Fall 2013

EMISSARY

Mathematical Sciences Research Institute

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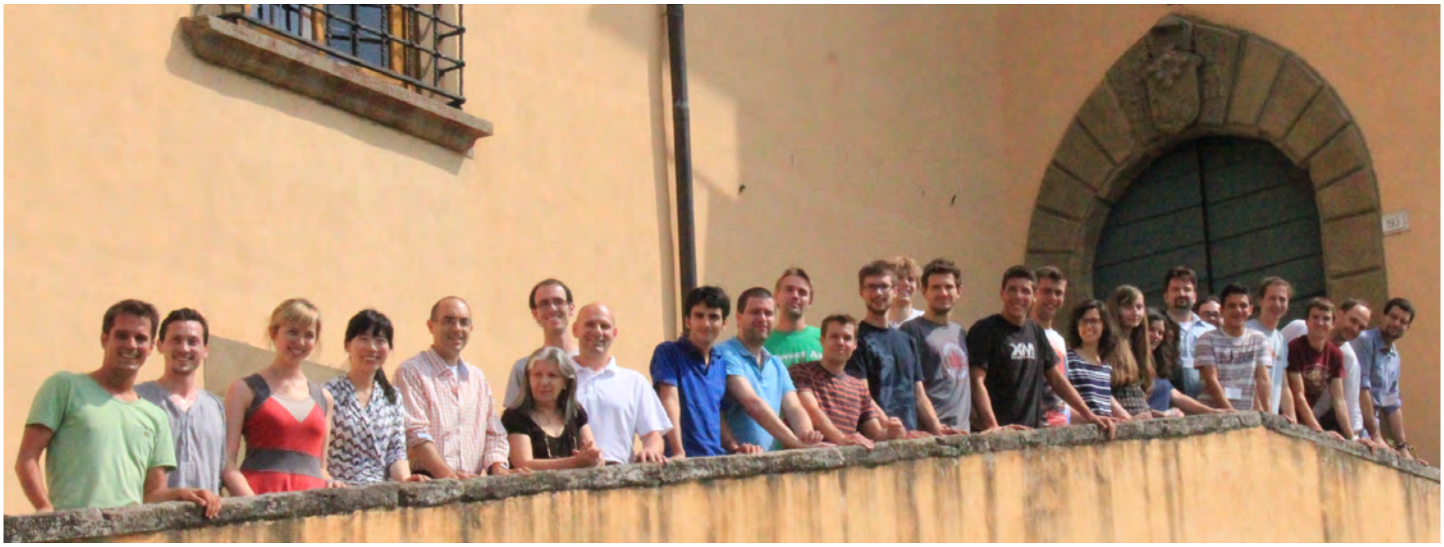


Participants in the 2013 summer school on mathematical general relativity, held in Cortona, Italy (see page 11).

Constancy in Change

David Eisenbud, Director

> . . . die Gunst der Musen
> Unvergängliches verheißt:
> Den Gehalt in deinem Busen
> Und die Form in deinem Geist.
>
> — J.W. von Goethe, from “Dauer im Wechsel”

On August 1, I succeeded Robert Bryant as Director of MSRI. We — the mathematical sciences community — owe Robert a great debt for his six years of devoted service, maintaining and further developing MSRI’s scientific reputation, solidifying its management systems, and obtaining a million-dollar increase in the NSF budget. The continued growth in the number of academic sponsors, the superb scientific programs, and most recently, the excellent reviews of an NSF site committee, all attest to his success.

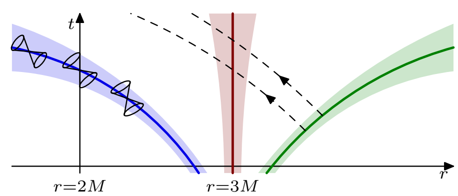
The two fall programs, Optimal Transport and Mathematical General Relativity, planned under Robert’s leadership, are up and running; the semester is off to an excellent start. Perhaps most telling of the health in which Robert left MSRI are the glowing “exit surveys” of members — it seems that for the great majority a stay at MSRI is highly prized and highly productive of new collaborations and learning.

I would translate the fragment of the poem quoted above as:

> . . . the grace of the Muses
> Holds eternal:
> The meaning in your breast
> And the form in your spirit.

This might (with apologies to Goethe) be a romantic view of mathematicians and mathematics! Though MSRI is less eternal than the poem’s subject, it, too, keeps its focus.

(continued on page 2)



Dynamics of null geodesic flow for a Schwarzschild black hole. For more on the GR program, see page 3.

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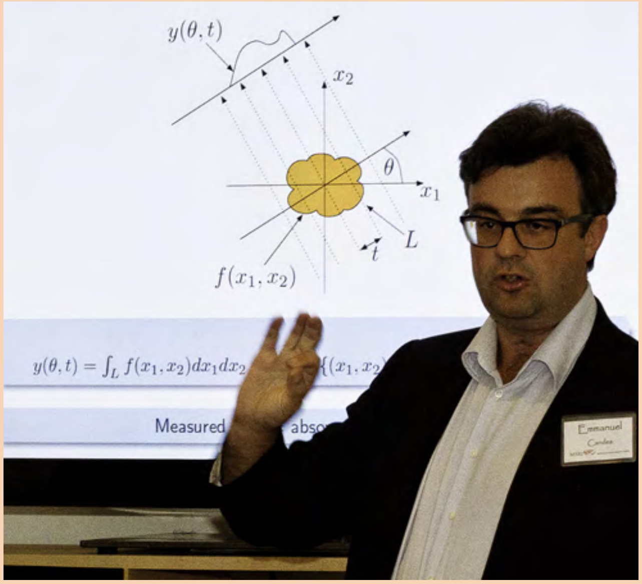


Xiomara Castro

Emmanuel Candès addresses Museion.

Museion Spring Dinner

On April 4, 2013, a Museion event was held in San Francisco, California, at Goodby, Silverstein & Partners, an award winning advertising agency. Jeff Goodby, co-founder, is a member of MSRI's Board of Trustees.

Professor Emmanuel Candès, Barnum-Simons Chair in Mathematics and Statistics at Stanford University, gave the lecture "Advancing medicine by progress in mathematics: The case of magnetic resonance imaging in pediatrics." The lecture was followed by a lively discussion and elegant dinner.

Archimedes Society members who make annual unrestricted contributions of $5,041 or more to MSRI are invited to become Museion members and are invited to the special Museion dinner/lecture series held in the Bay Area and in New York. The 2012–2013 Museion members are recognized in the list of MSRI donors on page 13.

A Word from the Director

(continued from page 1)

Even as Directors come and go, MSRI exists to foster mathematical research and the public's understanding of it.

"Why Did You Take This Job?"

It is surprising to me how frequently I am asked this question. I imagine this partly reflects an awareness of how big the job is — there are always administrative and financial matters that need attention as well as the core scientific planning — and partly the strongly held view of many in the math community that the only proper activity for a mathematician is research.

The truth is that I very much enjoyed my two terms as Director of MSRI from 1997 to 2007. The intense scientific activity around the institute, and the enthusiasm of the mathematical sciences community is very exciting! I took great pleasure in helping plan the programs, in gathering resources for them, and in personally working with organizers and members to make the programs fruitful. I was also glad to help connect the MSRI community with the challenge of teaching mathematics to schoolchildren, both through Math Circles and through workshops on math education. A further pleasure was in helping develop the many events for the public that MSRI sponsored over those 10 years, from the hilarious evening performance of Steve Martin, Robin Williams, and Bob Osserman ("Funny Numbers"), to the serious public conversations that Bob held with luminaries such as Tom Stoppard and Michael Frayne, to the big event on climate change held just at the end of my tenure. I did some mathematics I am proud of, too.

Irving Kaplansky, MSRI's second director, who had been chair at the University of Chicago (and one of my teachers there), once said to me, "Being Director of MSRI is like being chair of a very large math department that has no faculty." Put less flippantly: MSRI has significant resources to encourage science and great flexibility to execute good ideas.

Resources, and Why MSRI Has Them

The continuing generosity of the Simons Foundation has recently augmented MSRI's resources. As the Foundation does for the Kavli Institute of Theoretical Physics, it will begin to provide MSRI with substantial long-term funding. This will help address some building issues and bring more great researchers to MSRI. A further grant will enable MSRI to increase the national scope of its program for the public understanding of mathematics.

These new grants not only show the amazing reach of the Simons Foundation in supporting mathematics, they also underline the effectiveness of the NSF Institute model. NSF support since 1982, when MSRI first opened its programs, has put MSRI in a position to attract significant private funding; the two sources complement each other wonderfully. The partnership makes MSRI robust.

I believe that the most important factor convincing the NSF and the private sector to fund MSRI is support from the mathematical sciences community itself. One manifestation of this support is mathematicians' desire to attend and organize programs at MSRI; this has never been stronger. Financial support from MSRI's academic sponsors and from individual mathematicians and educators is also a very important sign.

Making MSRI function as community property was one of the terrific ideas of the founders, Shiing-Shen Chern, Calvin Moore, and Isadore Singer. Though no institution is eternal, that idea will help the institute maintain its vibrancy and usefulness for a very long time.

Mathematical General Relativity

Carla Cederbaum and Semyon Dyatlov

This fall's semester program in Mathematical General Relativity (GR) brings together researchers using various methodologies for attacking different questions within the scope of mathematical GR. At the heart of our subject lie the *Einstein equations*:

$$\mathrm{Ric} - \frac{1}{2} R g + \Lambda g = \frac{8\pi G}{c^4} T.$$

These couple the energy-momentum tensor T — capturing the matter content of the system — to the geometry of the spacetime. The geometry is modeled by a 4-dimensional Lorentzian metric g, a mathematical object from which we compute the curvature of the spacetime (see the figure below). Only the averaged curvature terms, like the Ricci tensor Ric and the scalar curvature R, enter the equations. Λ is the cosmological constant, c the speed of light, and G Newton's gravitational constant. Roughly speaking, the Einstein equations state that "matter tells spacetime how to curve, and spacetime tells matter how to move" (John Wheeler).

David Darling

The curvature of a spacetime S at an event $p \in S$ can be understood as the 4D analog of the limit of the quotient (excess of sum of interior angles in triangles $\triangle$ around p)/(area of $\triangle$) as the triangles shrink to p.

In coordinates, the Einstein equations are a system of non-linear second order degenerate hyperbolic PDEs for the components of the unknown metric g. Surprisingly, the equations do not immediately have the form of an initial value or evolution problem — as do most other dynamical equations from physics. In other words, it is not straightforward how to determine the time evolution of a relativistic system such as a star, a black hole, or a galaxy from its initial state (that is, its initial position and momentum). A major breakthrough was achieved in 1952 by Yvonne Choquet-Bruhat (profiled on page 5), who reformulated the equations as an initial value problem and proved local existence and uniqueness of solutions to the Einstein equations. Her result made it possible to systematically study

- general relativistic cosmology, the study of the universe as a whole;
- black holes and gravitational waves;
- long-time behavior such as dynamical stability;
- geometric and analytic properties of initial states solving so-called constraint equations;
- numerical algorithms modeling astrophysical systems (for example, neutron star and black hole binaries);
- the relationship with Newton's theory of gravity.

In the following, we sketch some examples of the various faces of contemporary research in mathematical GR.

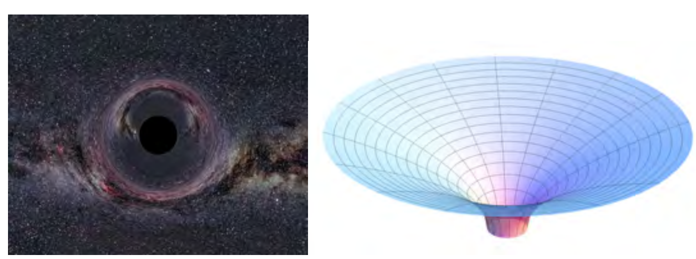
Constraint Equations: Initial States in GR

An initial state in GR is modeled by a 3-dimensional Riemannian manifold (M^3, h) ("position") and an additional symmetric $(0,2)$-tensor field K ("momentum") as well as initial matter and momentum densities ρ and J related to the energy-momentum tensor T. (M^3, h) must isometrically embed into its Lorentzian spacetime "future" while K arises as the second fundamental form of the embedding. Surprisingly, initial states must satisfy *constraint equations*

$$R_h + (\mathrm{tr}K)^2 - |K|^2 - 2\Lambda = \frac{16\pi G}{c^2}\rho,$$
$$\mathrm{div}(K - \mathrm{tr}K\, h) = -\frac{8\pi G}{c^4} J,$$

which are obtained by combining the Einstein equations with the Gauss–Codazzi equations. To model time evolution of astrophysical systems mathematically or numerically, we thus need to first find adequate solutions of the constraint equations. These are studied intensely both numerically — often using Newtonian systems as a starting point — and analytically, mainly with methods from conformal geometry and elliptic PDEs; see Bartnik and Isenberg's review arXiv:gr-qc/0405092.

Splitting off the constraint equations, the Einstein equations can be represented as pure time evolution describing all later states of a given system. All of those later states automatically also satisfy the constraint equations. Hence, many mathematical and physical questions about relativistic systems are formulated in terms of initial "data" (M^3, h, K, ρ, J) solving the constraint equations. While cosmology focuses on initial states modeling our entire universe, so-called asymptotically flat initial states receive a lot of attention as they model isolated systems such as stars, black holes, or galaxies; see the figure below.



Ute Kraus, Axel Mellinger; AllenMcC

Astrophysical picture and Schwarzschild's mathematical model of a black hole (initial state).

Black hole initial states are often modeled by asymptotically flat initial data containing marginally outer trapped surfaces (horizons), a generalization of minimal surfaces. They have very interesting geometric and analytic properties; see Andersson, Eichmair and Metzger's review arXiv:1006.4601.

Many recent results take the form of inequalities between physical and geometric properties of initial data. The first breakthrough was the positive mass theorem proved in 1981 by Schoen and Yau, and by Witten. They used minimal surface and spinor techniques, respectively, to prove that physically reasonable systems have nonnegative total mass. The (Riemannian, that is, $K = 0$) Penrose inequality, which bounds the total mass of any system with black holes from below by the surface area of the black hole horizons, was proved in 2001 by Huisken and Ilmanen, and by Bray. Both proofs use parabolic geometric evolution equations, namely extrinsic and intrinsic curvature flows, respectively. The general case ($K \neq 0$) of the Penrose inequality remains open; see Mars's review arXiv:0906.5566.

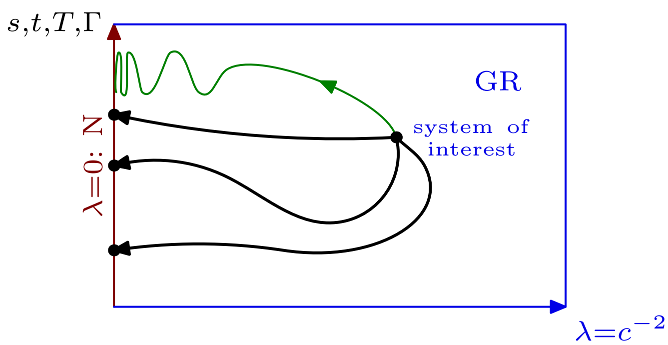
In recent years, Dain et al. have proven an inequality relating the angular momentum of axisymmetric black holes to the surface area of their horizons. They use methods from the calculus of variations and from harmonic maps; see the upcoming Living Review by Cederbaum, Dain, and Gabach-Clément.

Geometric Modeling and the Newtonian Limit

In defining physical quantities in mathematical GR, we necessarily rely on Newtonian ideas. For example, Arnowitt, Deser, and Misner's 1962 definition of the total mass m of an isolated system imitates the fall-off behavior of the Newtonian potential

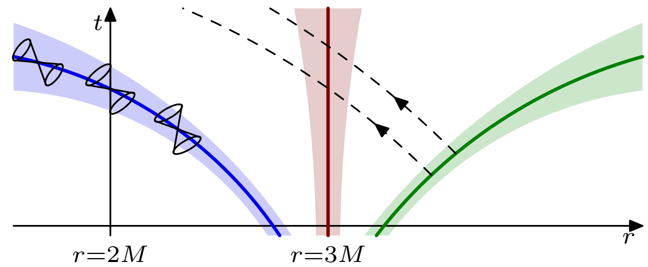
$$U = -\frac{mG}{r} + \mathcal{O}\left(\frac{1}{r^2}\right)$$

and other more abstract ideas from Hamiltonian mechanics. They also use an understanding of total mass in special cases such as the Schwarzschild and Kerr black holes. (See the Hyperbolic Equations section.) Moreover, they geometrize the definition to make it independent of choices of coordinates.



A frame theory picture of families tending (black) and not tending (green) to a Newtonian limit as $\lambda \downarrow 0$. The parameters s, t, T, Γ generalize g, T in GR and U, ρ in Newtonian gravity.

As our definitions claim physical relevance, it is important to rigorously investigate whether they capture what they are intended to capture. In the case of total mass, independence of coordinates was proved in the 1980s by Bartnik and by Chruściel. The positive mass theorem (see the Constraint Equations section) ensures that the total mass is always non-negative, and zero only in vacuum and in the absence of black holes, in support of the definition.



Dynamics of the null geodesic flow on Schwarzschild, showing cases a, b, and c (blue, green, and red, respectively). The shading illustrates the "blur out." The dashed arrows illustrate the "tail" effect of case b.

It is expected that total relativistic mass "converges" to Newtonian mass "in the Newtonian limit": the mass of a relativistic system should be well approximated by the mass of a "similar" Newtonian system if the speeds and masses in the system are small compared to the speed of light c. A first result was obtained for static (non-dynamical, non-rotating) isolated systems; see arXiv:1201.5433 (Cederbaum): whenever a family of static isolated relativistic systems, parametrized by $\lambda = c^{-2}$, tends to a Newtonian limit, that is, a static isolated Newtonian system, as $\lambda \downarrow 0$, then $\lim_{\lambda\downarrow 0} m(\lambda) = m_N$, where m_N is the mass of the limit; see the "frame theory" figure at left.

Rigorous Newtonian limit results are proved within Ehlers' frame theory, a generalization of semi-Riemannian geometry unifying Newtonian gravity and GR; again, see the "frame theory" figure. Ehlers, Rendall, Oliynyk et al. obtained rigorous existence results for families possessing a Newtonian limit for fluids, dust, etc.

Hyperbolic Equations: Dynamics of GR

We now discuss some of the dynamical properties of solutions to the Einstein equations. This requires us to go beyond the local existence theorem of Choquet-Bruhat and to understand whether solutions may develop singularities at some finite time t, and if not, what is the asymptotic behavior of g as $t \to \infty$?

We concentrate here on a single aspect: dynamical stability under perturbations, a property required for any physically observable solution. We focus on the stability of the Kerr family of metrics, modeling rotating black holes. The dynamical stability conjecture for Kerr states that, if an initial state is sufficiently close to a Kerr initial state, then its evolution exists for all times and rings down (that is, converges as $t \to +\infty$ in a specific way) to some other member of the Kerr family. Understanding ringdown will provide information about black holes as ringdown accompanies gravitational waves. Such waves should soon be observable by detectors such as aLIGO.

So far, dynamical stability has been proved for the Minkowski spacetime (also known as special relativity), by Christodoulou and Klainerman in 1993. The difficulty of the stability analysis arises from the complicated nature of the Einstein equations. A starting point is to understand the long time behavior of solutions to the initial value problem for the linear wave equation

$$\Box_g u = 0, \quad u|_{t=0} = f_0, \; \partial_t u|_{t=0} = f_1$$

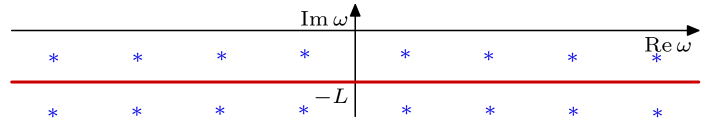
on a curved background spacetime with metric g. Here, $\Box_g$ denotes the d'Alembert–Beltrami operator, generalizing the wave operator $\partial_t^2 - \Delta_x$ to the curved spacetime setting.

At high frequencies, solutions u to this wave equation approximately travel along null geodesics γ (light rays). However, as $t \to \infty$, they *'blur out'* to neighboring null geodesics. As $t \to \infty$, one of the following phenomena occurs (note that here, we specialize to the Schwarzschild black hole):

(a) γ crosses the event horizon $\{r = 2M\}$, the boundary of the black hole region, at some time t_0. The causal structure at the event horizon (see the light cones in the figure at the top of the previous page) implies that γ never returns to the physically observable region, and the corresponding waves u are zero in that region after time t_0.

(b) γ escapes to spatial infinity, $r \to \infty$, and its escape takes infinite time. Waves u traveling along γ will radiate at low frequency in all directions, producing a "tail" that decays only polynomially in t.

(c) γ is trapped, that is, forever tangent to the photon sphere $\{r = 3M\}$. However, light rays close to γ do escape via (a) or (b); the "blur out" effect thus ensures that the corresponding waves decay exponentially in t.



Schwarzschild–de Sitter QNMs approximately lie on a lattice determined by the geometry of the photon sphere; see arXiv:1305.4603 (Dyatlov and Zworski).

Taken together, (a)–(c) assert polynomial decay of waves u in t, which was rigorously established for the Kerr family in the past ten years by a concerted effort of the community; see Dafermos and Rodnianski's review arXiv:1010.5137.

For modifications of the Kerr family in which case (b) does not occur (such as the Kerr–de Sitter family with $\Lambda > 0$), a quantitative description of decay is given by the following resonance expansion: for each $L > 0$,

$$u(t,x) = \sum_{\operatorname{Im}\omega_j > -L} e^{-it\omega_j} u_j(x) + \mathcal{O}(e^{-Lt}),$$

where $\{\omega_j\} \subset \mathbb{C}$ is a discrete set of frequencies, called quasi-normal modes (QNMs) and studied extensively in the physics literature because of their connection to gravitational waves; see the figure above and the Living Review by Kokkotas and Schmidt.

Focus on the Scientist: Yvonne Choquet-Bruhat

James Isenberg

Sixty-one years ago, Yvonne Choquet-Bruhat essentially invented the field of mathematical general relativity (GR). While a number of explicit solutions of the Einstein gravitational field equations had already been found, it was only after Yvonne's proof in 1952 of the well-posedness of Einstein's equations that GR became a topic of serious mathematical interest. In this epic work, published as her Thèse d'Etat when she was 28, Yvonne showed that if certain geometric fields representing the initial state of the gravitational field are chosen to satisfy constraint equations, then there is always a spacetime solution of the full system of Einstein's equations that is compatible with the initial state data set, representing its future and its past.

Yvonne Choquet-Bruhat

Yvonne's career since then has been one of remarkable achievement. In mathematical GR, she has made groundbreaking advances in the study of solutions of the Einstein constraint equations as well as in the analysis of the evolution of initial data into spacetime solutions of the Einstein field equations. A key aspect of Yvonne's work is its development of new mathematical tools as well as its invention of new approaches to applying these tools to problems of interest.

Besides her work in mathematical GR, Yvonne has made major contributions in her work on wave maps, spinor fields, supergravity, and fluid dynamics. She has published well over 200 research papers as well as three major research books. Her production continues to be strong, even after her 1992 "retirement" from her position as professor at Université Pierre-et-Marie-Curie (Paris VI). Since 2009, she has written 8 papers, has completed her wonderful 700-page monograph "General Relativity and the Einstein Equations" (Oxford University Press), and is now finishing another monograph on GR.

Among her wide range of distinguished honors, Yvonne became the first woman member of the Academie des Sciences de Paris in 1979. She has also been appointed Grand Officier de la Légion d'Honneur and Grand Croix de l'Ordre National du Mérite. She is an honorary member of the American Academy of Arts and Sciences and the Moscow Mathematical Society.

In the midst of her very long list of major honors and achievements, it is important to note that Yvonne is one of the warmest, kindest, and most approachable people I know. I look forward to her 90th birthday celebration in January at IHES.

Outreach Highlights from Spring/Summer 2013

Alissa S. Crans

Critical Issues in Mathematics Education

The tenth annual Critical Issues in Mathematics Education (CIME) workshop took place at MSRI this past April 3–5 (www.msri.org/workshops/696). The CIME workshops engage professional mathematicians in discussions with education researchers, teachers, and policy makers to improve mathematics education.

The 2013 workshop — organized by Mark Thames (University of Michigan), Kristin Umland (University of New Mexico), Noah Heller (Math for America), and Alan Schoenfeld (UC Berkeley) — explored the fundamental problems of trying to assess students' mathematical proficiency, seeking to take a more comprehensive perspective on what it is to learn, know, and use mathematics.

The advent of the Common Core State Standards both increases the demand and broadens the conception of what it is to be mathematically skillful, and so opens new opportunities and challenges to improving our ability to assess what students understand and can do. In keeping with CIME goals, participants were recruited from communities of mathematicians, K–12 teachers, and mathematics education researchers, in roughly equal numbers. The extensive involvement of Math for America teachers, a co-sponsor of this year's workshop, proved particularly successful.

MSRI-UP participants for 2013

MSRI-UP 2013

The seventh annual MSRI-Undergraduate Program (MSRI-UP) took place at MSRI June 15–July 28, 2013, under the leadership of the on-site director Ivelisse Rubio (University of Puerto Rico-Río Piedras) and co-directors Duane Cooper (Morehouse College), Ricardo Cortez (Tulane University), Herbert Medina (Loyola Marymount University), and Suzanne Weekes (Worcester Polytechnic Institute). The academic and research portion was led by Rosa Orellana (Dartmouth College), who provided the students with intensive training and directed the research in Algebraic Combinatorics.

MSRI-UP (www.msri.org/msri_ups/701) gives talented students, especially those from underrepresented groups, meaningful research opportunities in mathematics. It is also designed to give them the skills and knowledge necessary to participate in successful collaborations, as well as a community of academic peers and mentors who can advise, encourage and support them as they pursue graduate studies. Eighteen students from universities in nine different states, Puerto Rico, and the District of Columbia participated in the 2013 program.

This year's program resulted in six technical reports and an equal number of oral presentations in the Student Colloquium Series. Fourteen of the eighteen MSRI-UP students will present their research at the annual SACNAS Conference at San Antonio, Texas, in October 2013. We expect that many of the students will present their research at the Joint Mathematics Meetings in Baltimore in January of 2014.

The CIME workshops are generously supported by the National Science Foundation and Math for America. MSRI-UP receives generous support from the National Security Agency and the National Science Foundation.

CME Group–MSRI Prize in Innovative Quantitative Applications

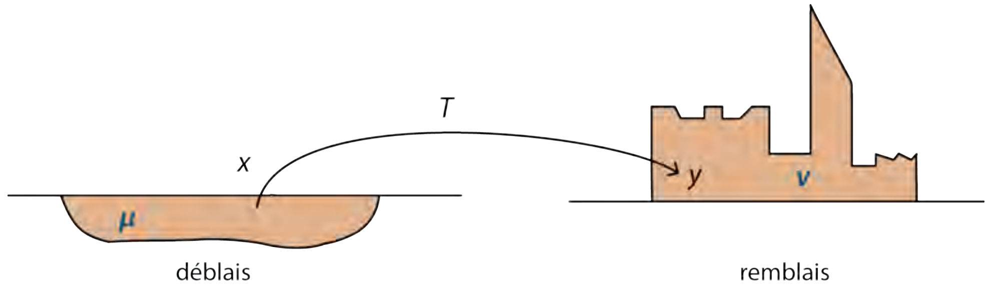
Bengt Holmstrom

The 8th annual CME Group-MSRI Prize in Innovative Quantitative Applications was awarded to Bengt Holmstrom on October 21 in Chicago. Dr. Holmstrom is the Paul A. Samuelson Professor of Economics at the Massachusetts Institute of Technology with a joint appointment in MIT's Sloan School of Management. Dr. Holmstrom has made many breakthroughs in the study of incentive conflicts in organizations, and he has also developed important insights into the supply of and demand for liquidity and liquid assets.

The annual CME Group-MSRI Prize recognizes 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. Three past winners subsequently won the Nobel prize! Read more about the prize at www.msri.org/general_events/20419.

Optimal Transport

Cédric Villani



The Monge–Kantorovich optimal transport problem: Which is the best way to rearrange matter from a prescribed initial distribution of mass (the déblais, in Monge's terminology, captured by a probability measure μ) to a prescribed final distribution (the remblais, probability measure ν) so as to minimize the total transport cost?

A certain day of summer 1998, reading a set of lecture notes by Ledoux, I learnt of an inequality relating optimal transport and entropy, which had been proven by Talagrand. I was intrigued, because I knew both notions from different points of view.

In those days, all of my mathematical work was related to Boltzmann's entropy in one way or the other. If ρ is a probability density on a probability space (X,ν), its entropy $S(\rho)$ is the negative of $H_\nu(\rho) = \int \rho \log \rho \, d\nu$. This functional is of tantamount importance in statistical mechanics, in relation with the notion of molecular chaos, but also in Shannon's information theory, Sanov's large deviation principle, or Nash's famous proof of the continuity of solutions of nonsmooth diffusions.

Optimal transport, on the other hand, tells about how much energy one has to spend to rearrange a given configuration of matter into another one. If μ and ν are two probability measures on a Polish space X, and $c(x,y)$ is the energy needed to transport one unit of mass from position x to position y, then the associated optimal transport cost is

$$C(\mu,\nu) = \inf\left\{ \int c(x,y)\,\pi(dx\,dy); \quad x_\#\pi = \mu,\ y_\#\pi = \nu \right\};$$

here π is a probability measure on $X \times X$, and I have abused notation by writing x for the map $(x,y) \to x$ — so $x_\#\pi$ is the first projection or first marginal of π, and similarly $y_\#\pi$ is the second marginal. Optimal transport has been used for a long time in statistics, economics, and statistical physics.

Now Talagrand's inequality states this: if γ is the standard Gaussian measure on $\mathbb{R}^n$, and $c(x,y) = |x-y|^2$ is the squared Euclidean distance, then for any probability density ρ on $(\mathbb{R}^n, \gamma)$,

$$C(\rho\gamma, \gamma) \leqslant 2 H_\gamma(\rho).$$

Developing an idea of Marton, Talagrand used his inequality to deduce strong results about concentration of measure. I was hooked by Ledoux's vivid account of this multi-faceted story.

It turns out that a few weeks before, I had met Felix Otto, who in a conference had presented a way to endow the space of probability measures with a formal Riemannian structure, in such a way that the cost functional C would be the square of the geodesic distance, and the gradient flow for the H functional would be the linear Fokker–Planck equation.

It suddenly occurred to me that Otto's formalism could be adapted to this situation, and lead to a new proof of the Talagrand inequality, based on the logarithmic Sobolev inequality, $\int \rho \log \rho \, d\gamma \leqslant (1/2) \int |\nabla \log \rho|^2 \rho \, d\gamma$. This inspiration was the start of all my works on optimal transport: I was now caught in the motion of a field which was evolving fast under the action of Brenier, McCann, Gangbo, Caffarelli, Evans... Otto and I wrote a joint article relating logarithmic Sobolev and Talagrand inequalities: this is now the most quoted of my papers, not so much for its results, as for the connection between functional inequalities, optimal transport, and Ricci curvature, which later would turn out to be more powerful than any of us, back at the turn of the millennium, could think of.

Already by the end of the 1990s, there was so much going on and so much to say! The Kantorovich duality: how to devise price functions best adapted to the minimization cost? Can one geometrically characterize the best way to match the x's and y's? Is this given by a mapping $y = T(x)$, and if yes, can one characterize T and establish its smoothness? What is the topology induced by the transport cost? How to gradually transform one configuration of matter into another one, at lowest cost (action)? What are the underlying geometric partial differential equations? How to encode geometric inequalities (Sobolev, isoperimetric, Brunn–Minkowski, concentration...) in terms of transport cost? How does optimal transport enrich our understanding of diffusion equations? How is it influenced by curvature? The field of optimal transport was being transformed by the contributions of many researchers, and even more would join later.

Some of the ramifications of the theory resulted in unexpected, striking applications outside the field of optimal transport. Let me give a short partial list of such issues, which have been driving some of the courses and lectures of the MSRI semester this fall.

Entropic Propagation of Chaos

Kac in the fifties introduced the following toy model for the evolution of large systems of colliding particles: let $(v_1, \ldots, v_N)$ be a random N-tuple of real-valued "velocities," such that the average kinetic energy $N^{-1} \sum v_i^2/2$ is equal to $1/2$. Every time a Poisson clock of time scale $1/N$ rings, pick up a random pair (i,j), a random angle θ with distribution law β, and change (v_i, v_j) for $(v_i', v_j') = R_\theta(v_i, v_j)$, where R_θ is the rotation of angle θ. If the particles are initially chaotic, or "nearly independent," then as $N \to \infty$, the distribution of one particle, say v_1, approaches a solution of the

Kac–Boltzmann equation

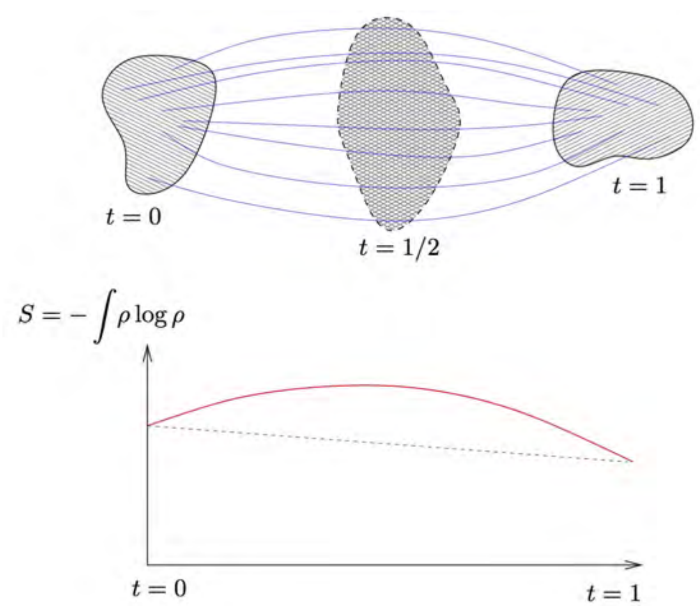
$$\frac{\partial f}{\partial t} = \int_{\mathbb{R}} \int_0^{2\pi} \beta(\theta)[f \otimes f(R_\theta(v,w)) - f(v)f(w)]\, d\theta\, dw.$$

Can one relate the microscopic mean entropy per particle to the limit entropy? In other words, if $f_t^n(v_1,\dots,v_N)$ is the law of $(v_1,\dots,v_N)$ at time t, and σ^N is the uniform distribution on $\mathbb{S}^{N-1}(\sqrt{2N})$, is it true that $N^{-1}\int f_t^n \log f_t^n \, d\sigma^N \longrightarrow H_\gamma(f_t)$? This problem was eventually solved by Mischler and Mouhot, using among other ingredients an information-theoretic interpolation inequality, involving optimal transport and entropy: if ν is log concave, then for any probability density f on $(\mathbb{R}^d, \nu)$,

$$H_\nu(\rho) \leqslant \sqrt{C(\rho\nu,\nu)} \sqrt{\int \frac{|\nabla f|^2}{f}\, d\nu}.$$

Stability of the Shape of the Cut Locus

Let x be a point in a compact manifold M. The tangent cut locus at x is the pre-image of the cut locus by the exponential map; in other words, this is the set of velocities v such that the geodesic curve $(\exp_x(tv))$, issued from x with initial velocity v, is minimizing only up to $t = 1$. The cut locus is notoriously unstable and nonsmooth, especially in presence of focalization and positive curvature. However, the following unexpected stability property holds: *If the sphere $\mathbb{S}^n$ is equipped with a metric g which is close enough, in C^4 topology, to the round metric, then all tangent cut loci are boundaries of uniformly convex sets.* To prove this, Rifford, Figalli, and I strongly relied on a curvature condition introduced by Ma–Trudinger–Wang for the study of the smoothness of optimal transport.



The Lazy Gas experiment: To detect the property of nonnegative Ricci curvature, impose that the gas goes from a given initial configuration to a final configuration in an optimal way (in particular, particles follow geodesic curves) and check that Boltzmann's entropy is always a concave function of time along the process.

Quantitative Isoperimetric Rigidity

If $\|\cdot\|$ is a norm on $\mathbb{R}^n$, let us write $V(A) = \mathcal{H}^n[A]$ and $S(\partial A) = \int_{\partial A} \|\omega(x)\|_* \mathcal{H}^{n-1}(dx)$, where $\mathcal{H}^s$ is the s-dimensional Hausdorff measure and ω is the outer normal vector (when it exists). Wulff's isoperimetric inequality states that for any ball B,

$$V(A) = V(B) \quad \Longrightarrow \quad S(\partial A) \geqslant S(\partial B),$$

and equality can hold only if A itself is essentially a ball. Figalli–Maggi–Pratelli refined this with a sharp reminder term:

$$S(\partial A) \geqslant \inf_{V(B)=V(A)} S(\partial B) \left[1 + c_n \left(\frac{V(A\Delta B)}{V(B)}\right)^2\right],$$

where Δ stands for symmetric difference and B varies in the set of all balls. The proof was strongly based on optimal transport, refining a strategy of Gromov.

Curved Brunn–Minkowski Inequality

The Brunn–Minkowski inequality reads $V(A+B)^{1/n} \geqslant V(A)^{1/n} + V(B)^{1/n}$, where A and B are arbitrary compact sets in $\mathbb{R}^n$ and $A + B = \{a + b,\ a \in A,\ b \in B\}$. This celebrated inequality has a number of geometric consequences. A Riemannian generalization was discovered by Cordero-Erausquin, McCann and Schmuckenschläger: if M is an n-dimensional Riemannian manifold with nonnegative Ricci curvature, and V now stands for volume measure, then for any two compact sets A and B in M,

$$V(m(A,B))^{\frac{1}{n}} \geqslant \frac{V(A)^{\frac{1}{n}} + V(B)^{\frac{1}{n}}}{2},$$

where $m(A,B)$ is the set of midpoints of A and B, that is, points which are located halfway between a point in A and a point in B. This curved Brunn–Minkowski inequality is based on the study of the volume occupied by a gas which starts uniformly distributed in A, and is optimally transported so as to end up uniformly distributed in B.

Synthetic theory of Ricci Curvature Bounds

Synthetic theories are those which eventually rely on properties rather than computations. For instance, Alexandrov's theory captures the property of nonnegative sectional curvature by requiring that any triangle has medians which are longer than those of an isometric Euclidean triangle — rather than computing the curvature and its sign. This theory makes sense in nonsmooth geodesic spaces, and has been widely studied. Around 2005, Lott, Sturm, and I introduced the foundations of a synthetic theory of Ricci curvature lower bounds, based on the evolution of entropy-type functionals in an energy-minimizing rearrangement.

For instance, one will say that a metric-measure space (X, d, ν) has nonnegative Ricci curvature (in the weak sense) if, for any two probability densities ρ_0 and ρ_1 on (X,ν), there is an action-minimizing path $(\rho_t)_{0\leqslant t\leqslant 1}$ such that $H_\nu(\rho_t) \leqslant (1-t)H_\nu(\rho_0) + tH_\nu(\rho_1)$ for all $t \in [0,1]$.

With this definition and its variants, one can define nonsmooth notions of lower bound on the Ricci curvature (and upper bound on the effective dimension), which lead to useful geometric inequalities, and are stable under the topology of measured Gromov–Hausdorff convergence. Petrunin has shown this notion of curvature bound to be compatible with Alexandrov's theory, and Ambrosio–Gigli–Savaré have shown that this condition allows one to construct a well-behaved heat flow, obtained as the gradient flow of H_ν.

Thus Otto's intuition from the end of the nineties turned out to be the working heart of the construction of a heat flow in the most general setting that one can think of! Ambrosio–Gigli–Savaré have also explored what happens to this synthetic theory when one adds the "Riemannian" assumption that the Sobolev space $W^{1,2}(X, d, \nu)$ (of functions with a square-integrable "gradient") is Hilbert; then, strikingly, one can develop all the core of classical Ricci curvature bounds (linear Laplace operator, splitting theorem, heat kernel estimates, cone curvature bounds, Bochner formula, etc.). This will be one of the many directions of discussion this fall at MSRI!

Four New Staff Members Join MSRI; One Returns

Arthur Bossé has been Operations Manager at MSRI since February. Before working at MSRI, Arthur worked in the behavioral health field, starting out as a front line addictions counselor until finding his niche in administration. He became Executive Director of a mid-size nonprofit in 2000. Arthur moved to San Francisco 17 years ago from Rhode Island with his partner of 22 years. He is a former nightclub disc jockey and shares and sells honey, lip balm, and candles that he makes from the beeswax produced in his apiary.


Arthur Bossé

Jacari Scott joins MSRI as the Scholar Services Coordinator, after having previously served as the Workshop Assistant during the summer. Jacari comes to us after a six-year stay at Nova Development, a software company where she worked as Office Manager and utilized her strong organizational and communication skills in order to ensure her team's success. She is a Bay Area native who loves to cook, travel, and spend quality time with her daughters, aged seven and thirteen.


Jacari Scott

Chelsea Whitman joins MSRI as the temporary Outreach Assistant for the Director. Before coming to MSRI, Chelsea was the director of an after school program in West Oakland elementary schools, where she focused on bringing in college students to improve the quality of education for local children. She also worked as a writing tutor on campus and assisted incoming freshmen with their transition to Cal through teaching in the Summer Bridge program. Chelsea is a San Diego native and currently lives in Oakland.


Chelsea Whitman

Mark Howard is the new Administrative and Facilities Coordinator. Prior to joining MSRI, Mark worked for several years at the Academy of Art University in San Francisco as the Business Operations Office Manager. Mark has developed a myriad of skills over the years working in various industries, from mortgage banking and securities to social services and architecture. Outside of work Mark enjoys traveling, hiking, and biking, and is an avid patron of the arts.


Mark Howard


Alaina Moore

Alaina Moore has rejoined MSRI as the Assistant for Scientific Activities. She comes back after a brief hiatus, prior to which she worked from 2011–2013 as the MSRI's Program Assistant. Alaina is a Bay Area native and was heavily involved in the theater scene, having worked for eight years as a freelance technician for theatres such as the Berkeley Rep, Center Rep, and the Willows Theatre. She considers herself a "Microsoft Excel whisperer" and likes to experiment with bass guitar and programming languages in her free time.

Focus on the Scientist: Yann Brenier

Jan Maas

Yann Brenier is one of the organizers of the Optimal Transport: Geometry and Dynamics program that is taking place at MSRI during Fall 2013. Yann is also the current UC Berkeley Chancellor's Scholar (described in further detail at the end of the article).

Yann Brenier

Yann is a leading expert in the fields of partial differential equations, numerical analysis, and the mathematics of fluid mechanics and plasma physics. While his research is strongly driven by physical applications, Yann obtained fundamental mathematical breakthroughs that continue to inspire mathematicians in many fields. Since any attempt to give a complete overview of his work in this brief space is doomed to fail, we focus on some of his pioneering contributions to optimal transport.

At the end of the 1980s, while working on the numerical analysis of incompressible fluids, Yann was led to consider the problem of finding a projection operator onto the non-convex set of volume-preserving maps. He solved this problem by proving a beautiful polar factorization theorem, which generalizes the classical Helmholtz decomposition theorem: every vector-valued map can be written as the gradient of a convex function composed with a volume-preserving transformation. As a byproduct, Yann solved the Monge problem of optimal mass transport. This seminal result constituted the most significant breakthrough on optimal transport since the development of Kantorovich's duality theory in 1942. It can be regarded as the starting point of the modern theory of optimal transport, which has become a vibrant research area.

Over the years, Yann discovered remarkable extensions of optimal transport with applications to relativistic heat equations and nonlinear electromagnetism. His recent work treats topology-preserving diffusion equations for divergence-free vector fields using optimal transport methods. Yann's work continues to have a deep impact in an increasingly broad range of applications ranging from image processing to density functional theory in quantum mechanics and robust hedging problems in mathematical finance.

Yann holds a CNRS position as *directeur de recherche* (senior researcher) at École Polytechnique in Paris. In 2005 he was awarded the Prix Petit-d'Ormoy of the French Academy of Sciences. He was an invited speaker at the International Congress of Mathematicians in 2002.

The UC Berkeley Chancellor's Scholarship award carries a purse of $50,000 and is open to nominees from MSRI only. Chancellor's Scholars must be top researchers and must also be known for excellent teaching. As a Chancellor's Scholar this semester, Yann is giving the Chancellor's Lecture Series entitled "Hidden convexity in nonlinear PDEs", a course which Berkeley graduate students may take for credit.

Forthcoming Workshops & Programs

Workshops

November 18–22, 2013: *Initial Data and Evolution Problems in General Relativity*, organized by Piotr Chruściel (Lead), Igor Rodnianski (Lead)

December 7–8, 2013: *Infinite-Dimensional Geometry*, organized by Lawrence Evans, Dmitry Jakobson, Robert McCann, Stephen Preston (Lead)

January 6–10, 2014: *Macaulay2 Workshop*, organized by Sonja Mapes, Frank Moore, David Swinarski

January 23–24, 2014: *Connections for Women: Algebraic Topology*, organized by Julia Bergner, Teena Gerhardt (Lead), Brooke Shipley

January 27–31, 2014: *Introductory Workshop: Algebraic Topology*, organized by Teena Gerhardt, Jesper Grodal, Kathryn Hess, Michael Hill (Lead)

February 3–7, 2014: *Introductory Workshop: Model Theory, Arithmetic Geometry and Number Theory*, organized by Elisabeth Bouscaren, Antoine Chambert-Loir, Rahim Moosa (Lead)

February 10–11, 2014: *Connections for Women: Model Theory and its Interactions with Number Theory and Arithmetic Geometry*, organized by Kirsten Eisentraeger, Julia Gordon, Deirdre Haskell

February 17–21, 2014: *Hot Topics: Perfectoid Spaces and their Applications*, organized by Sophie Morel, Peter Scholze, Richard Taylor (Lead), Jared Weinstein

March 26–28, 2014: *The Roles of Mathematics Departments and Mathematicians in the Mathematical Preparation of Teachers*

Programs

January 20–May 23, 2014: *Model Theory, Arithmetic Geometry and Number Theory*, organized by Ehud Hrushovski, François Loeser, David Marker, Thomas Scanlon, Sergei Starchenko, Carol Wood (Lead)

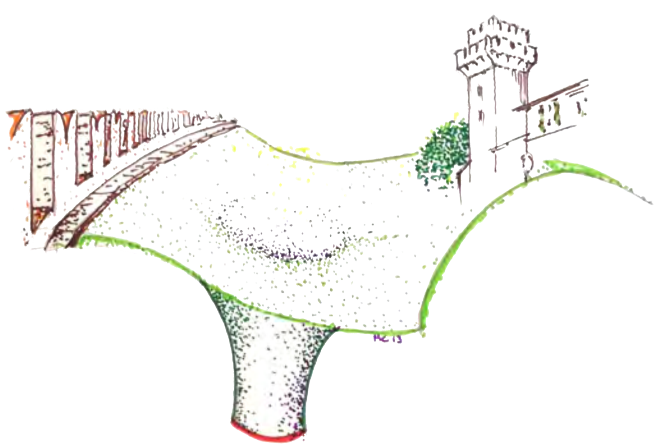
January 20–May 23, 2014: *Algebraic Topology*, organized by Vigleik Angeltveit, Andrew Blumberg, Gunnar Carlsson, Teena Gerhardt, Michael Hill (Lead), Jacob Lurie

For more information about any workshops or programs, please see www.msri.org/scientific.

INdAM, CMI, and MSRI meet in Cortona for Summer School

Justin Corvino

For two weeks last summer, three institutes — Istituto Nazionale di Alta Matematica (INdAM) in Italy, the Clay Mathematical Institute (CMI), and MSRI — collaborated to create a vibrant summer school on mathematical general relativity. The workshop largely reprised the successful summer graduate school that was held on this topic at MSRI in 2012. The 2013 summer school was held in Cortona, Italy, at Il Palazzone, an elegant Renaissance villa set on a hillside overlooking the Val di Chiana. The villa was built in the early 16th century by Cardinal Silvio Passerini, and was donated, in 1968, by one of his descendants to the Scuola Normale Superiore di Pisa.



Mauro Carfora

The elegant (and relativistic) setting in Cortona.

This school marks the second such joint venture between MSRI and INdAM (following the 2011 workshop on Toric Varieties in Cortona) and the first one among the three institutes, Clay, INdAM and MSRI. The twenty-seven graduate students who attended the school represented institutions across Europe and the USA. Members of this international group of students were at various stages of their graduate careers with interests ranging from geometric analysis to physics.

The organizing team consisted of the lead scientific organizer Justin Corvino (Lafayette College) with invaluable assistance from Hélène Barcelo (MSRI) and Giorgio Patrizio (Firenze), along with Pengzi Miao (Miami), not to mention the tireless patience of Chris Marshall (MSRI) and Silvana Boscherini (Cortona), and further assistance from TAs Peter McGrath (Brown University) and Andrea Santi (Parma).

The school was structured much like the 2012 program at MSRI. There were two morning lectures and an afternoon lecture, followed by sessions for students, who worked hard in groups at solving problems. Toward the end of the first week, students were given a suite of research articles from which to choose one or two to study carefully and discuss with fellow students, TAs, and lecturers.

There were five lecturers: Justin Corvino gave background lectures on the Einstein equations, including the initial value formulation and an introduction to the geometry of isolated systems, followed by topics lectures on scalar curvature deformation and general relativity. Fernando Schwartz (Tennessee) lectured on the Penrose inequality, Michael Eichmair (ETH) on the isoperimetric structure of initial data sets, Lan-Hsuan Huang (Connecticut) on the center of mass and constant mean curvature of initial data sets, and Mauro Carfora (Pavia) on the space of metrics and the relation between the Einstein constraint equations and the Ricci flow.

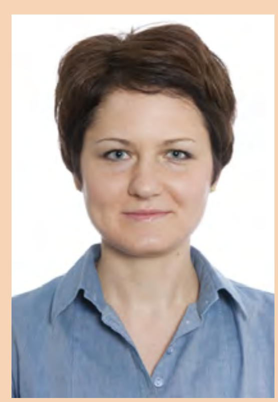
Thankfully the walls of Il Palazzone are made of thick stone, which helped to shield the students and lecturers from the intense summer heat. Participants shared meals together, as well as afternoon or evening walks up to the town of Cortona to enjoy ice cream (gelato) from the local gelaterie.

The school seems to have been a success. Students appreciated the coordination of the lectures, as well as the introductory material and problem sets. The students appeared to stay very engaged, despite the intense heat. Rumor has it that some students were still working problems on the train out of Cortona! One student noted "The lecturers fostered discussion and further thought, without being overbearing."

Viterbi Postdoc

Anna Sakovich, a member of the Mathematical General Relativity program, is the Fall 2013 Viterbi Endowed Postdoctoral Scholar. Anna did her undergraduate studies at the Belarusian State University in Minsk, Belarus. In the summer of 2007, she came to the Royal Institute of Technology in Stockholm, Sweden, for her doctoral studies, which she completed under the supervision of Mattias Dahl. Anna's work extensively expanded our knowledge of the asymptotically hyperbolic setting in general relativity; she has obtained results on solutions to the constraint equations, the notion of mass, and the Penrose inequality (for graphs).

The Viterbi Endowed Postdoctoral Scholarship is funded by a generous endowment from Dr. Andrew Viterbi. Dr. Viterbi is well known as the co-inventor of the Code Division Multiple Access (CDMA) based digital cellular technology and the Viterbi decoding algorithm, used in many digital communication systems. Dr. Viterbi is a member of the National Academy of Engineering, the National Academy of Sciences, and was a member of President Clinton's Information Technology Advisory Committee.



Anna Sakovich

Puzzles Column

Elwyn Berlekamp and Joe P. Buhler

One of us (EB) is involved in G4G (Gathering 4 Gardner) activities, including the upcoming eleventh such gathering in Atlanta in March 2014, and the many Celebrations of Mind around the world, including the one at MSRI on October 23, 2013. For details, see gathering4gardner.org. In this connection we start with three cryptarithms and a famous fact about shuffling.

		M	A	T	H
	M	A	G	I	C
+	G	4	G	1	1

		G	A	T	H	E	R
							4
	G	A	R	D	N	E	R
+	A	T	L	A	N	T	A
						0	N
			3	1	9	1	4

		G	A	T	H	E	R
							4
	G	A	R	D	N	E	R
+						0	N
			3	2	0	1	4
	A	T	L	A	N	T	A
						G	A

1. Solve the cryptarithms. All the usual rules apply (e.g., letters represent distinct digits), except that the solution is obviously not unique in one case. The "+" to the left of the summation line indicates that the terms above and below the line have the same sum.

2. A "perfect shuffle" of a deck with 52 cards begins by cutting the deck into two equal halves of 26 cards each, and the riffling them together (exactly) alternately. There are two choices for which card is dropped first: in the so-called out-shuffle the top and bottom cards remain on the top and bottom, and in the in-shuffle the bottom and top cards become the second-from-bottom and second-from-top respectively.

(a) Magicians know that after eight successive perfect out-shuffles the deck is returned to its original state. Find a simple explanation. (b) How many in-shuffles are needed to return the deck to its original position?

3. Let P be a convex polyhedron. A planar saw is used to cut off a tip of each vertex to create a new convex polyhedron with V vertices, E edges, and F faces. One of those numbers is equal to 1001. Find V, E, and F.

Comment: Due to Gregory Galperin.

4. A coordinated and well-rehearsed team of N players is outfitted with hats that might be either black or white. The distribution is completely random, and so all 2^N possibilities are equiprobable.

The players are lined up on a north/south line, all facing north, so that each can see only the hats in front of him or her. Then, starting from the southernmost player (who sees the hat color of everyone else), each player is asked to announce his "vote" as to the color of his hat. Everyone hears every vote, and the process continues northward until the northernmost player (who has heard all prior votes, but can't see any hats) votes. If there are V correct votes, then every player on the team receives V dollars.

What is the best strategy, and what is its expected value of V?

Comment: This is a charming instance of a "hat problem" that came up in conversation with Ashok Vaish, who was turned on to mathematics as an undergraduate at the Indian Institute of Technology, circa 1963, in a course taught there by Richard Guy (!).

5. You have 14 coins, dated 1901 through 1914. Seven of these coins are real and weigh 1 ounce each. The other seven are counterfeit and weigh 0.999 ounces each. You do not know which coins are real or counterfeit, and cannot tell which coins are real by look or feel.

Fortunately for you, Zoltar the Fortune-Weighing Robot is capable of making very precise measurements. You may place any number of coins in each of Zoltar's two hands and Zoltar will do the following: (a) If the weights in each hand are equal, Zoltar tells you so and returns all of the coins. (b) If the weight in one hand is heavier than the weight in the other, then Zoltar takes one coin, at random, from the heavier hand as tribute; then Zoltar tells you which hand was heavier and returns the remaining coins to you.

Your objective is to identify a single real coin that Zoltar has not taken as tribute. Find a strategy that guarantees this in a minimum number of weighings.

Comment: Due to Jeremy Copeland, this question appeared on the 2001 Math Olympiad, and, more recently, in the online *Numberplay* New York Times blog.

Huneke Postdoc

Emanuel Indrei

Emanuel Indrei, a member of the Optimal Transport program, is the second recipient of a Huneke Postdoctoral Fellowship at MSRI. The Fellowship is funded by a generous endowment from Professor Craig Huneke, who is internationally recognized for his work in commutative algebra and algebraic geometry.

Emanuel completed his undergraduate studies at Georgia Tech in 2007 and received his Ph.D. in 2013 from the University of Texas at Austin under the direction of Alessio Figalli. In 2012, he was awarded a NSF EAPSI Fellowship to study with Neil Trudinger at the Mathematical Sciences Institute in Canberra, where he returned in the summer of 2013 as a Postdoctoral Fellow at the Australian National University. Emanuel has obtained important results in the context of geometric and functional inequalities (in particular a sharp stability result for the isoperimetric inequality inside convex cones) and strong regularity results on the free-boundaries arising in the optimal partial transport problem.

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Named for the recognition event to which its members are invited, Museion, "the Hall of the Muses," was Ptolemy I's institute at ancient Alexandria. Scholars came to study and advance science, and the adjacent library was said to be the greatest in the world at the time. Museion members are invited to the special Museion dinner/lecture series held in the Bay Area and in New York.

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Plato $1,922 to $5,040

Plato, in The Laws, suggested that a suitable number of citizens for the ideal city would be that number which contained the most numerous and most consecutive subdivisions. He decided on 5,040, a number with 59 divisors (apart from itself). For purposes of war and peace 5,040 citizens can be divided by any number from 1 to 10.

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Noether $1,730 to $1,921

1921 is the year of publication of Noether's "Idealtheorie in Ringbereichen" — a landmark paper ushering in the beginning of the field of Abstract Algebra, which became a dominant theme of 20th Century mathematics and flourishes into the 21st.

Anonymous donors

Ramanujan $730 to $1,729

1,729 is the number of Hardy's taxicab which, Ramanujan reflected from his sick bed, is the smallest number expressible as the sum of two cubes in two different ways.

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Cubic $258 to $729

729 is a number important to Plato, and a cube that is the sum of three cubes.

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Fermat $90 to $257

257 is a Fermat number, and is equal to 2 to the 2 to the 3 plus 1.

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Fibonacci $34 to $89

Both the upper and lower end of this range are Fibonacci Numbers. 34 is also the magic constant of a 4 by 4 magic square.

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Call for Proposals

All proposals can be submitted to the Director or Deputy Director or any member of the Scientific Advisory Committee with a copy to proposals@msri.org. For detailed information, please see the website www.msri.org.

Thematic Programs

Letters of intent and proposals for semester or year long programs at the Mathematical Sciences Research Institute (MSRI) are considered in the fall and winter each year, and should be submitted preferably by **October 15** or **December 15**. Organizers are advised that a lead time of several years is required, and are encouraged to submit a letter of intent prior to preparing a pre-proposal. For complete details see http://tinyurl.com/msri-progprop.

Hot Topics Workshops

Each year MSRI runs a week-long workshop on some area of intense mathematical activity chosen the previous fall. Proposals for such workshops should be submitted by **October 15** or **December 15**. See http://tinyurl.com/msri-htw.

Summer Graduate Schools

Every summer MSRI organizes four 2-week long summer graduate workshops, most of which are held at MSRI. To be considered for the summer of year n, proposals should be submitted by **October 15** or **December 15** of year $n-2$. See http://tinyurl.com/msri-sgs.

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