about articles for consideration. Articles include features, memorials, communications, opinion pieces, and book reviews. The editor is also the person to whom to send news of unusual interest about other people’s mathematics research. Contact the editor-in-chief at: notices@math.wustl.edu.

The managing editor, Rachel L. Rossi, should be contacted for additions to “Mathematics People”, “Mathematics Opportunities”, “For Your Information”, and for any corrections. Contact the managing editor at: notices@ams.org.

Letters to the editor should be sent to: notices-letters@ams.org.

Permissions requests should be sent to: reprint-permission@ams.org.

Advertising requests should be sent to: notices-ads@ams.org.

Math Calendar additions should be sent to: mathcal@ams.org.

Book List additions should be sent to: notices-booklist@ams.org.

For full contact information, including postal addresses, see: www.ams.org/notices/contact.html.

Upcoming Deadlines

November 20, 2015: Applications for NRC-Ford Foundation Predoctoral Fellowships. See sites.nationalacademies.org/pga/fordfellowships/.


December 1, 2015: Applications for AMS Centennial Fellowship. See www.ams.org/ams-fellowships/.

December 1, 2015: Submissions for the John Riordan Prize of the OEIS Foundation. See the website https://oeis.org/wiki/RiordanPrize.

December 3, 2015: Nominations for 2016 Ferran Sunyer i Balaguer Prize. See ffsb.iec.cat.

December 15, 2016: Applications for 2016 AMS Epsilon Fund grants.

Where to Find It

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National Science Board—March 2015, p. 290

NRC Board on Mathematical Sciences and Their Applications—March 2014, p. 305

NSF Mathematical and Physical Sciences Advisory Committee—May 2015, p. 571

Program Officers for Federal Funding Agencies—October 2013, p. 1188 (DoD, DoE); December 2015, p. 1390 (NSF Mathematics Education)

Program Officers for NSF Division of Mathematical Sciences—November 2015, p. 1230


**December 18, 2015:** Registration for Department Chairs Workshop at 2016 Joint Mathematics Meetings. See bit.ly/1jIrL9S4 or contact AMS Washington Office at 202-588-1100; email: amsdc@ams.org.

**December 18, 2015:** Registration for Free Grant-Writing Workshop at 2016 Joint Mathematics Meetings. See the website bit.ly/1uUq9hU.

**December 21, 2015:** Proposals for AMS Short Courses for 2017 Joint Mathematics Meetings. Proposals should be sent via email to Associate Executive Director (aed-mps@ams.org) with a copy to Robin Hagan Aguiar (rha@ams.org).


**January 31, 2016:** Entries for Association for Women in Mathematics (AWM) essay contest. See https://sites.google.com/site/awmmath/home.

**February 1, 2016:** Applications for AWM Travel Grants, Mathematics Education Research Travel Grants, Mathematics Mentoring Travel Grants, and Mathematics Education Research Mentoring Travel Grants. See https://sites.google.com/site/awmmath/programs/travel-grants; telephone: 703-934-0163; or email: awm@awm-math.org; or contact Association for Women in Mathematics, 11240 Waples Mill Road, Suite 200, Fairfax, VA 22030.

**February 15, 2016:** Applications for AMS Congressional Fellowship. See www.ams.org/ams-fellowships/. For paper copies of the form, write to the Membership and Programs Department, American Mathematical Society, 201 Charles Street, Providence, RI 02904-2294; prof-serv@ams.org; 401-455-4096.

**March 31, 2016:** Nominations for 2016 Information-Based Complexity Prize. Nominations may be sent to Joseph F. Traub at traub@cs.columbia.edu.

**April 15, 2016:** Applications for fall 2016 semester of Math in Moscow. See www.mccme.ru/mathinmoscow, or by writing to: Math in Moscow, P.O. Box 524, Wynnewood, PA 19096; fax: +7095-291-65-01; email: mim@mccme.ru. Information and application forms for the AMS scholarships are available on the AMS website at www.ams.org/programs/travel-grants/mimoscow, or by writing to: Math in Moscow Program, Membership and Programs Department, American Mathematical Society, 201 Charles Street, Providence RI 02904-2294; email: student-serv@ams.org.

**May 1, 2016:** Applications for AWM Travel Grants and Mathematics Education Research Travel Grants. See https://sites.google.com/site/awmmath/programs/travel-grants; telephone: 703-934-0163; or email: awm@awm-math.org; or contact Association for Women in Mathematics, 11240 Waples Mill Road, Suite 200, Fairfax, VA 22030.

**October 1, 2016:** Applications for AWM Travel Grants and Mathematics Education Research Travel Grants. See https://sites.google.com/site/awmmath/programs/travel-grants; telephone: 703-934-0163; or email: awm@awm-math.org; or contact Association for Women in Mathematics, 11240 Waples Mill Road, Suite 200, Fairfax, VA 22030.

**NSF Mathematics Education Staff**

The Directorate for Education and Human Resources (EHR) of the National Science Foundation (NSF) sponsors a range of programs that support educational projects in mathematics, science, and engineering. Listed below is contact information for those EHR program officers whose fields are in the mathematical sciences or mathematics education. These individuals can provide information about the programs they oversee, as well as information about other EHR programs of interest to mathematicians. The postal address is: Directorate for Education and Human Resources, National Science Foundation, 4201 Wilson Boulevard, Arlington, VA 22230. The EHR web page is www.nsf.gov/dir/index.jsp?org=EHR.

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**Reference and Book List**

**IMU Executive Committee**
The Executive Committee of the International Mathematical Union (IMU) conducts the business of the Union. Following are the members of the Executive Committee for the term 2015–2018.

Shigefumi Mori, President  
Helge Holden, Secretary  
Alicia Dickenstein, Vice President  
Vaughan Jones, Vice President  
Benedict H. Gross, Member-at-Large  
John Francis Toland, Member-at-Large  
Vasudevan Srinivas, Member-at-Large  
Christian Rousseau, Member-at-Large  
Wendelin Werner, Member-at-Large  
Ingrid Daubechies, Ex-officio Member (Past President)

**Book List**
The Book List highlights recent books that have mathematical themes and are aimed at a broad audience, potentially including mathematicians, students, and the general public.

An * indicates a new addition to the book list.


Reference and Book List


Correction

The obituary Albert Baernstein II, 1941–2012 in the August issue of the *Notices* misattributed a quotation (on page 817) from Carlo Morpurgo (PhD 1993) to Luigi Fontana (PhD 1991).

I apologize to both Dr. Fontana and Dr. Morpurgo, as well as to the readers of the *Notices*.

—David Drasin
The most comprehensive and up-to-date Mathematics Calendar information is available on the AMS website at [www.ams.org/mathcal/](http://www.ams.org/mathcal/).

Please submit conference information for the Mathematics Calendar through the Mathematics Calendar submission form at [www.ams.org/cgi-bin/mathcal-submit.pl](http://www.ams.org/cgi-bin/mathcal-submit.pl).

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**December 2015**


3–4 *Workshop on Integrable Systems*, School of Mathematics and Statistics, University of Sydney NSW, Australia.

* 4–6 *Fifth Annual Tech Topology Conference*, Georgia Institute of Technology, Atlanta, Georgia.

**Description:** A weekend conference on geometry and topology, featuring seven invited talks and a lunchtime session of lightning-talks.

**Information:** ttc.gatech.edu.


7–11 *BioInfoSummer 2015*, The University of Sydney, Sydney, Australia.

7–11 *New Mathematical and Computational Problems involved in Cell Motility, Morphogenesis and Pattern Formation (CGPW04)*, Isaac Newton Institute for Mathematical Sciences, University of Cambridge, Cambridge, UK.

7–11 *Present Challenges of Mathematics in Oncology and Biology of Cancer*, CIRM, Marseille Luminy, France.

8–12 *International Conference on Function Spaces and Inequalities*, Department of Mathematics, South Asian University, New Delhi, India.


10–13 *Quasweekend II—Ten Years After*, Helsinki, Finland.

* 11 *Mathematics Days in Tirana*, Faculty of Natural Sciences, Department of Mathematics, Tirana, Albania.

**Description:** Mathematics Days in Tirana (MDT) is the first international conference organized from our department and is expected to be followed from other similar events in the future with the intent to bring together researchers from Albanian universities and abroad to discuss a wide variety of research themes whose aim is growth of the scientific working level of our staff and increase of academic performance of PhD students.

**Conference themes:** Topics of papers/presentations of participants will focus on the following areas: Theory of semigroups, Cryptography and coding theory, Homological algebra, Category Theory, Integration theory, 2-normed spaces, Fuzzy spaces, Fixed point theory, Topology, Low dimension homotopy, Differential equations, Riemannian geometry, Finite geometry, Mathematical education and teaching.

**Information:** https://sites.google.com/a/fshn.edu.al/mathdaysintirana/index.


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**This section** contains announcements of meetings and conferences of interest to some segment of 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. A complete list of meetings of the Society can be found in the Meetings & Conferences Section of each issue.

**An announcement** will be published in the *Notices* if it contains a call for papers and specifies the place, date, subject (when applicable), and the speakers; a second announcement will be published only if there are changes or necessary additional information. Once an announcement has appeared, the event will be briefly noted in every third issue until it has been held. Asterisks (*) mark those announcements containing new or revised information.

**In general,** announcements of meetings and conferences carry only the date, title of meeting, place of meeting, names of speakers (or sometimes a general statement on the program), deadlines for abstracts or contributed papers, and source of further information. If there is any application deadline with respect to participation in the meeting, this fact should be noted. All communications on meetings and conferences in the mathematical sciences should be sent to mathcal@ams.org. In order to allow participants to arrange their travel plans, organizers of meetings are urged to submit information for these listings early enough to allow them to appear in more than one issue of the *Notices* prior to the meeting in question. To achieve this, listings should be received in Providence eight months prior to the scheduled date of the meeting. The Mathematics Calendar, as well as Meetings and Conferences of the AMS, is now available through the AMS website: [www.ams.org/](http://www.ams.org/).
13-15 The 4th International Conference on Electrical Engineering, Boumerdés, Algeria.

14-16 International Conference “Relativity and Geometry” in Memory of André Lichnerowicz, Institut Henri Poincaré, Paris, France.

14-17 Geometric Aspects on Capillary Problems and Related Topics, Granada, Spain.

14-18 Geometric and Categorical Representation Theory, Sunshine Coast, Australia.


14-18 Workshop on Geometric Aspects of the Quantum Hall Effect, University of Cologne, Cologne, Germany.

15-17 15th IMA International Conference on Cryptography and Coding, St. Catherine’s College, University of Oxford, Oxford, UK.

15-17 The 8th International Seminar on Geometry and Topology (GT8), Amir Kabir University of Technology (Tehran Polytechnic), Tehran, Iran.


16-20 The 20th Asian Technology Conference in Mathematics (ATCM 2015), Leshan, China.


19-20 4th International Conference on Mathematical and Computational Sciences, Asian Institute of Technology Conference Center P.O. Box 4, Klong Luang, Pathumthani 12120, Thailand.

19-21 International Conference on Analysis and its Applications (ICAA-2015), Department of Mathematics, Aligarh Muslim University, Aligarh 202002, India.

Description: The purpose of ICAA-2015 is to bring together the mathematicians from all over the world working in analysis and its related areas to present their research, to exchange new ideas, to discuss challenging issues, to foster future collaborations and to offer exposure to young researchers.

Topics: ICAA-2015 covers all topics related to analysis and its applications, including, but not limited to: Nonlinear analysis; operator theory; fixed point theory; variational analysis including variational inequalities; convex analysis; smooth and nonsmooth analysis; wavelet analysis; Fourier analysis; modern methods in summability and approximation theory; sequence spaces and matrix transformations; orthogonal polynomials and special functions; differential equations.

Information: www.amu.ac.in/icaa15.jsp.


21-23 9th International Conference of IMBIC on "Mathematical Sciences for Advancement of Science and Technology (MSAST 2015)", IMBIC, Salt Lake City, Kolkata, India.

22 National Seminar on "Advances in Mathematical Sciences", Department of Mathematics, Gauhati University, Guwahati-781014, Assam, India.

Description: To commemorate the 128th birth anniversary of Srinivasa Ramanujan Iyengar (22nd December, 1887-26th April, 1920), FRS, an Indian mathematician and autodidact who, with almost no formal training in pure mathematics, made extraordinary contributions to mathematical analysis, number theory, infinite series, and continued fractions (Wikipedia). The platform of this event is expected to be helpful in promoting and expanding the mathematical legacy of this mathematician brilliant beyond comparison who inspired many great mathematicians.

Organizers: Assam Academy of Mathematics & Department of Mathematics, Gauhati University.

Information: https://sites.google.com/site/nsams2015/.

27-29 Modern Mathematical Methods And High Performance Computing in Science & Technology (M3HPCST-2015), Department of Mathematics Raj Kumar Goel Institute of Technology NH-58 Delhi Meerut Road, Ghaziabad UP 201003, INDIA.

28-30 Riemann Legacy Conference, Sanya, Hainan, China.

28-31 Ninth International Triennial Calculata Symposium on Probability and Statistics, Department of Statistics, University of Calcutta, 35 Ballygunge Circular Road, Kolkata 700019, West Bengal, India.

31-January 4 String Mathematics 2015, Sanya, Hainan, China.

January 2016

3-16 New Challenges in Reverse Mathematics, Institute for Mathematical Sciences, National University of Singapore, Singapore.

4 2016 AMSI Summer School, RMIT University, Melbourne, VIC, Australia.

* 4-8 Spectrum of Random Graphs, CIRM, Marseille Luminy, France.

Description: The spectral analysis of matrices defined on deterministic or random graphs is a topic which attracts growing attention in various branches of mathematics, computer science, and theoretical physics. The motivation comes from many distinct directions: random matrices, random Schrödinger operators, quantum ergodicity, countable groups or expander graphs with an emphasis on either eigenvalues or eigenvectors. We aim to focus on a variety of those themes.

Information: scientific-events.weebly.com/1186.html.

4-29 AMSI (Australian) Summer School, RMIT University, Melbourne, Australia.

5-9 Mathematical General Relativity, Sanya, Hainan, China.

9-13 Moduli Spaces, Integrable Systems, and Topological Recursions, Centre de recherches mathématiques, Université de Montréal, Pavillon André-Aisenstadt, Montréal, Canada.

10-12 ACM-SIAM Symposium on Discrete Algorithms (SODA16), being held with Analytic Algorithmics and Combinatorics (ANALCO16) and Algorithm Engineering and Experiments (ALENEX16), Crystal Gateway Marriott, Arlington, Virginia.

11-15 AIM Workshop: High and Low Forcing, American Institute of Mathematics, San Jose, California.


Description: This workshop plans to bring together researchers from different areas, interested in effective methods in analysis and geometry, and in the design and implementation of efficient and certified algorithms. Its objective is to stimulate discussions between communities that do not so often meet in traditional venues and to foster interactions between their different but complementary perspectives, in the tradition of the meetings of the MAP community. It will address perspectives from proof theory, type theory, constructive analysis, machine-checked mathematics, implementation of real/float/interval arithmetic, computer algebra systems, including those based on new paradigms like quantum computation.

Information: scientific-events.weebly.com/1508.html.
18–22 Nonequilibrium: Physics, Stochastics and Dynamical Systems, CIRM, Marseille Luminy, France.
Description: Statistical mechanics away from equilibrium is a field that is still in a formative stage in which general concepts slowly emerge. One of the major difficulties is to understand which aspects of the theory are model-dependent and which ones are universal. In the modeling of nonequilibrium both deterministic and stochastic models are used. We shall mainly focus on classical deterministic systems and stochastic systems such as interacting particle systems. We will also organize one specific day focused on three specialized themes, namely: KPZ universality, self-organized criticality and the Boltzmann equation.
Information: scientific-events.weebly.com/1434.html.
18–February 28 Semidefinite and Matrix Methods for Optimization and Communication, Institute for Mathematical Sciences, National University of Singapore, Singapore.
Description: The principal topic of the workshop will be algorithm development and mathematical analysis of computational probability in the context of complex systems. The aim is for a focused workshop, we do not plan to cover all approaches to uncertainty quantification. The main methodology will be Monte Carlo methods and themes will be sensitivity analysis with respect to modeling error, and the role of rare and extreme events. Topics include the analysis of Monte Carlo algorithms using tools from information theory, various methods and approaches to sensitivity analysis, and coarse graining and related methods for model approximation and simplification. Applications include, but are not limited to, problems in materials science, stochastic networks, finance, and risk management. The workshop is supported by the US Department of Energy Office of Science, Office of Advanced Scientific Computing Research, Applied Mathematics program under Award “Mathematical Foundations for Uncertainty Quantification in Materials Design” Number DE-SC-0010539 and the Institute for Pure and Applied Mathematics. This workshop will include a poster session; a request for posters will be sent to registered participants in advance of the workshop.
Organizing Committee: Paul Dupuis (Brown University), Peter Glynn (Stanford University), Markos Katsoulakis (University of Massachusetts Amherst, Mathematics and Statistics), Petr Plechac (University of Delaware).
25–29 Nexus of Information and Computation Theories, CIRM, Marseille Luminy, France.
Description: Over the past few decades, the theories of computation and information have been studied in separate academic circles, which have worked in near isolation from one another. More recently, several researchers have uncovered close connections between these two disciplines, both in terms of problem formulations and proof techniques. As a result, there is a growing interest in building bridges in order to make progress on topics of common interest. The aim of this winter school is to broaden and deepen the connections between Information Theory and the Theory of Computation (ToC). The program will consist of several tutorials and will also serve as a prelude to a 2016 Institut Henri Poincaré (IHP - Paris) thematic program. This workshop is part of the CARMIN initiative linking CIRM to IHP and other centres in France.
Information: scientific-events.weebly.com/1423.html.

February 2016
1–6 ICERM Semester Program on “Dimension and Dynamics”, Institute for Computational and Experimental Research in Mathematics (ICERM), Providence, Rhode Island.
1–March 4 Thematic Month on Statistics, CIRM, Marseille Luminy, France.
Description: This 5-week winter thematic held at CIRM will focus on various aspects such as Mathematical Statistics, Process, Extremes, Copulas and Actuarial Science, and will end with a week on Bayesian Statistics and Algorithms.

Information: scientific-events.weebly.com/1365.html.

1–April 30 Intensive Research Programme in Nonsmooth Dynamics, Centre de Recerca Matemàtica, Bellaterra, Barcelona, Spain.


* 8–12 Shape Analysis and Learning by Geometry and Machine, Institute for Pure and Applied Mathematics (IPAM), UCLA, Los Angeles, California.

Description: Fast acquisition and routine use of 3D data due to the advance of modern technology and computer power makes 3D description of the real world imminent and practical in many applications such as 3D cameras, 3D printing and prototyping, etc. Although many effective techniques and efficient computational tools are well developed for 2D images from acquisition to processing, analysis and understanding, their counterparts for 3D shape space are more challenging and less developed. There are still many important technological, mathematical, and computational issues that need to be addressed: for example, how to obtain, represent and reconstruct 3D models for complicated objects and scenes routinely as we do for images. Another question is how to make computers learn, analyze, and understand shapes and geometries like human vision and intelligence for the purpose of registration, comparison, recognition, classification and indexing. This becomes more and more important and urgent for efficiency.


15–19 Ergodic, Algebraic and Combinatorial Methods in Dimension Theory, Institute for Computational and Experimental Research in Mathematics (ICERM), Providence, Rhode Island.


22–26 Algebraic Geometry for Coding Theory and Cryptography, Institute for Pure and Applied Mathematics (IPAM), UCLA, Los Angeles, CA.

24–26 7th International Conference on Post-Quantum Cryptography (PQCrypto 2016), Kyushu University Nishijin Plaza, Fukuoka, Japan.

29–March 4 AIM Workshop: Hereditary Discrepancy and Factorization Norms, American Institute of Mathematics, San Jose, California.

March 2016

1–4 12th German Probability and Statistics Days 2016 - Bochumer Stochastik-Tage, Ruhr University Bochum, Bochum, Germany.

1–July 31 Intensive Research Programme on Constructive Approximation and Harmonic Analysis, Centre de Recerca Matemàtica, Bellaterra, Barcelona, Spain.

6–31 New Developments in Representation Theory, Institute for Mathematical Sciences, National University of Singapore, Singapore.

* 7–11 2016 ALEA Conference, CIRM, Marseille Luminy, France.

Description: The 2016 program of the recurrent ALEA school will mainly focus on themes dealing with analytical methods for divide-and-conquer algorithms and convergence in probability theory and the combinatorics of determinants. Lectures will present a panorama of the various thematic themes; slots will also be available for PhD students to present their research.

Information: scientific-events.weebly.com/1406.html.

* 7–11 Forty-Seventh Southeastern International Conference on Combinatorics, Graph Theory and Computing, Florida Atlantic University, Boca Raton, Florida.

Description: Celebrating its 47th year, the conference continues in the spirit of past conferences. It brings together mathematicians and others interested in combinatorics, graph theory and computing, and their interactions. The conference lectures and contributed papers, as well as the opportunities for informal conversations, have proved to be of great interest to other scientists and analysts employing these mathematical sciences in their professional work.

Plenary speakers: The 47th Conference will feature exceptional invited speakers: Arthur Benjamin; Simon Blackburn; Penny Haxell; Garth Isaak; Gary Mullen; Bryan Shader. There will be special sessions for: developments in graph theory; combinatorial matrix theory; finite fields. The organizing committee cordially invites participation by interested persons in the academic community as well as business, industry, and government. The 47th Conference is partially supported by the National Security Agency and the Institute of Combinatorics and its Applications.

Information: science.fau.edu/combinatorics/index.php.

7–June 10 Culture Analytics, Institute for Pure and Applied Mathematics (IPAM), UCLA, Los Angeles, California.

* 8–11 Culture Analytics Tutorials, Institute for Pure and Applied Mathematics (IPAM), Los Angeles, California.

Description: The tutorial session will bring participants up-to-speed on various methodologies that will be presented in the coming workshops. These intensive sessions taught by leaders in each area will focus on web crawling and scraping; natural language processing including named entity detection and sentiment detection; GIS; network analysis; supervised and unsupervised machine learning; audio and visual analysis; and library systems. These tutorials will have a series of target data sets that will be used as challenge data, and additional evening classes will be held during this first tutorial week to allow these participants greater access to the vocabulary of the ensuing workshops. We expect participants from the humanities, social sciences, computer science, and applied mathematics. There is no registration fee for tutorials, to encourage broad participation.

Information: www.ipam.ucla.edu/catut.

12–13 6th Ohio River Analysis Meeting (ORAM 6), University of Kentucky, Lexington, KY.

* 13–15 The 32nd Southeastern Analysis Meeting (SEAM), University of South Florida, Tampa, Florida.

Description: The Southeastern Analysis Meeting (SEAM) is one of the leading annual conferences on analysis, with a distinguished history, ongoing since 1985. It is traditionally held at various universities in the southeast. The research areas of the conference have focused on complex analysis, harmonic analysis, and operator theory. The conference has a broad participation, featuring leading researchers in the field, junior and minority participants, as well as a diverse audience including graduate students and postdoctoral scientists.

Information: math.usf.edu/research/conferences/.

* 14–18 Combinatorics on Words, CIRM, Marseille Luminy, France.

Description: The main goal of this event is to analyze the current state of the art of combinatorics on words and identify the major problems and perspectives of research in the field. Lectures emphasizing current open problems about avoidability, word equations, and transcendental and normal numbers, as well as lectures treating the connections to the areas of number theory, symbolic dynamics, and geometric group theory will be proposed.

Information: scientific-events.weebly.com/1429.html.

16–18 The 2016 IAENG International Conference on Operations Research, Royal Garden Hotel, Hong Kong, China.
**21–23 8th IMA Conference on Quantitative Modelling in the Management of Health and Social Care — Challenges and Opportunities in a Big Data Era, Asia House, London, United Kingdom.**  
*Description:* Quantitative modelling and computer simulation techniques have been shown to be increasingly valuable in providing useful information to aid planning and management; however, studies have often been limited in their attempts to exploit the wealth of data. The aim of the conference is to bring together health care managers, clinicians, management consultants, and mathematicians, operational researchers, statisticians, health economists, computing and data scientists from across the world with a view to bridging the gap between the respective communities and to exploring recent developments in quantitative modelling and identifying fruitful avenues for further research.  

**21–24 Culture Analytics Beyond Text: Image, Music, Video, Interactivity and Performance, Institute for Pure and Applied Mathematics (IPAM), UCLA, Los Angeles, California.**  
*Description:* This workshop focuses on developing computational and mathematical techniques for the analysis of large sets of cultural artifacts beyond text, and includes considerations of material and graphic design, architecture, fashion, interactive media, games, film, photography, music, painting, sculpture, performance, and the kinesthetic dimensions of culture. The analysis of audio and visual data requires a different set of quantitative techniques than those devised for textual analysis. This challenge has become all the more acute, as every day individuals and institutions produce and publish hundreds of millions of digital cultural artifacts that are not text. The big data revolution is not only a text-based one, and these enormous new resources of non-text culture require equally revolutionary techniques for meaningful analysis.  

**21–25 Dynamics of Evolution Equation, CIRM, Marseille Luminy, France.**  
*Description:* This conference is mainly devoted to the study of dynamical systems generated by ODEs and PDEs. We intend to develop the interactions between several domains such as finite-dimensional dynamical systems, PDEs, control theory, biological modeling, random dynamical systems, dynamical systems on networks or graphs. Besides classical research talks in the mornings, several thematic afternoons devoted to discussions, mini-courses, surveys and open problems will be organized. This conference is also the second of a series dedicated to the memory of Prof. Jack Hale emphasizing research programs in dynamical systems and training of doctoral students and young researchers.  
*Information:* [scientific-events.weebly.com/1335.html](http://scientific-events.weebly.com/1335.html).

**21–25 Kähler Geometry, Einstein Metrics, and Generalizations, Mathematical Sciences Research Institute, Berkeley, California.**

**22–23 IMA Conference on Theoretical and Computational Discrete Mathematics, The Enterprise Centre, University of Derby, Derby, U.K.**

**28–April 1 AIM Workshop: Sheaves and modular representations of reductive groups, American Institute of Mathematics, San Jose, California.**

**28–April 1 Hot Topics: Cluster Algebras and Wall-Crossing, Mathematical Sciences Research Institute, Berkeley, California.**

*29–April 2 Dynamics and Graphs over Finite Fields: Algebraic, Number Theoretic and Algorithmic Aspects, CIRM, Marseille Luminy, France.**  
*Description:* The proposed workshop will be a follow-up to the problems discussed at the workshop “The Art of Iterating Rational Functions over Finite Fields” (BIRS, Banff 2013), which was the first meeting to focus on DFF/DFR and their vast applications. The recent burst in activity in the study of functional graphs generated by algebraic maps over finite fields has come from several independent groups of researchers who were not aware of each other’s results prior to the aforementioned Banff workshop. The goal will be to set new coherent goals for future developments and the topics will center on: algebraic aspects, number theoretical aspects, graph theory aspects and algorithmic aspects.  
*Information:* [scientific-events.weebly.com/1391.html](http://scientific-events.weebly.com/1391.html).

**April 2016**

**1–2 Info-Metrics Institute Spring 2016 Conference: Information-Theoretic Methods of Inference, Clare College, Cambridge, United Kingdom.**  
*Description:* The objective of this workshop is to study new methods of statistical inference based on information-theoretic methods. Info-metric and Information-Theoretic ideas are being applied in variety of disciplines, such as biology, ecology, economics, finance and physics (for examples see Fall 2014 Conference celebrating the fifth anniversary of the Institute). The Spring 2016 workshop focuses on the use of info-metric and information-theoretic ideas in the development and analysis of statistical models. The aims of the workshop are to provide a forum for the dissemination of new research in this area and also to stimulate discussion between researchers across fields. The conference will consist of Invited Talks, Invited Sessions, and Submitted Papers.  

**4–8 Recent Trends in Nonlinear Evolution Equations, CIRM, Marseille Luminy, France.**  
*Description:* Evolutionary partial differential equations (PDEs) are at the core of several models coming from physics and a central part of the general theory of PDEs. The purpose of the conference is to assess the situation on the recent progress in the field in regards to their mathematical treatment. Thanks to techniques coming from harmonic analysis, the theory of elliptic PDEs and geometry, several major problems in the field have been resolved, generating several crucial advances in the area. The present conference plans to concentrate on three aspects: dispersive and hyperbolic equations, reaction-diffusion equations and porous media equations.  
*Information:* [scientific-events.weebly.com/1353.html](http://scientific-events.weebly.com/1353.html).

**4–8 Semester Workshop: Computation in Dynamics, Institute for Computational and Experimental Research in Mathematics (ICERM), Providence, Rhode Island.**

**5–8 SIAM Conference on Uncertainty Quantification (UQ16), SwissTech Convention Center, EPFL Campus, Lausanne, Switzerland.**

**11–15 International Conference on Differential Geometry, ICDG, Fez, 2016, Faculty of Sciences Dhar El Mehraz, Fez, Morocco.**

**11–15 Research School on the Mathematics of String Theory, CIRM, Marseille Luminy, France.**  
*Description:* The main goal of the school will be to prepare graduate students for the upcoming program on the Mathematics of string theory to be held at the Institut Henri Poincaré, Paris, from April to July 2016. Recent exciting developments in this field include open string mirror symmetry, wall crossing formulae, topological classification of D-branes and the derived category approach to D-branes on Calabi-Yau manifolds, geometric transitions, the relation of $N = 2$ instanton partition functions to conformal field theory, the matrix model approach to gauge theory, the relation between Langlands program and supersymmetric gauge theories, BPS counts and finally mock modular forms. The above are some of the areas to be explored during the week in Marseille. This workshop is part of the CARMIN initiative linking CIRM to IHP (Institut Henri Poincaré, Paris) and other centres in France.
Information: scientific-events.weebly.com/1413.html.

11–15 Workshop II: Culture Analytics and User Experience Design, Institute for Pure and Applied Mathematics (IPAM), UCLA, Los Angeles, CA.


* 18–20 2nd International Meeting on Clinical Case Reports, Dubai, United Arab Emirates.
Description: Clinical Case Reports-2016 is a best International platform which is anticipating several doctors, physicians, researchers, and students around the globe who can share their Cutting-edge knowledge and Clinical experience by giving lectures on various Session/Tracks.
Information: clinicalcasereports.conferenceseries.com/.

Description: Remarkable progress achieved recently in production of novel materials has raised important mathematical questions. The aim of the proposed workshop is to address these new challenges by bringing together mathematicians of different backgrounds with physicists. The emphasis will be on nano-materials (such as carbon nanotubes, graphen, graphynes, etc.), metamaterials (including photonic crystals and invisibility cloaking), and topological insulators.
Information: scientific-events.weebly.com/1399.html.

May 2016

2–6 AIM Workshop: Algebraic Vision, American Institute of Mathematics, San Jose, CA.

2–6 Geometric Flows in Riemannian and Complex Geometry, Mathematical Sciences Research Institute, Berkeley, California.

6–8 Mathematics in Automotive Security, Oakland University, Rochester, Michigan.

9–13 Cultural Patterns: Multi-scale Data-driven Models, Institute for Pure and Applied Mathematics (IPAM), UCLA, Los Angeles, CA.

11–13 International Arab Conference on Mathematics and Computations, The conference will held on Zarqa University, Zarqa, Jordan.


* 16–20 International Conference on Evolution Equations in conjunction with the 31st annual Shanks Lecture. With a special tribute to the work of Jan Prüss on the occasion of his 65th birthday, Vanderbilt University, Nashville, Tennessee.
Description: This conference will focus on recent developments in partial differential equations connected to evolution problems. Topics will include, but are not limited to, fluid dynamics, free boundary problems, dispersive equations, parabolic equations, Einstein’s equations, and non-linear wave equations. The activities will include fifty-minute talks by the keynote speakers, parallel focus sessions with twenty-five-minute presentations, and 10-minute contributed talks. Part of the conference will be a special tribute to the mathematical work of Jan Prüss on the occasion of his 65th birthday. The annual Shanks Lecture, delivered by Lawrence C. Evans from the University of California at Berkeley, will take place in conjunction with the conference. We expect to have funding for graduate students, recent PhDs, and underrepresented minorities.
Information: my.vanderbilt.edu/shanks2016/.


23–26 SIAM Conference on Imaging Science (IS16), Hotel Albuquerque at Old Town, Albuquerque, New Mexico.

* 23–27 Workshop IV: Mathematical Analysis of Cultural Expressive Forms: Text Data, Institute for Pure and Applied Mathematics (IPAM), Los Angeles, California.
Description: Comprehensive collections of texts data stretching back in time to the beginning of writing have become increasingly available in machine actionable form. Similarly, millions of “born digital” texts are flooding the virtual world on a daily basis, from tweets, to blog posts, to other cultural expressive forms. This workshop focuses on the leading approaches to (a) extracting entities, topics, or narrative patterns from large, unstructured collections of text and analyzing them to (b) derive meaning from textual data and (c) understand the dynamics of social interactions or historical change. These approaches include text mining tools, sentiment analysis, topic modeling, textual memes, cross-language information retrieval, trend analysis, information retrieval, recommendations, and predictions of whether something will go “viral”. Mathematical tools include Bayesian models, supervised and unsupervised machine learning, optimization, and statistical language modeling techniques.
Information: www.ipam.ucla.edu/ca/w4.


26–29 International Conference on Applications of Mathematics to Nonlinear Sciences (AMNS-2016), Kathmandu, Nepal.

29–June 3 Whitney Extension Problems: $C^k$ and Sobolev functions on subsets of $R^n$, Technion - Israel Institute of Technology, Haifa, Israel.

June 2016

* 5–10 5th European Seminar on Computing, Pilsen, Czech Republic.
Description:ESCO 2016 is the 5th event in a successful series of interdisciplinary international conferences. It promotes modern technologies and practices in scientific computing and visualization, and strengthens the interaction between researchers and practitioners in various areas of computational engineering and sciences.
2016 Main Themes: Computational electromagnetics and coupled problems, fluid-structure interaction and multi-phase flows, computational chemistry and quantum physics, computational civil and structural engineering, computational biology and bioinformatics, computational geometry and topology, petascale and exascale computing, hydrology and porous media flows, wave propagation and acoustics, climate and weather modeling, GPU and cloud computing, uncertainty quantification, open source software.

6–10 AIM Workshop: Markov Chain Mixing Times, American Institute of Mathematics, San Jose, California.

* 9–11 Workshop on Geosystems Mathematics, Institute of Applied Mathematics, Middle East Technical University, Ankara, Turkey.
Description: The workshop facilitates communication between scientists of varying backgrounds and provides a forum for exchange of ideas on the recent developments in mathematical models and computational methods in geosciences.
Topics: Include but are not limited to Inverse and ill-posed problems; potential methods, acoustic and elastic seismic tomography, image analysis, sampling and moment problems, signal analysis and processing of terrestrial and satellite data; oil, shale gas, and water exploration and improved resource recovery; uncertainty quantification: Bayesian approach, data assimilation, earthquake relocation; reservoir mechanics, groundwater flow, multi-phase flow in porous media; poroelasticity, multi-layered systems; oceanography, atmospheric modeling, climate change, volcanism, plumes and hotspots; energy resource modeling: geothermal energy, renewable energy; Geoscientific risk management. An optional Cappadocia Tour is also planned for Sunday June 12, 2016.
Information: geomath16.iam.metu.edu.tr/.
Mathematics Calendar


**Description:** ECMI conferences are promoted by the European Consortium for Mathematics in Industry with the aim to enforce the interaction between academy and industry, leading to innovation in both fields. They are one of the main forums where significant advances in industrial mathematics are presented, bringing together prominent figures from business, science and academia to promote the use of innovative mathematics to industry. They also encourage industrial sectors to propose challenging problems where mathematicians can provide insight and new ideas. ECMI2016 is jointly organized by the Department of Applied Mathematics of the University of Santiago de Compostela (USC) and the Spanish Network for Mathematics & Industry (math-in). We are looking forward to meeting you at Santiago de Compostela!

**Information:** [www.usc.es/congresos/ecmi2016/](http://www.usc.es/congresos/ecmi2016/).


13–24 *Algebraic, Enumerative, and Geometric Combinatorics — ECCO 2016*, Universidad de Antioquia, Medellin, Colombia.

13–24 *Michigan Summer School on Random Matrices*, Ann Arbor, Michigan, USA.

15–18 *Second International Congress on Actuarial Science and Quantitative Finance*, Universidad de Cartagena, Cartagena, Colombia.


19–25 *BIOMATH Young Scientists School*, Conference Center "Bachinovo", South West University, Blagoevgrad, Sofia.


27–July 1 3rd Barcelona Summer School on Stochastic Analysis, Centre de Recerca Matemàtica, Bellaterra, Barcelona, Spain.

27–July 1 3rd International Conference on Operator Theory, West University, Timisoara, Romania.

July 2016


3–8 *Conference on Rings and Polynomials*, Graz University of Technology, Graz, Austria.

4–8 *The 28th International Conference on Formal Power Series and Algebraic Combinatorics (FPSAC)*, Vancouver, British Columbia, Canada.

4–9 *14th International Conference on p-Adic Functional Analysis*, Auriillac, France.


6–8 *IMA Conference on Turbulence, Waves, and Mixing*, King’s College, Cambridge, United Kingdom.


12–14 *9th IMA International Conference on Modelling in Industrial Maintenance and Reliability (MIMAR)*, Imperial College, London, United Kingdom.

*18–22* *Transfinite methods in Banach spaces and algebras of operators*, Bedlewo Conference Center, Bedlewo, Poland.

**Description:** The conference will bring together experts on Banach spaces, set theory, topology and algebras of operators, with special emphasis on the various ways in which these areas interact. The list of speakers will include: Tristan Bice (Salvador), Christina Brech (Sao Paulo), Yemon Choi (Lancaster; tbc), Marek Cuth (Prague), Garth Dales (Lancaster), Alan Dow (North Carolina), Valentin Ferenczi (Sao Paulo), Joanna Garbulinska (Kielce), Gilles Godefroy (Paris VI), Bill Johnson (Texas A&M; tbc), Tomasz Kocanek (IM PAN), Jordi Lopez-Abad (ICMAT Madrid), Pavlos Motakis (Texas A&M), Grzegorz Plebanek (Wrocław), Jose Rodriguez (Murcia), Thomas Schlumprecht (Texas A&M), Jesus Suarez (Caceres) and Stevo Todorcevic (CRNS, Toronto).


*25–29* *14th International Conference on Integral Methods in Science and Engineering (IMSE 2016)*, University of Padova, Padova, Italy.

**Description:** The series of conferences on Integral Methods in Science and Engineering is an established forum where scientists from all over the world discuss their latest developments in original and effective methodologies relevant for solutions of mathematical models that describe physical phenomena, processes and related subjects. Participation is open to all scientists and engineers whose work makes use of analytical and numerical methods, integral equations, ordinary and partial differential equations, asymptotic and perturbation methods, boundary integral techniques, stochastic methods, symmetries and conservation laws, hybrid approaches, vortex methods, signal processing and image analysis, among others. One of the objectives is to promote new research tools, methods and procedures beyond the specific realms of Mathematics, the individual Exact or Technological Sciences besides their technological applications. Thus, the scope of the conference addresses academic and industrial interests.

**Information:** [events.math.unipd.it/imse2016/](http://events.math.unipd.it/imse2016/).


August 2016

1–5 *International Conference in K-theory*, University of Western Sydney, Sydney, Australia.

1–5 *XVI International Conference on Hyperbolic Problems: Theory, Numerics, Applications*, RWTH Aachen University, Aachen, Germany.

2–5 *31st Summer Conference on Topology and its Applications*, University of Leicester, University Road, Leicester, LE1 7RH, England, United Kingdom.


10–19 *Workshop and International Conference on Representations of Algebras (ICRA 2016)*, Syracuse University, Syracuse, NY.

15–December 16 **Geometric Group Theory (GGT2)**, Mathematical Sciences Research Institute, Berkeley, CA.

17–19 **Connections for Women: Geometric Group Theory**, Mathematical Sciences Research Institute, Berkeley, California.


*26–29 2nd International Conference on Algebra in Honour of Leonid Bokut and Surrender K. Jain, Balikesir University, Burhaniye/Balikesir, Turkey.

Description: The center of the conference is to bring together researchers and scientists working in all branches of “Algebra”. The proposed technical programme of the conference will include contributed talks and keynote lectures. This second annual meeting aims to present our special thankfulness to Professor Lenoid Bokut and Professor Surrender K. Jain. It is very obvious that not only their studies resulted in very unique developments in algebra but their personalities are also one of the best examples of algebraist worldwide. Therefore all algebraist (included not working in the same field of these respectable professors) are welcome to this honorific conference.

Information: ica.balikesir.edu.tr.

**September 2016**

8–13 4th Dolomites Workshop on Constructive Approximation and Applications (DWCAA16), Univ. of Verona, Val di Fassa, Trento, Italy.

*12–December 16 Understanding Many-Particle Systems with Machine Learning, Institute for Pure and Applied Mathematics (IPAM), Los Angeles, CA

Description: Interactions between many constituent particles (bodies) generally give rise to collective or emergent phenomena in matter. Even when the interactions between the particles are well defined and the governing equations of the system are understood, the collective behavior of the system as a whole does not trivially emerge from these equations. Examples of collective behavior are abundant in nature, manifesting themselves at all scales of matter, ranging from atoms to galaxies. Machine learning methods have been used in a wide variety of fields. It is the goal of this IPAM long program to bring together experts in many particle problems in condensed-matter physics, materials, chemistry, and protein folding, together with experts in mathematics and computer science to synergetically address the problem of tackling emergent behavior and understanding the underlying collective variables in many particle systems.

Information: www.ipam.ucla.edu/mps2016.

12–16 Workshop: Unusual Configuration Spaces, ICERM at Brown University, Providence, Rhode Island.

14–16 15th IMA Conference on Mathematics of Surfaces, University of Bath, Bath, UK.


26–30 **Machine Learning Meets Many-Particle Problems**, Institute for Pure and Applied Mathematics (IPAM), UCLA, Los Angeles, CA.

27–30 **Groups Acting on CAT(0) Spaces**, Mathematical Sciences Research Institute, Berkeley, California.

30–October 2 **SIAM Conference on Mathematics of Planet Earth (MPE16)**, DoubleTree by Hilton Hotel Philadelphia Center City, Philadelphia, Pennsylvania.

**October 2016**

8–11 **Mathematical Results in Quantum Physics (QMATH13)**, Georgia Institute of Technology, Atlanta, Georgia.


25–28 **Geometry of Mapping Class Groups and Out(Fn)**, Mathematical Sciences Research Institute, Berkeley, California.


**November 2016**


7–11 **Homological Mirror Symmetry: Methods and Structures**, Institute for Advanced Study, Princeton, New Jersey.

*14–18 Workshop III: Collective Variables in Quantum Mechanics, Institute for Pure and Applied Mathematics (IPAM), Los Angeles, California.

Description: Collective quasiparticle states (molecular orbitals, plasmons, phonons, polarons, excitons, etc.) are often employed to study and understand many particle systems in quantum mechanics (especially in extended systems). Can machine learning (ML) techniques generate such quasiparticle states or approximations thereof, given only the atomistic Hamiltonian as an input and macroscopic observables as an output? On a larger scale and going toward materials design (materials genomics): How can one generate the necessary and sufficient data to use ML approaches to infer the important collective variables (materials genes, scaling relations, etc.)? This workshop will gather experts in electronic structure methods together with mathematicians and computer scientists who are interested in or have already been applying ML methods in physics, chemistry, and materials sciences.

Information: www.ipam.ucla.edu/mps2016.


The following new announcements will not be repeated until the criteria in the next to the last paragraph at the bottom of the first page of this section are met.

**December 2016**

*5–9 **Synergies between Machine Learning and Physical Models**, Institute for Pure and Applied Mathematics (IPAM), UCLA, Los Angeles, California.

Description: The application of machine learning (ML) to the computer simulation of materials has features that are somewhat uncommon in ML: the data is often free of noise; in principle, unlimited amounts of data are available at known unit cost, and there is often considerable freedom in choosing data locations. This calls for the close examination of which ML strategies are best, and what their ultimate limitations are in practice. Can we create ML models of arbitrary accuracy? How can recent advances in online or active learning be utilised? What can more classical statistical interpolation methods contribute? Traditional, non-data-intensive models in the physical sciences are “extrapolative”; i.e., the parameters are determined by observing limited data in some domain, and the models are tested in extended or even wholly different domains, and the performance of such models is evaluated according to how well they do in such a situation.
January 2017

* 19–20 Connections for Women: Harmonic Analysis, Mathematical Sciences Research Institute, Berkeley, California.
Description: This workshop will highlight the work of several prominent women working in harmonic analysis, including some of the field’s rising stars. It will feature 3 mini courses by senior researchers, a number of talks by analysts at the postdoctoral level and above, and a poster session for graduate students. This workshop is open to all mathematicians.
Information: www.msri.org/workshops/802.

* 23–27 Introductory Workshop: Harmonic Analysis, Mathematical Sciences Research Institute, Berkeley, California.
Description: This week-long workshop will serve as an introduction for graduate students, postdocs, and other researchers to the main themes of the program. It will feature accessible talks by a number of leading harmonic analysts, including several short courses on the core ideas and techniques in the field. There will also be a problem session, to which all participants are encouraged to contribute.
Information: www.msri.org/workshops/803.

May 2017

* 1–5 Recent Developments in Analytic Number Theory, Mathematical Sciences Research Institute, Berkeley, California.
Description: This workshop will be focused on presenting the latest developments in analytic number theory, including (but not restricted to) recent advances in sieve theory, multiplicative number theory, exponential sums, arithmetic statistics, estimates on automorphic forms, and the Hardy-Littlewood circle method.
Information: www.msri.org/workshops/810.

* 22–26 Workshop III: Data Assimilation, Uncertainty Reduction, and Optimization for Subsurface Flow, Institute for Pure and Applied Mathematics (IPAM), UCLA, Los Angeles, California.
Description: There are major computational challenges and substantial uncertainties associated with model inversion and performance optimization in oil field applications. As production and (in some cases) 4D seismic and electromagnetic data are collected, there are inevitably discrepancies between the predicted and actual reservoir responses. This drives the need for data assimilation, usually referred to as history matching in petroleum engineering. History matching involves the solution of a computationally demanding, highly ill-conditioned, inverse problem. Key complications that arise are the uncertain nature of the geology (and thus the need to “properly” sample the posterior distribution), combined with the need to retain geological realism in history-matched reservoir descriptions. Additional complexity enters as a result of the unknown rock-physics quantities needed to integrate multiphysics data sets. Applications received by Monday, March 27, 2017, will receive fullest consideration.
Information: www.ipam.ucla.edu/oilws3.

August 2017

* 14–December 15 Geometric and Topological Combinatorics, Mathematical Sciences Research Institute, Berkeley, California.
Description: Combinatorics is one of the fastest growing areas in contemporary Mathematics, and much of this growth is due to the connections and interactions with other areas of Mathematics. This program is devoted to the very vibrant and active area of interaction between Combinatorics with Geometry and Topology. That is, we focus on (1) the study of the combinatorial properties or structure of geometric and topological objects and (2) the development of geometric and topological techniques to answer combinatorial problems. Key examples of geometric objects with intricate combinatorial structure are point configurations and matroids, hyperplane and subspace arrangements, polytopes and polyhedra, lattices, convex bodies, and sphere packings. Examples of topology in action answering combinatorial challenges are the by now classical Lovasz’s solution of the Kneser conjecture, which yielded functorial approaches to graph coloring, and the more recent, extensive topological machinery.
Information: www.msri.org/programs/309.

October 2017

* 9–13 Geometric and Topological Combinatorics: Modern Techniques and Methods, Mathematical Sciences Research Institute, Berkeley, California.
Description: This workshop will focus on the interaction between Combinatorics, Geometry and Topology, including recent developments and techniques in areas such as: polytopes and cell complexes; simplicial complexes and higher order graph theory; methods from equivariant topology and configuration spaces; geometric combinatorics in optimization and social choice theory; algebraic and algebro-geometric methods.
Information: www.msri.org/workshops/819.

November 2017

Description: This is the main workshop of the program “Geometric functional analysis and applications”. It will focus on the main topics of the program. These include: Convex geometry, Asymptotic geometric analysis, Interaction with computer science, Signal processing, Random matrix theory and other aspects of Probability.
Information: www.msri.org/workshops/811.
New Publications Offered by the AMS

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

Analysis

Trends in Harmonic Analysis and Its Applications

Jens G. Christensen, Colgate University, Hamilton, NY, Susanna Dann, Vienna University of Technology, Wien, Austria, Azita Mayeli, Queensborough Community College, CUNY, Bayside, NY, and Gestur Ólafsson, Louisiana State University, Baton Rouge, LA, Editors

This volume contains the proceedings of the AMS Special Session on Harmonic Analysis and Its Applications, held March 29–30, 2014, at the University of Maryland, Baltimore County, Baltimore, MD.

It provides an in depth look at the many directions taken by experts in Harmonic Analysis and related areas. The papers cover topics such as frame theory, Gabor analysis, interpolation and Besov spaces on compact manifolds, Cuntz-Krieger algebras, reproducing kernel spaces, solenoids, hypergeometric shift operators and analysis on infinite dimensional groups.

Expositions are by leading researchers in the field, both young and established. The papers consist of new results or new approaches to solutions, and at the same time provide an introduction into the respective subjects.


Contemporary Mathematics, Volume 650

Algebraic and Analytic Aspects of Integrable Systems and Painlevé Equations

Anton Dzhamay, University of Northern Colorado, Greeley, CO, Kenichi Maruno, University of Texas-Pan American, Edinburg, TX, and Christopher M. Ormerod, California Institute of Technology, Pasadena, CA, Editors

This volume contains the proceedings of the AMS Special Session on Algebraic and Analytic Aspects of Integrable Systems and Painlevé Equations, held on January 18, 2014, at the Joint Mathematics Meetings in Baltimore, MD.

The theory of integrable systems has been at the forefront of some of the most important developments in mathematical physics in the last 50 years. The techniques to study such systems have solid foundations in algebraic geometry, differential geometry, and group representation theory.

Many important special solutions of continuous and discrete integrable systems can be written in terms of special functions such as hypergeometric and basic hypergeometric functions. The analytic tools developed to study integrable systems have numerous applications in random matrix theory, statistical mechanics and quantum gravity. One of the most exciting recent developments has been the emergence of good and interesting discrete and quantum analogues of classical integrable differential equations, such as the Painlevé equations and soliton equations. Many algebraic and analytic ideas developed in the continuous case generalize in a beautifully natural manner to discrete integrable systems. The editors have
sought to bring together a collection of expository and research articles that represent a good cross section of ideas and methods in these active areas of research within integrable systems and their applications.

**Contents:** M. Noumi, Padé interpolation and hypergeometric series; T. Suzuki, A q-analogue of the Drinfeld-Sokolov hierarchy of type A and q-Painlevé system; H. Nagoya, Fractional calculus of quantum Painlevé systems of type $A_1^{(1)}$; C. M. Ormerod, Spectral curves and discrete Painlevé equations; A. Dzhamay and T. Takenawa, Geometric analysis of reductions from Schlesinger transformations to difference Painlevé equations; I. Rumanov, Beta ensembles, quantum Painlevé equations and isomonodromy systems; B. Prinari and F. Vitale, Inverse scattering transform for the focusing nonlinear Schrödinger equation with a one-sided non-zero boundary condition.

**Contemporary Mathematics, Volume 651**


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**Problems in Real and Functional Analysis**

Alberto Torchinsky, Indiana University, Bloomington, IN

It is generally believed that solving problems is the most important part of the learning process in mathematics because it forces students to truly understand the definitions, comb through the theorems and proofs, and think at length about the mathematics. The purpose of this book is to complement the existing literature in introductory real and functional analysis at the graduate level with a variety of conceptual problems (1,457 in total), ranging from easily accessible to thought provoking, mixing the practical and the theoretical aspects of the subject. Problems are grouped into ten chapters covering the main topics usually taught in courses on real and functional analysis. Each of these chapters opens with a brief reader’s guide stating the needed definitions and basic results in the area and closes with a short description of the problems.

The Problem chapters are accompanied by Solution chapters, which include solutions to two-thirds of the problems. Students can expect the solutions to be written in a direct language that they can understand; usually the most “natural” rather than the most elegant solution is presented.

**Contents:** Problems: Set theory and metric spaces; Measures; Lebesgue measure; Measurable and integrable functions; $L^p$ spaces; Sequences of functions; Product measures; Normed linear spaces. Functionals; Normed linear spaces. Linear operators; Hilbert spaces; Solutions: Set theory and metric spaces; Measures; Lebesgue measure; Measurable and integrable functions; $L^p$ spaces; Sequences of functions; Product measures; Normed linear spaces. Functionals; Normed linear spaces. Linear operators; Hilbert spaces; Index.

**Graduate Studies in Mathematics, Volume 166**


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**Differential Equations**

**Partial Differential Equations**

An Accessible Route through Theory and Applications

András Vasy, Stanford University, CA

This text on partial differential equations is intended for readers who want to understand the theoretical underpinnings of modern PDEs in settings that are important for the applications without using extensive analytic tools required by most advanced texts. The assumed mathematical background is at the level of multivariable calculus and basic metric space material, but the latter is recalled as relevant as the text progresses.

The key goal of this book is to be mathematically complete without overwhelming the reader, and to develop PDE theory in a manner that reflects how researchers would think about the material. A concrete example is that distribution theory and the concept of weak solutions are introduced early because while these ideas take some time for the students to get used to, they are fundamentally easy and, on the other hand, play a central role in the field. Then, Hilbert spaces that are quite important in the later development are introduced via completions which give essentially all the features one wants without the overhead of measure theory.

There is additional material provided for readers who would like to learn more than the core material, and there are numerous exercises to help solidify one’s understanding. The text should be suitable for advanced undergraduates or for beginning graduate students including those in engineering or the sciences.

**Contents:** Introduction; Where do PDE come from; First order scalar semilinear equations; First order scalar quasilinear equations; Distributions and weak derivatives; Second order constant coefficient PDE: Types and d’Alembert’s solution of the wave equation; Properties of solutions of second order PDE: Propagation, energy estimates and the maximum principle; The Fourier transform: Basic properties, the inversion formula and the heat equation; The Fourier transform: Tempered distributions, the wave equation and Laplace’s equation; PDE and boundaries; Duhamel’s principle; Separation of variables; Inner product spaces, symmetric operators, orthogonality; Convergence of the Fourier series and the Poisson formula on disks; Bessel functions; The method of stationary phase; Solvability via duality; Variational problems; Bibliography; Index.

**Graduate Studies in Mathematics, Volume 169**

Origami is a unique collection of papers illustrating the connections between origami and a wide range of fields. The papers compiled in this two-part set were presented at the 6th International Meeting on Origami in Science, Mathematics and Education (10–13 August 2014, Tokyo, Japan). They display the creative melding of origami (or, more broadly, folding) with fields ranging from cell biology to space exploration, from education to kinematics, from abstract mathematical laws to the artistic and aesthetics of sculptural design.

This two-part book contains papers accessible to a wide audience, including those interested in art, design, history, and education and researchers interested in the connections between origami and science, technology, engineering, and mathematics. This Part 1 contains papers on various aspects of mathematics of origami: coloring, constructability, rigid foldability, and design algorithms. This item will also be of interest to those working in math education and applications.


This two-part book contains papers accessible to a wide audience, including those interested in art, design, history, and education and researchers interested in the connections between origami and science, technology, engineering, and mathematics. This Part 2 focuses on the connections between origami and more applied areas of science: engineering, physics, architecture, industrial design, and other artistic fields that go well beyond the usual folded paper.

This item will also be of interest to those working in math education and applications.
This two-part book contains papers accessible to a wide audience, including those interested in art, design, history, and education and researchers interested in the connections between origami and science, technology, engineering, and mathematics. Part 1 contains papers on various aspects of mathematics of origami: coloring, constructability, rigid foldability, and design algorithms. Part 2 focuses on the connections between origami and more applied areas of science: engineering, physics, architecture, industrial design, and other artistic fields that go well beyond the usual folded paper.

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

Part 1 (MBK/95.1) and Part 2 (MBK/95.2) are sold separately. For a description of each part, see the New Publication entries that precede this one.

Part 1: January 2016, approximately 368 pages, Softcover, ISBN: 978-1-4704-1875-5, 2010 Mathematics Subject Classification: 00-XX, 01-XX, 51-XX, 52-XX, 53-XX, 68-XX, 70-XX, 74-XX, 92-XX, 97-XX, 00A99, Order code MBK/95.1

Part 2: January 2016, approximately 368 pages, Softcover, ISBN: 978-1-4704-1876-2, 2010 Mathematics Subject Classification: 00-XX, 01-XX, 51-XX, 52-XX, 53-XX, 68-XX, 70-XX, 74-XX, 92-XX, 97-XX, 00A99, Order code MBK/95.2

Geometry and Topology

Persistence Theory: From Quiver Representations to Data Analysis

Steve Y. Oudot, Inria Saclay, Palaiseau, France

Persistence theory emerged in the early 2000s as a new theory in the area of applied and computational topology. This book provides a broad and modern view of the subject, including its algebraic, topological, and algorithmic aspects. It also elaborates on applications in data analysis. The level of detail of the exposition has been set so as to keep a survey style, while providing sufficient insights into the proofs so the reader can understand the mechanisms at work.

The book is organized into three parts. The first part is dedicated to the foundations of persistence and emphasizes its connection to quiver representation theory. The second part focuses on its connection to applications through a few selected topics. The third part provides perspectives for both the theory and its applications. The book can be used as a text for a course on applied topology or data analysis.

Contents: Theoretical foundations: Algebraic persistence; Topological persistence; Stability; Applications: Topological inference; Topological inference 2.0; Clustering; Signatures for metric spaces; Perspectives: New trends in topological data analysis; Further prospects on the theory; Introduction to quiver theory with a view toward persistence; Bibliography; List of figures; Index.

Mathematical Surveys and Monographs, Volume 209


Mathematical Physics

Random Operators

Disorder Effects on Quantum Spectra and Dynamics

Michael Aizenman, Princeton University, NJ, and Simone Warzel, Technische Universität München, Germany

This book provides an introduction to the mathematical theory of disorder effects on quantum spectra and dynamics. Topics covered range from the basic theory of spectra and dynamics of self-adjoint operators through Anderson localization—presented here via the fractional moment method, up to recent results on resonant delocalization. The subject’s multifaceted presentation is organized into seventeen chapters, each focused on either a specific mathematical topic or on a demonstration of the theory’s relevance to physics, e.g., its implications for the quantum Hall effect. The mathematical chapters include general relations of quantum spectra and dynamics, ergodicity and its implications, methods for establishing spectral and dynamical localization regimes, applications and properties of the Green function, its relation to the eigenfunction correlator, fractional moments of Herglotz-Pick functions, the phase diagram for tree graph operators, resonant delocalization, the spectral statistics conjecture, and related results.

The text incorporates notes from courses that were presented at the authors’ respective institutions and attended by graduate students and postdoctoral researchers.

It has been almost 25 years since the last major book on this subject. The authors masterfully update the subject but more importantly present their own probabilistic insights in clear fashion. This wonderful book is ideal for both researchers and advanced students.

—Barry Simon, California Institute of Technology

This item will also be of interest to those working in probability and statistics and analysis.

Contents: Introduction; General relations between spectra and dynamics; Ergodic operators and their self-averaging properties; Density of states bounds: Wegner estimate and Lifshitz tails; The relation of Green functions to eigenfunctions; Anderson localization through path expansions; Dynamical localization and fractional moment criteria; Fractional moments from an analytical perspective; Strategies for mapping exponential decay; Localization at high disorder and at extreme energies; Constructive criteria for Anderson localization; Complete localization in one dimension; Diffusion hypothesis and the Green-Kubo-Streda formula; Integer quantum Hall effect; Resonant delocalization; Phase diagrams for regular tree graphs; The eigenvalue point process and a conjectured dichotomy; Elements of spectral theory; Herglotz-Pick functions and their spectra; Bibliography; Index.

Graduate Studies in Mathematics, Volume 168


Probability and Statistics

Fokker–Planck–Kolmogorov Equations

Vladimir I. Bogachev, Moscow State University, Russia, Nicolai V. Krylov, University of Minnesota, Minneapolis, MN, Michael Röckner, Bielefeld University, Germany, and Stanislav V. Shaposhnikov, Moscow State University, Russia

This item is also of interest to those working in probability and statistics and analysis.

Contents: Introduction; Fokker–Planck–Kolmogorov equations; Hitting times and fundamental solutions; HJB equations; Large deviations; Stability; Asymptotics for states of large weights; Personal communication; Bibliography; Index.

Graduate Studies in Mathematics, Volume 191

New AMS-Distributed Publications

This book gives an exposition of the principal concepts and results related to second order elliptic and parabolic equations for measures, the main examples of which are Fokker–Planck–Kolmogorov equations for stationary and transition probabilities of diffusion processes. Existence and uniqueness of solutions are studied along with existence and Sobolev regularity of their densities and upper and lower bounds for the latter.

The target readership includes mathematicians and physicists whose research is related to diffusion processes as well as elliptic and parabolic equations.

Contents: Stationary Fokker–Planck–Kolmogorov equations; Existence of solutions; Global properties of densities; Uniqueness problems; Associated semigroups; Parabolic Fokker–Planck–Kolmogorov equations; Global parabolic regularity and upper bounds; Parabolic Harnack inequalities and lower bounds; Uniquess of solutions to Fokker–Planck–Kolmogorov equations; The infinite-dimensional case; Bibliography; Subject index.

Mathematical Surveys and Monographs, Volume 207


Algebra and Algebraic Geometry

Algebraic Geometry II

David Mumford, Brown University, Providence, RI, and Tadao Oda, Tohoku University, Japan

Several generations of students of algebraic geometry have learned the subject from David Mumford’s fabled “Red Book”, which contains notes of his lectures at Harvard University. Their genesis and evolution are described by Mumford in the preface:

Initially, notes to the course were mimeographed and bound and sold by the Harvard mathematics department with a red cover. These old notes were picked up by Springer and are now sold as The Red Book of Varieties and Schemes. However, every time I taught the course, the content changed and grew. I had aimed to eventually publish more polished notes in three volumes...

This book contains what Mumford had then intended to be Volume II. It covers the material in the “Red Book” in more depth, with several topics added. Mumford has revised the notes in collaboration with Tadao Oda.


Analysis

Tempered Homogeneous Function Spaces

Hans Triebel, Friedrich Schiller University Jena, Germany

This book deals with homogeneous function spaces of Besov–Sobolev type within the framework of tempered distributions in Euclidean n-space based on Gauss–Weierstrass semi-groups. Related Fourier-analytical descriptions and characterizations in terms of derivatives and differences are incorporated after as so-called domestic norms. This approach avoids the usual ambiguities modulo polynomials when homogeneous function spaces are considered in the context of homogeneous tempered distributions.

These notes are addressed to graduate students and mathematicians having a working knowledge of basic elements of the theory of function spaces, especially of Besov–Sobolev type. In particular, the book might be of interest for researchers dealing with (nonlinear) heat and Navier–Stokes equations in homogeneous function spaces.

A publication of the European Mathematical Society (EMS). Distributed within the Americas by the American Mathematical Society.

Contents: Motivation and preliminaries; Spaces on $S' (\mathbb{R}^n)$; New approach; Bibliography; Symbols; Index.

EMS Series of Lectures in Mathematics, Volume 21

In the late 1990s, two initially unrelated developments brought free loop spaces into renewed focus. In 1999, Chas and Sullivan introduced a wealth of new algebraic operations on the homology of these spaces under the name of string topology, the full scope of which is still not completely understood. A few years earlier, Viterbo had discovered a first deep link between the symplectic topology of cotangent bundles and the topology of their free loop space. In the past 15 years, many exciting connections between these two viewpoints have been found. Still, researchers working on one side of the story often know quite little about the other.

One of the main purposes of this book is to facilitate communication between topologists and symplectic geometers thinking about free loop spaces. It was written by active researchers who approach the topic from both perspectives and provides a concise overview of many of the classical results. The book also begins to explore the new directions of research that have emerged recently. One highlight is the research monograph by M. Abouzaid, which proves a strengthened version of Viterbo’s isomorphism between the homology of the free loop space of a manifold and the symplectic cohomology of its cotangent bundle, following a new strategy.

The book grew out of a learning seminar on free loop spaces held at Strasbourg University in 2008–2009 and should be accessible to graduate students with a general interest in the topic. It focuses on introducing and explaining the most important aspects, rather than offering encyclopedic coverage, while providing the interested reader with a broad basis for further studies and research.

A publication of the European Mathematical Society. Distributed within the Americas by the American Mathematical Society.

Contents:
- A panorama of topology, geometry and algebra: D. Chataur and A. Oancea, Basics on free loop spaces; A. Oancea, Morse theory, closed geodesics, and the homology of free loop spaces; L. Menichi, Rational homotopy–Sullivan models; J.-L. Loday, Free loop space and homology; J. Latschev, Appendix to the chapter by J.-L. Loday; H. Abbaspou, On algebraic structures of the Hochschild complex; Y. Félix, Basic rational string topology; J. Latschev, Fukaya’s work on Lagrangian embeddings; II. Symplectic cohomology and Viterbo’s theorem by Mohammed Abouzaid: Symplectic cohomology of cotangent bundles; Symplectic cohomology of cotangent bundles; Operations in symplectic cohomology; String topology using piecewise geodesics; From symplectic cohomology to loop homology; Viterbo’s theorem: Surjectivity; Viterbo’s theorem: Isomorphism; Bibliography to Part II; List of contributors; Index.

IRMA Lectures in Mathematics and Theoretical Physics, Volume 24

In the late 1990s, two initially unrelated developments brought free loop spaces into renewed focus. In 1999, Chas and Sullivan introduced a wealth of new algebraic operations on the homology of these spaces under the name of string topology, the full scope of which is still not completely understood. A few years earlier, Viterbo had discovered a first deep link between the symplectic topology of cotangent bundles and the topology of their free loop space. In the past 15 years, many exciting connections between these two viewpoints have been found. Still, researchers working on one side of the story often know quite little about the other.

One of the main purposes of this book is to facilitate communication between topologists and symplectic geometers thinking about free loop spaces. It was written by active researchers who approach the topic from both perspectives and provides a concise overview of many of the classical results. The book also begins to explore the new directions of research that have emerged recently. One highlight is the research monograph by M. Abouzaid, which proves a strengthened version of Viterbo’s isomorphism between the homology of the free loop space of a manifold and the symplectic cohomology of its cotangent bundle, following a new strategy.

The book grew out of a learning seminar on free loop spaces held at Strasbourg University in 2008–2009 and should be accessible to graduate students with a general interest in the topic. It focuses on introducing and explaining the most important aspects, rather than offering encyclopedic coverage, while providing the interested reader with a broad basis for further studies and research.

A publication of the European Mathematical Society. Distributed within the Americas by the American Mathematical Society.

Contents:
- A panorama of topology, geometry and algebra: D. Chataur and A. Oancea, Basics on free loop spaces; A. Oancea, Morse theory, closed geodesics, and the homology of free loop spaces; L. Menichi, Rational homotopy–Sullivan models; J.-L. Loday, Free loop space and homology; J. Latschev, Appendix to the chapter by J.-L. Loday; H. Abbaspou, On algebraic structures of the Hochschild complex; Y. Félix, Basic rational string topology; J. Latschev, Fukaya’s work on Lagrangian embeddings; II. Symplectic cohomology and Viterbo’s theorem by Mohammed Abouzaid: Symplectic cohomology of cotangent bundles; Symplectic cohomology of cotangent bundles; Operations in symplectic cohomology; String topology using piecewise geodesics; From symplectic cohomology to loop homology; Viterbo’s theorem: Surjectivity; Viterbo’s theorem: Isomorphism; Bibliography to Part II; List of contributors; Index.

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Suggested uses for classified advertising are positions available, books or lecture notes for sale, books being sought, exchange or rental of houses, and typing services. The publisher reserves the right to reject any advertising not in keeping with the publication’s standards. Acceptance shall not be construed as approval of the accuracy or the legality of any advertising.

The 2015 rate is $3.50 per word with a minimum two-line headline. No discounts for multiple ads or the same ad in consecutive issues. For an additional $10 charge, announcements can be placed anonymously. Correspondence will be forwarded.

Advertisements in the “Positions Available” classified section will be set with a minimum one-line headline, consisting of the institution name above body copy, unless additional headline copy is specified by the advertiser. Headlines will be centered in boldface at no extra charge. Ads will appear in the classified section of the magazine in which they are submitted.

There are no member discounts for classified ads. Dictation over the telephone will not be accepted for classified ads.


U.S. laws prohibit discrimination in employment on the basis of color, age, sex, race, religion, or national origin. “Positions Available” advertisements from institutions outside the US cannot be published unless they are accompanied by a statement that the institution does not discriminate on these grounds whether or not it is subject to US laws. Details and specific wording may be found on page 1373 (vol. 44).

Submission: Promotions Department, AMS, P.O. Box 6248, Providence, Rhode Island 02904; or via fax: 401-331-3842; or send email to classifieds@ams.org. AMS location for express delivery packages is 201 Charles Street, Providence, Rhode Island 02904. Advertisers will be billed upon publication.
Assistant Professor position with an anticipated start date of August 2016.

The department is particularly interested in mathematicians specializing in the general areas of geometry and topology, but outstanding candidates in all areas of mathematics may also be considered. Candidates should have demonstrated excellence in research and a strong commitment to graduate and undergraduate education. A doctoral degree is required at the time of appointment.

To apply, please submit the following materials: letter of application and curriculum vitae, including your email address, telephone numbers, preferably with the standardized AMS Cover Sheet. Candidates should also arrange for at least three letters of recommendation that address research, at least one of which also addresses teaching skills. Please submit applications electronically through MathJobs at [www.mathjobs.org](http://www.mathjobs.org). In order to be considered for this position, applicants are also required to submit an electronic USC application; follow this job link or paste in a browser: [jobs.usc.edu/postings/52978](http://jobs.usc.edu/postings/52978).

Review of applications will begin October 15, 2015. Additional information about the USC Dornsife’s Department of Mathematics can be found at our website [dornsife.usc.edu/mathematics](http://dornsife.usc.edu/mathematics/).

USC is an Equal-Opportunity Educator and Employer, proudly pluralistic and firmly committed to providing equal opportunity for outstanding persons of every race, gender, creed and background. The University particularly encourages women, members of underrepresented groups, veterans and individuals with disabilities to apply. USC will make reasonable accommodations for qualified individuals with known disabilities unless doing so would result in an undue hardship. Further information is available by contacting uschr@usc.edu.

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**KANSAS**

**UNIVERSITY OF KANSAS**

Mathematics Department

The Department of Mathematics at the University of Kansas invites applications for a tenure-track faculty position in Computational Mathematics. Candidates must demonstrate an outstanding record of research and must be strongly committed to excellence in teaching. Requirements for the positions include a PhD in mathematics or a closely related field, expected by the start date of the appointment (August 18, 2016).

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**MARYLAND**

**JOHNS HOPKINS UNIVERSITY**

Non-Tenure-Track J. J. Sylvester Assistant Professor

Subject to availability of resources and administrative approval, the Department of Mathematics solicits applications for non-tenure-track Assistant Professor positions beginning Fall 2016.

The J. J. Sylvester Assistant Professorship is a three-year position offered to recent PhDs with outstanding research potential. Candidates in all areas of pure mathematics, including analysis, mathematical physics, geometric analysis, complex and algebraic geometry, number theory, and topology are encouraged to apply. The teaching load is three courses per academic year.

To submit your applications go to [www.mathjobs.org/jobs/jhu](http://www.mathjobs.org/jobs/jhu). Applicants are strongly advised to submit their other materials electronically at this site.

If you do not have computer access, you may mail your application to: 404 Krieger Hall, Baltimore, MD 21218.

Applications should include a vita, at least four letters of recommendation of which one specifically comments on teaching, and a description of current and planned research. Write to cpoole@jhu.edu for questions concerning these positions.

Applications received by December 1, 2015, will be given priority. Johns Hopkins University is committed to active recruitment of a diverse faculty and student body. The University is an Affirmative Action/Equal Opportunity Employer of women, minorities, protected veterans and individuals with disabilities and encourages applications from these and other protected group members. Consistent with the University’s goals of achieving excellence in all areas, we will assess the comprehensive qualifications of each applicant.

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**MASSACHUSETTS**

**BOSTON UNIVERSITY**

Department of Mathematics and Statistics

Tenure Track Position – Number Theory

The Department of Mathematics and Statistics invites applications for a tenure-track Assistant Professor level position in Number Theory. PhD required. The position will begin July 1, 2016. A strong commitment to research and teaching at the undergraduate and graduate levels is essential. A complete application will consist of a cover letter, CV, research statement, teaching statement, four letters of recommendation, at least one of which addresses teaching. Please submit all materials online to [mathjobs.org](http://mathjobs.org). Alternatively, please have hardcopies mailed to Number Theory Search, Department of Mathematics and Statistics, Boston University, 111 Cumming Mall, Boston, MA 02215. The application deadline December 15, 2015. We are an equal opportunity employer and all qualified applicants will receive consideration for employment without regard to race, color, religion, sex, national origin, disability status, protected veteran status, or any other characteristic protected by law. We are a VEVRAA Federal Contractor.
BOSTON UNIVERSITY  
Department of Mathematics and Statistics  
Post Doctoral Position – Geometry and Mathematical Physics

The Department of Mathematics and Statistics, at Boston University, invites applications for a three-year post-doctoral position in Geometry and Mathematical Physics, starting July 2016. Strong commitment to research and teaching is essential. Please submit all materials to mathjobs.org. Alternatively, send a cover letter, curriculum vitae, research statement, teaching statement, and at least four letters of recommendation, one of which addresses teaching, to Geometry and Mathematical Physics Postdoctoral Search Committee, Department of Mathematics and Statistics, Boston University, 111 Cummington Mall, Boston, MA 02215. Application deadline December 15, 2015.

Northeastern University is an Equal Opportunity, Affirmative Action Educational Institution and Employer, Title IX University. Northeastern University particularly welcomes applications from minorities, women, and persons with disabilities. Northeastern University is an E-Verify Employer.

NORTHEASTERN UNIVERSITY  
Department of Mathematics  
Assistant/Associate Professor Tenure-Track Position

The Department of Mathematics at Northeastern University invites applications for a tenure-track position at the Assistant/Associate Professor level in Applied Mathematics to start as early as fall of 2016.

Appointments will be based on exceptional research contributions in Mathematics combined with a strong commitment and demonstrated success in teaching. Applications from those with an interest and ability to connect across units in the university to the advantage of research at the interface of mathematics and other disciplines are a top priority. Outstanding candidates with research in statistics, probability, discrete mathematics and computational mathematics are encouraged to apply.

Candidates must have a PhD in Mathematics or a related field by the start date, strong record of research, and demonstrated evidence of excellent teaching ability. Responsibilities will include teaching undergraduate and graduate courses, mentoring students and conducting an independent research program.

Review of applications will begin immediately. Complete applications received by November 15, 2015, will be guaranteed full consideration. Additional applications will be considered until the position is filled.

To apply, visit “Careers at Northeastern” at https://neu.peopleadmin.com and clicking on “Full-time Faculty Positions” and search for the current position under the College of Science. You can also apply by visiting the College of Science website at www.northeastern.edu/cos and clicking on the “Faculty Positions” button. Research statements, reference letters, and teaching statements can be submitted to MathJobs along with the other materials requested there for preliminary review by the Search Committee.

Northeastern University is an Equal Opportunity, Affirmative Action Educational Institution and Employer, Title IX University. Northeastern University particularly welcomes applications from minorities, women, and persons with disabilities. Northeastern University is an E-Verify Employer.

WILLIAMS COLLEGE  
Department of Mathematics and Statistics

The Williams College Department of Mathematics and Statistics invites applications for two full-time visiting positions in mathematics for the 2016–2017 year. The teaching load is four courses. Preference will be given to candidates who will have a PhD in mathematics by September 2016.

Applicants can apply electronically at mathjobs.org. Evaluations of applications will begin on or after November 15, and will continue until the position is filled. All offers of employment are contingent upon completion of a background check. For more information on the Department of Mathematics and Statistics, visit math.williams.edu.

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

TEXAS

BAYLOR UNIVERSITY  
Jean and Ralph Storm Endowed Chair in Mathematics

The Department of Mathematics invites applications to fill the Jean and Ralph Storm Chair of Mathematics. The successful candidate, who is expected to be at the full-professor level, will be an excellent mathematician, with national and international recognition for scholarship, demonstrated excellence in teaching at the undergraduate and graduate levels and a history of successful, sustained grantmanship. This endowed position provides an annual discretionary research fund to the successful candidate. Applications in all areas of mathematics will be considered. Active research areas in the department are in the general areas of algebra, analysis, differential equations, mathematical physics, numerical analysis, computational mathematics, representation theory, and topology. Faculty in the department are engaged in interdisciplinary research with other departments on campus. Baylor encourages women, minorities, veterans, and individuals with disabilities to apply. Detailed information about the department can be found at www.baylor.edu/math.

To ensure full consideration, complete applications must be submitted by 02/15/16. Applications will be reviewed immediately after this date and will be accepted until the position is filled.

We encourage all applicants to submit their materials online at www.mathjobs.org. Candidates should possess an earned doctorate in the appropriate field of study. A complete application includes a cover letter of application (please refer to the job number BQ 34499), at least three letters of recommendation, a current curriculum vitae, original doctoral transcripts, and a statement of support for Baylor’s Christian mission (see www.baylor.edu/profuturis/check-policy). For information about the Department of Mathematics, visit math.williams.edu. For additional information about the department can be found at http://www.math.williams.edu/.

Baylor is a private Christian university and a nationally ranked research institution, consistently listed with highest honors among The Chronicle of Higher Education’s “Great Colleges to Work For” Chartered in 1845 by Dr. Lance L. Littlejohn, Department of Mathematics, Baylor University, One Bear Place #97328, Waco, TX 76798-7328. Baylor University is a private not-for-profit university affiliated with the Baptist General Convention of Texas. As an Affirmative Action/Equal Opportunity employer, Baylor is committed to compliance
with all applicable anti-discrimination laws, including those regarding age, race, color, sex, national origin, marital status, pregnancy status, military service, genetic information, and disability. As a religious educational institution, Baylor is lawfully permitted to consider an applicant’s religion as a selection criterion.

UTAH

UNIVERSITY OF UTAH
Department of Mathematics

The Department of Mathematics at the University of Utah invites applications for the following positions:

• Full-time tenure-track or tenured appointments at the level of Assistant, Associate, or Full Professor in all areas of statistics. These positions are part of a University-wide cluster hiring effort in statistics, with particular emphasis in mathematics, computer science, and bioengineering. Successful candidates will have strong interdisciplinary interests.
• Three-year Burgess, Tucker, and Wylie Assistant Professor Lecturer positions.
• Research Training Group (RTG) postdoctoral positions in Algebraic Geometry and Topology. Please see our website at www.math.utah.edu/positions for information regarding available positions and application requirements. Applications must be completed through www.mathjobs.org/jobs/Utah. Completed applications received before January 1, 2016, will receive full consideration. The University of Utah is an Equal Opportunity/Affirmative Action employer. Women, minorities, veterans, and those with disabilities are strongly encouraged to apply. Veterans, preference is extended to qualified veterans. Reasonable disability accommodations will be provided with adequate notice. For additional information about the University’s commitment to equal opportunity and access see: www.utah.edu/nondiscrimination.

VIRGINIA

UNIVERSITY OF VIRGINIA
Department of Mathematics
Open Rank in Mathematics

The Department of Mathematics at the University of Virginia, Charlottesville, VA, invites applications for open rank (tenure-track and tenured) full-time positions, to begin in the Fall semester of 2016. Applicants must present evidence of outstanding accomplishments and promise in both research and teaching. We seek candidates dedicated to our mission and passionate about teaching in a world-class institution.

In addition to developing external funding to support research endeavors, candidates will be expected to teach at the graduate and undergraduate levels and provide service to the University, Department, and professional organizations. The appointment start date will be August 25, 2016. Applicants must be on track to receive a PhD in the relevant field by May, 2016, and must hold a PhD at the time of appointment. Preference will be given to applicants whose research program is in Analysis or Topology, but all candidates whose research interests complement the strengths of the department’s current faculty will be considered. In targeted areas, evidence of computational research is a plus.

To apply candidates must submit a Candidate Profile through Jobs@UVa [https://jobs.virginia.edu], search on posting number 0617007 and electronically attach the following: a cover letter of interest describing research agenda and teaching experience, a curriculum vitae, and contact information for four references.

Review of applications will begin November 1, 2015; however, the positions will remain open until filled.

In addition, please submit the following required documents electronically through [www.MathJobs.org]: A cover letter, an AMS Standard Cover Sheet, a curriculum vitae, a publication list, a description of research, and a statement about teaching interests and experience. The applicant must also have at least four letters of recommendation submitted, of which one must support the applicant’s effectiveness as a teacher.

Questions regarding the application process in Jobs@UVa should be directed to: Zvezdana Kish, zk4g@virginia.edu (434) 924-9437.

For additional information about the position contact: math-employment@virginia.edu.

The University will perform background checks on all new faculty hires prior to making a final offer of employment.

The University of Virginia is an Equal Opportunity and Affirmative Action Employer. Women, minorities, veterans, and persons with disabilities are encouraged to apply.

UNIVERSITY OF VIRGINIA
Department of Mathematics
Postdoctoral Fellow and Lecturer in Mathematics

The Department of Mathematics at the University of Virginia invites applications for several postdoctoral positions, including Whyburn Instructorships and the Mary Ann Pitts Postdoctoral Fellow and Lecturer in Mathematics, beginning August 25, 2016. These positions carry a three-year appointment. Preference will be given to candidates who have received their PhD within the last three years. Applicants must be on track to receive a PhD in the relevant field by May, 2016, and must hold a PhD at the time of appointment. Applicants must present evidence of outstanding accomplishments and promise in both research and teaching. Preference will be given to applicants in Commutative Algebra, Mathematical Physics, Probability, Representation Theory, and Topology, but all candidates whose research interests complement the strengths of the department’s current faculty will be considered. Information about the department may be found at www.math.virginia.edu.

Review of applications will begin on November 15, 2015; however, the positions will remain open until filled.

To apply candidates must submit a Candidate Profile through Jobs@UVa [https://jobs.virginia.edu], search on posting number 0617068 and electronically attach the following: a cover letter of interest describing research agenda and teaching experience, a curriculum vitae, and contact information for four references.

Questions regarding the application process in Jobs@UVa should be directed to: Zvezdana Kish, zk4g@virginia.edu (434) 924-9437.

For additional information about the position contact: math-employment@virginia.edu.

The University will perform background checks on all new faculty hires prior to making a final offer of employment.

The University of Virginia is an Equal Opportunity and Affirmative Action Employer. Women, minorities, veterans, and persons with disabilities are encouraged to apply.
Meetings & Conferences of the AMS

New Brunswick, New Jersey

Rutgers University

November 14–15, 2015
Saturday – Sunday

Meeting #1115
Eastern Section
Associate secretary: Steven H. Weintraub
Announcement issue of Notices: September 2015
Program first available on AMS website: October 1, 2015
Issue of Abstracts: Volume 36, Issue 4

Deadlines
For organizers: Expired
For abstracts: Expired

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/sectional.html.

Invited Addresses

Lee Mosher, Rutgers University, Newark, The geometry of the outer automorphism group of a free group.

Jill Pipher, Brown University, Harmonic analysis and elliptic boundary value problems.

David Vogan, Department of Mathematics, MIT, Matrices almost of order two.

Wei Zhang, Columbia University, The Euler product and the Taylor expansion of an L-function.

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 www.ams.org/cgi-bin/abstracts/abstract.pl.

Advances in Valuation Theory, Samar El Hitti, New York City College of Technology, City University of New York, Franz-Viktor Kuhlmann, University of Saskatchewan, and Hans Schoutens, New York City College of Technology, City University of New York.

Algebraic Geometry and Combinatorics, Elizabeth Drellich, University of North Texas, Erik Insko, Florida Gulf Coast University, Aba Mbirika, University of Wisconsin-Eau Claire, and Heather Russell, Washington College.

Applications of CAT(0) Cube Complexes, Sean Cleary, City College of New York and the City University of New York Graduate Center, and Megan Owen, Lehman College of the City University of New York.
Aspects of Minimal Surfaces in Riemannian Manifolds, Zheng Huang and Marcello Lucia, City University of New York, Staten Island and Graduate Center.

Aspects of Resolutions and Syzygies in Commutative Algebra, Courtney Gibbons, Hamilton College, and Denise Rangel Tracy, Syracuse University.

Commutative Algebra, Laura Ghezzi, New York City College of Technology, City University of New York, and Jooyoun Hong, Southern Connecticut State University.

Difference Equations and Applications, Manos Drymonis, Providence College, Evelina Lapierre, Johnson and Wales University, and Michael Radin, Rochester Institute of Technology.

Geometric Analysis, Paul Feehan, Manos Maridakis, and Natasa Sesum, Rutgers University.

Geometric Topology: A Celebration of Jim West’s 70th Birthday, Alexandre Dranishnikov, University of Florida, Steve Ferry, Rutgers University, and Boris Goldfarb, State University of New York at Albany.

Geometry and Combinatorics of Polytopes, Egon Schulte, Northeastern University, and Asia Ivic Weiss, York University.

Geometry of Groups, Surfaces and 3-manifolds, Abhijit Champanerkar, College of Staten Island and The Graduate Center, City University of New York, Feng Luo, Rutgers University, and Joseph Maher, College of Staten Island and The Graduate Center, City University of New York.

Invariants of Knots, Links and 3-Manifolds, I, Ilya Kofman, College of Staten Island and The Graduate Center, City University of New York, and Adam Lowrance, Vassar College.

Modern Schubert Calculus, Anders Buch and Chris Woodward, Rutgers University.

Multiple Combinatorial Numbers and Associated Identities, Hasan Coskun, Texas A & M University-Commerce.

Multiscale Methods in Cell and Developmental Biology, Anastasios Matzavinos, Brown University, and Chuan Xue, Ohio State University.

Nonlinear Waves in Differential Equations, Linghai Zhang, Lehigh University.

Number Theory, Spectral Theory, and Homogeneous Dynamics, Dubi Kelmer, Boston College, and Alex Kontorovich, Rutgers University.

Partial Differential Equations in Geometric Analysis, Jeffrey Case and Alice Chang, Princeton University, and Yi Wang, Johns Hopkins University and Institute for Advanced Study.

Probability, Combinatorics and Statistical Mechanics, Nayantara Bhatnagar, University of Delaware, Brian Rider, Temple University, and Douglas Rizzolo, University of Delaware.

Representation Theory, Vertex Operator Algebras, and Related Topics, Corina Calinescu, New York City College of Technology, City University of New York, Andrew Douglass, New York City College of Technology and Graduate Center, City University of New York, and Joshua Sussan, Medgar Evers College, City University of New York.

Representations of Reductive Groups, Jeffrey Adams, University of Maryland, Stephen D. Miller, Rutgers University, and David Vogan, Massachusetts Institute of Technology.


Topological Data Analysis: Computations, Statistics, and Applications, Miroslav Kramar and Rachel Levanger, Rutgers University.

Seattle, Washington

Washington State Convention Center and the Sheraton Seattle Hotel

January 6-9, 2016
Wednesday – Saturday

Meeting #1116

Joint Mathematics Meetings, including the 122nd Annual Meeting of the AMS, 99th 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: October 2015

Program first available on AMS website: November 1, 2015

Issue of Abstracts: Volume 37, Issue 1

Deadlines

For organizers: Expired
For abstracts: Expired

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/national.html.

Joint Invited Addresses

Jennifer Chayes, Microsoft Research, Network Science: From the Online World to Cancer Genomics (MAA-AMS-SIAM Gerald and Judith Porter Public Lecture).
Kristin Estella Lauter, Microsoft Research, How to Keep your Genome Secret (AMS-MAA Invited Address).
Xiao-Li Meng, Harvard University, Statistical Paradises and Paradoxes in Big Data (AMS-MAA Invited Address).

AMS Invited Addresses

Panagiota Daskalopoulos, Columbia University, Ancient solutions to parabolic partial differential equations.
Alex Eskin, University of Chicago, The SL(2, R) action on moduli space.
W. Timothy Gowers, University of Cambridge, UK, Quasirandom sets, quasirandom graphs, and applications (AMS Colloquium Lectures: Lecture I).
W. Timothy Gowers, University of Cambridge, UK, Arithmetic progressions of length 4, quadratic Fourier analysis, and 3-uniform hypergraphs (AMS Colloquium Lectures: Lecture II).
W. Timothy Gowers, University of Cambridge, UK, Fourier analysis on general finite groups (AMS Colloquium Lectures: Lecture III).
Marta Lewicka, University of Pittsburgh, Prestrained elasticity: curvature constraints and differential geometry with low regularity.
Daniel Alan Spielman, Yale University, Graphs, Vectors, and Matrices (AMS Josiah Willard Gibbs Lecture).
David Vogan, Massachusetts Institute of Technology, Conjugacy classes and group representations (AMS Retiring Presidential Address).
Steve Zelditch, Northwestern University, Chaotic billiards and vibrations of drums.

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 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.

Advances in Free Analysis: the Theory and Applications of Noncommutative Functions, Inequalities, and Domains, Joseph A. Ball, Virginia Polytechnic Institute, and Paul S. Muhly, University of Iowa, Iowa City.
Advances in the Theory and Application of Reaction Diffusion Models, Jerome Goddard, II, Auburn University, Montgomery, and Ratnasingham Shivaji, University of North Carolina, Greensboro.
Algebraic Theory of Differential and Functional Equations, Taylor Dupuy, Hebrew University of Jerusalem and University of Vermont, and Alexey Ovchinnikov, CUNY Queens College, New York.
Algebraic and Topological Methods in Combinatorics, Andrew Berget, Western Washington University, Steven Klee, Seattle University, and Isabella Novik, University of Washington, Seattle.
Analysis and Geometry in Nonsmooth Metric Measure Spaces, Luca Capogna, Worcester Polytechnic Institute, and Jeremy Tyson, University of Illinois at Urbana-Champaign.
Analysis, Geometry, and Data, Kevin R. Vixie, Washington State University, Pullman, and Bala Krishnamoorthy, Washington State University, Vancouver.
Analytic Function Spaces and Operators on Them, Tim Ferguson and Hyun Kwon, University of Alabama, Tuscaloosa.
Analytic Methods in Geometry, Eric Bahuaud and Dylan Helliwell, Seattle University.
Applications of Logic, Model Theory, and Theoretical Computer Science to Systems Biology, James Lynch, Clarkson University, and Leo Marcus, Santa Monica, CA (AMS-ASL).
Applied and Computational Topology, Pawel Dlotko, INRIA Saclay, France, Nicholas Scoville, Ursinus College, and Matthew Wright, IMA University of Minnesota.
Arithmetic Dynamics, Matthew Baker, Georgia Institute of Technology, and Joseph Silverman, Brown University.
Big Demand for Big Data: How Do We Create the Big Supply?, Rick Cleary, Babson College, and Xiao-Li Meng, Harvard University.
Classification Problems in Operator Algebras, Marcel Bischoff and Ben Hayes, Vanderbilt University.
Combinatorial Design Theory, Esther R. Lamken, California Institute of Technology.
Commutative Algebra, Karen Smith, University of Michigan, Ann Arbor, Emily Witt, University of Utah, and Irena Swanson, Reed College (AMS-AWM).
Commutative Algebra and Its Interactions with Algebraic Geometry, Daniel Hernández, University of Utah, Jack Jeffries, University of Michigan, Ann Arbor, and Karl Schwede, University of Utah (AMS-AWM).
Commutative Algebra, I (a Mathematics Research Communities Session), Linquan Ma, University of Utah, Sarah Mayes-Tang, Quest University, and Jonathan Montaño, University of Kansas.
Current Areas of Interest in the Mathematical Sciences of Medieval Islam, Mohammad K. Azarian, University of
Evansville, and Mohammad Javaheri and Emelie A. Kennedy, Siena College.

Data-Intensive Modeling in Ecology, Nikolay Strigul, Washington State University, Vancouver, and Bala Krishnamoorthy, Washington State University, Vancouver.

Difference Equations and Applications, Michael A. Radin, Rochester Institute of Technology.


Distribution of Zeros of Entire Functions, Matthew Chasse, Rochester Institute of Technology, Tamás Forgács, California State University, Fresno, and Andrzej Piotrowski, University of Alaka Southeast, Juneau.

Early Career Female Mathematicians in Algebra and Topology, Jocelyn Bell, United States Military Academy, West Point, Bethany Kubik, University of Minnesota, Duluth, and Candice Price, Sam Houston State University.

Equations of Fluid Motion, Elaine Cozzi and Radu Dascaliuc, Oregon State University, and James P. Kelliher, University of California Riverside.


Financial Mathematics, I (a Mathematics Research Communities Session), Triet Pham, Rutgers University, Wilber A Ventura, University of Texas at Arlington, and Kim Weston, Carnegie Mellon University.

Fractal Geometry and Dynamical Systems, John Rock, Cal Poly Pomona, Machiel van Frankenhuijsen, Utah Valley University, and Michel L. Lapidus, University of California, Riverside.

Geometric and Categorical Methods in Representation Theory, Anthony Licata, Australian National University, and Julia Pevtsova, Universityof Washington, Seattle.

Global Harmonic Analysis, Steven Zelditch, Northwestern University, Hart Smith, University of Washington, Seattle, and Chris Sogge, Johns Hopkins University.

Graduate Mathematics Courses and Programs for Secondary Mathematics Teachers, James J. Madden, Louisiana State University, Baton Rouge, and James A. Mendoza Epperson, University of Texas, Arlington.

Graph Products, Richard Hammack and Dewey Taylor, Virginia Commonwealth University.

Higher Genus Curves and Fibrations of Higher Genus Curves in Mathematical Physics and Arithmetic Geometry, Andreas Malmendier, Utah State University, Logan, and Tony Shaska, Oakland University, Rochester.

Innovative Ideas in Enhancing Success in Mathematics Classes, Natali Hritonenko, Prairie View A&M University, Ellina Grigorieva, Texas Woman's University, and Michael A. Radin, Rochester Institute of Technology (AMS-MAA).

Integrable Systems, Painlevé Equations, and Random Matrices, Anton Dzhamaev, University of Northern Colorado, Christopher M. Ormerod, California Institute of Technology, and Virgil U. Pierce, University of Texas-Pan American.

Interactions between Noncommutative Algebra, Algebraic Geometry, and Representation Theory, Ellen Kirkman, Wake Forest University, and James Zhang, University of Washington.

Knots in Washington (State), Allison Henrich, Seattle University, Sam Nelson, Claremont McKenna College, Jozef Przytycki, George Washington University, and Radmilja Sazdanovic, North Carolina State University, Raleigh.

Mathematical Information in the Digital Age of Science, Patrick Ion, University of Michigan, Ann Arbor, Olaf Teschke, zbMATH, Berlin, and Stephen Watt, University of Western Ontario.

Mathematical Programming on Integral Inexivity, Ram Verma, Texas State University, San Marcos, and Alexander Zaslavski, Israel Institute of Technology.

Mathematics and Public Policy, Paul Dreyer, RAND Corporation.


Metrical and Topological Fixed Point Theory with Applications, Clement Boateng Ampadu, Boston, MA, Talat Nazir, Mälardalen University, Sweden, and Hudson Akewe, University of Lagos, Nigeria.

Modular Forms, q-Series, and Mathematics Inspired by Ramanujan, Chris Jennings-Shaffer, University of Florida, Gainesville, and Oregon State University, Corvallis, and Holly Swisher, Oregon State University, Corvallis.

Moduli Spaces in Algebraic Geometry, Yaim Cooper, Harvard University.

Moduli Spaces in Symplectic Geometry, Nathaniel Bottman, MIT, Joel Fish, IAS, Princeton, and the University of Massachusetts, Boston, Sheel Ganatra, Stanford University, and Katrin Wehrheim, University of California Berkeley.

Nonlinear Algebra, Bernd Sturmfels, University of California Berkeley, and Rekha Thomas, University of Washington, Seattle.
Nonlinear Waves and Coherent Structures, Natalie Sheils and Chris Swierczewski, University of Washington, Seattle.

Number Theory and Cryptography, Matilde Lalin, University of Montreal, Michelle Manes, University of Hawai‘i, Honolulu, and Christelle Vincent, University of Vermont.

Operators, Function Spaces, and Models, Alberto Condori, Florida Gulf Coast University, Fort Myers, and William Ross, University of Richmond.

Origami Methods and Applications, Erik Demaine, MIT, Thomas C. Hull, Western New England University, and Robert J. Lang, Lang Origami.

Parabolic Geometries, Twistor Theory, and the AdS/CFT Correspondence, Jonathan Holland and George Sparling, University of Pittsburgh, and Daniela Mihai, Carnegie Mellon University.

Partial Differential Equations in Complex Analysis, Debraj Chakrabarti, Central Michigan University, and Yunus Zeytuncu, University of Michigan, Dearborn.

Problems and Challenges in Financial Engineering and Risk Management, Matthew Lorig, University of Washington, Seattle, and Haijun Li and Hong-Ming Yin, Washington State University, Pullman.

Problems in Geometry and Design of Materials, Marta Lewicka, University of Pittsburgh, and Petronela Radu, University of Nebraska.

Pseudorandomness and Its Applications, Timothy Gowers, University of Cambridge, and Jozsef Solymosi, University of British Columbia.

Quantum Walks, Quantum Markov Chains, Quantum Computation and Related Topics, Chaobin Liu, Bowie State University, Takuya Machida, Japan Sociey for the Promotion of Science, Salvador E. Venegas-Andraca, Tecnológico de Monterrey, Mexico, and Nelson Petulante, Bowie State University.

Random and Complex Dynamics of Reaction-Diffusion Systems, Michael Anton Hoegele, Universidad de Los Andes, Bogota, Colombia, and Yuncheng You, University of South Florida, Tampa.

Recent Advances in Dynamical Systems and Mathematical Biology, Guihong Fan, Columbus State University, Jing Li, California State University Northridge, and Hongying Shu, Tongji University, China.

Recent Advances in Orthogonal Polynomials and Special Functions, Xiang-Sheng Wang, Southeast Missouri State University, Cape Girardeau.

Recent Developments in Dispersive Partial Differential Equations and Harmonic Analysis, William Green, Rose-Hulman Institute of Technology, Terre Haute, and Jennifer Beichman, University of Wisconsin, Madison.

Representation Theory of Algebraic Groups, Daniel K. Nakano, University of Georgia, and Cornelius Pillen, University of South Alabama.

Research by Postdocs of the Alliance for Diversity in Mathematics, Aloysius Helminck, North Carolina State University, Raleigh, and Michael Young, Iowa State University, Ames.

Research from the 2014 and 2015 Rocky Mountain-Great Plains Graduate Research Workshop in Combinatorics, Michael Ferrera, University of Colorado, Denver, Greeley, Leslie Hogben, Iowa State University, Ames, Paul Horn, University of Denver, and Derrick Stolee, Iowa State University, Ames.

Research in Mathematics by Undergraduates and Students in Post-Baccalaureate Programs, Darren A. Narayan and Jobby Jacob, Rochester Institute of Technology, Tamas Forgacs, California State University, Fresno, and Ugur Abdulla, Florida Institute of Technology (AMS-MAA-SIAM).

Set-Valued Optimization and Variational Problems with Applications, Baasansuren Jadamba and Akhtar A. Khan, Rochester Institute of Technology, Mau Nam Nguyen, Portland State University, Miguel Sama, Universidad Nacional de Educacion a Distancia, Spain, and Christiane Tammer, Martin Luther University of Halle-Wittenberg.

Special Functions and q-Series, Richard Askey, University of Wisconsin, Madison, Mourad E. H. Ismail, University of Central Florida and King Saud University, Riyadh, and Erik Koelink, Radboud University, Nijmegen, The Netherlands.

Stochastic Effects in Models for Mathematical Biology and Ecology, Olcay Akman, Illinois State University, Timothy D. Comar, Benedictine University, and Daniel Hrozencik, Chicago State University.

Stochastic Models in Population Biology, Brian Dennis, University of Idaho, Moscow, and Eddy Kwessi, Trinity University.

Surreal Numbers, Philip Ehrlich, Ohio University, Athens, and Ovidiu Costin, Ohio State University, Columbus (AMS-ASL).

Tensor Decompositions and Secant Varieties, Zach Teitler, Boise State University.

The History of Mathematics, Patti Hunter, Westmont College, Adrian Rice, Randolph-Macon College, Sloan Despeaux, Western Carolina University, and Deborah Kent, Drake University (AMS-MAA).

The Mathematics of Computation, Susanne C. Brenner, Louisiana State University.

Topological Graph Theory: Structure and Symmetry, Jonathan L. Gross, Columbia University, and Thomas W. Tucker, Colgate University.
Topological Representation Theory, Charles Frohman, University of Iowa, Iowa City, and Helen Wong, Carleton College.

Water Waves, John Carter, Seattle University, Bernard Deconinck, University of Washington, Seattle, and Katie Oliveras, Seattle University.

What’s New in Group Theory? Arturo Magidin, University of Louisiana at Lafayette, and Elizabeth Wilcox, Oswego State University of New York.

Algorithmic Structures in Knot Theory (Code: SS 5A), Sam Nelson, Claremont McKenna College, and Mohamed Elhamdadi, University of South Florida.

Algebraic Structures in Mathematical Physics: Lie Algebras, Vertex Algebras, Quantum Algebras (Code: SS 19A), Iana I. Anguelova, College of Charleston, and Bojko Bakalov, North Carolina State University.

Algebraic and Combinatorial Methods in Mathematical Biology (Code: SS 25A), Elena Dimitrova and Svetlana Poznanovic, Clemson University.

Bioinformatics and Molecular Biology: Dynamic Models, Structural Analysis, and Computational Methods (Code: SS 26A), Christine Heitsch, Chi-Jen Wang, and Haomin Zhou, Georgia Institute of Technology.

Combinatorial and Computational Algebra (Code: SS 7A), Huy Tai Ha, Tulane University, Kuei-Nan Lin, Penn State Greater Allegheny, and Augustine O’Keefe, Connecticut College.

Commutative Algebra (Code: SS 6A), Jon F. Carlson, University of Georgia, and Andrew Kustin, University of South Carolina.

Discrete and Applied Algebraic Geometry (Code: SS 18A), Cynthia Vinzant, North Carolina State University, and Josephine Yu, Georgia Institute of Technology.

Elliptic Curves (Code: SS 1A), Abbey Bourdon and Pete L. Clark, University of Georgia.

Experimental Mathematics (Code: SS 23A), Frank Garvan, University of Florida, and Andrew Sills, Georgia Southern University.

Financial Mathematics (Code: SS 27A), Arash Fahim and Alec Kercheval, Florida State University.

Harmonic Analysis and Applications (Code: SS 28A), Irina Holmes, Georgia Institute of Technology, and Brett D. Wick, Washington University.

Interactions Between Algebraic and Tropical Geometry (Code: SS 13A), Matthew Ballard, University of South Carolina, Noah Giansiracusa, University of Georgia, and Jesse Kass, University of South Carolina.

Invariant Measures of Dynamical Systems (Code: SS 24A), Miaohua Jiang and Chris Johnson, Wake Forest University, and Martin Schmoll, Clemson University.

Lie Theory, Representation Theory, and Geometry (Code: SS 3A), Shrawan Kumar, University of North Carolina, and Daniel K. Nakano and Paul Sobaje, University of Georgia.

Low-dimensional Topology and Geometry (Code: SS 15A), David Gay and Gordana Matic, University of Georgia.

Mathematical Physics and Spectral Theory (Code: SS 4A), Stephen Clark, Missouri University of Science and Technology, and Roger Nichols, The University of Tennessee at Chattanooga.

Mathematics and Music (Code: SS 14A), Mariana Montiel, Georgia State University, and Robert Peck, Louisiana State University.
Meetings & Conferences

Moduli Spaces and Vector Bundles (Code: SS 8A), Patricio Gallardo and Anna Kazanova, University of Georgia.

New Developments in Discrete and Intuitive Geometry (Dedicated to the 75th birthday of Wlodzimierz Kuperberg) (Code: SS 16A), Andras Bezdek, Auburn University, Oleg Musin, University of Texas at Brownsville, and Gabor Fejes Toth, Renyi Institute of Mathematics, Hungary (AMS-AAAS).

Numerical Methods and Scientific Computing (Code: SS 17A), Michele Benzi, Emory University, and Edmond Chow, Georgia Institute of Technology.

PDE Analysis in Fluid Flows (Code: SS 21A), Geng Chen, Ronghua Pan, and Yao Yao, Georgia Institute of Technology.

Probabilistic and Analytic Tools in Convexity (Code: SS 29A), Kabe Moen, University of Alabama, Leonid Slavin, University of Cincinnati, and Alex Stokolos, Georgia Southern University.

Symplectic and Contact Geometry (Code: SS 20A), Yi Lin and Stefan Müller, Georgia Southern University, Michael Usher, University of Georgia, and François Ziegler, Georgia Southern University.

The Combinatorics of Symmetric Functions (Code: SS 9A), Sarah K. Mason, Wake Forest University, and Elisabeth Niese, University of Virginia.

Theory and Applications of Graphs (Code: SS 12A), Colton Magnant and Hua Wang, Georgia Southern University.

Topics in Graph Theory (Code: SS 11A), Guantao Chen, Georgia State University, and Songling Shan, Vanderbilt University.

Topology and Dynamical Systems (Code: SS 10A), Alexander Blokh, University of Alabama at Birmingham, Krystyna Kuperberg, Auburn University, and John Mayer and Lex Oversteegen, University of Alabama at Birmingham.

Stony Brook, New York

State University of New York at Stony Brook

March 19–20, 2016
Saturday – Sunday

Meeting #1118

Eastern Section

Associate secretary: Steven H. Weintraub
Announcement issue of Notices: January 2016
Program first available on AMS website: February 9, 2016
Issue of Abstracts: Volume 37, Issue 2

Deadlines

For organizers: Expired
For abstracts: February 2, 2016

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/sectional.html.

Invited Addresses

Simon Donaldson, Stony Brook University, Title to be announced.

Dmitry Kleinbock, Brandeis University, Title to be announced.

Irena Lasiecka, University of Memphis, 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 www.ams.org/cgi-bin/abstracts/abstract.pl.


Commutative Ring Theory (Code: SS 7A), Alan Loper, Ohio State University, and Nick Werner, State University of New York at Old Westbury.

Complex Geometric Analysis (Code: SS 11A), Xiuxiong Chen, Stony Brook University, Weiyong He, University of Oregon, and Ioana Suvaina, Vanderbilt University.

Evolution of Partial Differential Equations and their Control (Code: SS 15A), George Avalos, University of
Nebraska, and Irena Lasiecka and Roberto Triggiani, University of Memphis.

G.2 Geometry (Code: SS 9A), Sergey Grigorian, University of Texas, Rio Grande Valley, Sema Salur, University of Rochester, and Albert J. Todd, University of South Alabama.

Geometric Measure Theory and Its Applications (Code: SS 2A), Matthew Badger, University of Connecticut, and Christopher J. Bishop and Raanan Schul, Stony Brook University.

Graph Vulnerability Parameters and their Role in Network Analysis (Code: SS 16A), Michael Yatauro, Pennsylvania State University-Brandywine.

Holomorphic Dynamics (Code: SS 4A), Artem Dudko and Raluca Tanase, Stony Brook University.

Homogeneous Dynamics and Related Topics (Code: SS 12A), Dmitry Kleinbock, Brandeis University, and Han Li, Wesleyan University.

Invariants of Closed Curves on Surfaces (Code: SS 1A), Ara Basmajian, Hunter College and Graduate Center, City University of New York, and Moira Chas, Stony Brook University.

Mathematical General Relativity (Code: SS 3A), Lan-Hsuan Huang, University of Connecticut, Marcus Khuri, Stony Brook University, and Christina Sormani, Lehman College and City University of New York Graduate Center.

Mathematicians in Mathematics Education (Code: SS 8A), Lisa Berger, Stony Brook University, and Melkana Brakalova, Fordham University.

PDE Methods in Geometric Flows (Code: SS 5A), Mihai Baillesteanu, Central Connecticut State University, and Andrew Cooper, North Carolina State University.

Teichmüller Theory and Related Topics (Code: SS 6A), Sudeb Mitra and Dragomir Saric, Queens College of the City University of New York and City University of New York Graduate Center.

Topology and Combinatorics of Arrangements (In honor of Mike Falk) (Code: SS 14A), Daniel C. Cohen, Louisiana State University, and Alexander I. Suciu, Northeastern University.

Vertex Algebra and Related Algebraic and Geometric Structures (Code: SS 13A), Katrina Barron, University of Notre Dame, Antun Milas, State University of New York at Albany, and Jinwei Yang, University of Notre Dame.

Salt Lake City, Utah

University of Utah

April 9-10, 2016
Saturday – Sunday

Meeting #1119
Western Section
Associate secretary: Michel L. Lapidus
Announcement issue of Notices: January 2016
Program first available on AMS website: To be announced
Issue of Abstracts: Volume 37, Issue 2

Deadlines
For organizers: Expired
For abstracts: February 16, 2016

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/sectional.html.

Invited Addresses
- Daniel Bump, Stanford University, From Whittaker Functions to Quantum Groups.
- James McKernan, University of California, San Diego, Classification of algebraic varieties.
- Ravi Vakil, Stanford University, Cutting and pasting in algebraic geometry (Erdős Memorial Lecture).
- Stephanie van Willigenburg, University of British Columbia, Vancouver, An introduction to quasisymmetric Schur functions.

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 www.ams.org/cgi-bin/abstracts/abstract.pl.

- Algebraic Combinatorics (Code: SS 5A), Susanna Fishel, Arizona State University, Edward Richmond, Oklahoma State University, and Stephanie van Willigenburg, University of British Columbia.
- Algebraic Geometry (association with the Erdős Lecture by Ravi Vakil) (Code: SS 1A), Ravi Vakil, Stanford University, and Christopher Hacon and Karl Schwede, University of Utah.
- Automorphic Forms, Combinatorics and Representation Theory (Code: SS 6A), Anna Puskás, University of Alberta, Daniel Bump, Stanford University, Paul Gunnells,
Meetings & Conferences

University of Massachusetts Amherst, and Solomon Friedberg, Boston College.

CR Geometry and Partial Differential Equations in Complex Analysis (Code: SS 4A), Yuan Yuan, Syracuse University, and Yuan Zhang, Indiana University-Purdue University Fort Wayne.

Combinatorial and Computational Commutative Algebra and Algebraic Geometry (Code: SS 10A), Hirotachi Abo, University of Idaho, Zach Teitler, Boise State University, Jim Wolper, Idaho State University, and Alex Woo, University of Idaho.

Commutative Algebra (Code: SS 7A), Adam Boocher and Linquan Ma, University of Utah.

Descriptive Set Theory and its Applications (Code: SS 9A), Christian Rosendal, University of Illinois at Chicago, and Alexander Kechris, California Institute of Technology.

Extremal Problems in Graph Theory (Code: SS 8A), Andre Kundgen and Mike Picollelli, California State University San Marcos.

Fusion Categories and Topological Phases of Matter (Code: SS 11A), Paul Bruillard, Pacific Northwest National Laboratory, and Julia Plavnik, Texas A&M University.

Inverse Problems (Code: SS 2A), Hanna Makaruk, Los Alamos National Laboratory (LANL), and Robert Owczarek, University of New Mexico, Albuquerque and UNM, Los Alamos.

Representations of Reductive p-adic Groups (Code: SS 3A), Shiang Tang and Gordan Savin, University of Utah.

Topics in Probability (Code: SS 13A), Tom Alberts and Arjun Krishnan, University of Utah.

Topics in Stochastic Partial Differential Equations (Code: SS 12A), Jingyu Huang and Davar Khoshnevisan, University of Utah.

Fargo, North Dakota

North Dakota State University

April 16–17, 2016
Saturday – Sunday

Meeting #1120

Central Section
Associate secretary: Georgia Benkart
Announcement issue of Notices: February 2016
Program first available on AMS website: To be announced
Issue of Abstracts: Volume 37, Issue 2

Deadlines
For organizers: Expired
For abstracts: February 23, 2016

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/sectional.html.

Invited Addresses

Rodrigo Banuelos, Purdue University, Title to be announced.

Laura Matusevich, Texas A&M University, Title to be announced.

Jeff Viaclovsky, University of Wisconsin-Madison, 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 www.ams.org/cgi-bin/abstracts/abstract.pl.

Algebraic and Geometric Combinatorics (Code: SS 16A), Kevin Dilks and Jessica Striker, North Dakota State University.

Applications of Microlocal Analysis: Eigenfunctions and Dispersive PDE (Code: SS 20A), Hans Christianson and Jason Metcalfe, University of North Carolina.

Combinatorial Ideals and Applications (Code: SS 10A), Laura Matusevich and Christopher O’Neill, Texas A&M University.

Commutative Algebra and Its Interactions with Combinatorics and Algebraic Geometry (Code: SS 4A), Susan Cooper, North Dakota State University, and Adam Van Tuyl, McMaster University.

Commutative Ring Theory (Code: SS 6A), Catalin Ciuperca and Sean Sather-Wagstaff, North Dakota State University.

Contemporary Issues in Mathematics Education (Code: SS 8A), Abraham Ayebo, North Dakota State University.

Convexity and Harmonic Analysis (Code: SS 2A), Maria Alfonseca-Cubero, North Dakota State University, and Dmitry Ryabogin, Kent State University.

Discrete Probability (Code: SS 9A), Jonathon Peterson, Purdue University, and Arnab Sen, University of Minnesota.

Dynamics, Inverse Semigroups, and Operator Algebras (Code: SS 15A), Benton Duncan, North Dakota State University, and David Pitts, University of Nebraska-Lincoln.

Ergodic Theory and Dynamical Systems (Code: SS 1A), Dogan Comez, North Dakota State University, and Mrinal Kanti Roychowdhury, University of Texas Rio Grand Valley.

Extremal Graph Theory (Code: SS 13A), Michael Ferrara and Stephen Hartke, University of Colorado Denver.
Meetings & Conferences

Frames, Harmonic Analysis, and Operator Theory (Code: SS 7A), **Gabriel Picioroaga**, University of South Dakota, and **Eric Weber**, Iowa State University.


Integrable Dynamical Systems and Special Functions (Code: SS 5A), **Oksana Bihun**, University of Colorado, Colorado Springs.

Interactions with Algebraic Geometry (Code: SS 19A), **Julie Rana** and **Kaisa Taipale**, University of Minnesota.

Low Dimensional and Symplectic Topology (Code: SS 12A), **Anar Akhmedov**, University of Minnesota, and **Josef G. Dorfmeister**, North Dakota State University.

Mathematical Finance (Code: SS 3A), **Indranil SenGupta**, North Dakota State University.

Matrix and Operator Theory (Code: SS 14A), **Shaun Fallat** and **Douglas Farenick**, University of Regina.

Probabilistic and Extremal Combinatorics (Code: SS 17A), **Jonathan Cutler**, and **Jamie Radcliffe**, University of Nebraska-Lincoln.

Probability and Complex Analysis Inspired by Schramm and Loewner (Code: SS 21A), **Michael Kozdron**, University of Regina.

Topological and Smooth Dynamics (Code: SS 18A), **Azer Akhmedov** and **Michael Cohen**, North Dakota State University.

Brunswick, Maine

Bowdoin College

September 24–25, 2016
Saturday – Sunday

Meeting #1121

Eastern Section

Associate secretary: Steven H. Weintraub
Announcement issue of Notices: June 2016
Program first available on AMS website: July 27, 2016
Issue of Abstracts: Volume 37, Issue 3

Deadlines

For organizers: February 24, 2016
For abstracts: July 19, 2016

Invited Addresses

**Tim Austin**, New York University, *Title to be announced*.
**Moon Duchin**, Tufts University, *Title to be announced*.
**Thomas Lam**, University of Michigan, *Title to be announced*.

Denver, Colorado

University of Denver

October 8–9, 2016
Saturday – Sunday

Meeting #1122

Western Section

Associate secretary: Michel L. Lapidus
Announcement issue of Notices: August 2016
Program first available on AMS website: To be announced
Issue of Abstracts: Volume 37, Issue 3

Deadlines

For organizers: March 8, 2016
For abstracts: August 16, 2016

The scientific information listed below may be dated. For the latest information, see [www.ams.org/amsmtgs/sectional.html](http://www.ams.org/amsmtgs/sectional.html).

Invited Addresses

**Henry Cohn**, Microsoft Research, New England, *Title to be announced*.
**Ronny Hadani**, University of Texas, Austin, *Title to be announced*.
**Chelsea Walton**, Temple University, Philadelphia, *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 [www.ams.org/cgi-bin/abstracts/abstract.pl](http://www.ams.org/cgi-bin/abstracts/abstract.pl).

**Algebraic Logic** (Code: SS 1A), **Nick Galatos**, University of Denver, and **Peter Jipsen**, Chapman University.
**Analysis on Graphs and Spectral Graph Theory** (Code: SS 2A), **Paul Horn** and **Mei Yin**, University of Denver.
**Nonassociative Algebra** (Code: SS 3A), **Izabella Stuhl**, University of Debrecen and University of Denver, and **Petr Vojtěchovský**, University of Denver.
**Noncommutative Geometry and Fundamental Applications** (Code: SS 4A), **Frederic Latremoliere**, University of Denver.
Operator Algebras and Applications (Code: SS 5A), Alvaro Arias, University of Denver.

Recent Trends in Semigroup Theory (Code: SS 6A), Michael Kinyon, University of Denver, and Ben Steinberg, City College of New York.

Set Theory of the Continuum (Code: SS 7A), Natasha Dobrinen and Daniel Hathaway, University of Denver.

Unimodularity in Randomly Generated Graphs (Code: SS 8A), Florian Sobieczky, University of Denver.

Vertex Algebras and Geometry (Code: SS 9A), Andrew Linshaw, University of Denver, and Thomas Creutzig, University of Alberta.

Zero Dimensional Dynamics (Code: SS 10A), Nic Ormes and Ronnie Pavlov, University of Denver.

Minneapolis, Minnesota

University of St. Thomas

October 28–30, 2016

Friday – Sunday

Meeting #1123

Central Section

Associate secretary: Georgia Benkart

Announcement issue of Notices: August 2016

Program first available on AMS website: To be announced

Issue of Abstracts: Volume 37, Issue 4

Deadlines

For organizers: March 22, 2016
For abstracts: August 30, 2016

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/sectional.html.

Invited Addresses

Thomas Nevins, University of Illinois Urbana-Champaign, Title to be announced.

Charles Rezk, University of Illinois Urbana-Champaign, Title to be announced.

Christof Sparber, University of Illinois at Chicago, Title to be announced.

Samuel Stechmann, University of Wisconsin-Madison, Title to be announced.

Raleigh, North Carolina

North Carolina State University at Raleigh

November 12–13, 2016

Saturday – Sunday

Meeting #1124

Southeastern Section

Associate secretary: Brian D. Boe

Announcement issue of Notices: September 2016

Program first available on AMS website: To be announced

Issue of Abstracts: Volume 37, Issue 4

Deadlines

For organizers: April 12, 2016
For abstracts: September 13, 2016

The scientific information listed below may be dated. For the latest information, see www.ams.org/amsmtgs/sectional.html.

Invited Addresses

Ricardo Cortez, Tulane University, Title to be announced.

Jason Metcalfe, University of North Carolina at Chapel Hill, Title to be announced.

Agnes Szanto, North Carolina State University, 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 www.ams.org/cgi-bin/abstracts.abstract.pl.

(Code: SS 1A), Alina Iacob and Saeed Nasseh, Georgia Southern University.
Meetings & Conferences

Atlanta, Georgia

Hyatt Regency Atlanta and Marriott Atlanta Marquis

January 4–7, 2017
Wednesday – Saturday

Meeting #1125

Joint Mathematics Meetings, including the 123rd Annual Meeting of the AMS, 100th Annual Meeting of the Mathematical Association of America, 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, with sessions contributed by the Society for Industrial and Applied Mathematics (SIAM).

Associate secretary: Brian D. Boe
Announcement issue of Notices: October 2016
Program first available on AMS website: To be announced
Issue of Abstracts: Volume 38, Issue 1

Deadlines
For organizers: April 1, 2016
For abstracts: To be announced

Charleston, South Carolina

College of Charleston

March 10–12, 2017
Friday – Sunday

Meeting #1126

Southeastern Section

Associate secretary: Brian D. Boe
Announcement issue of Notices: To be announced
Program first available on AMS website: To be announced
Issue of Abstracts: To be announced

Deadlines
For organizers: November 10, 2016
For abstracts: To be announced

Bloomington, Indiana

Indiana University

April 1–2, 2017
Saturday – Sunday

Meeting #1127

Central Section

Associate secretary: Georgia Benkart
Announcement issue of Notices: To be announced
Program first available on AMS website: To be announced
Issue of Abstracts: To be announced

Deadlines
For organizers: To be announced
For abstracts: To be announced

Pullman, Washington

Washington State University

April 22–23, 2017
Saturday – Sunday

Meeting #1128

Western Section

Associate secretary: Michel L. Lapidus
Announcement issue of Notices: To be announced
Program first available on AMS website: To be announced
Issue of Abstracts: To be announced

Deadlines
For organizers: To be announced
For abstracts: To be announced

New York, New York

Hunter College, City University of New York

May 6–7, 2017
Saturday – Sunday

Meeting #1129

Eastern Section

Associate secretary: Steven H. Weintraub
Announcement issue of Notices: To be announced
Program first available on AMS website: To be announced
Issue of Abstracts: To be announced
Meetings & Conferences

Deadlines
For organizers: September 14, 2016
For abstracts: March 21, 2017

Montréal, Quebec Canada

McGill University
July 24–28, 2017
Monday – Friday

Meeting #1130
The second Mathematical Congress of the Americas (MCA 2017) is being hosted by the Canadian Mathematical Society (CMS) in collaboration with the Pacific Institute for the Mathematical Sciences (PIMS), the Fields Institute (FIELDS), Le Centre de Recherches Mathématiques (CRM), and the Atlantic Association for Research in the Mathematical Sciences (AARMS).

Associate secretary: Brian D. Boe
Announcement issue of Notices: To be announced
Program first available on AMS website: To be announced
Issue of Abstracts: To be announced

Deadlines
For organizers: July 31, 2016
For abstracts: To be announced

Buffalo, New York

State University of New York at Buffalo
September 16–17, 2017
Saturday – Sunday
Eastern Section

Associate secretary: Steven H. Weintraub
Announcement issue of Notices: To be announced
Program first available on AMS website: To be announced
Issue of Abstracts: To be announced

Deadlines
For organizers: February 14, 2017
For abstracts: To be announced

Riverside, California

University of California, Riverside
November 4–5, 2017
Saturday – Sunday
Western Section

Associate secretary: Michel L. Lapidus
Announcement issue of Notices: To be announced
Program first available on AMS website: To be announced
Issue of Abstracts: To be announced

Deadlines
For organizers: To be announced
For abstracts: To be announced

San Diego, California

San Diego Convention Center and San Diego Marriott Hotel and Marina
January 10–13, 2018
Wednesday – Saturday

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
Meetings & Conferences

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

Issue of Abstracts: To be announced

Deadlines

For organizers: April 1, 2017
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 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: Michael Lapidus

Announcement issue of Notices: October 2020

Program first available on AMS website: November 1, 2020

Issue of Abstracts: To be announced

Deadlines

For organizers: April 1, 2020
For abstracts: To be announced

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: Brian D. Boe

Announcement issue of Notices: October 2020

Program first available on AMS website: November 1, 2020

Issue of Abstracts: To be announced

Deadlines

For organizers: April 1, 2020
For abstracts: To be announced
Meetings and Conferences of the AMS

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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 in the table of contents 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. Up-to-date meeting and conference information can be found at [www.ams.org/meetings/](http://www.ams.org/meetings/).

### Meetings:

#### 2015
- **November 14–15**: New Brunswick, New Jersey p. 1414

#### 2016
- **January 6–9**: Seattle, Washington Annual Meeting p. 1415
- **March 5–6**: Athens, Georgia p. 1419
- **March 19–20**: Stony Brook, New York p. 1420
- **April 9–10**: Salt Lake City, Utah p. 1421
- **April 16–17**: Fargo, North Dakota p. 1422
- **September 24–25**: Brunswick, Maine p. 1423
- **October 8–9**: Denver, Colorado p. 1423
- **October 28–30**: Minneapolis, Minnesota p. 1424
- **November 12–13**: Raleigh, North Carolina p. 1424

#### 2017
- **January 4–7**: Atlanta, Georgia Annual Meeting p. 1425
- **March 10–12**: Charleston, South Carolina p. 1425
- **April 1–2**: Bloomington, Indiana p. 1425
- **April 22–23**: Pullman, Washington p. 1425
- **May 6–7**: New York, New York p. 1425
- **July 24–28**: Montréal, Quebec, Canada p. 1426
- **September 16–17**: Buffalo, New York p. 1426

#### 2018
- **January 10–13**: San Diego, California Annual Meeting p. 1426
- **November 4–5**: Riverside, California p. 1426

#### 2019
- **January 16–19**: Baltimore, Maryland Annual Meeting p. 1427

#### 2020
- **January 15–18**: Denver, Colorado Annual Meeting p. 1427

#### 2021
- **January 6–9**: Washington, DC Annual Meeting p. 1427

### Important Information Regarding AMS Meetings

Potential organizers, speakers, and hosts should refer to page 200 in the February 2015 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](http://www.ams.org/meetings/) is necessary to submit an electronic form, although those who use [LaTeX] may submit abstracts with such coding, and all math displays and similarly coded material (such as accent marks in text) must be typeset in [LaTeX]. Visit [www.ams.org/cgi-bin/abstracts/abstract.pl](http://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.

### Conferences in Cooperation with the AMS

(See [www.ams.org/meetings/](http://www.ams.org/meetings/) for the most up-to-date information on these conferences.)

**December 16–19, 2015**: Amrita School of Engineering hosts the International Conference on Graph Theory and its Applications, Tamil Nadu, India (For further information see [https://www.amrita.edu/site/icgta15/](https://www.amrita.edu/site/icgta15/).)
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</tbody>
</table>

AMS Short Course: Rigorous Numerics in Dynamics (1/4-1/5)

<table>
<thead>
<tr>
<th>AMS Short Course: Rigorous Numerics in Dynamics (1/4-1/5)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Member of AMS</td>
<td>US$ 110</td>
</tr>
<tr>
<td>Nonmember</td>
<td>US$ 165</td>
</tr>
<tr>
<td>Student, Unemployed, Emeritus</td>
<td>US$ 58</td>
</tr>
</tbody>
</table>

MAA Minicourses (see listing in text)

I would like to attend: ☐ One Minicourse ☐ Two Minicourses Please enroll me in MAA Minicourse(s) #______ and #______ Price: US$ 85 for each minicourse. (For more than 2 minicourses, call or email the MMSB.) $______

Graduate School Fair

<table>
<thead>
<tr>
<th>Graduate School Fair</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Graduate Program Table</td>
<td>US$ 75</td>
</tr>
<tr>
<td>(includes table, posterboard &amp; electricity)</td>
<td>US$ 75</td>
</tr>
</tbody>
</table>

Receptions & Banquets

<table>
<thead>
<tr>
<th>Receptions &amp; Banquets</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Graduate Student/First-Time Attendee Reception (1/6) (no charge)</td>
<td></td>
</tr>
<tr>
<td>NAM Banquet (1/8) US$63</td>
<td>#______Chicken</td>
</tr>
<tr>
<td>#_____Kosher</td>
<td></td>
</tr>
<tr>
<td>AMS Dinner (1/9) Regular Price #_____US$ 69</td>
<td>Student Price #_____US$ 29</td>
</tr>
</tbody>
</table>
| (Additional fees may apply for Kosher meals.) | $______

Total for Registrations and Events $______

Payment

<table>
<thead>
<tr>
<th>Payment</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Registration &amp; Event Total (total from column on left)</td>
<td>$ __________</td>
</tr>
<tr>
<td>Hotel Deposit (only if paying by check)</td>
<td>$ __________</td>
</tr>
</tbody>
</table>

Total Amount To Be Paid $______

Method of Payment

☐ Check. Make checks payable to the AMS. For all check payments, please keep a copy of this form for your records.

☐ Credit Card. All major credit cards accepted. For your security, we do not accept credit card numbers by postal mail, email or fax. If the MMSB receives your registration form by fax or postal mail, it will contact you at the phone number provided on this form. For questions, contact the MMSB at mmsb@ams.org.

Signature: ____________________________

☐ Purchase Order # ____________________________ (please enclose copy)

Other Information

Mathematical Reviews field of interest ____________________________

☐ I am willing to serve as a judge for the MAA Undergraduate Student Poster Session

☐ For planning purposes for the MAA Two-year College Reception, please check if you are a faculty member at a two-year college.

☐ I am a mathematics department chair.

☐ Please do not include my name and postal address on any promotional mailing lists. (The JMM does not share email addresses.)

☐ Please do not include my name on any list of JMM participants other than the scientific program if I am, in fact, making a presentation that is part of the meeting.

☐ Please ✓ this box if you have a disability requiring special services.

Deadlines

<table>
<thead>
<tr>
<th>Deadlines</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Eligible for the complimentary room drawing:</td>
<td>Nov. 2, 2015</td>
</tr>
<tr>
<td>Nov. 17, 2015</td>
<td></td>
</tr>
<tr>
<td>Housing reservations, changes/cancellations</td>
<td>Dec. 14, 2015</td>
</tr>
<tr>
<td>through the JMM website:</td>
<td>Dec. 22, 2015</td>
</tr>
<tr>
<td>Advance registration for the Joint Meetings, short course, minicourses, and tickets:</td>
<td>Jan. 2, 2016*</td>
</tr>
<tr>
<td>50% refund on banquets, cancel by</td>
<td>Dec. 31, 2015*</td>
</tr>
<tr>
<td>50% refund on advanced registration, minicourses, and short course, cancel by</td>
<td></td>
</tr>
<tr>
<td>*no refunds issued after this date</td>
<td></td>
</tr>
</tbody>
</table>

Mailing Address/Contact:

Mathematics Meetings Service Bureau (MMSB)

P. O. Box 6887

Providence, RI 02940-6887 Fax: 401-455-4004 Email: mmsb@ams.org

Telephone: 401-455-4144 or 1-800-321-4267 x4144 or x4137
2016 Joint Mathematics Meetings Hotel Reservations – Seattle, WA

(Please see the hotel page in the announcement or on the web for detailed information on each hotel.) To ensure accurate assignments, please rank hotels in order of preference by writing 1, 2, 3, etc. in the column on the left and by circling the requested bed configuration. If your requested hotel and room type is no longer available, you will be assigned a room at the next available comparable rate. Please call the MMSB for details on suite configurations, sizes, availability, etc. All reservations, including suite reservations, must be made through the MMSB to receive the JMM rates. Reservations made directly with the hotels before December 14, 2015 may be changed to a higher rate. All rates are subject to applicable local and state taxes in effect at the time of check-in; currently 15.6% state tax PLUS an additional US$2 per night for travel and tourism tax. Guarantee requirements: First night deposit by check (add to payment on reverse of form) or a credit card guarantee.

- Deposit enclosed (see front of form)
- Hold with my credit card. For your security, we do not accept credit card numbers by postal mail, email or fax. If the MMSB receives your registration form by postal mail or fax, we will contact you at the phone number provided on the reverse of this form.

Date and Time of Arrival __________________________ Date and Time of Departure __________________________ Number of adult guests in room ____________ Number of children ____________

Name of Other Adult Room Occupant(s) __________________________ Arrival Date ____________ Departure Date ____________

Housing Requests: (example: rollaway cot, crib, nonsmoking room, low floor)

- I have disabilities as defined by the ADA that require a sleeping room that is accessible to the physically challenged. My needs are: __________________________
- I am a member of a hotel frequent-travel club and would like to receive appropriate credit. The hotel chain and card number are: __________________________
- I am not reserving a room. I am sharing with __________________________, who is making the reservation.

<table>
<thead>
<tr>
<th>Order of choice</th>
<th>Hotel</th>
<th>Single</th>
<th>Double 1 bed-2 people</th>
<th>Double 2 beds-2 people</th>
<th>Triple 3 adults-2 beds</th>
<th>Quad 4 adults-2 beds</th>
<th>Rollaway Cot Fee (add to special requests if reserving online)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sheraton Seattle (headquarters)</td>
<td>US$ 166</td>
<td>US$ 166</td>
<td>US$ 166</td>
<td>US$ 191</td>
<td>US$ 216</td>
<td>Rollaways available only in king-bedded rooms at no charge</td>
</tr>
<tr>
<td></td>
<td>Deluxe Rate</td>
<td>US$ 186</td>
<td>US$ 186</td>
<td>US$ 186</td>
<td>US$ 211</td>
<td>US$ 236</td>
<td>Rollaways available only in king-bedded rooms only for a nightly charge of US$15</td>
</tr>
<tr>
<td></td>
<td>Club Level</td>
<td>US$ 206</td>
<td>US$ 206</td>
<td>US$ 206</td>
<td>US$ 231</td>
<td>US$ 256</td>
<td>Rollaways available only in king-bedded rooms for a one-time $15 fee</td>
</tr>
<tr>
<td></td>
<td>Student Rate</td>
<td>US$ 124.50</td>
<td>US$ 124.50</td>
<td>US$ 124.50</td>
<td>US$ 149.50</td>
<td>US$ 174.50</td>
<td>Rollaways available only in king-bedded rooms at no charge; sleeper sofas in some rooms</td>
</tr>
<tr>
<td></td>
<td>Grand Hyatt</td>
<td>US$ 159</td>
<td>US$ 159</td>
<td>US$ 159</td>
<td>US$ 184</td>
<td>US$ 209</td>
<td>Rollaways available only in king-bedded rooms at no charge</td>
</tr>
<tr>
<td></td>
<td>Student Rate</td>
<td>US$ 125</td>
<td>US$ 125</td>
<td>US$ 125</td>
<td>US$ 150</td>
<td>US$ 175</td>
<td>Rollaways available only in king-bedded rooms at no charge</td>
</tr>
<tr>
<td></td>
<td>Fairmont Olympic Hotel Seattle</td>
<td>US$ 152</td>
<td>US$ 152</td>
<td>US$ 152</td>
<td>US$ 182</td>
<td>US$ 212</td>
<td>Rollaways available only in king-bedded rooms only for a nightly charge of US$15</td>
</tr>
<tr>
<td></td>
<td>The Westin Seattle</td>
<td>US$ 139</td>
<td>US$ 139</td>
<td>US$ 139</td>
<td>US$ 169</td>
<td>US$ 199</td>
<td>Rollaways available only in king-bedded rooms at no charge</td>
</tr>
<tr>
<td></td>
<td>Student Rate</td>
<td>US$ 104</td>
<td>US$ 104</td>
<td>US$ 104</td>
<td>US$ 134</td>
<td>US$ 164</td>
<td>Rollaways available only in king-bedded rooms at no charge</td>
</tr>
<tr>
<td></td>
<td>Renaissance Seattle Hotel</td>
<td>US$ 139</td>
<td>US$ 139</td>
<td>US$ 139</td>
<td>US$ 159</td>
<td>US$ 179</td>
<td>Rollaways available only in king-bedded rooms at no charge</td>
</tr>
<tr>
<td></td>
<td>Student Rate</td>
<td>US$ 129</td>
<td>US$ 129</td>
<td>US$ 129</td>
<td>US$ 149</td>
<td>US$ 169</td>
<td>Rollaways available only in king-bedded rooms at no charge</td>
</tr>
<tr>
<td></td>
<td>The Paramount Hotel Seattle</td>
<td>US$ 130</td>
<td>US$ 130</td>
<td>US$ 130</td>
<td>US$ 150</td>
<td>US$ 170</td>
<td>Rollaways available only in king-bedded rooms at no charge</td>
</tr>
<tr>
<td></td>
<td>Student Rate</td>
<td>US$ 120</td>
<td>US$ 120</td>
<td>US$ 120</td>
<td>US$ 140</td>
<td>US$ 160</td>
<td>Rollaways available only in king-bedded rooms at no charge</td>
</tr>
<tr>
<td></td>
<td>Hyatt Olive 8 Seattle</td>
<td>US$ 125</td>
<td>US$ 125</td>
<td>US$ 125</td>
<td>US$ 150</td>
<td>US$ 175</td>
<td>Rollaways available only in king-bedded rooms at no charge</td>
</tr>
<tr>
<td></td>
<td>The Inn at the Washington Athletic Club</td>
<td>US$ 125</td>
<td>US$ 125</td>
<td>US$ 125</td>
<td>US$ 145</td>
<td>US$ 165</td>
<td>Rollaways are extremely limited, inquire directly with the MMSB</td>
</tr>
<tr>
<td></td>
<td>Crowne Plaza Seattle Downtown</td>
<td>US$ 125</td>
<td>US$ 125</td>
<td>US$ 125</td>
<td>US$ 145</td>
<td>US$ 165</td>
<td>Rollaways available only in king-bedded rooms for a one-time $25 fee</td>
</tr>
<tr>
<td></td>
<td>Student Rate</td>
<td>US$ 115</td>
<td>US$ 115</td>
<td>US$ 115</td>
<td>US$ 135</td>
<td>US$ 155</td>
<td>Sofa beds are available in all rooms</td>
</tr>
<tr>
<td></td>
<td>The Roosevelt Hotel</td>
<td>US$ 120</td>
<td>US$ 120</td>
<td>US$ 120</td>
<td>US$ 140</td>
<td>US$ 160</td>
<td>Sofa beds are available in all rooms</td>
</tr>
</tbody>
</table>

People interested in suites should contact the MMSB directly by email at mmsb@ams.org or by calling 800-321-4267, ext. 4137 or 4144 (401-455-4137 or 401-455-4144).
Open hours:
Wednesday, January 6, 8:00 a.m. - 5:30 p.m.
Thursday, January 7, 8:00 a.m. - 5:30 p.m.
Friday, January 8, 8:00 a.m. - 5:30 p.m.
Saturday, January 9, 9:00 a.m. - noon

Visit www.ams.org/emp-reg for registration instructions.
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Barry Simon, California Institute of Technology, Pasadena, CA

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