The Year in Review
Revisiting Control Theory

It has been over 20 years since the IMA devoted an entire year to control theory. The 2015-2016 Annual Thematic Program on Control Theory and its Applications was an opportunity to revisit the topic. The field has changed remarkably in these two decades, as many cutting-edge ideas considered hot topics in 1992 are now mature technology. Control technology is so well integrated in our daily lives that it is nearly invisible to the user. Now, as we usher in the era of the internet-of-things (IOT), modern power systems, and autonomous vehicles, research in control theory becomes ever more important.

Reflected in the three fall workshops was a sustained focus on the important subject of control over networks. It is through an interdisciplinary approach, something the IMA fosters, that progress could be made in this challenging topic. The workshop on Optimization and Parsimonious Modeling in the spring was remarkable for bringing ideas from data science to control. The May workshop centering around the energy market and the power grid was timely. It brought mathematicians, engineers, economists, and policy-makers together to address a problem of great societal importance.

As is typical in an annual program, senior long-term visitors served as “anchors” around which key activities revolved. Visitors and postdocs organized seminars, offered tutorials, conducted research, and had many informal discussions, creating an exciting atmosphere at the IMA.

Truly rewarding was the return of postdocs from the 1992-93 annual program, now established in their careers. Among them were Anders Rantzer, Mary Ann Horn, Bo Bernhardsson, Li Qiu, and Scott Hansen. For the 2017-18 academic year, rather than an annual thematic program, the IMA will offer several programs of different lengths and scale. These programs take advantage of the IMA’s flexibility, and the exciting topics reflect the IMA’s nimbleness and willingness to take risks. Highlights of the programs are:

- **The Industrial Mathematics Clinic: Tackling Collaboratively Emerging Problems in Industry** will promote modern business mathematics research through collaborative working groups consisting of senior faculty, industry leaders, and junior faculty.
- **Innovative Statistics and Machine Learning for Precision Medicine** is an emerging practice of medicine that uses a patient’s specific characteristics to guide treatment decisions. The program will bring together statisticians, biostatisticians, data scientists, and healthcare domain experts.
- **Modeling, Stochastic Control, Optimization, and Related Applications** brings together a multidisciplinary community to discuss recent progress in (i) stochastic control, computation methods, and applications, (2) queueing theory and networked systems, (3) ecological and biological applications, and (4) finance and economics applications.
- **Multiscale Mathematics and Computing in Science and Engineering** addresses emerging topics in multiscale modeling and computational challenges in the context of materials modeling, with the goal of launching new collaborative research communities of mathematicians, scientists, and engineers.
- **SageMath Coding Sprints** will further develop this open-source, general purpose mathematical software system by designing and implementing new algorithms and computational tools that will be of use to academic and industrial scientists.

Additionally, several standalone workshops are planned on topics such as phase retrieval, application of sheaf theory, and smart urban transportation.

Reshaping the IMA

Over the last two years, I have been touched by the level of support for the IMA and encouraged by the number of people who have helped us create a plan for the future. After a lot of effort, I am happy to say that I see a path forward.

Our vision is for the IMA to become a powerhouse in data science research able to address challenges from industry, government, and other disciplines. We are finalizing strategic partnerships with two major corporations that will pave the way towards a sustainable model of industrial collaboration. The IMA Data Science Lab, now in its second year, will play a central role in this development. At the same time, we will leverage our strength to serve the Department of Energy research community. Implementation of these strategies will allow the IMA to continue to be a global leader in the mathematical sciences. Opening career pathways for young mathematical scientists will remain an important part of our mission. The Math-to-Industry Boot Camp (full story on pg. 15) will continue in the summers of 2017 and 2018. Noted in the article are two early success stories of the camp—a data scientist position with the Milwaukee Brewers for one participant and a summer internship at the Federal Reserve for another. New in 2017 is the Data Science Fellowship. Run as a partnership with Amlana, a cloud and data science consulting company, the eight-week program will train recent Ph.D.s and students near completion in the basic techniques and tools used in data science and provide them with the opportunity to work in teams on real-world industrial projects.

Lastly, the Participating Organization program remains vital to the IMA, and we are exploring ways to provide more value to our partners. They have already contributed in essential ways to several programs this past year and next, and I anticipate that they will be even more involved in shaping the programs at the IMA.

As my two-year extension as director comes to an end, I am pleased by how far we have gotten since the NSF announced its decision to ramp-down its support of the IMA. I am optimistic that with your help, support, and engagement, the IMA will continue to flourish.

Fadil Santosa
Director
As new technologies have emerged, the field of control theory has evolved alongside. By the time the first IMA program on control theory was held in 1992-93, the field had developed a clear identity with a common language, themes, and problems to solve.

“[That year produced] some beautiful mathematics. Impactful in several important application areas,” said organizer Tryphon Georgiou (University of Minnesota, Twin Cities).

The field of control theory entered a new era with the transition to wireline and wireless networking and the development of sensors, powerful computers, and complex software, as this enabled new collaborations and a broader use in applications. Current research plays a key role as an “enabling technology” in a wide range of applications from autopilots, navigation, and robotics to telecommunications, cellular phones, and power systems.

“In fact, almost everywhere you turn, there is a control application,” Georgiou said. “We are at a point where the field has a lot of applications and a lot of open problems, but not so much the same language. We develop theory as a field, and at the same time, we’re searching for language so we can communicate problems.”

An example of the language gap is the term “network,” which has different meanings in different disciplines—is it a communication network, a logical network, or a graph? The first three workshops all pertained to networks, showcasing the different ways they are used. Organizer Anders Rantzter (Lund University) noted that the program had a strong presence of presentations demonstrating how the internet economy is interacting with control—one of the reasons why the large network is becoming a predominant feature to study.

Many talks also addressed problems that currently or will impact society, such as in transportation when city traffic comes to a standstill or biological networks where something happens to a cell that causes it to become cancerous. A recurring theme was understanding the inherent feedback mechanisms and how local events can have a global effect.

“When you discuss impact, and when you ask engineers what impact did the theory have, it’s very few of the engineers who actually have a big picture of all the impact of control because it’s very, very hidden,” Rantzter explained. “It’s not noticeable until the technology fails.”

But this program has “put all the people with slightly different angles on the same thing in the same room having to hear each other and discuss with each other,” Georgiou said. “The IMA is fostering a better language between us and a more coherent and cohesive set of mathematical ideas and tools.”

In 2015-16, the IMA hosted more than 40 long-term visitors and had 13 postdoctoral fellows in residence.

More information, including videos of the lectures, is available online at www.ima.umn.edu/2015-2016.
New Directions Professor Juan Cockburn Explores Future Research

A sabbatical opportunity and previous ties with the University of Minnesota and the IMA brought Juan Cockburn (Rochester Institute of Technology) back for the program on control theory.

After finishing a Ph.D. in electrical engineering at the University of Minnesota in 1994, he spent a year at the IMA as an industrial postdoc working at the Honeywell Technology Center.

“That was the [program] year of Waves and Scattering (1994-95), and despite not being my research area, I had the chance to interact with other postdocs, give presentations, and participate in the IMA workshops,” he said. “That year at the IMA left a profound impact on me; it embodied the ideal environment to conduct research and discuss new ideas.”

When Cockburn was looking for a place to interact with researchers from other universities and explore new ideas for further research, he learned that the IMA was going to have a program on Control Theory and Applications and knew he could not miss it.

“One of my sabbatical objectives was to explore future research directions in networked control systems,” he explained.

Throughout the year, Cockburn learned about current approaches for modeling, analysis, and control over networks and the mathematical framework developed to study these problems in different application domains, including biological, transportation, power, and other networked control systems.

“At the Rochester Institute of Technology, there is an ongoing initiative to develop technologies for the use of unmanned aerial vehicles (UAVs) for imaging applications that arise in infrastructure inspection,” he said. “I plan to use my new understanding gained at the IMA to develop algorithms for coordination and control of ensembles of UAVs to optimize their image acquisition tasks.”

Cockburn also learned about new developments in polynomial optimization and convex relaxations.

“My interest in polynomial optimization problems and their numerical solution via semidefinite relaxations led me to interesting and fruitful discussions with Farhad Jafari (University of Wyoming), who was working in moment problems and positive matrix completion problems,” he noted. “These problems are related by duality with linear measure optimization problems.”

That led to a collaboration with Jafari which has already produced a paper presented at the 2016 International Symposium on Mathematical Theory of Networks and Systems, as well as other papers in preparation. In this same vein, Cockburn’s collaboration with Tay Netoff (University of Minnesota, Twin Cities) explores the use of hybrid systems identification methods, which can be reduced to polynomial optimization problems, in the study and modeling of seizure signals.

“The IMA offered me the opportunity to meet in person, and have interesting discussions with, many well-known researchers, whose work I knew from reading their papers,” Cockburn added. “This level of interaction would not have happened at a conference meeting. It has been a unique experience.”
Embracing Interdisciplinary Connections

As a neuroscientist in the biomedical engineering department, Tay Netoff (University of Minnesota, Twin Cities) brought a new perspective to the IMA’s workshops on control theory.

“I feel that control theory has made little impact on optimizing therapies for neurological disorders such as epilepsy and Parkinson’s disease,” Netoff said. “These workshops provided the opportunity to discover cross-discipline fertilization and bring control approaches into more medical-type problems.”

Netoff is particularly interested in using sophisticated feature extraction tools and fitting computational models to data to characterize neuronal behaviors.

“[Seeing the wide variety of control theory applications] let me identify tools and collaborate with experts in the field to translate some of this work into a biomedical field,” Netoff noted. “I was inspired by many people and tried to follow up on potential projects.”

These projects included:

• Working with Juan Cockburn (Rochester Institute of Technology) on applying switching autoregressive models fit to recordings from animal models of epilepsy to identify and quantify when changes in dynamics occur during seizures and perhaps changes in dynamics leading up to a seizure.

• Discussing with Ian Manchester (University of Sydney) on how to apply his multivariate autoregressive fitting algorithms with stability constraints to EEG recordings from patients with epilepsy to identify pathological interactions that might identify a seizure focus. Utilizing algorithms for clustering graphs from Carolyn Beck (University of Illinois at Urbana-Champaign) to help identify neurons when the signals measured from them are non-stationary over time. “She and I have discussed approaches for using her analysis tools with our neural recordings.”

• Using Caroline Uhler’s (Massachusetts Institute of Technology) MTP2 algorithm to help with parcellation of fMRI data. “She has provided me with code, and I am working with a graduate student to use her tools in data sets we already have.”

• Conversing with Mihailo Jovanovic (University of Minnesota, Twin Cities) about using his tools for leader identification in network data to identify areas of the brain that might be responsible for initiating seizures.

Perhaps most inspiring was the talk given by Rodolphe Sepulchre (University of Cambridge).

“It transformed my thinking of the importance of the balance of excitation and inhibitory loops in the brain,” Netoff explained. “He used a closed-loop feedback control theory approach to understanding how the brain keeps excitation and inhibition in balance and how they work at different time scales. This talk was truly transformative for me, and I have recommended his paper to many people since.”
POSTDOC PROGRAM

Reviewing More Than 30 Years of IMA Postdoctoral Fellowships

The IMA's postdoctoral program is highly regarded for its contributions to expanding the talent base engaged in applied mathematical research and interdisciplinary investigations.

More than 200 postdoctoral candidates from around the world compete each year for a limited number of two-year fellowships and the opportunity to work with distinguished researchers at the IMA. Not only do IMA postdocs have the chance to engage in research in an interactive, collaborative environment, but they receive mentoring, career development, and training as well.

The “regular” postdoctoral fellowship dates back to the IMA’s inception in 1982. Regular postdocs are immersed in the unique environment offered through the IMA’s annual thematic program, which focuses on a broad field of interdisciplinary mathematics. Postdocs are mentored by both a faculty member at the University of Minnesota and a long-term visitor connected with the annual thematic program. The IMA counts 295 individuals as having participated in this fellowship, with many going on to become leaders in their field (see sidebar “Leading the Way”). Nearly 85 percent of IMA regular postdocs currently work in academia. Of the 70 percent of postdocs employed at U.S. universities, 87 percent are at a top-tier research, or Ph.D.-granting, university.

The IMA’s industrial program also dates back to the inception of the IMA as the idea was included in the original proposal to the National Science Foundation. It wasn’t until Avner Friedman became the IMA’s second director in 1987, however, that the focus on industrial activities increased. Friedman started connecting with companies and inviting industrial scientists to come to the IMA to talk about the types of problems they worked on and how mathematics figured into those problems. As Friedman often worked on these problems himself, he became the editor of a series of 10 “Mathematics in Industrial Problems” books within the IMA Volumes series published by Springer.

In 1990, Friedman hired the first four postdocs to work at Honeywell, 3M, and Alliant Techsystems. The idea of the industrial postdoctoral fellowship grew from Friedman’s discussions with industrial scientists, who envisioned this as a way to prepare postdocs for research careers in industry or those involving industrial interaction in academia. The industrial postdoc divides their time between a company-directed project and their own research. Each postdoc is paired with a mentor at the industry site and at the IMA.

“It has been very widely successful and has been viewed as one of the most valuable activities that the IMA has for industry. A number of them have gone on to work for the companies that we collaborated with on the project,” said current IMA Director Fadil Santosa. “The fact that there is a prestigious appointment as an industrial postdoc at the IMA means they can come here for two years and find out for themselves what working in industry would be like. If that doesn’t fit with their plans, they can use this as a way to springboard to a different career.”

Of the 64 individuals who have been an industrial postdoc, 41 percent have continued to work in industry.

LEADING THE WAY

Many former IMA postdocs have gone on to become prominent leaders in the field. Names below are specified by postdoc year, current affiliation, and fields of study.

1982-1983  C. Eugene Wayne (Boston University)  dynamical systems, nonlinear PDEs
1984-1985  Carme Calderer (University of Minnesota, Twin Cities)  applied mathematics, materials science
1984-1985  Panagiotis Souganidis (University of Chicago)  PDEs
1985-1986  Ruth Williams (University of California, San Diego)  probability theory, stochastic processes
1986-1987  Chi-Wang Shu (Brown University)  numerical analysis
1987-1988  Bernd Sturmfels (University of California, Berkeley)  algebraic geometry
1989-1990  Mary Silber (University of Chicago)  dynamical systems
1993-1994  Lenore Cowen (Tufts University)  discrete mathematics, algorithms
1998-1999  Trachette Jackson (University of Michigan, Ann Arbor)  mathematical biology
1999-2000  Yalchin Efendiev (Texas A&M University)  numerical analysis, geophysics
2000-2001  Selim Esedoglu (University of Michigan, Ann Arbor)  applied mathematics
2001-2002  Anna Mazzucato (Pennsylvania State University)  analysis, PDEs, inverse problems
2003-2004  Gerard Awanou (University of Illinois at Chicago)  numerical analysis
2006-2007  John Voight (Dartmouth College)  algebraic geometry, number theory
This is substantially higher than the percentage of regular postdocs currently working in industry, which stands at 15 percent.

Eighteen percent of all former IMA postdocs are employed in industry, where they work in a wide variety of sectors (see figure "Industry Sectors Where IMA Postdocs Work"). Interviews with six former postdocs show that the IMA was instrumental in preparing them for positions in industry (page 6). In the past year, the IMA has increased its industrial activities with the introduction of a new Data Science Lab (page 12) and Math-to-Industry Boot Camp (page 15).

**INDUSTRY SECTORS WHERE IMA POSTDOCS WORK**

- AUTOMOTIVE: 2
- BROADCAST MEDIA: 1
- COMPUTER SOFTWARE: 9
- DEFENSE AND SPACE: 4
- ENGINEERING: 3
- FINANCIAL SERVICES: 8
- GOVERNMENT ADMINISTRATION: 1
- INFORMATION TECHNOLOGY: 5
- INSURANCE: 2
- INTERNET: 5
- LAW PRACTICE: 1
- MANAGEMENT CONSULTING: 1
- NONPROFIT ORGANIZATION MANAGEMENT: 1
- OIL AND ENERGY: 5
- PHARMACEUTICALS: 3
- REAL ESTATE: 1
- RESEARCH CENTER: 12
- RETAIL: 1
- SEMICONDUCTOR MANUFACTURING: 1

**POSTDOC PROGRAM**

**How the IMA Prepared Six Postdocs for Working in Industry**

*Answers have been edited for space.*

**How did being an IMA postdoc help prepare you for your present position?**

**BA:** It helped me see how it is to work in industry, that there are challenging math problems arising from industry, and that mathematicians can do research and publish in academic journals while working in the industry. I met a few fellow IMA visitors and colleagues who were instrumental in guiding me in my decision of accepting an industrial job offer.

**JB:** Managing projects independently from a variety of fields with various deadlines helped me to prepare for the many disparate problems I encounter as an industrial mathematician.

**BG:** I was a postdoc during the year on optimization, and I found the program to be ideal for someone like myself trying to decide between pursuing an academic career or working in the industry.

**LL:** The opportunity to work with a team of mathematicians and engineers showed me how applicable math can be to many different areas. Just being at the IMA gives you an amount of exposure to other fields and applications that is invaluable in opening your eyes to all of the opportunities that exist for mathematicians.

**BM:** Working with Siemens gave me valuable training and insight into how a mathematician can contribute to a larger industrial research group, as well as how industrial research integrates effectively into the company’s goals. The work presented opportunities for cross-discipline collaboration, to participate in project identification and development, and for exposure to value and constraints associated with industrial research projects.

**Was the IMA helpful in setting you off on your career?**

**JB:** There were many opportunities to meet industrial mathematicians. Personally, connections through the IMA led directly to the position I currently hold.

**RH:** It gave me a great comparison mechanism for academia vs. industry and provided me tools to make a decision of where I envisioned myself in my future career.

**LL:** My first job was actually with the company that I worked with as an industrial postdoc. I partnered with the Applied Math Group at Boeing Research & Technology and got hired on permanently after two years.

*continued, next page*
BM: My experience gave me perspective on what a career in industry could be like, as well as the research opportunity that helped lead to my receiving a National Science Foundation Postdoctoral Fellowship. During the NSF postdoc, I began working in mathematical finance, which ultimately led to my career in the financial industry in quantitative risk management.

In your opinion, what are the most valuable contributions a mathematician brings to industry?

BA: Mathematicians make the most difference by being thorough in their solution, tackling a problem unbiased, and offering out-of-the-box solutions to challenging problems.

JB: Technical imagination, a fresh perspective, and we are trained to generalize and see commonalities between problems.

BG: Rigor and critical thinking provide unique perspectives for solving real-world problems. The conceptual reasoning that comes with exposure to abstract math is also a big advantage for mathematicians who are interested in an industry career.

RH: A researcher with an extensive applied mathematical background has the versatility to work on a wide range of problem in real-life settings. The ability to apply your knowledge to a broad range of fields and to solve problems in realistic situations is powerful and well-received in industry.

LL: I think mathematicians bring the skill of abstract thinking. That abstraction allows us to not just solve the problem in front of us, but develop a solution that will be useful for an entire class of problems.

BM: Rigor, the ability to pose well-defined problems, and the ability to assess the quality of solutions. It is not uncommon to see incorrect conclusions drawn from statistical analysis of data due to lack of understanding of the methodology, knowledge of the underlying assumptions, or limitations such as small sample size. Mathematical rigor helps avoid these issues and provides a framework for the critical assessment of results.

What advice do you have for students interested in industrial jobs?

JB: Attend conferences and workshops outside of pure and applied mathematics. Computer science conferences may see half of all accepted papers and presentations submitted by industrial mathematicians.

BG: Be curious about real-world problems and dig deeper into the finer nuances to see where the math is really being applied. Other advice would be to know at least one programming language very well and have a good conceptual understanding of big data technologies used in large-scale mathematical models.

LL: Get as much exposure to industry and engineering while in graduate school. Summer internships are a great, low-risk way to try out a new field, so don't be afraid to step out of your comfort zone. Also, learn to code! It’s a highly marketable skill and an excellent way to make math usable by others. Python is a great language to start with.

BM: Focus on communications with colleagues and seeking to minimize complexity of solutions wherever possible. It is essential to communicate the intuition behind an approach to have it implemented as part of a larger system or product. Ability to code well and work with data is essential. Documentation and validation of models is also increasingly important.

“The conceptual reasoning that comes with exposure to abstract math is a big advantage for mathematicians who are interested in an industry career.” – BALAJI GOPALAKRISHNAN
While Needell received this recognition for her contributions to sparse approximation, signal processing, and stochastic optimization, and Ward received this recognition for her contributions to the mathematics of machine learning and signal processing, much of their research overlaps. It is not surprising that Needell and Ward are frequent collaborators, as both are lauded by their peers as being among the most talented applied analysts in the country. Their most oft mentioned work in respect to this award was their 2013 paper on “Stable image reconstruction using total variation minimization,” published in the SIAM Journal on Imaging Sciences.

“This gave theoretical guarantees for total variation minimization in compressed sensing, which prove that given undersampled measurements of some signal (e.g. an image), one can search for the signal with the same measurements that has the lowest variation—that is, smallest gradient—and that this reconstruction yields near-optimal error,” Needell explained.

A particularly striking application of these principles arises in medical imaging. Consider magnetic resonance imaging (MRI), where the underlying image to be recovered is, say, a horizontal section of a brain or neck. Like most natural images of interest, this section can be thought of as a two-dimensional function that will be constant or slowly varying over most of the domain, interrupted only by sharp changes across a low-dimensional set of values corresponding to edges.

At the same time, each measurement in an MRI scan corresponds to a Fourier transform component, representing the response of the image to a particular frequency. Each measurement takes time and costs money, and thus it is desirable to obtain high-quality MRI reconstructions using as few measurements as possible.

“My work has answered questions like: what is a good subset of frequencies to take if the total scan time is limited to one hour, or alternatively, if one has a fixed budget of frequencies? And how should one reconstruct the underlying image from these frequencies?” Ward said. “The joint work with Deanna gave theoretical guarantees for a popular reconstruction method used in practice, total variation minimization, and suggested a stochastic sampling strategy for selecting frequencies which achieves these guarantees.”

Needell says that “rather than measuring in every ‘direction’ as in a typical MRI, compressed sensing promotes measuring in a small number of random directions, and it turns out that is enough to still ensure accurate image reconstruction.”

Other applications for this type of data acquisition and analysis include sensor and distributed networks, statistical problems, compression, and image processing problems.

Ward credits her Ph.D. advisor, Ingrid Daubechies, for getting her interested in these types of problems.

“She construction of compactly supported smooth wavelets. The combination of practicality and mathematical beauty blew my mind,” Ward said.

Needell's Ph.D. advisor, Roman Vershynin, had a large influence on her career as well, having introduced her to the field and to her first experience in real mathematical research. It also helped that she enjoyed classes in probability and analysis, and it turned out that these topics were used in a lot of results of compressed sensing.

“Even though compressed sensing is an applied field, it uses many tools from ‘pure math.’ So for me, it is an area that is the best of both worlds,” Needell noted.

Needell is also expanding her research horizons into methods for stochastic and combinatorial optimization.

“Often, these methods involve intriguing geometric and probabilistic problems which are fun to solve, and also have a wide array of important applications,” she said. “I’m also interested in using these kinds of techniques along with other compressive methods to analyze large-scale medical data, a personal passion of mine.”

Ward plans to spend a sabbatical year working in industry doing machine learning research.

“It will be good for me to get out of the ivory tower for a while and face the applications head on,” she added.

The IMA Prize in Mathematics and its Applications is awarded annually to a mathematician who has made a transformative impact on the mathematical sciences and their applications. The award recognizes an individual who has received his or her Ph.D. degree. The award recognizes an individual who has made a transformative impact on the mathematical sciences and their applications. The prize can recognize either a single notable achievement or acknowledge a body of work. The prize consists of a certificate and a cash award of $3,000. Funding for the IMA Prize in Mathematics and its Applications is made possible by generous donations of friends of the IMA.
Nash and Nirenberg received the 2015 Abel Prize for their striking and seminal contributions to the theory of nonlinear partial differential equations (PDEs) and its applications to geometric analysis.

According to organizer Robert Kohn (New York University), the most obvious connections between Nash and Nirenberg’s works are by area—geometric analysis and regularity theory are among the subjects where both made fundamental advances—but a more subtle connection is that each introduced important methods and tools which have become essential parts of the fabric of the field. As the Abel Committee’s citation puts it: “Their impact can be felt in all branches of the theory [of nonlinear partial differential equations], from fundamental existence results to the qualitative study of solutions, both in smooth and nonsmooth settings.”

Nash spent the latter part of his career at Princeton University, where he was a senior research mathematician, but much of his mathematical work was done while at the Massachusetts Institute of Technology (MIT) during the period from 1951 to 1959. Nirenberg carried out his entire career at New York University’s Courant Institute of Mathematical Sciences, where he is now a professor emeritus.

Organizer Ragnar Winther (University of Oslo) opened the conference, followed by remarks from Nirenberg. Tragically, Nash and his wife Alicia were killed in an automobile accident on May 23, 2015, as they returned home from Norway after receiving the Abel Prize.

Nirenberg talked about how he first knew of Nash through Nash’s papers and how each time Nirenberg read one of Nash’s papers, he would think, “I would never have thought of that.” Nirenberg finally met Nash in 1956 when Nash was on leave from MIT at Princeton because Nash would often visit New York University. They became friends, talking about mathematics, where Nash asked Nirenberg for his opinion regarding interesting problems Nash could work on.

Nirenberg then explained how Nash got started working on the problem of isometric embedding: “While at MIT, Nash was sometimes critical of his young colleagues, saying, ‘Oh, that’s not very interesting what you’re doing. You should be working on better problems.’ So one day, Warren Ambrose said to him: ‘Well, John, you’re so smart. Why don’t you work on this old problem in geometry?’ And that’s exactly what he did.”

Many participants expressed their appreciation for being able to meet Nirenberg in person and learning more about Nash.

“Professor Nirenberg holds a special place in my career, and I am very familiar with his research, but this conference gave me a historical timeline about how it formed. And it was very pleasant to learn this. In addition, learning about Professor Nash was very valuable for me,” said a workshop participant.

Overall, the conference invited “experts of different ages,” as stated by one participant. “It is good to communicate with both the older and younger experts.” Another participant noted the “high research level of the younger speakers.”

Yet another participant concluded that “the workshop gathered researchers involved in the study of different aspects of PDEs, and the mix was perfect for everyone to profit.”

The Abel Conference series honors the Able Prize Laureates and is a collaboration between the Norwegian Academy of Sciences and Letters and the IMA. Videos from the conference can be seen at ima.umn.edu/2015-2016/SW11.2-4.15.

The IMA gratefully acknowledges the generous support of Schlumberger-Doll Research, the University of Minnesota College of Science and Engineering, and the University of Minnesota School of Mathematics for this annual conference series.
Linguistics, Statistics, and Artificial Intelligence in the Big Data Era

Presenting the seventh annual Arnold Family Lecture in February, Lillian Lee, computer and information scientist at Cornell University, discussed machines and their current ability to talk to people. This field of study is known as natural language processing, in which the goal is to create systems that use human language as input and/or output. Applications include speech-based interfaces (such as Siri), information retrieval/question answering (such as the Google search engine), automatic summarization (reducing text to key points), and automatic translation (of foreign languages).

“It’s not just about science fiction movies, but this is actually about helping people do things better,” she said.

Alan Turing, the father of modern computer science, founded the field of artificial intelligence by proposing a benchmark for describing when artificial intelligence has been achieved by machines. A machine could be termed “intelligent” if it responded to queries in a manner that was completely indistinguishable from a human being. Or as Lee puts it: “I don’t know what intelligence is, but I know it when I see it.”

Siri and Watson, the computer that won on Jeopardy, are examples of intelligent machines. Both had to learn natural language to not only understand the questions being asked of them, but to also provide the answers. Thus, it appears that the Turing test has been passed. Lee argued that, despite these examples, machines are still imperfect—especially when what Siri hears doesn’t transcribe properly or when Watson provides an obviously wrong answer.

Why is understanding language so hard then? Many words sound the same, sentences don’t just have one meaning, and context matters. Consider these two sentences:

“It’s hard to recognize speech” versus “It’s hard to wreck a nice beach.”

“There are so many possible meanings behind language. How can we possibly build systems that are able to extract the right ones?” Lee asked.

This is where probability and statistics come into play to figure out what people intended or are likely to say. Language models can be built to estimate the probability of which meaning is more accurate. In essence, a machine would select one message from a set of possible messages.

“The fact that we have so much [text] data [from the web] allows us to get better estimate sizes and employ better models,” Lee explained. “Models of language that integrate well with data-driven approaches have really led to a lot of successes that we’ve had in the field.”

Modeling Tsunamis and Other Geohazards

The 2004 tsunami in the Indian Ocean and the 2011 tsunami off the coast of Japan were generated from some of the largest earthquakes ever recorded on a seismograph, at magnitudes of 9.1 and 9.0, respectively, resulting in catastrophic property damage and an overwhelming number of fatalities.

It is fitting that this public lecture was held in March because it coincided with the fifth anniversary of the Japanese earthquake and tsunami. While devastating, this event provided a wealth of data that Randy LeVeque, an applied mathematician at the University of Washington, uses to validate his mathematical modeling methods to develop a better understanding of these phenomena.

The data comes from the Deep-ocean Assessment and Reporting of Tsunamis (DART) buoy system that was expanded after the 2004 events to create a better real-time warning system. As LeVeque explains it, the system consists of pressure gauges at the bottom of the Pacific Ocean that measure the weight of the water as it goes up and down; a buoy floats on top to transmit data to a nearby satellite.

Math is used to develop and analyze models of fluid dynamics and wave propagation and then to develop and analyze numerical or computational methods to solve these complex equations for an approximate solution.

“What I started out doing mostly in my career was developing numerical methods for solving partial differential equations and then analyzing them,” he said. “Then I got more and more interested in implementing these methods in software that could be used for a wide variety of problems.”

LeVeque started the Clawpack open source software project in 1994 and since 2004 has been heavily involved in developing and using the GeoClaw branch for tsunami modeling and hazard assessment.

“It’s an important thing to keep in mind as an applied mathematician that any time you write down a mathematical model, it’s not going to be exactly right no matter how complex you make it.” LeVeque explained. “And it may or may not be useful. Sometimes simple models are even more useful than complex models. It depends on what you’re trying to do, and a big part of being an applied mathematician is figuring out what’s the right model to model the phenomenon that you’re looking at and how can you make it work.”

Recorded public lectures are available on the IMA website at ima.umn.edu/public-lecture.
IMA Hosts Industry-related Workshops

IMA workshops are well suited to foster interdisciplinary connections.

The IMA works closely with members of its Participating Corporations (PC) program to connect academic research to the scientific needs of industry. Three workshops united researchers from academia, industry, and government labs in an effort to develop new collaborations.

Research Collaboration Workshop: Optimization and Uncertainty Quantification in Energy and Industrial Applications

Optimization and uncertainty quantification have broad applicability to industrial problems in design, manufacturing, transportation, scheduling, product support, and more. The need for greater efficiency and confidence is driving industries to embrace techniques from these fields in their work processes. Knowing cutting-edge tools are vital for solving open problems, the IMA held a workshop in February that provided a forum for researchers from industry and energy laboratories to discuss these types of problems arising in their practice.

“Department of Energy labs have expertise in optimization and uncertainty due to their work in energy and national security applications,” explained organizer Bruce Hendrickson (Sandia National Laboratories). “As both producers and consumers of this research, they are well positioned to help industry figure out how to employ these technologies.”

To demonstrate the potential impact of government and industry collaborations, keynote speaker Loren Miller (DataMetrics Innovations) opened the workshop by describing a collaboration between Sandia National Labs and Goodyear Tire & Rubber Company that saved the company from bankruptcy.

The workshop also featured talks from academia and energy laboratory representatives on recent developments in mathematical algorithms and software tools.

“Lior Horesh (IBM) gave a thought-provoking presentation on the challenge of selecting appropriate models to balance competing requirements for accuracy, flexibility and rapid response,” Hendrickson said. “Karl Kempf (Intel) built upon these ideas in his presentation on the need to consider the human decision maker in the overall optimization process.”

Workshop participants expressed their appreciation for the balanced mix of speakers from different backgrounds.

“I was especially impacted by the various complementary approaches to optimization—some were refreshers, some were new, all were useful,” said one participant. “It’s good to be jolted out of one’s standard thinking by other creative thinkers working on related problems.”

Control at Large Scales: Energy Markets and Responsive Grids

Held in May, the seventh and final workshop of the annual program on Control Theory and its Applications featured big-picture discussions regarding the state and
direction of power systems. Interest in power and energy research has surged in recent years with the advent of “smart grid” initiatives that use digital communications technology to detect and react to changes in usage. According to organizer Sean Meyn (University of Florida), this workshop presented an opportunity to educate participants about the complexity of the power grid and how the increased usage of renewable and energy-efficient resources is transforming planning and operational patterns.

“Innovation in power systems is slow. This is true in part because of the enormous cost in investment,” he added. “A highly efficient ‘gas turbine’ generator costs about $1 billion U.S. dollars. It is now believed that storage is required to mitigate the impact of volatility from renewables. The cost of installation of large battery systems, or virtual storage from flexible loads, also runs in the billions of dollars.”

Cost leads to another important aspect of the workshop: economics. Meyn believes that many practitioners and academics have a naïve view of economics, where “marginal cost” is a meaningful metric for payments, but this ignores more than 50 percent of the cost of generating and delivering power.

As one workshop participant put it, “the interplay between controls and markets is highly important and needs to be understood.”

The workshop included presentations related to the policy and economics of energy markets, an aspect greatly appreciated by workshop participants. David Spence, a law and policy professor at the University of Texas at Austin, gave a survey of economics and explained the gaps in focusing on the marginal cost analytical framework for power market design.

“It was a tremendously scholarly lecture that challenged prevailing views,” Meyn said. “We need a scientific foundation for economics that takes in all of the issues; people like Spence need to partner with mathematicians and control theorists.”

Frontiers in PDE-constrained Optimization

PDE-constrained optimization focuses on finding an optimal solution to questions that are naturally constrained to obey physical laws, something that arises in a wide variety of disciplines. Recent theoretical and algorithmic advances in scientific areas such as inverse problems, topology optimization, and uncertainty quantification, combined with the continuing increase in computing capabilities, have allowed researchers to consider new classes of challenging industrial problems.

“Having a workshop with participation from a broad range of disciplines helps raise awareness about the industrial problems that can now be solved,” said organizer Martin Lacasse (ExxonMobil). “These problems range from designing novel materials through additive manufacturing to optimizing the design of pumps, engines, airplanes, or chemical reactors to imaging the human body or the earth subsurface.”

According to Lacasse, though high-quality software is available, PDE-constrained optimization remains a difficult topic as many concepts must be mastered before using these tools to solve a given problem.

The first two days of the June workshop consisted of tutorials designed to provide a broad and uniform introduction to graduate students, postdocs, and young researchers desiring to learn more about this topic. About two dozen participants attended the nine tutorials, which covered every aspect of PDE-constrained optimization from basics to implementation to industrial-scale applications.

The second part of the workshop brought together practitioners of different disciplines from industry, national laboratories, and academia to establish collaborations. The goal was to expose academia to industry-scale problems and discuss state-of-the-art approaches to solve PDE-constrained optimization problems.

“The variety of the tutorial and technical talks was great and fostered interactions between industry and different fields of mathematics and computational engineering,” said organizer Drew Kouri (Sandia National Laboratories).

“The Neil Aage (Technical University of Denmark) and Francois Jouve (University of Paris VII) talks were well received by Boeing, who has a significant interest in structural optimization,” added organizer Harbir Antil (George Mason University).

“On the other hand, the talk from Martin Lacasse (ExxonMobil) and the tutorial from Jeremy Brandman (ExxonMobil) raised scientific curiosity among the academic attendees.”

Organizers also hope these real-life, industrial examples will increase awareness amongst graduating students that industry is offering challenging and competitive career opportunities.

Generous support of this workshop was given by ExxonMobil.
IMA Establishes New Data Science Lab

The lab is led by Gilad Lerman, professor of mathematics and director of the Minnesota Center for Industrial Mathematics in the School of Mathematics at the University of Minnesota, Twin Cities.

The lab aims to serve as a hub for collaboration between industry and academic researchers and to provide industry with access to academic research and tools for data analysis.

“The creation of the lab is driven by the need to develop tools for the analysis of big data in various application domains,” Lerman said. “Mathematics plays a significant role as it provides a framework for identifying significant quantitative tasks, as well as helping establish effective algorithms in addressing these tasks.”

The low cost of collection, ubiquity of sensors, and abundance of storage have created an enormous amount and diversity of data, from scientific and medical to business, traffic, and social. All of these sources generate high-dimensional and high-volume data. Currently, the ability to generate and store vast quantities of data far outpaces the ability to analyze, process, and understand it. The directive of the lab is to work with industry and be inspired by recent developments and market needs.

In the area of data analysis, this year Lerman and his team of seven graduate students have worked on problems related to robust and scalable dimension reduction, distributed computing, effective analysis in high dimensions, non-convex optimization, structure from motion, geospatial imaging, and decision-making under distributional ambiguity.

The lab also launched a seminars series featuring leading researchers in data science. The seminars provide a forum for academic and industrial scientists to discuss and learn about recent developments. According to Lerman, the seminars held over the past year were an opportunity to showcase data science research being conducted across different departments at the University of Minnesota.

“It’s important to bring people together and combine different aspects of various disciplines, especially when we want to train students to work in industry,” Lerman explained. “By collaborating with several departments within the University, we have created a multidisciplinary group that is able to work on current and relevant problems while integrating different components and disciplines.”

Additionally, the seminars enable the lab to make connections with industry and learn about the issues they face and how the lab can address their challenges with theoretical work.

“The lab helps its industrial partners attract excellent, local talent in data science,” Lerman said. “Building the relationship between companies and academia allows both parties to work symbiotically and with mutual interest—sharing talent, resources, and focus.”

In May 2016, the IMA hosted the lab’s first annual review in which Lerman described research activities and directions of the lab to 30 industrial scientists, with short talks given by each of the lab members. More than 20 companies from a wide variety of industry sectors were represented, ranging from healthcare and finance to automotive and aerospace.

“The IMA has more than 30 years of experience leading collaborations between mathematicians and industry, and the Data Science Lab utilizes and extends this experience to connect with industries working in data science,” Lerman noted. “Industry is invited to explore what the lab has to offer.”
Resource Trade-offs: Computation, Communication, and Information

From May 16 to May 19, 2016, experts on data analysis and large-scale machine learning exchanged ideas and identified new opportunities in this emerging research area.

When working with large data sets or high-dimensional data, a variety of different computational and statistical resources may be required. For example, one particular data set may need more runtime or more memory to be analyzed efficiently while another large data set may be stored on different processors that need to communicate with each other and there is a limit on how much information can be communicated. As for machine learning algorithms, one of the required resources is the number of training samples.

Various constraints influence these resources, such as data privacy, robustness of the algorithm to corruption (as points that deviate from the rest of the points can affect the accuracy of the algorithm), and partial access to the data.

"Traditionally, people would study these things completely separately and deal with each resource or each constraint on its own," explained workshop organizer Gilad Lerman (University of Minnesota, Twin Cities). "But there are several recent, interesting works that try to study how the different resources and constraints affect and correlate with each other."

Research has shown that for certain learning tasks, if there is a large training sample, resources can be reduced, be it required runtime, memory size, or the amount of communication—all while overcoming the previously mentioned constraints. As another example, analyzing the computational runtime required to achieve a certain statistical accuracy has proven to be a useful framework to study learning algorithms and their performance in a variety of settings.

“When you work with high-dimensional, real-world data which exists on multiple processors that communicate with each other, there are a lot of limitations,” Lerman said. “It’s important to explore how to effectively process and analyze such data in view of these limitations."

In addition to stimulating new discussions and collaborations, the workshop included social activities, such as an afternoon cruise along the Mississippi river. Many participants expressed their appreciation for this aspect, as one said the “community that came seemed quite diverse, and the discussions were lively.”
Mathematical Optimization

The IMA held a two-week New Directions Short Course on Mathematical Optimization from August 1 to August 12, 2016.

Optimization algorithms are essential tools in many areas of science and engineering, especially with the increasing availability of large amounts of data. Optimization models are also used in a wide variety of business problems, such as transportation operations (in trucking and airline industries), electricity generation and distribution, and workforce planning and scheduling.

"First, the analysis of data to build meaningful predictive models—like statistical and machine learning—requires efficient methods for fitting such models, and optimization models and algorithms are critical to this task," explained organizer Jim Luedtke (University of Wisconsin, Madison). "Second, the eventual goal of most organizations is to use data to make better decisions."

Broadly speaking, mathematical optimization includes translation of problems into models, analysis of the properties applied to the models, design of algorithms to solve these models, and effective computational implementations of the algorithms.

"Optimization problems have a wide variety of mathematical structures, such as whether decisions are discrete or continuous, what types of constraints are imposed on the decisions, and how much uncertainty there is in the data," Luedtke said. "Each of these different structures requires different techniques for analyzing and solving the associated models."

In two intensive weeks, participants learned about a wide variety of these models and gained a basic understanding of the potential and challenges of several different classes (continuous, stochastic, and discrete) of optimization problems.

"The topics discussed were exactly in sync with my research interests. As a beginning Ph.D. student, this workshop helped me figure out where the boundary is in cutting edge research in optimization."

—WORKSHOP PARTICIPANT

“We hope participants will recognize when a problem they face may benefit from being formulated as an optimization model and be able to create such a formulation,” Luedtke said. “Understanding the theory behind the methods to solve these models will help them formulate models that are more likely to be solvable by available methods.”

In addition, participants learned many of the basic algorithms for solving these problems and gained experience with implementing some of them, a practical skills aspect that was much appreciated.

“Students worked extremely hard in problem sessions to implement advanced models and algorithmic techniques in both stochastic and discrete optimization,” said organizer Jeff Linderoth (University of Wisconsin, Madison). “For many of them, they were learning AMPL, A Math Programming Language, for the first time.”

Ultimately, the short course will enable more people to solve their problems better by making use of optimization tools.

“Understanding the theory behind optimization algorithms enables the design of new methods that may exploit the structure appearing in a problem to solve the problem at scales otherwise not possible,” Luedtke noted.
IMA Launches Innovative Program for Training Graduate Students

In summer 2016, the IMA replaced its long-running Math Modeling in Industry workshop with the new Math-to-Industry Boot Camp.

Over the past several decades, there has been a rising gulf between the number of students completing Ph.D.s in pure mathematics and the decreasing percentage of traditional tenure-track positions in four-year colleges and universities. At the same time, there is a growing recognition that industry is increasingly relying on jobs that require sophisticated mathematical techniques and that the use of mathematics and algorithms can be a source of tremendous value. As most Ph.D. students in mathematics are being trained for dwindling tenure-track jobs in the academic sphere, they are left unaware of and unprepared for careers in business, industry, and government.

When the Division of Mathematical Sciences at the National Science Foundation began soliciting program proposals that provide enriched doctoral training in the mathematical sciences, the IMA directorship saw this as an opportunity to show students how mathematics is used in industrial applications and how a mathematician can thrive in an industry environment. The boot camp was proposed as an intense six-week session designed to train graduate students for employment outside of academia.

“The idea was to make the IMA’s math modeling workshop more accessible to a greater variety of students with different backgrounds, different interests, and different educational training,” explained IMA Director Fadil Santosa. “Students who don’t have a computational or modeling background can participate in the camp and work on projects—we did this by providing training to get them ready for the projects.”

The first three weeks of camp introduced 32 participants to the basics of programming (MatLab, Java, Python, and C), data analysis (basic statistics and machine learning), and mathematical modeling (probabilistic and physical modeling) to help them obtain the technical skills they would need to succeed in industry. In addition to the lectures, students had hands-on sessions with COMSOL, multi-physics solver, and the statistical package R, as well as working in small groups on problems provided by instructors.

Training also included helping students acquire soft skills that companies would expect good job candidates to have, such as teamwork, project management, running meetings, and making effective presentations. A career center counselor showed students how to craft a resume instead of a curriculum vitae and how to set up a professional LinkedIn webpage. Participants also benefited from informal interactions with local industrial mathematicians who were invited to discuss their careers and experiences from working in industry.

The second half of the boot camp focused on two projects. The first was a small-scale project designed to introduce the concept of solving open-ended problems, to get accustomed to working in teams, and to work within a finite amount of time. The teams then presented their results, received feedback on shortcomings, and made revisions for a second presentation.

“It was a drastic improvement between the first presentation and the second presentation of the project,” Santosa noted. “I think one of the things they were able to learn from the experience was how to limit the scope of inquiry so that they didn’t have a lot of open-ended questions to chase after.”

The second set of, or capstone, projects were posed by industry scientists from VivaQuant, Oneirix Labs, Revon Systems, Target, Whitebox Advisors, and Spiceworks, who also served as mentors for the teams. Problems included a remote ECG-monitoring wearable device, using human guided machine vision to detect roads, predicting asthma triage based on patient health, creating a universal identifier for users and customers, and other engaging challenges.

It did not escape the attention of Alfonso Limon (Oneirix Labs) that many students had not been trained in their home institutions on sufficiently applied methods to be able to tackle industrial problem without further training.

“In my team, which required understanding of signal and image processing, none of the students had studied these subjects. Despite their applied deficiencies, the IMA in just over a month’s time had taught them enough programming, machine learning and mathematical modeling that they were able with a little additional training to bring a tough problem to a preliminary conclusion to the satisfaction of Oneirix in just under a week,” he said. “That is an impressive task, as it shows that with minimal additional training, by the IMA, you can get a good mathematician to understand enough to solve real industrial problems.”

Chris Bemis (Whitebox Advisors), having previously participated in IMA programs as an industry mentor, noticed the similarities between the math modeling workshop and boot camp, but could also see what a difference the first few weeks of training made for the students.

“The students came into my project with a confidence and a familiarity with the general approach of ‘working in industry’ that I haven’t experienced elsewhere,” he noted. “The result was a bit more calm, some more focused questions, and a very competent presentation and report from the students.”

The desired outcome of the boot camp is the development of a powerful work force that meets the needs of industry and contributes to the economic well-being of the U.S.

“We hope to create a culture change where the student is empowered to make an informed career decision,” Santosa said.
Support the IMA

The IMA values and honors each and every gift, and thanks you for your continuing and generous support. Please consider giving online to the IMA at ima.umn.edu/giving.

Starting with its initial years in the early 1980s, and continuing to the present day, IMA has been a leader in defining how a mathematics institute can have impact. The heart of its vision is that well-chosen programs (with well-chosen leaders) can catalyze scientific activity—accelerating progress and even creating communities that did not previously exist. Who else would have been bold enough to hold full-year programs such as Applications of Algebraic Geometry (2006–7), Mathematics and Chemistry (2008–9) or Scientific and Engineering Applications of Algebraic Topology (2013–14)? I am proud to be a supporter of this unique organization.

—ROBERT KOHN, New York University

I obtained a Ph.D. degree in applied mathematics from the University of Minnesota. During my studies, I had the opportunity to take courses with, be advised by, and/or be a teaching assistant for professors that have been heavily engaged with the IMA, including four of its five current directors. So, although I was not involved with the IMA, I was still highly aware of the IMA’s mission and how passionately its directors carry it out year round. It is because of my gratitude to my former professors that I started donating to the IMA in the first place.

With so many other organizations addressing important issues out there, why do I keep donating to the IMA? As stated in its website, the IMA connects scientists, engineers, and mathematicians in order to address scientific and technological challenges in a collaborative, engaging environment, developing transformative, new mathematics and exploring its applications, while training the next generation of researchers and educators. To me, it does not get more important than that. The IMA provides a unique environment for collaboration. Visitors and postdocs at the IMA tackle very tough problems whose solutions positively impact our whole society. From that point of view, donating to the IMA is not really donating; it is paying back just a little bit of the immeasurable debt we all owe to it.

—JOSE OROZCO RODRIGUEZ, Vision-Ease Lens

I have chosen to support the IMA for its strong impact in applied mathematics, especially in training of junior researchers, and in fostering new research directions and interdisciplinary collaboration at all levels of the profession.

I have had the privilege to be a postdoctoral fellow, as well as a long-term visitor, at the IMA. In both instances, the time I spent at the IMA has had a profound and lasting impact on my career as a mathematician, effecting directly my employment and allowing me to start fruitful collaborations in new areas of my field of research, which is continuum mechanics and partial differential equations.

On a more personal note, the IMA environment and staff have shown me how welcoming and inclusive mathematics and mathematics people can be. I would not be where I am now without in part the support of the IMA.

—ANNA MAZZUCATO, Pennsylvania State University
IMA Partners

The IMA is a partnership of the National Science Foundation, the University of Minnesota, and a broad consortium of affiliated universities, government laboratories, and corporations. Affiliation brings many benefits to members, including access to research, influence over the IMA’s agenda, collaboration within the IMA’s network, and opportunities to participate in workshops, short courses, and tutorials.

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IMA Institute for Mathematics and its Applications

The Institute for Mathematics and its Applications connects scientists, engineers, and mathematicians in order to address scientific and technological challenges in a collaborative, engaging environment, developing transformative, new mathematics and exploring its applications, while training the next generation of researchers and educators. It receives major funding from the National Science Foundation and the University of Minnesota.

The University of Minnesota is an equal opportunity educator and employer. The University’s mission, carried out on multiple campuses and throughout the state, is threefold: research and discovery, teaching and learning, and outreach and public service.

This publication/material is available in alternative formats upon request. Direct requests to Georgia Kroll, workshop coordinator, at kroll@ima.umn.edu.

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