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Courant Newsletter

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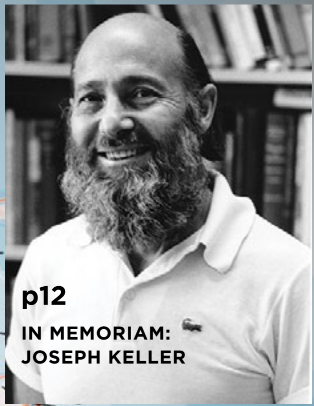

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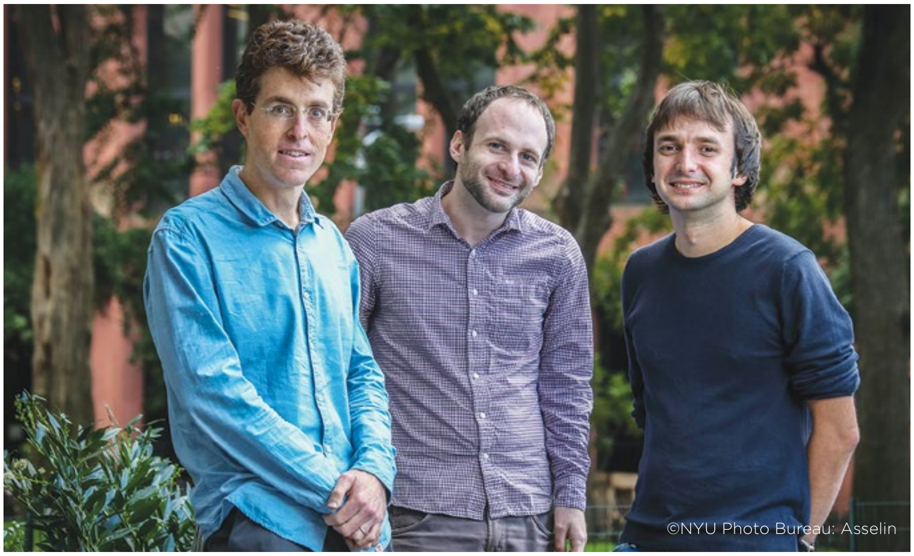
Encryption for a post-quantum world
With Oded Regev

by April Bacon



(From left to right) Oded Regev with Ph.D. students Noah Stephens-Davidowitz and Alexander (Sasha) Golovnev.

Oded Regev established a landmark lattice-based encryption system, which could help keep the internet secure in a post-quantum computing world.

Oded Regev has been fascinated by lattices ever since they were first introduced to him in the final semester of his Ph.D. program at Tel Aviv University, fifteen years ago. A lattice is "a regular arrangement of points in space, as formed by atoms in a crystal, when packing oranges in a crate, or by a honeycomb in a beehive," explains Oded, who has been a Professor of Computer Science at the Institute for four years. Lattices first became a subject of mathematical inquiry in some early work in number theory in the 19th century. The real foundation, though, was built in the early 1900s by Hermann Minkowski, who also gave the area of study its name: geometry of numbers. Cryptographic applications of lattices were first proposed by Miklós Ajtai in the 90s, and it is within that context that Oded has found many deep questions regarding their mathematical and computational properties. One of his most foundational scientific contributions to the area is known as Learning with Errors, a problem that serves as the basis for a multitude of efficient lattice-based cryptographic constructions, and in particular public-key encryption.

Public-key encryption is "one of the main conceptual discoveries of the 20th century," says Oded. Discovered in the 70s, it allows information to be securely sent across the otherwise insecure internet and phone lines. "Everyone is listening. Still, we can communicate securely." How is that possible? "The key is that what's in my brain is something only I know. I randomly choose a secret. I will tell you something about the secret, and what I tell you will allow you to send me encrypted information," he says. "We've gotten used to it perhaps — but that this exists is amazing."

Cryptographic systems pave the way for many daily activities in our technologically advanced society. They verify signatures on documents; secure our emails, ATMs, and chip cards; block or allow access to websites and cable TV; and authenticate a business's website. "Cryptography also offers us lots of advanced tools beyond encryption and authentication. E.g., it offers solutions for anonymity, deniability, and even online voting," says Oded.

But a breakthrough discovery made by Peter Shor (MIT) in the mid-90s showed that systems like RSA (which stands for Rivest-Shamir-Adleman), which are currently securing these everyday activities, could be broken if quantum computers are built. Like other systems of encryption, RSA is assumed secure because the problem on which it is based — in this case, factoring very large numbers — is assumed very hard. "The key to almost all quantum algorithms is something called the quantum Fourier transform," says Oded. "It allows quantum computers to easily identify periodicity [occurrences at regular intervals], which, as it turns out, allows to solve the integer factorization problem." By using Shor's algorithm, quantum computers will be able to break systems used today very quickly — it is thought in a matter of seconds.

The speed is "not because the computer is fast – this is a common misconception," says Oded. "It just does things in different ways." Whereas a regular computer has bits that alternate between state "0" and "1," a quantum computer – by putting photons, electrons, and other quantum objects to work as "qubits" – can take advantage of a quantum phenomenon called superposition. Superposition allows each qubit to be in state "0," "1," or a combination of both, a phenomenon that "stacks" when multiple qubits operate together, enabling "a huge superposition of all those qubits together, coherently doing calculations," explains Oded.

Now in the prototype phase, fully operable quantum computers would be the scientific achievement of a lifetime. It's an advance that many experts say could be a reality within one to two decades and a prospect that keeps cryptographers up at night. "We need alternatives," says Oded. "If in a year or two someone finally makes this breakthrough, chaos will ensue, because no one will have any way to encrypt. We would have no way to communicate securely anymore."

Learning with Errors

The answer, it turns out, is in error. The key to lattice-based cryptography is in introducing error and thereby disrupting periodicity, something not easily accomplished with RSA and other number theoretic schemes. To show how it works, Oded offers a simplified demonstration of Learning with Errors (LWE):

Bob wishes to send Alice a secret yes or no message. To initiate the communication process, Alice chooses a large, odd number, ideally over 100 digits. For sake of ease, we'll use something smaller here: 1,001. This number itself remains a secret. She sends Bob a list of numbers which are multiples of 1,001 with some small, even numbers (the "error") added in: 65,069 (1,001 times 65 plus 4), 17,023 (1,001 times 17 plus 6), 144,146 (1,001 times 144 plus 2), and a couple dozen or so other such numbers. Bob then randomly chooses some numbers from this list. For simplicity, say he chooses the first and the last included above. He adds these together to get 209,215 and if his message is "yes," he sends that number as-is. If his message is "no," he adds a one and sends 209,216 instead. Alice then divides by her secret key – 1,001 – which will yield an even remainder (6) for "yes" or an odd remainder (7) for "no."

"If you don't add the small, even numbers in the first step, it's not secure because all these numbers will be divisible by 1,001. In this case, you could easily determine the secret," says Oded. "Euclid knew that. It's a 2,000-year-old technique."

Part of the beauty of LWE is in its simplicity. "Learning with Errors is probably the easiest encryption scheme you can imagine," Oded says. "It's mainly adding numbers and dividing. There's not more to it than that. There's no deep math in the system itself — the math appears in the security proof."

Security without Q.E.D.

It is always possible that a brilliant mathematician or computer scientist will devise an algorithm powerful enough to break a code. In other words, as Oded says: "In cryptography, there is no Q.E.D. We can never be absolutely sure that a system is secure." Instead, we can substantiate a system's level of security by proving that breaking a system implies solving a particular intractable (i.e. very hard) problem.

Oded has shown that if LWE is broken, we would then have a fast algorithm for finding short vectors in lattices, a classical hard problem in the geometry of numbers. The sheer size of high-dimensional space makes them hard to find, a phenomenon referred to as the curse of dimensionality. "We believe this should take time that is exponential in the dimension of the lattice," says Oded.

"One surprising and unique aspect of this security proof is that it requires ideas from quantum computation," he adds. "This is totally unexpected since the cryptosystem itself has nothing quantum in it — just adding and dividing numbers."

Encryption in the cloud

LWE is a landmark contribution which brought lattice-based encryption systems into the realm of the possible. By now the most advanced and deeply-researched scheme for encryption in a post-quantum world, it could also prove useful for other important cryptographic applications such as digital signatures. But perhaps the most surprising application of LWE is in constructing a cryptographic primitive known as fully homomorphic encryption. Craig Gentry (IBM) discovered "encryption in the cloud" – its trendier alias – which allows companies to work on users' encrypted data without having to decrypt it. Inefficiencies are still being worked out, but once it is ready for prime time, it will allow a company to, for example, analyze someone's DNA in encrypted form without the company being able to look inside the file. "It sounds like a contradiction," says Oded. "But it's not, because the answer they send is also encrypted – they can't even read the answer. Only you can later open the envelope. For many decades, people didn't even know this exists. Now we know these things can be constructed based on Learning with Errors." ■

A famous theorem in reverse

Hermann Minkowski's 1910 paper "Geometry of Numbers" proved the most celebrated theorem of the area, known as Minkowski's first fundamental theorem. It proves that if you look at a lattice's cloud of points from afar and there are a lot of points, and you then zoom in, "there will be a small area around the origin where you will also have a lot of points," says Oded. In other words: Global density implies local density.

While thinking about this classic paper, Daniel Dadush, a former postdoc at the Institute who is now a researcher at the National Research Institute for Mathematics and Computer Science (CWI) in the Netherlands, asked if the theorem would hold in reverse: Does local density also imply global density?

"It's a fantastic question that was waiting to be asked for over a century; I know of very few researchers that can come up with such conjectures," says Oded. Motivated by the beauty of the problem, Oded and Daniel began working about five years ago to prove that the reverse version of the famous theorem is true. The conjecture found some applications in cryptography, as well as in additive combinatorics, in analysis of Brownian motions, and in the integer programming problem. "That's nice," says Oded. "It shows that Daniel's conjecture is natural."

It is especially useful in problems for which the global picture is known but the local one is not – by analogy think of something that appears sharp to the naked eye but blurs under a magnifying glass, says Oded. "In the application to additive combinatorics, we need to understand the structure of random lattices. There are some beautiful theorems that tell us what the global picture looks like, but when it comes to the local behavior, it seems very hard. This conjecture tells us locally you will not have too many points, because if you had too many points locally, you would also have too many points globally, and we know this doesn't happen. So we're using it in the contrapositive."

Building on work done earlier with Daniel, Oded and his Ph.D. student Noah Stephens-Davidowitz proved the conjecture just this November.

"With this work, it was magical," says Oded. "If you asked me a few months ago, I would say there's no chance. We'll never prove it, because it seems so hard. Then someone comes with the right idea. It's fun. It doesn't happen that often in life – but sometimes it happens."

Modeling the Unseen Earth
With Georg Stadler

by April Bacon

Georg Stadler (seated) with Ph.D. students Yair Daon and Karina Koval.

Georg Stadler and collaborators have developed fast algorithms to simulate the flow of Earth's mantle on the global scale, and inverse methods to improve our knowledge of the mantle from surface observations. These methods also turn out to help in understanding Antarctic ice sheets.

What we know about the structure of the Earth, we know largely because of seismic waves. Earthquakes, which are caused by the sudden movement of tectonic plates, have played a necessary and starring role in helping us to see what we otherwise could not: the shape, density, depth, and approximate composition of the Earth and its layers. Much of this work was done by geologists and geodynamicists, with first strides made in the early 1900s, but not really taking hold and shaping what we know today until mid-century. The field is relatively young — and is providing rich questions for mathematicians like Georg Stadler, who, along with collaborators, received the 2015 Association for Computing Machinery's Gordon Bell Prize for the team's "trailblazing approach to modeling Earth's geological processes."

Using the IBM Sequoia — one of the fastest supercomputers in the world — and the team's innovative and carefully designed, scalable algorithms, they developed a groundbreaking simulation of the flow of the Earth's mantle and the corresponding motion of tectonic plates. The mantle is the layer of the Earth just under the tectonic crust. It begins at just over 20 miles down (the deepest we have physically drilled is just over 7.5 miles) and, in total, is about 1,800 miles deep. The mantle moves by convection. That is, it is heated from below, causing plumes of warmed mantle to rise toward the surface, in much the same process as water set to boil on a stove. Mantle convection occurs very slowly — over millions of years. The Earth's tectonic plates are formed when mantle rock cools at the Earth's surface. Convection and buoyancy forces cause them to press down and sideways through the mantle in a process called subduction, moving no more than 10 cm per year, and other rock with very different viscosities flows at different speeds. "We have some basic idea about how [convection in the mantle] works, but there are fundamental uncertainties because we can't look inside," says Georg.

In order for Georg and collaborators to build an accurate model, they had to develop algorithms that could handle the highly heterogeneous contents of the mantle, as well as resolve features at both local and global scales. While the Earth's circumference is approximately 24,900 miles, the model also had to account for the subduction dynamics of plates, which occurs in the narrow plate boundary regions that are only a few miles thick.

"Algorithms have to focus on small-scale features when you need them to, but on large-scale features when you don't," says Georg. "It's very useful if you can put down a fine mesh — many degrees of freedom, many unknowns — where you need them. In other regions, you don't want to do this. This is what's called adaptive mesh refinement." The computational mesh in figure 1, a zoomed-in section of the mantle, consists of cubes, each of which represents a nonlinear equation. "We have 500 (and more) million of those equations, which we cannot fit on a single computer, so we have to fit them on thousands of computers – a cluster. It's not trivial to use these supercomputers. They are composed of many regular computers connected to each other; they each have separate memory, and algorithms have to coordinate how computers talk to each other to exchange information."

Often, solving mathematical equations that describe physical processes requires explicit solvers, which are relatively easy to use on supercomputer clusters. But with problems like mantle convection that have a huge range of time and space scales, explicit solvers don't work. "To do a simulation of waves that travel through some medium — through the Earth, for instance — [explicit solvers are] enough," says Georg. However, "for these mantle convection fluid dynamics problems, they cannot be used as the physics simply does not allow that."

Implicit solvers require solving linear and nonlinear tightly coupled matrix systems, which is difficult for very large problems. Our desktop computers and even cell phones are capable of quickly solving matrix systems when the equations number into the hundreds and thousands. But very complex, huge systems — like those describing the flow of the Earth's mantle — demand equations numbering into the billions. It is very difficult to efficiently use cluster computers to solve such systems. "These systems are so large and so difficult that the challenge, in some way, is to figure out how to solve them using the computer hardware we have today," says Georg. The genius of the method devised by the team amounts to figuring out how to design implicit solvers that are scalable — that is, they get faster with each addition of a new computer in the cluster.

Their work made interdisciplinary gains in mathematics, geodynamics, and computing. As the ACM's Bell Prize citation states, "The group's submission demonstrates that, contrary to conventional wisdom, implicit solvers can be designed that enable efficient global convection modeling of the Earth's interior, allowing researchers to gain new insights into the geological evolution of the planet." And IBM reports that "the team's code reached an unprecedented 97 percent parallel efficiency in scaling the solver to 1.6 million cores, a new world record." A large group from IBM Zurich helped to tune the algorithms for the supercomputer, to make them faster. They were one part of the team, contributing their

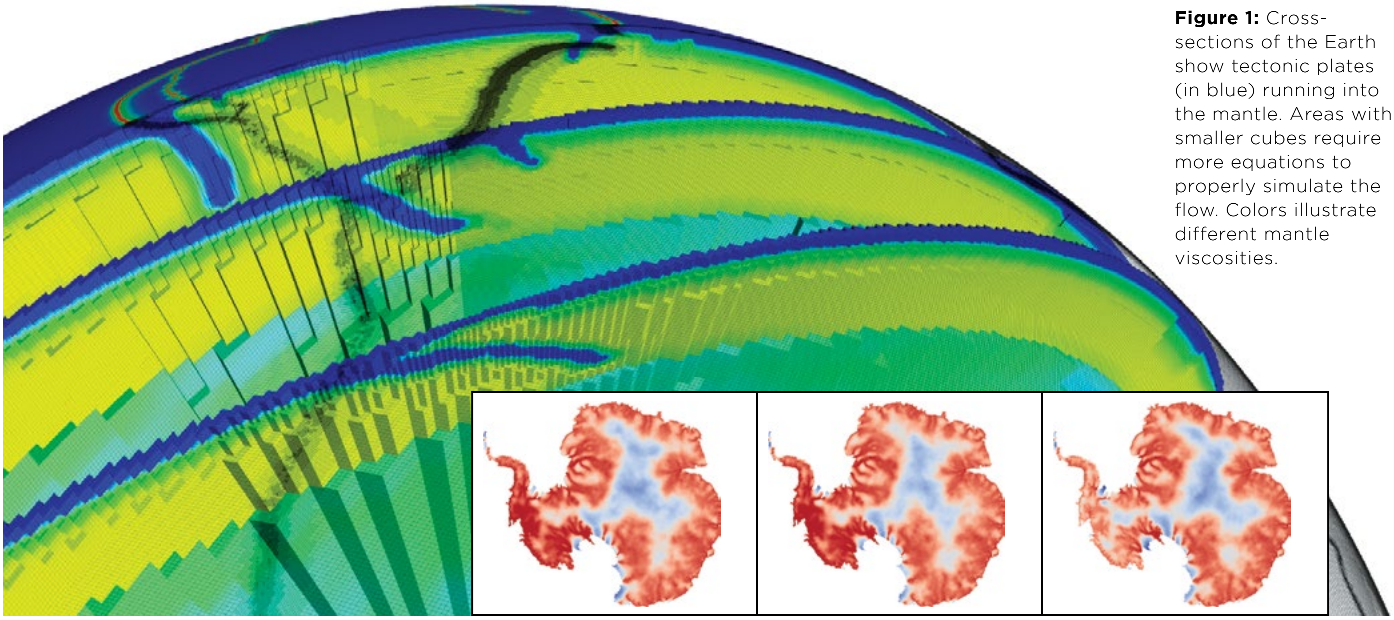


Figure 1: Cross-sections of the Earth show tectonic plates (in blue) running into the mantle. Areas with smaller cubes require more equations to properly simulate the flow. Colors illustrate different mantle viscosities.

Figure 2: The three maps show three different possibilities for how strongly the ice is connected to the ground, with blue indicating the strongest connection, red the weakest connection. We can be more confident that our basal map is accurate in areas that are consistent across the images.

expertise along with Georg and other applied mathematicians, and geophysicist Michael Gurnis, director of the Seismological Lab at the California Institute of Technology.

Shedding light on a cold case

Some of Georg's colleagues at research labs are using similar methods to develop a model that can predict, under different climate conditions, how much land ice might be lost into oceans and contribute to sea-level rise. "In terms of the mathematical equations, this [forward modelling] looks very similar to mantle convection," he says. "One is very hot; one is very cold. The timescales are very different. One is hundreds of millions of years; one is maybe tens of years – but mathematically, it's really not that different. It's a very similar PDE [Partial Differential Equation] called the Stokes equation. That's nice, because that shows that math gives you tools that can be applied universally."

One barrier to improving the estimation of sea-level rise is that we lack a complete model for Antarctic ice sheet dynamics. The challenge is that there is no way to directly observe what's happening at the boundary between land ice and the ground on which it sits, but Georg has developed a way to apply sophisticated inverse methods to uncover what's likely to be happening at that interface.

"Many problems are inherently inverse problems because they involve things we cannot observe directly," explains Georg. "But we can infer what we can't observe by combining mathematical models with things we can observe. In the Antarctic ice problem, this means finding the boundary conditions at the ice's base from satellite observations of surface flow velocities. For the mantle flow problem, we can observe plate motion, mountain building, and the location of Earthquakes, each of which allows us a glimpse of what is happening inside our planet. The inverse problem uses that information to constrain mechanisms and forces in the mantle. Medical imaging techniques such as MRI or PET are other examples of inverse problems."

There are different approaches for solving inverse problems. A deterministic model yields an Occam's razor kind of solution — a single best guess of conditions. This method is still the one most employed today and is used, for example, by oil companies to make decisions about where to drill. "A deterministic inverse-problem approach [for ice sheets] would show a single map that gives you an estimate of how much resistance the ice experiences when sliding over the bedrock," says Georg. "It's your best guess, but it's not going to be the reality."

A newer, probabilistic approach to inverse problems called "uncertainty quantification" provides a more complete answer because, in addition to predictions, it includes a measure of how confident we can be in this prediction (see figure 2). "Good simulation results should come with some measure of uncertainty," Georg says. "This probabilistic approach to an inverse problem would give you many possible maps that describe the connection between the ice and rock. This reflects the level of uncertainty inherent in inverse problem solutions, due to observation and model errors, and the fact that inverse problems are so-called ill-posed mathematical problems – that is, different maps can lead to very similar observations."

The mathematics behind this approach is, of course, more complex, but Georg is developing methods to make it more feasible. "Mathematically it is very interesting because several fields come together," he explains. "Your model is usually a partial differential equation. Then aspects of optimization and probability theory come in. Finally, numerical methods and computing are required to approximate the problem solution."

"Some science goals are so challenging that we might not be able to achieve them any time soon. For instance, probabilistic inverse problems that combine various observational data with fully resolved, three-dimensional, complex models —such as time-dependent mantle flow or ice sheet dynamics — are likely to remain grand challenge problems," concludes Georg. "But I can make two or three steps towards these goals. That's a great motivation for me — to develop and analyze the mathematics and algorithms that will be useful for specific applications, and hopefully also for many others." ■

At the boundary of two fields: A Courant story

by April Bacon

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Aukosh Jagannath and Ian Tobasco

Friends and recent Courant Ph.D. grads stumbled upon a problem during their graduate studies that made them collaborators.

Aukosh Jagannath and Ian Tobasco both joined Courant as Ph.D. students in Fall 2011 and became fast friends. The former studies probability theory—more specifically, mathematical questions arising from statistical physics—and the latter calculus of variations and partial differential equations (PDEs), especially those arising in elasticity theory. Neither expected that in just a few years they would be collaborators, tackling problems that arise in 'spin glass' systems—work that just so happens to require the joint expertise of their two disciplines.

Spin glasses are a kind of highly disordered magnet first studied by physicists. Unlike a simple magnet where all of the "arrows" of magnetism point in predictable directions, each atom in a spin glass is magnetized in a randomized direction. This is pretty useless as a magnet, but the mathematical models used to understand its behavior turn out to have applications in real-world problems like scheduling, message encoding and pattern recognition. They are also core to our understanding of solid matter itself, and the models are deeply interesting to mathematicians. "There are many beautiful problems of pure probability that statistical physicists have encountered that have been out of the reach of current mathematical techniques," says Aukosh. "Using their rather ingenious methods they've been able to develop beautiful theories for how to solve these problems." Mathematicians in this area are working to add mathematical rigor to those theories and to describe the nature of spin glasses.

Aukosh, advised by Professor Gérard Ben Arous, presented his first project as a Ph.D. student on spin glass-related work at the Banff International Research Station. Afterwards, attendees suggested that he should think about the stronger version of his underlying theory. "So now the question was, 'Can you quantify this conjecture?'" he says. "I realized with time that there was a more concrete question to ask, that sounded more manageable, about studying the properties of free energy, rather than their fluctuations. I beat my head against this problem for a while, and then I realized that I wouldn't be able to answer it until I understood how to solve a certain variational calculus question." Lucky for him, his best friend and peer was studying in that very area.

Aukosh found the point of entry for the collaboration in a paper by Antonio Auffinger (a former student of Ben Arous's) and Wei-Kuo Chen. And so in early fall 2014 over lunch in Warren Weaver Hall's 13th floor lounge, Aukosh presented a particular PDE to Ian and asked: "Do you recognize this formula?"

"The formula involved solving what's called the Hamilton-Jacobi-Bellman PDE by a stochastic optimal control approach," says Ian. "At the time we weren't using that language, because we hadn't identified it as such. Auffinger and Chen were solving this PDE by writing down an optimization formula. I told Aukosh that it reminded me of this Hamilton-Jacobi theory that I had studied with my advisor, [Professor] Bob Kohn. Naturally, I went to Bob and asked, 'Is there a version of this theory for the elliptic PDE instead of just the first order PDE?' And he said, 'Yes, that's stochastic optimal control rather than the usual optimal control. That's the difference. You add some randomness.' If you go back to the paper that Auffinger and Chen wrote you can see traces of this connection. It's just not enunciated in the same language."

"From there on, it was just trying to analyze this variational question," says Aukosh.

There was a difference in mathematical languages to sort out, but "we had the advantage of being good friends," says Ian. "We had been talking about math for some time, working on homework assignments together and studying for the oral exams and so on."

The next big step came one night when the two were doing calculations on the board. Ian wrote an expression that Aukosh recognized. "I went and dug up an old textbook, and I realized that what he had written was the equation for this very famous conjectured phase boundary in these problems called the de Almeida-Thouless line." For a classic model of spin glass, de Almeida and Thouless were able to describe a curve (the "AT line") which laid out the boundary between "replica symmetry" and "replica symmetry breaking." If a spin glass system is found within replica symmetry, it was then predicted to be ordered; and in replica symmetry breaking, disordered.

"Very early in my training with Gérard," continues Aukosh, "he mentioned that a big driver of research in this field was in trying to prove that this line was actually the correct phase boundary in these systems. In the end, nobody really got a satisfactory answer. But Ian and I got a new foothold on the problem."

"We were able to prove that a certain natural generalization of the AT Line was correct in all of phase space except for a compact set," says Ian. "Meaning, practically speaking, a set that you might attack on a computer. For the classical mean field spin glass model—the Sherrington Kirkpatrick model—this means that we now know that the AT Line is the correct phase boundary everywhere that our methods apply."

The pair wrote an initial paper thinking of new ways to look at the result from Auffinger and Chen's paper, a second on the above-mentioned work with the AT line, and two more looking at replica symmetry breaking in spherical spin glasses, a type of spin glasses which physicists invented to be a simpler form of a disordered system.

Setting bounds on complexity

In metallurgy, annealing is the process of heating up and then cooling a sword in order to beat it into shape. As Aukosh explains, the "mathematical ramifications of this physically intuitive idea can be very profound. The idea is that if you want to study the smallest the energy could ever be for a system, you heat the system up and then cool it down to zero temperature. I had this idea that maybe you could formalize this move by using a technique in the calculus of variations called 'Gamma convergence,' at least for the kinds of models we study."

The two set out to study spherical spin glasses at zero temperature, quickly turning the probabilistic question into a variational one, but then were unsure of how to get a hold on it so searched instead for a 'dual' problem.

"We fell back to what we had learned under Bob," explains Aukosh. "Oftentimes, when you study a problem in mathematics, especially in variational calculus, what you find is that there's the problem that's given to you by the world, by physics, and the question is very natural, but trying to get a foothold on it is very difficult. The idea is that you find a problem that's the mirror image of this problem. If you can solve the dual problem, it is exactly the same as solving the original problem."

After a short period, Ian sent Aukosh a message: "I found the dual. You're really going to like it when you see it." The dual is in a general class of problems known as obstacle problems. Ian offers an example which comes from his field: Think of a tablecloth pulled tight over a flat or spherical table. One can describe mathematically where the cloth meets the table, which is the obstacle, and also what happens in-between.

With the dual in hand, Aukosh and Ian studied spherical spin glasses at zero temperature and then broadened what they learned from that work to other temperatures. "What we found was something very astounding, unexpected," says Ian. "For the spherical spin glass models, even though replica symmetry breaking happens, there is a way once and for all to limit the complexity of the disordered phase and limit it in a very precise way."

Going back to the table and the tablecloth, Ian completes the analogy for how they were able to set limits on the complexity. It's simple to understand where the cloth meets a flat or spherical table. But now imagine the cloth pulled taut across a bumpy table—the points of contact become more complex. "What a bound on this complexity would mean is that, given the shape of the table, you are able to limit the number of disjoint components of the contact set," says Ian, "and specify further where amongst all the bumpiness these components can lie."

"In the end we were able to resolve this picture," says Aukosh. "It was a very beautiful, old question, this obstacle problem." A big moment for the pair, he adds, was learning from Professor Sylvia Serfaty, an expert in the area, that using an obstacle problem as a dual is not only a natural move, but also one which has driven a lot of progress in her area of the variational community.

Aukosh and Ian graduated in 2016 and their collaboration continues across borders—Aukosh is now an NSF postdoctoral fellow at the University of Toronto and Ian is the James Van Loo Post-Doctoral Fellow at the University of Michigan.

"I was really lucky that it turned out that my best friend is an expert exactly in the field in which I needed help," concludes Aukosh. "If the cards played out differently, we never would have stumbled upon these really synergistic connections."

"This has been a very fruitful collaboration because it is a variational problem, that's what my speciality is," says Ian. "But it says lots of very deep things about a probabilistic system, that's what Aukosh's specialty is. I'd say we're very fortunate. At the same time, maybe that's the magic of Courant." ■

Changing of the Guard

Gérard Ben Arous steps down; Richard Cole steps in as Interim Director.

Gérard Ben Arous has stepped down as Director of the Courant Institute to continue his service as Professor of Mathematics. He held the directorship at Courant from fall 2011 through August 2016, having served an additional year as Acting Director from 2009-2010. Gérard made significant strides for the Institute and University during his ardent and influential directorship.

"To me, directorships are best judged through the recruitment of excellent faculty, and during Gérard's time as Director of Courant, the Institute's faculty improved greatly, with many outstanding mathematicians and computer scientists joining the Institute," says Dave McLaughlin, Professor at Courant, who served as Courant's Director from 1994 to 2002 and NYU's Provost from 2002 through this past summer.

With a growing faculty and a steep increase in students, Gérard was also a champion for resources for the Institute. "He focused on the development of Computer Science at Courant, first by finding additional new space for members of Computer Science and Data Science in the Forbes building," says Dave. The building, located on Fifth Avenue and 12th street, is now in final preparations to receive its new tenants.

In addition to Director of the Institute, Gérard served as Vice Provost for Science and Engineering Development during a time that saw significant growth in those areas at NYU, including the 2014 merger with Polytechnic University in Brooklyn, now NYU's Tandon School of Engineering, and the establishment of new global research centers at NYU in Abu Dhabi and Shanghai.

Additionally, Gérard "initiated the very successful Center for Data Science at NYU, as an outgrowth from the excellence in machine learning in Computer Science," says Dave. Math and computer science are at the foundation of the Center, which brings together researchers and professors from 18 schools and colleges across NYU.

As Dave concludes, "In Gérard, Courant had an outstanding Director."

Richard Cole, Silver Professor of Computer Science at the Institute, graciously agreed to serve as Interim Director until a new permanent Director is named. Richard has provided leadership in several capacities in his over thirty years at the Institute, and will be filling this particular role for the second time. ■

For the love of math:
CMT nurtures mathematically talented, underserved kids

by April Bacon

Ph.D. student Morten V. Pedersen (pointing to a math problem) and CMT summer program students.

Through its in-house activities and partnerships, Courant's Center for Mathematical Talent has reached thousands of mathematically talented students across New York City since its inception in 2010.

No classroom goes unused at Courant's Warren Weaver Hall, even when regular classes are finished — during summers, weekends, and off hours, primary and secondary school students enter its halls, eager to deepen their knowledge of mathematics. More than three hundred students come to Courant over the weekends throughout the year for New York Math Circle groups. Over one-hundred students with the NYC Math Team also meet regularly at the Institute to prepare for competitions all around the United States. And BEAM (Bridge to Enter Advanced Mathematics), a nonprofit organization that runs programs for mathematically talented students without access to opportunities, has continued mentoring alumni from their summer programs at Courant, about two hundred to date. All of these programs have free access to the space under the auspices of Courant's Center for Mathematical Talent (CMT), funded by the Alfred P. Sloan Foundation, whose generous support has helped encourage others to invest in the program and the students it serves.

"We're the hub of a lot of math enrichment programs in New York," says Berna Falay Ok, who joined Courant in November 2015 as the new Director for the CMT. The Center, now in its sixth year, pursues its mission of reaching mathematically talented pre-college students in a great variety of ways, and providing space for these programs is just one of them.

In-house Programs

The CMT also runs its own math circles for talented students. James Fennell, a fourth-year Ph.D. student, was first brought on to co-lead the Center's math circles in both semesters of academic year 2014-15. Over ten weeks, he taught transformational geometry—with a brief foray into non-Euclidean geometry—to students recruited from two of New York City's strongest schools for math and science. And this past spring, James ran a math circle on the mathematics of games (focusing on invariance) with 23 alumni from BEAM's summer program. The change in recruitment strategies from the former to the latter is part of the CMT's broadened mission to meet the needs not only of the city's most mathematically advanced students, but also of talented students from underserved communities.

"There was a core group of fifteen students [BEAM alumni] who came in voluntarily over ten weeks to take the program," says James. "These students were very capable in mathematics but clearly hadn't had many opportunities to do something like this before. They enjoyed it a lot. It's all kind of new to them, so it was very nice." At the Sunday classes, students were introduced to games that evolved into math challenges such as: Can you develop a strategy in which player one (or player two) always wins? "That's how you transition from a fun activity to then talking about mathematics," adds James. As a capstone experience, the kids participated in an exhibition day at the end of the program, and taught the games and accompanying strategies to their parents and friends.

This summer commenced another of the CMT's internal programs: a three-week, non-residential summer program. The goal, explains Selin Kalaycioglu, Clinical Associate Professor at Courant and Principal Investigator on the grant from the Sloan Foundation, is to develop it into a nationwide, credited course that will be the Center's signature program.

"We have 21 students right now," says Berna. "We find talented kids, some from underserved communities, and get them to Courant, give them a feel for what university life is and show them why we love math. They come here four out of five weekdays from ten o'clock to four. They sit down with people that they've never met before, with people from similar grades all across NYC, and just do math. You should see how excited they are; during lunchtime, to take a break from math, they have been playing other math games!"

The students are taking three courses: Combinatorics and Graph Theory are taught by James and another graduate student, Morten Pedersen, and Introduction to Proofs is taught by Courant Professor Emeritus Fred Greenleaf. They also enjoy a few hours of math games and puzzles at the end of each week.

"You should see the way the kids interact with Fred," says Berna. "I'm so glad he's in the program. These are their first interactions with a working mathematician in their lives. Math teachers they know—math teachers are pressured for time to prepare you for your upcoming state exam. But Fred is different. He takes them through a journey: If you fail, you continue, and you come up. That's what a true mathematician is, to me at least. It's all about struggling and staying in there to solve the problem. It's not just about the right answer."

"I think the kids do need that role model," says Selin. "Our grad students are very good. They are leading amazing sessions. But the presence of a known professor—it makes a big difference."

Partnering Up

With the vision of becoming a unifying force for all math enrichment activities across New York City, partnerships are a key component of the CMT's everyday operations. "There are so many organizations—some of them are quite big and organized and known, and some of them are just using their own resources within their schools," says Selin.

Through alliances with these organizations, expertise and resources are combined to best serve students, and the Center can keep track of students better and use referrals to ensure that they are not abandoned at any point in their development. "The center's mission is to create a pipeline that can take a student from a very early age, starting in elementary school, and then mentor them through various enrichment activities until they finish high school," says Selin. "For example, if we detect an elementary school kid who's very talented, after completing a math circle cycle a few years with us, then we can direct them to New York Math Circle."

One partnership, with the NYC Department of Youth and Community Development (DYCD), has been ongoing since 2012. Candace Reyes-Dandrea is Deputy Director of the Capacity Building Unit at DYCD and a recent addition to the CMT Advisory Board. She has worked with the Center for several years, originally forging the connection by meeting its former director, Mark Saul, at the New York Academy of Sciences. She was there seeking ways to introduce more math into low income communities, and a partnership was promptly formed.

The Center now teaches its "Finding Math" curriculum to instructors who take that curriculum into DYCD-funded afterschool programs. Just this past spring, the CMT taught 54 instructors. "It's sort of like a 'wow moment' with the staff," says Reyes-Dandrea of the instructors' reactions to the curriculum. "They're like, 'I didn't know this was math! I didn't realize this is what math is about!' And I went through that transition also. It's really changed my perspective. Math is really about asking why and plugging away—it's about using reasoning and logic skills and thinking more deeply about what questions are being asked."

There is special attention given to keep the activities fun, and the students really take to the math games. "We were teaching elementary kids how to do ciphers at the school in Harlem," says Berna, "and one of the kids in the group would test her parents every day as she learned things." After the program, the student's mother wrote to Berna to say, "Just a couple of weeks ago, on mother's day, [my daughter] hid 'secret codes' everywhere in our apartment and asked me to find and decipher them to get clue 1, clue 2, clue 3." After a very full and challenging morning of deciphering the clues, she found her way to a hidden treasure from her daughter: "A sweet mother's day card made by herself!"

In just the fall of 2015 and spring of 2016, the CMT and DYCD partnership reached 498 students. In past years they were in middle schools, but this year went

Continued on page 10

Find out more about the Center for Mathematical Talent at its recently relaunched website: **http://cims.nyu.edu/cmt/**

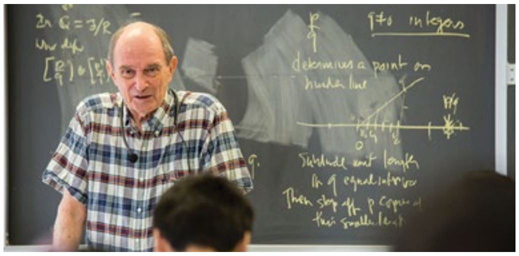
in to two elementary schools, one in East Harlem and one in East Elmhurst. The change is part of a new CMT effort to reach kids at a younger age. “Finding talented students early and nurturing them throughout the years is very important,” says Berna, “because kids get stressed about math very early on, and then they hold on to that nervousness.”

“We’re not giving up on the idea of working with middle school kids,” says Reyes-Dandrea, “but are thinking a little more strategically. If we can start working with elementary school kids and follow them through, then there’s a greater possibility of changing attitudes to learning. So I’m hopeful. And I appreciate the opportunity to just talk with Berna and the team, because I’m learning as I go along. The way I look at it is, I have an understanding of the after school world in public education, Berna has an understanding of math—our combined knowledge can work to the benefit of these kids.”

The Center, which has been guided and bolstered by support from Courant faculty such as Gérard Ben Arous, Sylvain Cappell, and Chuck Newman, has also provided as-needed advanced instruction for New York Math Circle students from Courant Professors; organized math circles for BEAM’s summer program alumni to continue “Finding Math”; in spring 2016, subsidized the cost of attending New York Math Circles’ programs for 67 students from low-income families; and, this October, with the National Association of Math Circles and Mathematical Sciences Research Institute (MSRI), hosted at Courant a three-day National Association of Math Circles meeting, which gathered math facilitators from all around the U.S. to the Institute.

All of the above activities approach math outreach as an ecosystem by working toward the Center’s overall mission from many angles and at many levels, and each is driven by the common heart of the program, as Berna expresses: “The love we have for math, we want to pass it on to kids.”

Selin Kalaycioglu and Berna Falay Ok



Professor Emeritus Fred Greenleaf

Ph.D. student James Fennell (left) and students.

In Memoriam: Eliezer Hameiri *(September 28, 1947 to June 14, 2016)*

Eliezer Hameiri spent his entire career at the Courant Institute, first joining as a Ph.D. student in 1972. After graduating, having written a dissertation under the supervision of Harold Weitzner, he was immediately hired as a Research Scientist and then tenure track professor, attaining his full professorship in 1988. He was a critical part of the plasma physics group at Courant, which was founded in 1956 by Harold Grad and grew to include faculty members Paul Garabedian, Harold Weitzner, Elie, and at times Steve Childress.

“Elie was a very strong embodiment of the Courant tradition,” says Professor Amitava Bhattacharjee, who is head of the Princeton Plasma Physics Theory program, and a collaborator and longtime friend of Elie’s. “Often, fundamental problems arise for which the Courant group have time and again provided rigorous and beautiful solutions that the whole community has benefited from. It has always been a small but exceptionally talented group. Elie belonged to this distinguished group. He was trained in that tradition, and carried that legacy forward.”

Elie was dedicated to developing a thorough and precise understanding of the properties and dynamics of plasmas. He “repeatedly uncovered previously unknown properties of plasmas and corrected numerous misunderstandings concerning plasma dynamics,” said Gérard Ben Arous, as Director of Courant, in a message after Elie’s passing in June. And Elie’s work was significant and impactful both mathematically and for the physical sciences. “He was one of the people who could do both, and he did them extremely well,” says Harold Weitzner. “He was a very fine mathematician.”

When Elie was a graduate student, “I gave him a relatively mundane problem,” recalls Harold. “He saw how to do much, much more with it. And that’s the mark of a first-rate scientist. He was extremely original and a very fine scholar in the classical sense… In the years following getting his Ph.D., he was able to turn the problem into a major piece of work for the field in developing the underlying structure of ideal magnetohydrodynamics.”

In their remembrance for Elie, Fusion Power Associates, an educational foundation that advocates for fusion power, wrote that Elie’s “studies of the spectrum of linearized ideal magnetohydrodynamics was the first complete characterization of the problem and had major implications for the understanding of flow stability problems and the role of ‘ballooning modes’ in a plasma.”

Another significant body of work, around mid-career, resulted in an early and fairly complete analysis on the relaxation and evolution of turbulent plasma states. While much literature on turbulence problems is “a bit of a mess,” says Harold, Elie and collaborators released a series of papers with “very clean, very straight-forward results.

WELCOME TO THE INSTITUTE'S NEWEST FACULTY!

Scott Armstrong, Associate Professor of Mathematics, received his Ph.D. in Mathematics from the University of California, Berkeley. His research interests are partial differential equations, probability theory, and stochastic homogenization. Armstrong previously held positions at Louisiana State University, the University of Chicago, and the University of Wisconsin, Madison. Most recently, he was a research scientist at Université Paris-Dauphine.

Joan Bruna, Assistant Professor of Computer Science with affiliation in mathematics and in association with the Center for Data Science, holds a Ph.D. in Applied Mathematics from l'École Polytechnique. Before moving to Courant, he was an Assistant Professor of Statistics at the University of California, Berkeley. Bruna's research interests include invariant signal representations, pattern recognition, harmonic analysis, stochastic processes, and machine learning.

Hesam Oveys, Clinical Assistant Professor of Mathematics, holds a Ph.D. in Mathematics from the University of Missouri. His research interests include probability theory and stochastic calculus. He is the recipient of several teaching awards. Prior to joining Courant, Oveys was a Faculty Instructor of Mathematics at the University of Missouri. He has also taught at Stephens College in Columbia, Missouri.

Sylvia Serfaty, Professor of Mathematics, holds a Ph.D. in Mathematics from the Université Paris-Sud. Her research interests revolve around the analysis of partial differential equations and variational problems coming from physics, in particular the Ginzburg-Landau model of superconductivity, and recently the statistical mechanics of Coulomb systems. She was a Courant faculty member from 2001 to 2008, and, most recently, a Professor of Mathematics at Université Pierre et Marie Curie-Paris 6 as well as a Global Distinguished Professor at Courant.

Fan Ny Shum, Clinical Assistant Professor of Mathematics, holds a Ph.D. in Mathematics from the University of Connecticut. Her research interests are stochastic analysis, partial differential equations, and sub-Riemannian geometry. Prior to joining NYU, she was a research supervisor for Math Research Experience for Undergraduates (REU) at the University of Connecticut.

But this is what I look for in Elie's work." As Bhattacharjee says, "whatever he published was deeply instructive and often definitive." Phil Morrison of the University of Texas, a plasma physicist who also specializes in the mathematical side of research, encountered Elie through the years at conferences where the two mutually enjoyed one another's presentations and conversation. Morrison echoes the celebration of Elie's papers, saying that they were "distinguished by their crispness and clarity, and enriched our field by maintaining the careful and mathematically informed style of Harold Grad and other early plasma researchers."

At the time of his death, Elie was continuing with work that began in the early 2000s to determine the basic physics and phenomena of Hall magnetohydrodynamics with which he could build a model that lived up to his standards of accuracy, robustness, and elegance both mathematically and physically. "In recent years, people have become aware that it is important to have this more complex model for a plasma," says Harold. "More commonly people use what is called magnetohydrodynamics or ideal or dissipative magnetohydrodynamics." There are a good number of people who work on these one-fluid models, he explains. There are also a number who work on two-fluid models, such as the Hall model, but none which are really "clean and fully consistent" as Elie's models have unfailingly been.

Though often blunt in dialogue, after a little bit of time spent with Elie, one came soon to realize that, as Harold says, he was "a very kind-hearted and dear soul." Genuine and caring toward others and in his work, he drew a recurring group of visitors from all over, ranging from postdocs to senior faculty. "It was clear that they saw Elie as somebody that had something substantial to offer that one couldn't easily get from other people or Institutions," says Harold.

"The likes of Elie don't come about easily," says Bhattacharjee. "We were lucky that somebody of his talents in mathematics was as deeply interested in plasma physics as he was. He was a dear friend. One I trusted. I did some of my best work with him."

In addition to his interests in mathematics and physics, Elie cared about music, as well as the study of religion, especially Judaism, and the development of the State of Israel, where he grew up. Elie was steadfast in these areas, too, and had great depth in the history of religions, especially in the pre-Biblical period. His interest led him to obtain a degree from the Jewish Theological Seminary. "It was always very instructive to listen to him because he knew so much," says Harold. "It was quite an exceptional thing."

"Elie's collaborators and coworkers consistently looked to him for new insights," concludes Gérard. "He will be sorely missed by his many students, collaborators, colleagues and friends at Courant." ■

In Memoriam: Joseph Keller *(July 31, 1923 – September 7, 2016)*

Photo of Joe Keller at the Courant Institute, taken in the early 70s.

Joseph Keller was one of the leading applied mathematicians of his generation. "He showed us how powerful applied mathematics could be," says Dave McLaughlin, Silver Professor of Mathematics and Neural Science at Courant. "If you think about the breadth of his work throughout the sciences, the social sciences, the health sciences — it is truly remarkable. His curiosity was without equal."

"Joe Keller was equally knowledgeable in mathematics and physics, and he was willing to look at a very wide variety of problems," says Courant Professor Emeritus Peter Lax. Joe in fact received both of his graduate degrees in physics (B.A. in math and physics in '43; M.S. and Ph.D. in physics in' 46 and '48, all from NYU). He then joined the faculty at Courant, which was just under fifteen years old. He played an integral part in building applied math at the young Institute over the next thirty years, including leading a large group at NYU's former Heights campus uptown.

While at the Institute, Joe developed his geometric theory of diffraction, contributions for which he later received a National Medal of Science. The work analyzed how waves propagate. As stated in Stanford's obituary for Joe, "The theory can be applied whether the waves are acoustic, electromagnetic, elastic or fluid, and has become an indispensable tool for engineers and scientists working on applications such as radar, stealth technology and antenna design."

In 1974, Andy Majda, now Professor of Mathematics and the Samuel F. B. Morse Professor of Arts and Science at Courant, sat in on Joe's random wave propagation course. "I saw for the first time that you can do very complex problems where there's no hope of doing rigorous analysis for the next century," says Andy, who was then a Courant Instructor. "It could be done by very concise, mathematically-based formal asymptotic analysis. I was taken with that topic. For the rest of my career I've done complex multi-scale asymptotic modeling of phenomena."

Joe used asymptotic analysis as his main tool for studying a vast range of problems and phenomena. "He would apply that to PDEs, to integral equations, to ordinary differential equations; it was throughout the field of analysis," says Dave.

"It's an art, and Joe was the highest practitioner of the art," says Charlie Peskin, Silver Professor of Mathematics and Neural Science at Courant. "Joe had an incredibly distinctive style. You could suggest a methodology in shorthand just by referring to his name."

Joe's lasting impact can be understood not only in terms of his mathematical achievements, but also of his mathematical heritage. "He was such a great mentor to generations of young mathematicians and scientists," says Dave. "He worked with so many people, essentially showing them how to use applied mathematics." Joe had 60 students — 40 while he was at NYU — according to the Mathematics Genealogy Project. But as Dave notes, this large number doesn't include the many mathematicians, such as himself, whom Joe mentored when they were postdocs or junior faculty.

The round table is emblematic of Joe and the personable way in which he inspired others to delight in mathematics. In his years at Courant, he could be found at lunchtime at one of the round tables in the 13th floor lounge, a group gathered eagerly around him. "Many of the junior people would go up early, just to make sure that there was a seat available at his table," says Dave. There, Joe would present the group with mathematical challenges found from everyday life. Andy remembers Joe asking: Why does old paint curl up on a wall? Charlie recalls the question: When you put a drop of water on paper, why does it spread out a certain distance and then stop? Professor Emeritus Steve Childress remembers discussing how lichen grows on a rock at that round table, which, he says, "was the social event of the day. It occupied us for years, and Joe was always at the heart of it."

Andy remembers attending Joe's holiday lecture on another such question: What is the optimal way to run a mile? "He set it up as a control problem," says Andy. "The answer was that you should keep running faster and faster until the end of your mile, accelerating constantly at a fixed rate, and then you should die at the end of your run! It made for a lot of laughs at the holiday lecture." Two other "everyday life" problems Joe worked on – one describing the motion of a runner's ponytail and another showing how to make a teapot that doesn't drip — earned him Ig Nobel awards, given for work that makes readers both think and laugh.

In 1978, Joe moved to Stanford for the remainder of his career. He continued to visit the Institute each year. "I think Joe really had a great affinity for the Courant Institute," says Steve. "I think he still considered it his home." Joe's returns did feel like homecomings. He would light up doorways, enliven seminars, and rekindle conversations with friends as if no time had passed. ■

The Joseph B. and Herbert B. Keller Professorship in Applied Mathematics

With a generous gift, Joseph Keller established a professorship in applied mathematics in his and his brother's name, for "a noted scholar, researcher and teacher in the field of applied mathematics." Upon hearing of Professor Keller's bequest, then Director Gérard Ben Arous said that "the Joseph B. Keller and Herbert B. Keller Professorship is a special tribute to these brothers' formative years at NYU and Courant, their many distinguished years of service to applied mathematics, and their great accomplishments in the field. It will be an inspiration to the faculty members who hold it through the years ahead of us."

Herbert Keller, who passed away in 2008, earned his M.A. and Ph.D. at the Courant Institute in '48 and '54, respectively, and then joined the faculty. While at Courant, he was Associate Director of the Atomic Energy Commission's Computing and Applied Mathematics Center, under Peter Lax. In 1967, he moved to the California Institute of Technology for the remainder of his career.

Find Me Quickly

by Dennis Shasha
Professor of Computer Science

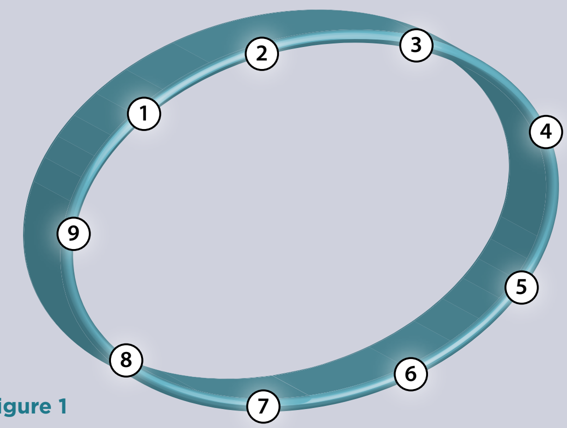


Figure 1

In this cooperative game, two players on a graph want to meet each other as quickly as possible. Meeting each other means both players are at the same node at the same time or cross each other on an edge. Each player moves or stays put each minute. A move takes one player from one node across an edge to a neighboring node in the given undirected graph. For a graph consisting of a single cycle and where each player knows his or her position but not the position of the other player, which strategy—from among the following—is best? One player stays put and the other moves around the cycle; both agree to move to some specific node; or some third option.

Warm-up: Suppose the two players are in a graph consisting of a cycle of *n* nodes (see Figure 1). The nodes are numbered, and each player knows both the topology and the number of the node where he or she is placed. If both players move, say, clockwise, they may never meet. If player A does not move (the "stay-put" strategy) and player B moves in one direction, player B will find player A in n–1 minutes in the worst case. Alternatively, if both agree to move as quickly as possible to some node, say, node 4, and stay there, then the latter of the two will arrive at node 4 in $n/2$ minutes at most. Is there any other strategy that has a worst-case time complexity of $n/2$ minutes but also a better average-case time complexity than the go-to-a-common-node strategy?

Solution to warm up. Player A can always move clockwise (given a map of the graph for which clockwise makes sense), and player B can always move counter-clockwise. They will meet each other in at most $n/2$ minutes in the worst case, with an expected value less than the go-to-a-common-node strategy.

A graph consisting of a single cycle is, of course, a special case. For an arbitrary graph of size *n*, where each player knows his or her own position and the topology of the graph and where every node has a unique identifier, is there a solution that will take no more than $n/2$ minutes in the worst case?

Solution. Go to the centroid of the graph, or the node to which the maximum distance from any other node is minimized. If there are several such nodes, go to the one with the lexicographically minimum node id. Note that such a centroid cannot have a distance greater than $n/2$ to any other node.

We are just getting started. Now consider situations in which each player knows the topology but not where he or she is placed and the nodes have no identifiers.

Start by considering a graph consisting of a single path. If player A stays put and player B moves in one direction and bounces back from the end if player B does not find A, the worst-case time could be $2n$–3 minutes. Is there a strategy that takes no more than *n* minutes in the worst case?

Solution. Yes, each player goes in some direction, and when that player hits an end he or she bounces back. In the worst case, this strategy takes n–1 minutes, with an expected value of approximately $3n/4$.

Now here are two questions I don't know the answers to. We'll call them upstart questions.

UPSTART 1. ***Better than staying put***. When both players do not know where they are placed, nodes are unlabeled and the graph has at least one cycle, find a strategy that is better in the worst case than the one-player-stays-put strategy.

UPSTART 2. ***Also better than staying put***. In the same setting as Upstart 1, say we allow both players to leave notes on nodes they have visited. Is there an approach that takes $n/2$ minutes for the two players to meet up in the worst case? If not, is there an approach that takes $3n/2$ minutes in the worst case? Please specify whichever approach you come up with.

THE GENEROSITY OF FRIENDS

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Correction: Changyang Ryoo was incorrectly listed as the recipient of the Math Master's Thesis Prize in our spring issue. Though Ryoo was selected for the prize, he declined to accept it.

Simulated tectonic plate motion in the North Eastern Pacific. Arrows show plate velocities and colors Earth structure. Read more about Georg Stadler's work on mantle convection and plate tectonics on page 4.