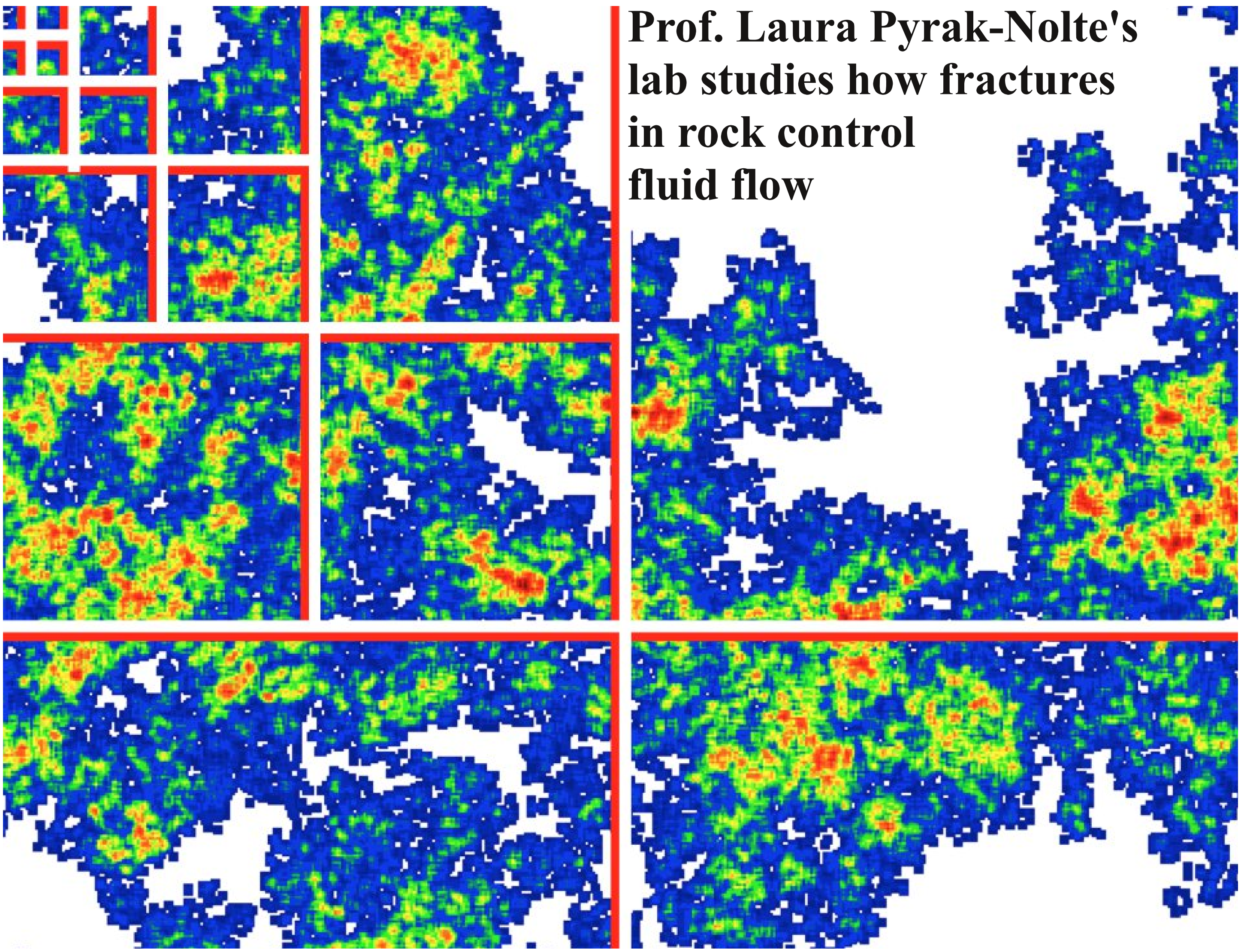
Physics INTERACTIONS

A NEWSLETTER HIGHLIGHTING THE DEPARTMENT OF PHYSICS AND ASTRONOMY AT PURDUE UNIVERSITY

2016

Prof. Laura Pyrak-Nolte's lab studies how fractures in rock control fluid flow



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Credits

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Front Cover Credit: Prof. Laura Pyrak-Nolte

From the Head

Well, we have made it through another trip around the Sun. This time of year brings together family and friends to share memories and look forward to a brighter future. It is also time for me to reach out to you, our loyal alums, to provide an update on the goings-on in the Department of Physics and Astronomy. I am now into my second year as department head and I must say the position keeps me on my toes. However, it is always good to reflect on the year that was so here is what I can tell you.

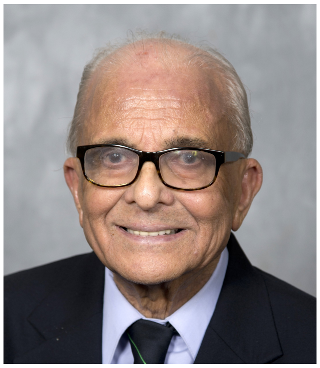
We welcomed Assistant Professor Qi Zhou at the beginning of the academic year after an extensive international search. Qi comes to us from the Chinese University of Hong Kong where he was an assistant professor. Qi's research interests are in theoretical Atomic, Molecular and Optical (AMO) Physics. It was an eventful year for departures. After 60 years of devoted service to the department and Purdue University Prof. Anant K. Ramdas retired in the summer. Many of you will remember Anant and his quick wit and outstanding teaching during your time here. We also had Prof. Thomas Moffett retire after 41 years of devoted service. Tom was the torchbearer of astronomy in the department for many years. Finally, Prof. Jiangping Hu accepted a position with the Chinese Academy of Sciences in Beijing, China after 12 years of service to Purdue. JP was a fixture in our advanced graduate courses.

We also had a continuing accumulation of awards by our faculty. Prof. Carlson was elected to the Executive Committee of the Division of Condensed Matter of the APS. Two of our colleagues, Prof. Yong Chen and Prof. Leonid Rokhinson, were elected Fellows of the APS. Prof. Chens citation reads, "*For significant contributions to the material physics of chemical vapor deposition; and to the development of intrinsic 3-D topological insulators with transport dominated by Dirac surface states*." while Prof. Rokhinson's states, "*For contributions to the field of mesoscopic semiconductors*." Only ½ of 1 percent of members are distinguished this way by the APS. Prof. Tongcang Li was the recipient of an NSF CAREER award while Prof. Norbert Neumeister was named an LHC Physics Center Distinguished Researcher. The department can only bask in the glow of these noteworthy accomplishments. Of course this is not an exhaustive list and all the accomplishments and recognitions of our faculty, students and staff are detailed inside.

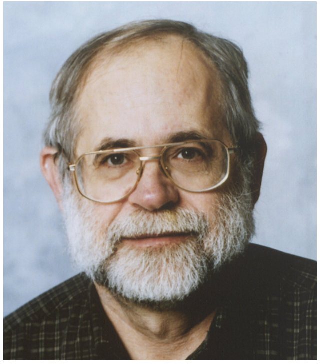
This was also the kickoff year of the Charlotte Ida Litman Tubis Award which recognizes a graduate student's ability to communicate their research to the non-expert. The inaugural award was won by Brianna Dillon-Thomas who was a student of Prof. Hisao Nakanishi. You can read her winning contribution about her work on Pg. 6 of this newsletter.

We also honored you, our alumni, with awards for your contributions to society and science. Last year's Outstanding Alums and Distinguished Alums were a truly worthy class and an absolute pleasure to welcome back to campus. You can read about them and their accomplishments on page 13. I am always amazed at the genuine outpouring of appreciation that our alums shower upon the department. It is both motivating and humbling and I treat it as a challenge to make Purdue Physics and Astronomy better and worthy of your affinity. Here's hoping your new year is a productive and successful one!

Farewells



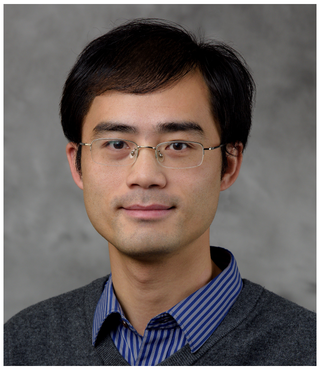
Anant Ramdas, Lark-Horovitz Distinguished Professor of Physics and Astronomy, retired in May 2016. Prof. Ramdas joined the Purdue faculty in 1960 as an assistant professor after having been hired as a research associate in 1956 by Prof. Lark-Horovitz himself. Ramdas' research in spectroscopic measurements of semiconductors produced 35 PhD students, over 200 publications and numerous professional recognitions including fellowships in the American Physical Society, Indian Academy of Sciences, Optical Society of America, and American Association for the Advancement of Science. In 1994 he won the Isakson Prize of the APS for Optical Effects in Solids. He holds a B.S. from Poona University (India) and a M.Sc. and Ph.D. from the Raman Research Institute (India) under the direction of Nobel Laureate Sir C. V. Raman.



Thomas Moffett, Professor of Physics and Astronomy, retired in May 2016. Prof. Moffett began his Purdue career in 1975 and conducted research in optical astronomy, focusing on galaxies in the Local Group, variable stars, and flare stars. Over the course of his career Prof. Moffett taught all of the undergraduate astronomy and astrophysics courses offered by the department. He earned a B.S. and M.S. from Louisiana State University and a Ph.D. from the University of Texas.

Jiangping Hu started in the department in 2004 as an Assistant Professor in the area of theoretical condensed matter physics. He was promoted to Associate Professor in 2009. He accepted a position at the Institute of Physics, Chinese Academy of Sciences, Beijing, in August 2016.

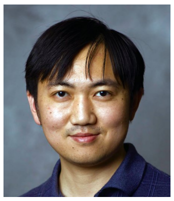
Arrivals



Qi Zhou, Assistant Professor of Physics and Astronomy, joined the department in September 2016. He specializes in atomic, molecular, and optical (AMO) physics with research interests in topological studies of ultracold atoms, strongly interacting fermions and bosons, quantum hall states of ultracold atoms, universal relations in quantum dilute systems, strongly correlated systems in optical lattices, and quantum dynamics of multi-component atoms. Prof. Zhou comes to the department from the Chinese University of Hong Kong where he was an assistant professor. He holds a B.S. from Tsinghua University (China) and a Ph.D. from the Ohio State University.

Faculty Honors

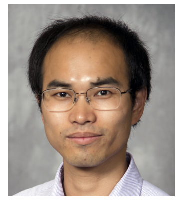
Erica Carlson was elected to the Executive Committee of the Division of Condensed Matter of the American Physical Society.



Yong Chen was promoted to Professor and elected as a Fellow of the American Physical Society.

Gabor Csathy was promoted to Professor and received the Purdue College of Science Research Award.

Sergei Khlebnikov received the Ruth and Joel Spira Award for Outstanding Graduate Teaching.



Tongcang Li received a National Science Foundation CAREER Award.

Andrew Mugler received the Ruth and Joel Spira Award for Outstanding Undergraduate Teaching.

Norbert Neumeister was named a Large Hadron Collider Physics Center Distinguished Researcher.

Leonid Rokhinson was elected as a Fellow of the American Physical Society.

Staff Recognitions

College of Science Customer Service Award
Jim Corwin
Tom Miller
Keith Schmitter
Hattie Sturgill

College of Science Engagement Award
Matt Weisner

College of Science Leadership Award
William Fornes
David Sederberg

College of Science Professional Achievement Award
Debra Nahlik

Staff Awardees (from left to right): Department Head John Finley, David Sederberg, William Fornes, Hattie Sturgill, Keith Schmitter, Matt Weisner, Debra Nahlik, Associate Dean George McCabe.

Graduate Student Awards

AAPT Outstanding Teaching Assistant
Michael Meier
Cyrus Vandrevala

Akeley-Mandler Award for Teaching Excellence
Ian Arnold

Bilsland Dissertation Fellowship
Shayne Reichard
Valentyn Stadnytski
Haoyu Wang

Charlotte Ida Litman-Tubis Writing Award
Brianna Dillon-Thomas
(see page 6 for the winnning essay)

Dr. Warner L. Black Award
Brendan Sullivan

Edward S. Akeley Award
Matthew Eiles

Gabriele F. Giuliani Award
Amartya Dutta

George W. Tautfest Award
Shayne Reichard

H.Y. Fan Award
Brendan Sullivan

Karl Lark-Horovitz Award
Jordan Steckloff

Lijuan Wang Award
Katherine Schreiber

Teaching Academy Graduate Teaching Award
Andrew Hesselbrock
Kelsie Niffenegger

Undergraduate Student Awards

Arthur N. Pozner Scholarship
Gavin Cox

Frederik J. Belinfante Scholarship
Andrew McNutt

College of Science Outstanding Student Award
Nathan Glotzbach (Fr)
Joshua Leeman (So)
Nicholas Cinko (Jr)
Samuel Higginbotham (Sr)

David G. Seiler Physics Scholarship
Alaina Glidden
Megan Harwell

Judith Peters Humnicky Memorial Award
Jenny Cho

Kenneth S. and Paula D. Krane Scholarship
Nathan Glotzbach
Zachary Schroeder

Lijuan Wang Award
Alison Hoe
Rachel Maxwell

Margie and Don Bottorff Physics Scholarship
Scott Behmer
Nicholas Cinko
Charles Guinn
Yang Mo
Elisha Rothenbush

Richard W. King Award
Scott Behmer (Jr)
Hui Yu (Sr)

Mortara '61 Scholarship
Kathryn Bowen
Oscar Dillman
Nathan Shrum
Caleb Widerhold

Shalim and Paul Sargis Memorial Scholarship
Joshua Leeman
Shaun Owens

Spira Summer Research Award
Joshua Leeman

Graduate Research Focus

Quantum Percolation: Electrons in a Maze

Brianna Dillon-Thomas

Ms. Dillon-Thomas was advised by Prof. Hisao Nakanishi and received her PhD in August 2016. Her article was the winning entry in the department's Charlotte Ida Litman Tubis competition to promotre clear and concise communication of scientific ideas beyond the physics and astronomy community.

Physicists, especially theoretical physicists, love to make models of the world to help us understand it. We weigh various effects against each other, pick out key features, make simplifying assumptions, and reduce a physical phenomenon to its simplest, most tractable mathematical description to get an approximation to reality. Then, bit by bit, we add layers to our mathematical models to create a richer, more complex, and more accurate description of what we observe. While this approach sometimes makes us the brunt of good-natured jokes ("assume a spherical cow…"), our method nonetheless has considerable value. The physical world is incredibly complex, and it is by joining our models with experimental studies that we physicists are able to explain "why the world does what it does" and make predictions about new phenomena not yet observed.

One simplified model is the quantum percolation model, which helps physicists understand electrical conduction. Physicists identify two key factors in electrical conduction: the interactions between electrons (they repel each other), and the disorder of the underlying material (e.g., impurities). The quantum percolation model is one of a few models that look *only* at the effects of disorder (or randomness) on conduction. This is, admittedly, where the model is simplified - in reality, a material has many electrons, so interactions between them will be important. However, the idea is that by ignoring interactions, we can get a better grasp on the role disorder plays in conduction. Once we have done that, we can combine the disorder-only model with one of the interactions-only models for a more complete picture. The quantum percolation model is particularly interesting because the electron behavior it models in two dimensions contradicts the expectations that were set forth by physicists studying a different disorder-only model, the Anderson model. In 1979, E. Abrahams and his colleagues used a mathematical method called scaling theory to predict that even a very small amount of disorder in a two-dimensional system would destroy conduction and make the entire system become insulating (Phys. Rev. Lett. **42**, 673). From the electron's perspective, this meant that the electron would always be *localized* (confined to a small area), as opposed to being *delocalized* as it would be in a conducting material. The scaling theory prediction proved true for the original Anderson model, which is why electron localization due to disorder is often called Anderson localization. It was initially expected that the scaling theory result would be valid for other disorder-only models in two dimensions, but as we will discover, adding disorder in the quantum percolation model does not always result in electrons being localized.

To understand the quantum percolation model, we first need to take a step back and look at the *classical* percolation model. The word "percolation" might remind you of coffee-making, and there's reason for that! "Percolation" simply means the process of one substance passing through another substance that has many holes in it at random locations. Much as the water in your coffee pot must find a way through the spaces between coffee grounds to make your morning coffee, a particle in the percolation model must find a path through a lattice of points that has many empty sites (holes) in it – the only difference being that in the percolation model, the "holes" are what impede transmission, not allow it. This type of percolation, with some sites removed, is called site percolation; alternatively, we could remove links between sites instead, which is called bond percolation (see Fig. 1a and 1b). In both cases, the only way a particular lattice can transmit a particle is if there is a connected path between the start point and the end point (for instance from the upper left corner to the lower right corner in Fig. 1), just like a maze. If we dilute the lattice too much, there won't be any transmission – all possible paths from the start point will lead to dead ends! For classical percolation on a square lattice (ie a square grid of points), this occurs when we've removed 41% of sites (in site percolation) or 50% of bonds (in bond percolation). Of course, even for dilutions less than that critical percentage (q_c), say, at only q=10% sites removed, it is possible to get a *particular* arrangement that has only deadend paths between our chosen start point and end point. However, *on average* for all different ways of arranging a $q<q_c$ dilution, we have a non-zero chance that our chosen input and output will be connected and a 100% chance of finding

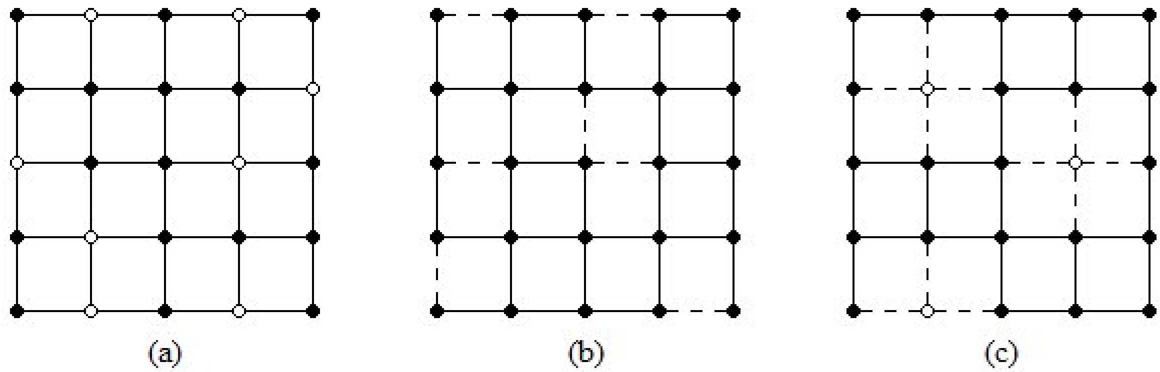


Figure 1: Example lattices for (a) site percolation, (b) bond percolation, and (c) the modified site percolation used in our study.

some connected path across the lattice (while not necessarily between the two arbitrary points we chose), meaning the lattice is conducting. For $q > q_c$ there is zero chance of finding a connected path across the lattice no matter what two start and end points we choose, therefore the lattice is insulating.

Quantum percolation modifies the classical percolation model in one small but very significant way: instead of sending an ordinary particle through the lattice, we use a quantum-mechanical particle, in this case, an electron (though we ignore many electron properties because of our model being a simplified one). You may know that electrons exhibit particle-wave duality, that is, they have the properties of both particles and waves. It is the wavelike nature of electrons that makes the quantum percolation model more complex, because the electron wave function can interfere with itself, analogous to how light interferes with itself to create a pattern of light and dark spots when shined through two very narrow slits (Young's double-slit experiment). This characteristic means that the electron may not be transmitted even when a connected path is present on the lattice, since its wave function can reflect off of the infinite-energy barriers created by the removed sites/bonds, resulting in the electron interfering with itself (just like a wave of water interferes with itself when reflecting off a wall). Because of these interference effects, we expect that the critical dilution above which there is on average no transmission will be a lower dilution than in the classical percolation model.

In our study of the quantum percolation model, we look at a modified version of site percolation: at a given dilution q, we randomly remove q% of the sites on a square lattice with *NxN* sites, and as we do so we also remove the four bonds connecting that site to its neighbors, since an electron on one of those neighbors now has nothing to hop to (Fig 1c). By removing the site, it's as if we have put an infinitely tall wall around it; no matter how much energy an electron has, it can't get over the walls to get to that site. Thus, as the electron spreads across the lattice, whenever part of its wave function encounters a diluted site, that part is reflected back, while the rest of the wave function continues on through the lattice. At low dilutions, the disordered lattice is like a room with scattered infinitely-tall pillars – only a small part of the wave function will be reflected overall. At high dilutions, the lattice is like a maze with many twisting corridors and dead-ends – there will be much more reflection and interference, enough that the chance of the electron getting through is very low (if not zero) even if there is a connected path across the lattice. Having diluted the lattice, we send an electron with some energy E into the one corner of the lattice, and, using a combination of quantum mechanics and computational methods, we calculate the electron's transmission through the opposite corner. We repeat the process several hundred times for different *realizations* of the *NxN* lattice (that is, different ways of arranging the q% diluted sites) to get the average transmission for that lattice dilution and electron energy.

To establish whether the electron is delocalized at a given dilution q and energy E, however, we must measure not just the average transmission, but also the average transmission on different sized lattices, in order to scale up to a macroscopic system - physicists call this the *thermodynamic limit*. After all, even just a nanogram of matter contains trillions of atoms, so a 100x100-atom lattice is not very realistic! Starting with a lattice of just 10x10 sites, we calculate the average transmission over successively larger lattices, up to *NxN* with $N \approx 900$. We then plot the average transmission T vs the lattice size N to determine the trend as $N \to \infty$. If the transmission eventually levels off to some non-zero value, we know that the electron is *delocalized*. If the transmission decays to zero, the electron is *localized*; how quickly the transmission decreases tells us whether the electron is strongly or weakly localized, i.e. whether it is stuck in a very small area of the lattice or is spread over a somewhat larger area that is still small enough to keep the electron from travelling across the lattice.

So far we've discussed these calculations in general terms: some energy *E*, a given dilution *q*. In actuality, we calculated the average transmission for six electron energies *E* and about a dozen dilutions *q* between 2% and 38%. Combining the results for all energy and dilution pairs gives us a phase diagram for the 2D quantum percolation model (Fig 2). The phase diagram tells us that, within the energy range we studied, it is in fact possible to have a delocalized electron state for low dilutions. This discovery suggests that disorder does not always prevent conduction in two dimensions, in contrast to the Anderson model results (the other disorder-only model) and the scaling theory predictions! Instead, the relationship between disorder and conduction in two dimensions is more complex. Disorder has a stronger effect at smaller energies, as seen by the decrease in the phase boundaries for $E<0.1$, a result which is consistent with previous related studies. Additionally, as disorder increases, there is not an abrupt shift from delocalized to strongly localized, but rather, there is a region of weak localization between the two for all but the smallest energies. For all energies, our results indicate that the critical dilution at which the electron is always strongly localized is in fact lower than the classical percolation threshold for zero transmission, as we predicted.

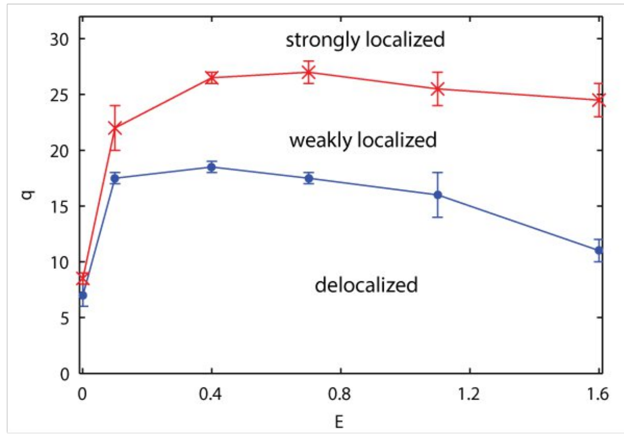


Figure 2: The dilution q vs. energy E phase diagram for the quantum percolation model, showing the phase boundaries beetween the delocalized, weakly localized, and strongly localized phases that the model exhibits.

Having established that disorder does not necessarily prevent conduction in the two dimensional quantum percolation model, an interesting question to consider is how important it is for the diluted sites to be completely disconnected from the rest of the lattice, or, in physics terms, what happens if we introduce the possibility of *tunneling*. When a classical particle encounters a barrier, it is reflected unless it has enough energy to go over that barrier. For a quantum mechanical particle like an electron, complete reflection only occurs for infinite energy barriers. For finite barriers, it might be reflected, but there is also some probability that it could be *transmitted through* the barrier instead, which is called tunneling. We can introduce the possibility of tunneling in our model by making the bonds attached to diluted sites weaker than available-site bonds, but not completely nonexistent as in the original model. This gives the quantum percolation model a parameter for diluted-site bond strength, which we call w, that has values between 0 and 1. For $w=0$ (no bond) the model is the same as the regular quantum percolation model; for $w=1$ (full bond) the model is the same as a perfect fully-connected lattice. For $0 < w < 1$, diluted sites all have the same bond strength that is some fraction of the available-site bond strength $w=1$, meaning they are still partially connected to the other sites and the electron may be able to tunnel through the diluted sites. Using the maze analogy, it's as if we have changed the infinitely tall walls around the diluted sites into finite walls ranging from very very tall (small w, similar to the w=0 case) to short shallow bumps (large *w*, similar to an ordered lattice). Our intuition is that at higher values for *w*, the modified quantum percolation model will behave similarly to a perfectly ordered system, with no localized states, but we are unsure of how quickly the model's behavior will change when increasing *w* from 0. If completely disconnecting diluted sites is what gives the quantum percolation model its characteristic three phases, we expect to see localized states eliminated for even small w when we introduce tunneling by making the diluted site bond strength nonzero. If having a binary disorder (that is, having two bond strengths, one for available sites and one for diluted sites) is the more important aspect of the quantum percolation model, we expect to see the localized phases persist for some range of *w*.

To study our modified quantum percolation model, we perform the same calculations as described for the original model, but repeat the process a few dozen times for different values of *w*. Everything except *w* is the same for each round – we use the same six energies, the same lattice sizes, the same dilutions, and even the same sets of disorder realizations! This ensures that any changes observed in the model's behavior are truly the effect of changing the diluted site bond strengths. Having done this, we organize our results into phase diagrams showing the effects of bond strength *w* and dilution *q* for each of the six energies studied. The phase diagrams for three of those energies are given in Fig. 3. Two features stand out in these diagrams. First, for the larger two energies, the phase boundaries are level at least to *w*=0.05, and even up to *w*=0.3 for the largest energy. It is surprising that we can make such a substantial change to the model without seeing any quantitative change in its behavior! In fact, even though the phase boundaries shift as we increase bond strength, the three phases characteristic of the quantum percolation model persist; the localized states do not disappear completely for all energies until the bond strength is just over half of its maximum. Again, the model's behavior is surprisingly stable! These results suggest that having a binary disorder is much more important than having the diluted sites isolated from the rest of the lattice. The second interesting feature is that the lower the energy, the more rapid the change in the phase boundaries as w increases. In fact, for the smallest energy, *E*=0.001, increasing the bond strength to a mere *w*=0.01 (100th of the maximum strength) tips the system into wholly-delocalized states for *q*<14% (we did not study *q*>14% for this energy because it was computationally expensive; *E*=0.001

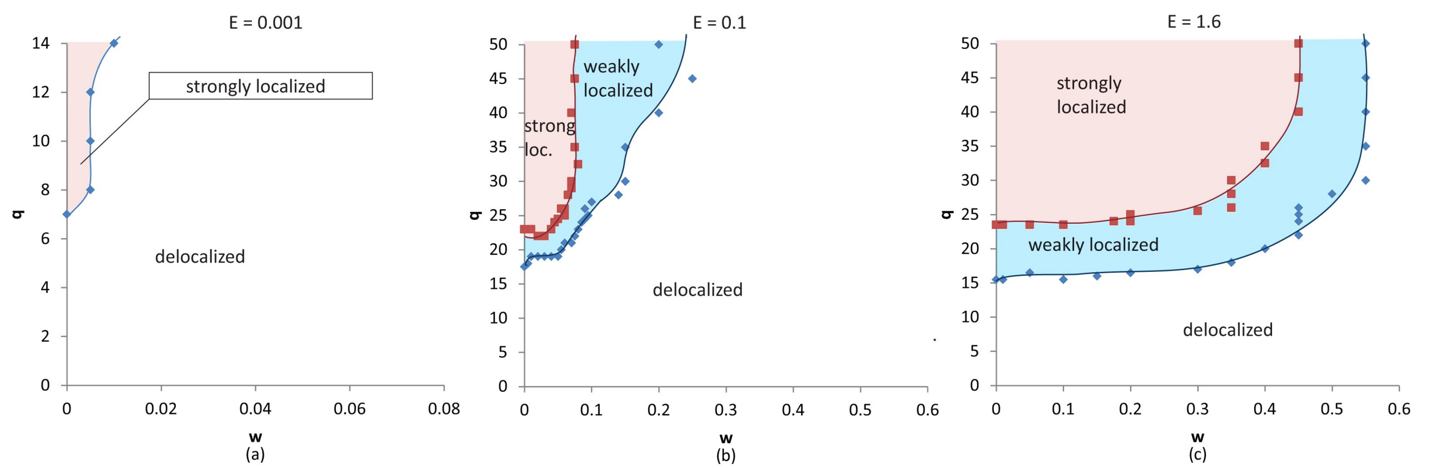


Figure 3: Dilution q vs bond strength with phase diagrams for the modified quantum percolation model at (a) E=0.001, (b) E=0.1, and (c) E=1.6.

calculations are very slow). We are not entirely certain why the quantum percolation model is more susceptible to small changes at low energies, but the result is consistent with the original model's behavior, in which localized states appear for smaller dilutions than all the other energies.

In the end, what does our study of the two-dimensional quantum percolation model tell us? First, it defies expectations for two dimensional systems by actually allowing delocalized states at low disorder, instead of even a small amount of disorder in the system automatically destroying conduction. Secondly, the phase characteristics of the quantum percolation model appear to depend predominantly on the disorder being binary, rather than the strength of the connection between disordered and ordered sites. This makes the quantum percolation model applicable in a wider variety of situations than its original form, such as situations in which it might be unrealistic to model the disorder (such as impurities in a material) as completely isolated from the rest of the material. In the future, the modified model discussed here will need to be further modified to account for interactions, allowing it to be applied to even more situations. However, even in its highly simplified form, we have found that quantum percolation can give us a rich picture of the role disorder plays in determining electrical conduction.

Did You Know?

The department welcomed 32 incoming graduate students and 63 incoming undergraduate students this fall.

Faculty Research Focus

Geophysics of Fractures

Laura Pyrak-Nolte

On any walk through a city or along a mountain trail, it is common to see "fractures" in the sidewalk or rocks along the trail. A fracture may first catch the eye as a flaw in an expanse of otherwise perfect concrete, or as features that define blocks of rocks. It may at first appear as a linear or curvilinear feature along the surface of a sample or a rock outcrop. On closer inspection, this linear feature is seen to be two rough surfaces in contact, defining a geometry that controls the amount of fluid that flows through a rock as well as the stability of a rock mass. The ability to detect and monitor the dynamic evolution of fracture systems in the Earth, such as fractures in geothermal systems, aquifers, hydrocarbon reservoirs, subsurface sequestration sites or fault zones, using geophysical methods requires a link between a remotely-measured geophysical response and a characteristic property (or properties) controlled by the geometry of a fracture (Figure 1).

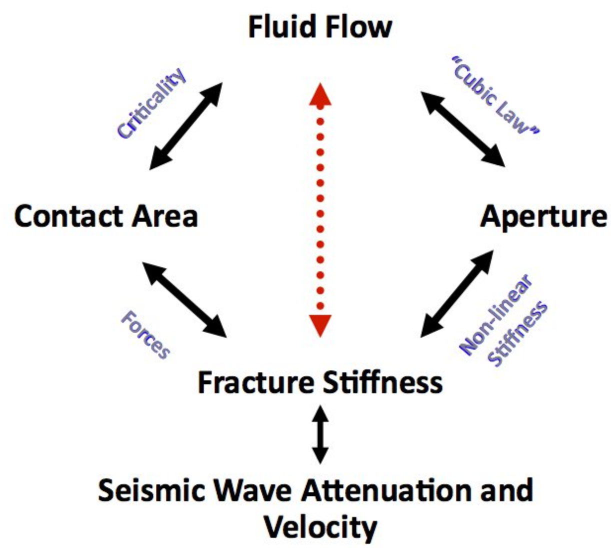


Figure 1: Fracture geometry controls fluid flow and fracture stiffness.

A complication is that mechanical discontinuities (i.e. cracks, fractures, joints, faults, etc.) occur on all length scales (µm to km) and are easily perturbed by natural (e.g. earthquakes) and/or induced processes associated with subsurface projects (e.g., storage of anthropogenic waste, unconventional resource development). The complexity of multiple length scales is illustrated by the problem of seismically monitoring the redistribution of fluid in a fracture. To generate significant seismic scattering, a fracture must have a size comparable to the wavelength of the seismic signal (frequencies from 1 Hz to 1 kHz, wavelengths from 1000's to 10's of meters). However, fluid redistribution in a fracture is controlled by the length scales associated with the aperture distribution in the fracture, and how these length scales are altered by fluid stresses that can open or close a fracture (i.e. length scales on the orders of microns to centimeters). Therefore, the seismic and hydraulic length scales differ by several orders of magnitude, yet both play an important role in stress redistribution of fluids. Thus an accurate assessment of fractures using geophysical methods requires a fundamental understanding of the length scales that control seismic scattering, fracture deformation and fluid migration along a fracture.

In 1992, Neville G. W. Cook noted that "intuitively the effect of joints on mechanical, hydraulic, and seismic properties are primarily a function of the geometry of the asperities of contact between two rough surfaces and of the void spaces adjacent to these asperities." [Cook, 1992]. This concept is embodied in Figure 1 that shows four relationships among the mechanical and hydraulic properties of a single fracture subjected to normal stress. Fluid flow depends on the size and shape of the connected voids in a quasi-two dimensional plane. The probabilistic aperture distribution of the voids controls the magnitude of the flow (Figure 2), while the 2D spatial distribution of the voids controls the connectivity of the flow paths through a fracture (inset in Figure 2).

Fracture specific stiffness is defined from laboratory measurements as the ratio of an increment of stress to the increment of displacement caused by the deformation of the void space in a fracture. As stress on a fracture increases, the contact area between the two fracture surfaces also increases, raising the stiffness of the fracture. Fracture specific stiffness depends on the elastic properties of the rock and depends critically on the amount and distribution of contact area in a fracture that arises from the two rough surfaces in contact. Fracture specific stiffness is an effective parameter that condenses the micro-mechanical heterogeneity in aperture and contact area distributions into a single property.

Because fluid flow and fracture specific stiffness depend on the geometry of the fracture, this suggests that fluid flow through the fracture and fracture specific stiffness are implicitly related through the fracture geometry. For more than two decades, the key questions have been (1) does such a relationship between fluid flow and fracture specific stiffness exist; and (2) if it exists, will the relationship be universal and/or scale. We performed a Monte Carlo study to address these questions. For a relationship between fracture properties to be considered “universal” and “scalable”, a wide variety and a large number of fracture aperture distributions were analyzed as a function of observation scale, i.e. the length of a fracture. A numerical study was performed that used a stratified percolation approach to generate ensembles of spatially correlated pore-scale (microns) fracture void geometries for fractures that spanned in length from 0.0625 m to 1.0 m. For each scale and all realizations, fracture deformation as a function of stress was simulated by accounting for deformation of the asperities, short and long-range interactions among the asperities, and deformation of the solid matrix [Petrovitch et al., 2013; Petrovitch et al., 2014]. A flow network model was used on the deformed fractures to simulate fluid flow, fluid velocity and fluid pressures within a fracture.

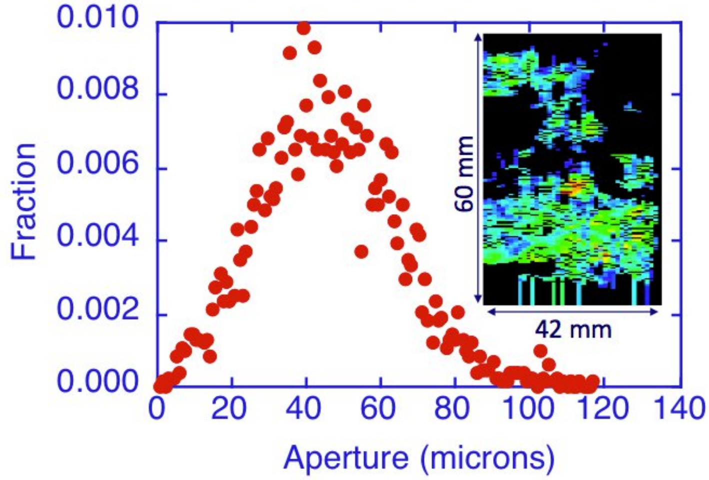


Figure 2: Size distribution of apertures and a contour plot of spatial distribution of apertures within a fracture in coal under stress. Inset: Black – contact area, blue-red represents increasing apertures.

From this study, fracture specific stiffness was determined to be a surrogate for fracture void area. Fracture specific stiffness captures the deformation of the fracture void geometry, including both changes in contact area and aperture. The data from all of the simulations for the different correlation lengths collapsed to a single curve (Figure 3). The collapse exhibits two regimes as a function of scaled stiffness, $(k - kc)\ (aL)^{1/m}$. Scaled flow is in an effective medium regime when $(k - kc)\ (aL)^{1/m} < -1.0$. In the effective medium regime, the permeability/flow is dominated by the porosity of the fracture void space. Fractures with highly channelized flow from chemical erosion fall into this regime, as well as larger-scale fractures at low stress. When $(k - kc)\ (aL)^{1/m} > 0.0$, scaled flow is in the critical percolation regime where permeability is controlled by the connectivity of the flow paths. Small-scale fractures may contain only one flow path whose connectivity is strongly affected by small changes in stress. The transition between the effective medium regime and the percolation regime occurs depends on aperture and connectivity playing competing or supportive roles in the maintenance of flow. The break in behavior occurs at $(k - kc)\ (aL)^{1/m} \sim -1.0$ which captures a fundamental change in the velocity field (Figure 3 inset) as it changes from relatively homogeneous flow paths to flow fields at high stress dominated by the critical path.

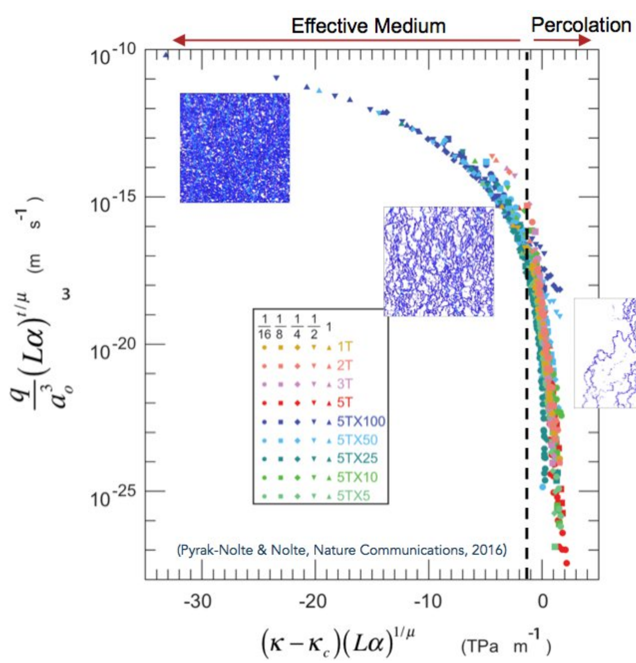


Figure 3: Scaled fluid flow as a function of scaled fracture specific stiffness for weakly correlated (1T), correlated (5T) and channelized from erosion (5TX5 - 5TX100) aperture distributions. Insets show the velocity field as the scaled stiffness increases (after Pyrak-Nolte & Nolte, 2016).

By using an appropriately scaled fracture specific stiffness, the scaling relationship between fluid flow and fracture specific stiffness was discovered to be valid for a broad range of fracture geometries under laminar flow [Pyrak-Nolte and Nolte, 2016]. The collective data collapse of a wide range of fracture topologies and scales is an important step forward to capture the complexity of mechanical deformations and the effects on fracture topology that control fluid flow through a fracture. To claim universality, the thermal, mechanical, geochemical and/or pore-filling fracture alteration scenarios that affect flow and mechanical deformation will need to be explored, as well as flow regimes that span from laminar to turbulent.

This scaling relationship can be applied to predict changing flow rates caused by changing stress in subsurface fractured reservoirs. For example, near-surface fractures subjected to less overburden could be treated with an effective medium approach, while fractures at great depth would be in the percolation regime, exhibiting dramatic changes in flow rate with small changes in stress. Furthermore, remote seismic monitoring can probe the subsurface using a range of frequencies enabling it to sample a fractured media at difference scales, which could be used with the flow-stiffness scaling relationship developed here, to predict relative flow in subsurface processes.

Our research has focused on establishing the consequences of fracture topology on the hydraulic, mechanical and seismic behavior of fractures. We have made advances in the understanding of energy partitioning of seismic body waves and interface waves that propagate along and across single and parallel fractures (see http://www.physics.purdue.edu/rockphys/). Our current focus is on the behavior of fluids and particulate transport inside fracture topology. Physics graduate student Zhenyu Xu is exploring gravity-driven chemical dynamics that control the distribution of calcium carbonate precipitates in a fracture to remotely seal fractures through mineralization. Chven Mitchell, a graduate student in Earth, Atmospheric and Planetary Science at Purdue, is simulating particle swarm transport through fractures as a new mechanism for subsurface sensor delivery or contaminant remediation. With Xuhui Zhou, a graduate student in Physics, we are studying the dynamic redistribution of fluids in a fracture in response to internal microscopic perturbations and their connections to external macroscopic behavior. Mr. Zhou has developed an electro-wetting method to internally manipulate fluid saturations in micro-fluific channels to examine film depinning. We are also extending our elastic wave studies in fractured media to examine the effect of fracture intersections on propagating waves. Liyang Jiang, a physics graduate student, is measuring the effect of fracture intersections on a propagating wavefront to determine how energy is partitioned at the intersection between two non-orthogonal fractures. All of these projects contribute to our long-term research goal to broaden our understanding of the fundamental topological and hydrodynamic controls on transport in fractured media.

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Pyrak-Nolte, L. J., and D. D. Nolte (2016), Approaching a universal scaling relationship between fracture stiffness and fluid flow, *Nature Communications*, 7, Article Number 10663.

2016 Distinguished Alumni Award

Robert W. Warr (MS 1951)

Robert Warr was the first African-American to become an Engineering Consultant at Corporate GE. His responsibilities in that role included consulting on all new GE products to assure product reliability and training GE Engineering and Production personnel in the development and production of reliable products, visiting all GE plants in the United States during the course of his career. Mr. Warr was manager of the Microelectronic Reliability & Design Review Center at GE Electronics Laboratory from 1970-1977. He was a contributing engineer to the 1st GE smoke alarm, the 1st GE microwave oven, and the 1st GE Point of Sales Unit. In 1974 he received the General Electric Gerald L. Phillippe Award for Public Service. Mr. Warr holds a BA in Physics from Fisk University and a MS in Physics from Purdue University. While at Purdue, he was advised by Prof. Hubert Yearian.

Michael P. Moses (BS 1989)

Mike Moses was named president of Virgin Galactic in October 2016. Prior to his appointment, he oversaw the commercial suborbital spaceflight program for Virgin Galactic as Senior Vice President of Operations, leading the team in all aspects of safe and successful spaceline operations. From 2008 through July 2011, he served at the NASA Kennedy Space Center as the Launch Integration Manager, where he led all space shuttle processing activities from landing through launch. Mike also chaired the Mission Management Team where he provided ultimate shuttle launch decision authority. Other NASA experience includes working as a Flight Director at the Johnson Space Center and as a flight controller in the Shuttle Propulsion and Electrical Systems Groups. Mr. Moses attended Purdue University, earning a bachelor's degree in physics and a master's degree in aerospace engineering. He also earned a master's degree in space sciences from Florida Institute of Technology. He is a two-time recipient of the NASA Outstanding Leadership Medal, as well as other NASA commendations and awards.

2016 Outstanding Alumni Award

Wai-Kwong Kwok (PhD 1987)

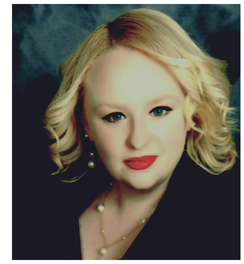
Wai-Kwong Kwok is a Senior Scientist at Argonne National Laboratory and currently serves as a Group Leader of the Superconductivity and Magnetism Group in Argonne's Materials Science Division and as co-Director and Theme Leader of the EFRC's Center for Emergent Superconductivity. Wai-Kwong received a B.A from Kenyon College in 1979 and a Ph.D from Purdue University in 1987. He joined Argonne's Superconductivity and Magnetism Group in 1988 as a staff member. He was a co-recipient of the Department of Energy's Materials Science Award in 1990 and 1997 and in 1998 he was co-recipient of the University of Chicago Awards for Distinguished Performance at Argonne National Laboratory for work on vortex lattice melting in superconductors. He became a Fellow of the American Physical Society in 1999.

Amy Connolly (BS 1996)

Prof. Amy Connolly is originally from Cincinnati, Ohio and completed her B.S. degree in physics from Purdue University in 1996. She earned her PhD from the University of California, Berkeley where she carried out a search for the Higgs Boson decaying to tau leptons with data from the Collider Detector at Fermilab (CDF). In 2003, she started a postdoc at UCLA working in a field that was in its infancy, using a radio technique to search for ultra-high energy neutrinos. From 2006-2010 she continued work in the same field at University College London (UCL) before returning to Ohio as a professor at The Ohio State University. Her research spans simulation, analysis, instrumentation and theoretical interpretation of experimental results.

From the Director of Development

Greetings from West Lafayette!



It is beautiful here this time of year, and I would love to see you back on campus soon! Since taking the role of Director of Development in March of this year, I have had the pleasure to meet many of our alumni and friends across the United States. As a fellow Boilermaker, I am excited to continue meeting with Physics and Astronomy alumni and friends in order to celebrate your education, your career and discuss the ways the department is able to continue producing strong professionals able to succeed in a variety of disciplines.

Publicly launched last October with a goal of $2.019 billion, the Ever True campaign is the largest fundraising effort in Purdue history. The campaign spans July 1, 2012, through June 30, 2019, concluding in the University's 150th anniversary year. This campaign will propel the Purdue Moves initiatives—Affordability & Accessibility, STEM Leadership, World-Changing Research, and Transformative Education—and reinforce the University's overarching commitment to keep a rigorous college education within students' financial reach. As of September 30th, 2016, the campaign has reached $1,311,777,015 (64.91%) of the $2,020,968,452 goal.

Your gifts to Physics and Astronomy help achieve those goals in STEM Leadership – no matter the size! 86% of our donors have given $1,000 or less. EVERY GIFT MATTERS. Ongoing needs in the department include the five million dollar renovation of the Condensed Matter lab used by multiple faculty and graduate staff to produce data crucial to ongoing research, and the Physics and Astronomy building renovation which will cost several million dollars. Extremely significant needs also include faculty professorships, graduate fellowships and undergraduate scholarships necessary for attracting and retaining high quality students to Purdue's Physics and Astronomy department.

I would like to extend a personal invitation to join other fellow Boilermakers, through private giving and personal involvement, to help achieve our goals—and, in doing so, to boldly advance our University as a national and global leader that continues to move the world forward. Our students, faculty and administration cannot thank you enough for your continued generosity and loyalty!

Ever Grateful,
Becky Spears, '06 '10
Director of Development
bmspears@prf.org

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