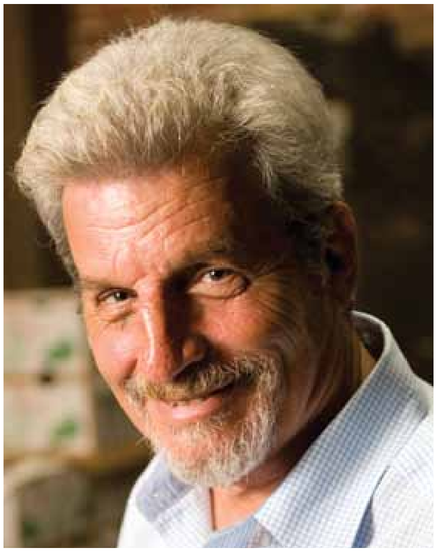
Quantum Leap
University of South Carolina
Department of Physics and Astronomy

Emeritus Professor Wins National Medal of Science



Yakir Aharonov

In October 2010, Yakir Aharonov, distinguished professor emeritus of physics, was awarded the National Medal of Science for his groundbreaking work on quantum mechanics. Aharonov is best known for his discovery (with the late David Bohm) in 1960 of the Aharonov-Bohm effect. Aharonov and Bohm showed how electrons and other charged particles could exhibit interference when they moved around (but not through) a magnetic field. This meant that the particles responded to the presence of the field even though they never themselves passed through a region where the field was nonzero and hence never experienced any magnetic forces. This discovery completely revolutionized the study of both quantum mechanics and magnetic fields. The Aharonov-Bohm effect was controversial for more than 20 years, until it was confirmed by several experiments in the 1980s. Citations to the original paper by Aharonov and Bohm number in the thousands, because its concept has broad application in many areas of theoretical physics. Just this discovery alone would have merited the National Medal of Science; however, Aharonov has continued to this day to enlighten the field with his unique insights into the foundations of quantum theory. In fact, he was mentioned in several publications as a prime candidate for the 2009 Nobel Prize in physics.

But, that is far from the end of the story. Aharonov and his team of students and colleagues have published more than 165 refereed articles, mainly on subjects related to the foundations of quantum theory. He made fundamental advances in the theory of quantum measurement, nonlocal quantum effects, interference, stimulated radiation, gauge symmetry, transition probabilities for quantum systems, quark confinement, and extending quantum measurements to the domain of special relativity. Together with Aharon Casher, he discovered a dual effect to the Aharonov-Bohm effect. Both the Aharonov-Bohm and Aharonov-Casher effects are topological effects, and these contributions have revealed the fundamental importance of topology in physics. Aharonov and his colleagues have developed and applied new conceptual tools to reveal a host of surprising and fundamental quantum effects, including the possibility of a quantum time machine and of measuring negative kinetic energy. The official citation announced he was being honored "for his contributions to the foundations of quantum physics and for drawing out unexpected implications of that field, ranging from the Aharonov-Bohm Effect to the theory of weak measurement."

During his lengthy association with the USC Department of Physics and Astronomy, Aharonov worked mainly with Professors Pawel Mazur and Jeeva Anadan (now deceased), key members of USC's Foundations of Quantum Theory Group, on the subjects mentioned above; however, he was always approachable by anyone with need of his keen insight. For many years, Aharonov headed the Summer Institute on the Foundations of Quantum Theory at USC. The institute activity attracted a number of internationally renowned scholars in the field and was a source of significant excitement and stimulation for many of our faculty and students.

The National Medal of Science, the United States' most prestigious award for scientific achievement, was created by Congress in 1959 and is administered by the National Science Foundation. Awarded annually, the medal recognizes several individuals each year who have made outstanding contributions to science and engineering. Nominees are selected by a committee of presidential appointees based on their advanced knowledge in, and contributions to, the biological, behavioral/social, or physical sciences, as well as chemistry, engineering, computing, and mathematics.

UNIVERSITY OF SOUTH CAROLINA

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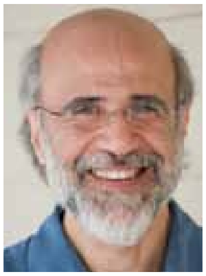
"The extraordinary accomplishments of these scientists, engineers, and inventors are a testament to American industry and ingenuity," President Barack Obama said in announcing the 2010 awards. "Their achievements have redrawn the frontiers of human knowledge while enhancing American prosperity, and it is my tremendous pleasure to honor them for their important contributions."

Professor Yakir Aharonov had a 41-year-long, close relationship with the University of South Carolina. He was attracted to the Columbia campus in 1965 by Professor Edward Lerner and spent summers and various periods of time at USC until 1973. From that year until he retired from USC in 2006, he held joint appointments at USC and the University of Tel Aviv in Israel. He is currently professor of theoretical physics and James J. Farley Professor of Natural Philosophy at Chapman University. At age 78 he is as active and intellectually keen as ever. In addition to the National Medal of Science, his codiscovery of the Aharonov-Bohm effect earned him numerous other awards and accolades, including the 1998 Wolf Prize in physics and the 1995 Hewlett-Packard Europhysics Prize.

A Message from the Chair



Chaden Djalali

Exciting, Challenging Times

It is my great pleasure to welcome our dear alumni and friends to the 2010 issue of the Department of Physics and Astronomy's newsletter, *Quantum Leap*. As this calendar year comes to an end, I want to give you a quick update on the status of our department.

As you might expect, the serious state of the economy has affected us in an unprecedented way. After several years of flat funding, our base budget has been reduced by 5 percent this fiscal year, and we are preparing for an additional 5 percent cut in the next fiscal year. These are permanent cuts, so the lost funds will not be restored even after an economic recovery. Although nominally a public institution, USC is undergoing a transition to a funding mode dominated by tuition and philanthropy, with negligible state support. However, while this change brings considerable challenges, there are also some opportunities. I cannot help but be amazed by our students, staff, and faculty, who, undeterred by the cuts, have reaffirmed their commitments to excellence in teaching, research, and service. More than ever, if we are to survive and thrive, we need to rely on, and forge a closer relationship with, our current and former students, as well as with our friends in the community at large.

In spite of all the difficulties we are facing, I have been pleased by the many outstanding accomplishments of our students and faculty. We recently learned the great news that Professor Emeritus Yakir Aharonov has been awarded the prestigious 2010 National Medal of Science; please join me in congratulating Yakir. I am also delighted to report that Professor Thomas Crawford was granted tenure, while Professors David Tedeschi and Varsha Kulkarni were promoted to full professors. This past summer, the University of Zaragoza in Spain conferred an honorary doctorate on Professor Frank Avignone in recognition of his many contributions to the field of particle astrophysics. This is Dr. Avignone's second honorary degree. Our undergraduate and graduate students continue to win departmental, college, and University-wide awards. The quality of the research conducted by our faculty has been recognized by funding agencies, and our extramural funding more than doubled last year. We feel fortunate in having been able to hire a new faculty member. Dr. Matthias Schindler (Ph.D. 2007), who is currently a research associate in the Department of Physics at George Washington University, will be joining our faculty as an assistant professor in January 2011. His primary interest is in theoretical nuclear physics and fundamental symmetries.

The administration of the department has also seen some changes. We have a new business manager, Lisa Saxon, who came to us from the English department. Professor David Tedeschi has stepped down as director of graduate studies to take a well-deserved sabbatical, and Professor Vladimir Gudkov has accepted the position as our new director of graduate studies. Last but not least, the whole department had to be temporarily relocated to 516 Main Street while the asbestos abatement of the Jones Physical Science Center was carried out. As you may imagine, it was quite an endeavor! We will be moving back to our regular location before the end of the calendar year.

As far as the future is concerned, I have no doubt that together we will make it through these tough financial times and come out as a stronger and more focused department. I want to thank our generous alumni and friends, whose contributions and support have tremendously helped us in critical areas, such as student scholarships and awards, outreach programs, and the colloquium series.

Please stay in touch with us, and feel free to contact me at 803-777-4318 or by e-mail at chair@physics.sc.edu.

From the Director of Undergraduate Studies

By Jeffrey Wilson

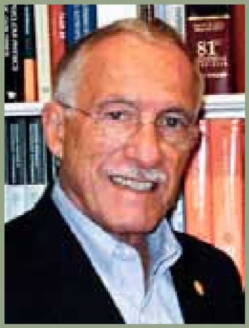
The department's undergraduate program has maintained positive momentum throughout the 2009–2010 academic year. We have 78 physics majors as of fall 2010, with 10 students having graduated in 2010, following 10 more graduates in 2009. This is the most productive two-year stretch in the history of the program, and this fall we have filled up several of our introductory physics courses with new physics majors. If our enrollment continues to follow this trend next year, we will be forced to add more sections for Physics 199—something we had never imagined. The new biophysics course (Physics 521) currently being taught by Professors Bazaliy and Crittenden is also full. This increase in enrollment at the 500 level is especially encouraging because we may now find it possible to meet the minimum enrollment levels required to offer other new courses. A larger variety of courses is something both faculty and students would enjoy.

The new biophysics capstone course follows our recent trend toward increasing the quality and number of research opportunities available to our undergraduates. Many of the questions asked by prospective students and their families relate to the availability of research work for undergraduates. As an answer, we can point to our capstone courses, as well as the many opportunities students have to be mentored by faculty in their own research labs. It is not unusual for incoming freshmen to be recruited by research groups before they even arrive on campus.

As I write this, we are currently gearing up to host the R.L. Childers Midway Physics Day at the South Carolina State Fair again this year, thanks to the generous sponsorship of the State Fair Organization. Last year, the event attracted about 3,000 students from nearly 50 high schools around the state, with about the same number registered for this fall's event. We were quite surprised that the attendance did not seem to be impacted by the poor economy. The rides at the State Fair offer wonderful examples of physics in action, and we decided to enhance that theme by doing away with our traditional stage show and offering a tent full of hands-on activities for the high school students to interact with. This is also a highly beneficial service-learning experience for our own students who serve as the mentors for the hands-on activities.

The physics award winners from the spring 2010 awards ceremony were: Gary D. Hollis, College of Arts and Sciences Rising Senior Award; Andrew Michael Scott, Nina and Frank Avignone Fellows Fund; and Dominik Ralf Gothe, Rudy Jones Physics Award. Dominik Gothe also won the Jeong S. Yang Award for excellence in mathematics.

Frank Avignone Receives Second Honorary Degree



Frank Avignone

On June 21, 2010, the University of Zaragoza in Spain conferred an honorary doctorate on Professor Frank Avignone in recognition of his many contributions to the field of particle astrophysics. The formal ceremony followed a 500-year-old format, in which he gave his acceptance speech in Spanish. This was Avignone's second honorary doctoral degree, the first one having been bestowed by the University of Buenos Aires in 2004.

Avignone joined the USC faculty in January 1965, and although he retired as a state employee in 1998, he has worked full-time under contract at USC as a research professor ever since. He continues to hold the title of Carolina Endowed Professor of Physics and Astronomy and is the leader of the Particle Astrophysics Group. He served as chair of the department from May 1979 until he took his new position in July 1998.

Staff News

By Beth Powell

Can it be that 2010 is really almost over? Time flies when you're having fun! Here are a few snapshots of what the staff has been up to since our last update:

Bob Simmons retired from his position as business manager at the end of September 2009, giving him much more time to spend spoiling his grandchildren. We're pretty sure they're a lot more fun than preparing for budget cuts.

In the beginning of November 2009, we were very fortunate to have Lisa Saxon join our team as the new business manager. She came to us from the Department of English Language and Literature, with more than 17 years of experience at USC. Despite her years on "the other side of campus," Lisa settled in quickly, embracing her inner geekiness with enthusiasm.

Robert Sproul, Dee Brown, Mary Papp, Ray Edmonds, and I are still working hard and having fun, too. What have we all been doing for fun? Well, if you haven't already read Robert's article about our move (p. 11), you must! We've all become quite knowledgeable in the areas of asbestos abatement and packing/unpacking. What a task it was to move our whole department in time for asbestos removal to begin! Although we have sort of enjoyed our home away from home, we're ready to get settled back into PSC. If only we could figure out how to get everything to pack and move itself.

That's our news for now. We wish all of you the best and hope you will stop in and see us whenever you're in the neighborhood.

New Advanced Biophysics Course Offered This Fall

By Scott Crittenden

The first of three optical tweezers under construction by recent physics department graduate Robert Hedrick. Rob wants to continue working in a scientific or industrial laboratory and is in the market for a permanent position.

This fall marks the debut of a new advanced undergraduate laboratory course in biophysics (Physics 521), developed and taught jointly by Professors Scott Crittenden and Yaroslaw Bazaliy.

For this first offering of the class, the most important focus of the laboratory sessions was on optical tweezers. An optical tweezer uses focused laser light to exert forces on small objects, allowing for the manipulation of such things as red blood cells, algae, chloroplasts, bacteria, and larger eukaryotic cells. The students will get extensive experience working with modern industrial- and research-grade equipment.

Optical tweezers, like the atomic force microscope (AFM) that is Crittenden's primary research tool, are ultimately micro- and nano-scale force measurement instruments. While the AFM has better spatial resolution, it is limited to making measurements on surfaces, whereas the optical tweezers can reach inside cells to grab individual components and pull on them; with the right conditions, the tweezers can even impart a torque, causing objects to spin.

Because both Bazaliy and Crittenden are interested in biophysics, they are both participating in teaching the course, with Bazaliy conducting the lectures and Crittenden supervising the laboratory sessions. In addition, Bazaliy has been testing two-way video conferencing software during the weekly departmental condensed matter seminar and is now able to apply it to the class by broadcasting his lectures in real time over the Web. The lectures, including student questions and the resulting discussions, are recorded and posted online for ease of review.

Besides being a new course, this biophysics class is the next step in the department's recent effort to revamp and enhance our advanced undergraduate laboratory courses. Previously, Professor Thomas Crawford had modernized both the solid state and optics courses by adding a large amount of new laboratory equipment, including a clean room and optical lithography system. He is currently in the process of building a laser atom trap so that students will be able to study macroscopic quantum effects through Bose-Einstein condensation.

Bazaliy's lectures cover topics including diffusion, friction, movement in the low Reynolds-number world, the importance of entropy and free energy, entropic and chemical forces, self-assembly, molecular machines, and membranes. The laboratory experiments will explore Brownian motion, bacterial motility, red blood cell elasticity, and the functioning of muscle motor proteins. Future students should relish the challenge of making the most of their opportunity to study this interdisciplinary field and to work with cutting-edge equipment.

From the Director of Graduate Studies

By Vladimir Gudkov

Our graduate education program remains strong, with a present total of 36 students. This year, we welcomed seven new students to the department, coming from four countries (two from the United States, three from China, one from Iran, and one from Romania). We are quite pleased with the strength and diversity of our program.

Our students continue to excel. Inti Sodermann (advisor: Yaroslaw Bazaliy) was selected as USC's 2011 Outstanding Thesis Award winner for the ETD category; his master's thesis exemplified an innovative application of technology to scholarship. Alejandro Ferrero (advisor: Brett Altschul) was selected for the Graduate Student Research Award, and Rebecca Bowers, Robert Steinman, and Julian Martinez for the Graduate Student Teaching Awards. In addition, our department awarded a total of 11 graduate degrees within the last year. The M.S. and Ph.D. graduates continue to find positions in private industry, government, and universities throughout the region and country.

Congratulations to doctoral graduates Jae Jun Kim, Jiajie Ling, Haiyun Lu, Carlos Martinez, Pawel Morawiec, and Zhiwen Zhao and master of science graduates Eric Graham, Jing Yang, Julian Martinez, Robert Steinman, and Yunjin Wang!

The Department of Physics and Astronomy is continuously working to improve the quality of the program and better fulfill the needs of our students. We look forward to another productive and prosperous year ahead.

Experimental Nuclear Physics

Probing Within the Proton

The intermediate-energy Experimental Nuclear Physics Group is one of the largest research groups in the Department of Physics and Astronomy at USC. It consists of five faculty members: Professors Chaden Djalali, Ralf Gothe, Yordanka Ilieva, Steffen Strauch, and David Tedeschi. Other members of our group include three postdoctoral researchers, six graduate students, and several undergraduates. This past year was a very dynamic one for the group, and it produced a great deal of exciting news.

The study of the atomic nucleus and its constituents on the quark level is at the core of the group's research. Members of the group are leading nine experiments at one of the flagship facilities for nuclear physics research in the United States, the Thomas Jefferson National Accelerator Facility (Jefferson Lab, or JLab), in Newport News, Va. The experimental studies focus on quantum chromodynamics and the substructure of nuclei. The main questions the research addresses are: What is the internal landscape of the nucleon? How do the properties of strongly interacting particles change in the nuclear medium? What governs the transition of quarks and gluons into pions and nucleons? And what is the nature of the nuclear force that binds protons and neutrons into nuclei? In the past year alone, the members of the

Experimental Nuclear Physics Group presented their research findings on these topics in 30 invited talks and seminars at the national and international levels, illustrating the broad recognition the group has received. The research also led to dozens of journal articles.

One of the highlights of the past year was the first results from the JLab experiment E03-104, which is searching for possible modifications of the proton structure when the proton is inside the dense environment of a nucleus. Since the proton is itself a complex system of strongly interacting quarks and gluons, nuclear matter may modify its characteristic behavior. Despite many theoretical and experimental studies, there is no conclusive understanding of this fundamental phenomenon. The results from the experiment (published as M. Paolone et al., *Physical Review Letters* 105, 072001 [2010]) were very exciting. They showed excellent agreement with several theoretical models that predict in-medium modifications of the proton. However, surprisingly enough, the measurements also agreed with a different model calculation, one that did not include medium modifications but employed a different treatment of in-medium nucleon interactions. More results from E03-104 are about to be published, and they may resolve this puzzle. The new data are directly sensitive to the effects of in-medium nucleon interactions and, in combination with the earlier data, may lead to a definitive statement about whether medium modification of the proton is or is not an important effect.

The high-impact achievements of this research, as outlined above, would not be possible without critical contributions from all the members of the group. In these difficult years of economic crisis, the Experimental Nuclear Physics Group has worked very hard to secure substantial external funds, which allow the group to continue to be extremely productive. Thanks to continued funding from the National Science Foundation and additional funding that was negotiated with Jefferson Lab, the group was able to hire two new postdoctoral research associates, Slava Tkachenko (who received a Ph.D. from Old Dominion University) and Gleb Fedotov (a Ph.D. graduate of Moscow State University). Tkachenko is tackling the problem of how particles containing a strange quark interact with other particles; this may help us understand the properties of neutron stars. Fedotov is studying how three very light quarks interact together to produce much heavier objects such as nucleons.

Some younger members of the group won competitive prizes in 2009 and 2010. Postdoc Simona Malace was awarded the prestigious Jefferson Science Associates Postdoctoral Research Fellowship and later accepted a new position with the Medium Energy Physics Group at Triangle Universities Nuclear Laboratory. Undergraduate Weizhi Xiong won a 2010 Magellan Scholarship from USC and was awarded a travel grant by the American Physical Society, which allowed him to present his work on statistical methods for data analysis at the APS Division of Nuclear Physics fall meeting in New Mexico. The group also produced three graduates during this period: Haiyun Lu (Ph.D.), Zhiwen Zhao (Ph.D.), and Robert Steinman (M.S.), all of whom are currently very well placed in research or teaching positions. Lu and Zhao are continuing to pursue nuclear physics research as postdoctoral fellows at Carnegie Melon University and the University of Virginia, respectively, while Robert has embarked on a teaching career with The Hill School in Pennsylvania.

As we approach the end of a very successful year, the Experimental Nuclear Physics group is looking forward to several exciting new developments. The group is actively involved in Jefferson Lab's 12 GeV upgrade through the design and development of a new addition to the time-of-flight (TOF) spectrometer for the CLAS detector in Hall B and the development of a kaon detection system for Hall C. Testing and prototyping of the TOF detector elements has been done in the Neutron Generator Building at USC, and work on this detector is at a very advanced stage. Production work should begin in early 2011, and the installation at Jefferson Lab in fall 2013. In preparation for the years when data collection at JLab will shut down for the construction for the 12 GeV upgrade, the group is also developing new collaborations to conduct research at other laboratories, such as J-PARC in Japan and MAMI in Germany.

Nuclear Theory

Quarks, Gluons, and Neutrinos

Continuously funded by the National Science Foundation since 1982, the Nuclear Theory Group (consisting of Professors Fred Myhrer and Kuniharu Kubodera) studies the relationship between nuclear phenomena and the underlying fundamental dynamics of quarks and gluons. The study of the neutrinos (fundamental particles emitted in, for example, nuclear β-decay) and nuclear astrophysics are also major research topics.

Over the years, the Nuclear Theory Group has served as a hub for active international collaborations, and during the last twelve months, the group carried out joint research projects in neutrino physics and astrophysics with a prominent visitor: Professor Toru Sato, from Osaka University, in Japan.

Reflecting the established international recognition of the USC group, the faculty members were solicited to contribute review articles for three invitational review journals: the *Journal of Physics*, *Reviews of Modern Physics*, and the *Annual Review of Nuclear and Particle Science*. These three review publications were all published in 2010. The faculty were also invited to two international conferences to present their research, one in Australia and one in Korea.

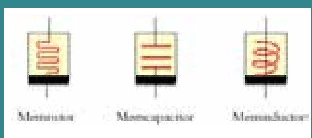
This summer, a new postdoctoral fellow, Dr. Udit Raha, will join the Nuclear Theory Group. Originally from India, he obtained his Ph.D. at Bonn University in Germany and has previously held postdoctoral positions in Basel, Switzerland, and Taipei, Taiwan.

The group has also been guiding two students working on the physics of γ-ray bursts. Rebecca Bowers is writing a master's thesis on this topic, and Jim Talbert is working on a senior thesis on this topic, as well as on the evaluation of *bremsstrahlung* from antineutrino-hydrogen reactions.

Computational Condensed Matter

Circuit Elements with Memory

During the past year, Professor Yuriy Pershin's Computational Condensed Matter Group has generated significant advances in the area of nano-electronics. Together with colleagues from the University of California at San Diego and UC Berkeley, Pershin has generalized the concept of memory devices to capacitors and inductors, thus defining two new classes of circuit elements: memcapacitors and meminductors. These complement the already known class of memristors (which are resistors with memory). The new symbols introduced to represent these elements in circuit diagrams are shown in the figure below.



In these newly defined devices, the capacitance and inductance, respectively, depend on the state and history of the system. In addition, these elements show pinched hysteretic loops in the two constitutive variables that define them: charge versus voltage for the memcapacitor, and current versus flux for the meminductor. Memcapacitors and meminductors open up a whole new world of possibilities in electronics and provide us with new tools and a new perspective from which to study old scientific problems. This work was published in 2009 in the *Proceedings of the IEEE*, which is the most highly cited general interest journal in electrical engineering and computer science.

Together with a graduate student, Julian Martinez (who received a master's degree for this work in 2010), Pershin has identified two experimental systems showing memcapacitive behavior. One of the systems relies on having a slow polarization rate in the dielectric medium between the plates of an ordinary capacitor. To achieve the memcapacitance, a multilayer structure embedded in a capacitor could be used. The proposed memcapacitor shows hysteretic charge-voltage and capacitance-voltage curves; it may also display either negative or divergent capacitance under the correct conditions. This proposal can be easily realized experimentally and suggests the possibility of using memcapacitive systems to store information. The paper reporting these remarkable results was published in *Physical Review B* and was selected as an Editor's Pick, highlighting it as important and of particularly broad interest.

The second possible memcapacitative system uses a strained elastic membrane as one plate of a parallel-plate capacitor. Changing the applied stress would switch between the low and high capacitance configurations of the system. Using numerical modeling, Martinez has demonstrated that a voltage pulse of appropriate amplitude can be used to reliably switch the memcapacitor from one state to another. This system displays (in addition to hysteresis) a regime of chaotic behavior; in fact, this membrane memcapacitor connected to an AC voltage source comprises one of the simplest possible single-element chaotic circuits.

Recently, Pershin has established a promising collaboration with the group of Professor V. Slipko from Ukraine, working on semiconductor spintronics. The collaboration focuses on theoretical and computational studies of spin relaxation in semiconductor materials. Together with Professor Slipko, a novel long-lived spin polarization structure, the radial spin helix, was identified and its relaxation investigated. One very unusual and important property of the helix's spin polarization structure was discovered: the spin polarization at the center of the radial spin helix stays almost unchanged at short times. The results of this study were accepted for publication in *Physical Review B.*

Particle Theory

The Fundamental Physics of Time Reversal

This is an active time for the Particle Theory Group, led by Professors Pawel Mazur, Vladimir Gudkov, and Brett Altschul. Moreover, a new faculty member, Professor Matthias Schindler, will be joining the group in January 2011. Schindler earned his Ph.D. in 2007 at the Johannes Gutenberg University in Mainz, Germany. Since finishing his doctorate, he has been a postdoctoral research associate at Ohio University and then George Washington University, in Washington, D.C.

Schindler is an expert on effective field theories for hadrons and their use in tests of fundamental symmetries, such as parity (P), charge conjugation (C), and time reversal (T). This is a very exciting time for precision research on nucleons because experiments at the Spallation Neutron Source (SNS), located at the Oak Ridge National Laboratory in Oak Ridge, Tenn., should provide a tremendous amount of new and interesting data. Fundamental neutron physics is also the main focus of Professor Gudkov's research, and USC has developed a very strong relationship with Oak Ridge.

The SNS is the most powerful neutron source in the world. It produces neutrons by colliding an accelerated beam of protons with target nuclei. Each collision produces a spray of neutrons, and the neutrons are split into up to eighteen beams, which will be used for different types of experiments. Some of the beam lines are complete, with operational instruments installed, while some are still in various stages of preparation. Of particular interest is the SNS's Fundamental Neutron Physics Beam Line (FNPB), which started operating in 2008. While most of the beam lines use neutrons as probes for studying other materials, the focus of the PNPB is on the neutrons themselves. For example, the beam line will produce large numbers of neutrons, which can be used for precision measurements of the neutron mean lifetime; while this lifetime is known to be approximately 880 seconds, the precise value is a subject of energetic dispute.

The SNS will also be used to search for evidence of a neutron electric dipole moment (nEDM), which would indicate a violation of time-reversal invariance that is not associated with the known T violation in the standard model of particle physics. Understanding T violation is important for several reasons. Perhaps the most important reason is that it is needed to explain why there is more matter than antimatter in the universe. The matter-antimatter asymmetry requires CP violation well beyond the small amount of CP violation that exists in the standard model. Assuming that the combined CPT is valid symmetry, the discovery of any new form of T violation would also indicate a new form of CP violation. The sensitivity at the SNS will be such that this new CP violation could be discovered in the next generation of nEDM searches if it is associated with new interactions at the TeV scale. Professor Gudkov has funding from the Department of Energy to work on getting a full understanding of these and other exciting new neutron experiments that will be going on at the SNS. A new postdoctoral researcher, Young-Ho Song, began working with him in fall 2010.

Even more exotic forms of symmetry breaking are also possible, and Professor Brett Altschul works on such unusual forms of new physics. One possibility that he has been looking at with a graduate student, Alejandro Ferrero, is that the "constants" of nature, such as the electron charge, the proton mass, and the strength of the weak interaction that is responsible for the decay of neutrons and many other particles, may actually be changing with time. Ferrero won the department's graduate student research award for his work on this topic.

One particularly interesting topic that Altschul and Ferrero have looked at is measuring the strength of the weak interaction in earlier epochs by looking at light curves from type Ia supernovae. Such explosions are important standard references, providing the best data about the expansion history of the universe. Because of this fact, there has been a great deal of attention paid to them in the last decade, and the brightness of many supernova events have been precisely measured. A supernova continues to glow for months after it reaches its peak brightness, gradually fading away. In the weeks following the height of the light emission, the main energy source powering the luminescence is the beta-decay of ^{56}Ni and ^{56}Co, which are produced in huge quantities during the early phases of the supernova explosion. The supernova brightness therefore tracks the decay rates of these isotopes, and so the rate of decay of the light curve can be used to infer the beta-decay lifetime (and hence the weak interaction strength) at the time the supernova took place. Looking at supernovae with red shifts $z < 0.1$, it was possible to infer that the weak coupling had changed by less than 1 percent over the last 10 million years. And this result can probably be improved by two orders of magnitude by considering the data from much older explosions.

Another way to look for evidence of varying constants is to perform extremely sensitive laboratory measurements years apart. Altschul is collaborating with the atomic spectroscopy group at the Max Planck Institute of Quantum Optics in Garching, Germany, who are the world leaders in this kind of repeated precision measurement. Altschul is working with them to determine what related forms of exotic physics their measurements may also be sensitive to and how they can modify their techniques to enhance such sensitivities further.

Professor Pawel Mazur has worked extensively on the physics of black holes. He is currently working with a Ph.D. student, Andres Sanabria, studying the possible trajectories of objects orbiting rotating black holes. These orbits differ from conventional ones in several important ways. The satellites may zoom in and out, tracing out novel patterns, and they are also affected by the gravitomagnetic field, which, according to the general theory of relativity, is generated by all massive rotating objects.

Particle Astrophysics

Identifying the Constituents of Cold Dark Matter

The Particle Astrophysics Group at USC consists of Professors Frank Avignone, Richard Creswick, Horacio Farach (emeritus) and Carl Rosenfeld; and graduate students Leila Mizouni, Seth Newman, and Nicholas Chott. A number of other students who have also contributed to the group in recent years have now completed their Ph.D. work: George S. King (in 2007), Todd Hossbach (2009), and Carlos Martinez (2009). Iulian Banadac, who was a postdoctoral research associate in the group, has now moved to a permanent position in Canfranc, Spain.

Particle astrophysics focuses on phenomena in astrophysics and cosmology that are associated with the properties of elementary particles, ranging from neutrinos to Weakly Interacting Massive Particles (WIMPS), which are hypothesized constituents of the cold dark matter (CDM) that fills much of the universe. The USC group entered this field early, when it performed the first terrestrial CDM search. CDM is needed to explain the dynamics of galaxies and is an important feature of cosmological models used to explain the evolution of the universe. The gravitational effects of CDM on the velocity distribution of stars in spiral galaxies is well established; it was first motivated by the discovery in 1933 by Fritz Zwicky that far more mass was needed to explain the orbital dynamics of globular clusters than was visible in the forms of stars and dust. In 1985, the USC group, inspired by the astrophysics group at the Max Planck Institute in Munich, led the first terrestrial search for the CDM, with an experiment performed underground in the Homestake gold mine in Lead, South Dakota. The experiment used a unique detector developed in collaboration with the Pacific Northwest National Laboratory (PNNL). This collaboration remains active today, although involved in a different experiment. The initial CDM experiment was able to eliminate the possibility that heavy Dirac neutrinos might be the major component of the CDM. In the intervening years, similar searches have now become popular throughout the world, with vast improvements in detector technology.

The USC group also played an important role in searches for elementary particles called axions emitted by the sun. Axions appear in a theory developed by Roberto Peccei and Helen Quinn that explains why the strong interactions of quantum chromodynamics do not violate charge-parity (CP) symmetry. The axion experiment was based on an analysis developed at USC by an international collaboration led by Richard Creswick. It used the coherent conversion of axions to photons in large single crystals. This kind of conversion could occur when an axion's trajectory from the solar core to the detector satisfied a Bragg condition. This technique has subsequently been used by other groups worldwide.

The USC group now concentrates on two experimental searches for the exotic phenomenon of zero-neutrino nuclear double beta-decay ($0\nu\beta\beta$-decay), which is only possible if neutrinos have mass and are their own antiparticles. (Spin-1/2 particles with this property are known as Majorana particles.) $0\nu\beta\beta$-decay also violates the law of lepton number conservation. Neutrino oscillation experiments imply that neutrinos may well have enough mass to allow this decay to be measurable, but the oscillation experiments can only measure mass differences. The direct observation of this process would prove that neutrinos are their own antiparticles and are Majorana particles. Moreover, the measurement of the decay rate would determine the absolute masses of all three neutrino mass eigenstates.

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The USC group was the U.S. lead group in the CUORICINO double-beta decay experiment in the Gran Sasso Laboratory in Assergi, Italy, from the very beginning until it was discontinued in July 2008. CUORICINO set a lower limit on the half-life for the $0\nu\beta\beta$-decay of ^{133}Te of 2.8×10^{24} years. CUORICINO was an array of 42 kg of TeO_2 cryogenic detectors operating at 0.008 K. The current effort, however, is in the construction of a 760 kg version called CUORE. The group's main responsibility is the production of the electronics system, led by Carl Rosenfeld. The group also has the U.S. leadership role in the construction and operation of the first TeO_2 tower for CUORE (CUORE-Zero), which will begin operating in 2011 in the CUORICINO cryostat. The USC group also played a key role in establishing the Majorana ^{76}Ge double-β decay project, which is a research and development project to establish the feasibility of building and operating a one-ton experiment in the U.S. Deep Underground Science Laboratory (DUSL), located in the former Homestake mine. The group has the leadership in setting up and operating a facility to purify and refine the necessary germanium (enriched with the ^{76}Ge isotope) to make the detectors. All these activities are supported by major grants from the National Science Foundation.

Experimental Condensed Matter and Nanoscale Physics

Table-Top Physics: Electronics to Bacteria

The renaissance in condensed matter and nanoscale physics continues. With strong successes obtaining funding, new laboratories nearing completion, and exciting projects ongoing or recently launched, the condensed matter and nanoelectronics faculty (Professors Thomas Crawford, Scott Crittenden, Timir Datta, James Knight, Milind Kunchur, and Richard Webb) offer a feast of on-campus, table-top experimental and theoretical research opportunities for students and research associates. They expect this excitement to continue to build as the new research programs ramp their output to full steam.

More than 50 faculty members and students are using our facilities for their research. The USC Nanoelectronics Center is clearly a success when judged by the amount of external funding received, the number of publications in peer review journals, and the number of national and international invited talks our personnel have given since its founding in 2004.

Assembling Matter at the Nanoscale

With support from the National Science Foundation, the Laboratory for Picoscale Metrology and Nanomagnetics is taking ~10 nm diameter particles suspended in fluid and deliberately placing them on a surface where they can assemble a complex, programmable pattern through a patent-pending technology called Reprogrammable Parallel Nanomanufacturing. This technology employs the tightly confined magnetic fields emanating from the surface of a magnetic recording disk to trap Fe_2O_3 nanoparticles. These fields can be encoded onto the media surface with arbitrary nanoscale patterns using a magnetic recording head. After assembling the nanoparticles, the disk is coated with an air-curable polymer. Once cured, the polymer is peeled from the surface, transferring the nanoparticle pattern to a flexible and optically transparent substrate.

The notion of using magnetic particles to identify magnetic structure via stray magnetic fields was first published in the *Physical Review* by Francis Bitter in 1931 while he was at Westinghouse Electric and Manufacturing Inc. in Pittsburgh, Pa. Bitter's technique continues to be employed in the study of magnetically recorded marks via scanning electron microscopy. However, little attention has been paid to the process by which the magnetic nanoparticles are removed from the fluid carrying them and made to assemble on a programmed array of magnetic fields. In fact, precisely assembled architectures of nanoparticles could lead to entirely new devices, useful in fields as diverse as renewable energy and biotechnology.

USC undergraduate physics major Jason Henderson has made several critical breakthroughs toward establishing this approach to nanomanufacturing. First, he invented a multistep process for laying the nanoparticles down on the surface. The physics of this coating process is nontrivial as the particles are themselves coated with an electrically charged surfactant to prevent them from sticking together in fluid. Their repulsive electrical force is balanced by the magnetic force arising from the large magnetic field gradient at the disk's surface. Henderson's approach involves neutralizing the surfactant charge at just the right moment in the assembly process, to fix the nanoparticles in place. In addition, Henderson has explored the coating's dependence on both the spacing between magnetic field sources and on the presence of an external magnetic field. After magnetizing the nanoparticles with an external field, the particles are repelled from local magnetic fields pointing in the opposite direction. With precise control over these fields, Henderson has demonstrated control over the height and periodicity of the structures, creating a bimodal topography in the assembly.

Henderson's research supervisor, Professor Thomas Crawford, notes, "I'm a big supporter of undergraduate research. Being able to participate in meaningful research helps motivate undergraduates to study hard, as well as to bring new perspectives to ongoing projects. I can't overstate Henderson's contribution to this project." Looking at the nanoscale striations that remain on polished aluminum disks [whose alignment can be measured to +/- 1 nm via atomic force microscopy (AFM)], Henderson has been able to establish the repeatability of multiple nanoparticle coatings at the 25 +/- 11 nm scale. Henderson gave an oral presentation on his repeatability findings at this fall's Magnetism and Magnetic Materials meeting and has submitted his work for publication as the first author.

While a fully quantitative explanation of how the forces present in this kind of ferrofluid has not been achieved, Professor Crawford's team has made progress using a simple one-dimensional model balancing the magnetic force against Stokes drag in the fluid, and they look forward to extending this model to include other physics, such as the three-dimensional spatial field dependence and dynamical changes in the assembly process as the nanoparticles modify both the magnitude and gradient of the medium magnetic field. Ultimately, Crawford looks forward to studying the magnetic properties of the nanoparticles and how they interact once they are immobilized in these arrays in a dielectric medium: "We intend to observe few- and potentially even single-nanoparticle dynamics by exciting the polymer film mechanically at sub-nanosecond time scales and watching the nanoparticle magnetization dynamics evolve in a magnetic field."

Do Bacteria Manufacture Conductive Bionanowires?

Although there are officially only three other people in Professor Scott Crittenden's Biological Physics Group—Dr. Bharat Kulkarni, graduate student Jason Giamberardino (BS in physics, 2010), and undergraduate Chris Pasco—many collaborations, both new and continuing, bring a host of students into the lab on a regular basis. In particular, graduate student Mojtaba Samiee, from the group of Professor Henry Rack of Clemson University's Department of Materials Science, is investigating the electrical properties of grain boundaries on titanium surfaces in the hopes of making better components for replacement joint implants. And Professor Qian Wang's (USC chemistry) graduate student, Fiona Oberbeck, continues her work investigating the effect of adding nanowires to microbial fuel cells to understand charge transport in these complex systems.

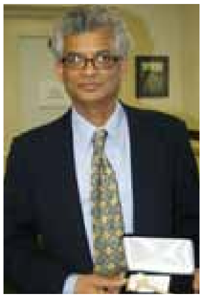
Budding collaborations exist with Professor Linda Shimizu (USC chemistry) and her student Yuewen Xu to measure the conductivity of polydiacetylene nanowires; Professor Richard Long (USC biology) and his undergraduate student Matt Olive to investigate the electrogenicity of bacteria isolated from microbial mats in a hypersaline pond on San Salvador Island, Bahamas; and Professor Rich Goodwin (USC medicine) and his graduate student Stefanie Biechler, who are using the AFM to determine the material properties of tissue-engineered heart valves.

As for the three group members from the physics department, Kulkarni, in addition to being "Mr. AFM" and supervising all the other people who come in to routinely use the force microscope, is focused on the U.S. Army grant to study the conductivity of the bio-nanowires produced by some electrogenic bacteria. Also in support of the Army grant, Giamberardino is engaged in producing high quality self-assembled monolayers of small molecules on gold to test nonorganic analogs of the bacterial bionanowires and has made good progress in very short period of time. As part of this effort, Professor Brett Altschul is involved in attempting to develop an analytical model of charge transfer over surfaces in electrolytes. Pasco divides his time between growing bacteria for the Army grant and trying to produce carbon-nanotube-based supercapacitors as part of a Science Undergraduate Research Fellowship he was awarded this summer.

Just like last year, Professor Crittenden hosted a half dozen high school students for a week during the Nanoscience Summer School organized by Professor Wang. They spent two to three hours a day in the laboratory, building microbial fuel cells under the watchful eyes of Fiona Oberbeck and Rob Hedrick.

Finally, the $118,000 Crittenden received from the University to create an advanced 500-level biophysics lab course last year has been used to purchase three sets of optical tweezers. Over the summer, Rob Hedrick (BS in physics, 2010) assembled and modified the first system to verify its performance and then completely disassembled it in preparation for the first class this fall. Now the first group of students is busily rebuilding the instruments themselves, gaining realistic experience with experiments that are not mere push-button affairs; they have to put together their own instruments, test them, tune them, and calibrate them. Only then can they move on to making measurements. Later in the semester, after reading, interpreting, and adapting a technique described in a journal article, they will modify their systems to make them capable of trapping two objects each. They will finish out the semester with some experiments on the elastic properties of individual red blood cells. In addition, the biophysics course collaboration with Professor Yaroslaw Bazaliy continues; he is teaching the lecture section of the course and has been making extensive use of new technology by simulcasting and recording every lecture.

Gravitation and the Macroscopically Quantum



Professor Timir Datta with his Key to the City of Columbia

The researchers associated with Professor Timir Datta continue to work on experimental gravitation, quantum optics, and macroscopic quantum effects. James Gambrell, an undergraduate, was awarded a STEM fellowship again in summer 2010, and Yunjin Wang finished her M.S. thesis on entanglement and quantum optics in the spring. Yeuncheol Jeong, who has a Ph.D. in astronomy from UCLA, joined this group to do another Ph.D. in gravitational physics. Professor Jeong started his dissertation work in the summer of 2010 and is currently back at his university faculty position in Seoul, South Korea. He expects to combine his past experience in astronomy, working on cosmic microwave background radiation data, with the skills he acquires working on experiments with gravity.

Datta continues to be a resource in the area of superconductivity; he is a referee for a number of publishers including the Institute of Physics and the American Institute of Physics. Recently he was interviewed by a reporter from *Science News* about a paper on fractal ordering in a high-T_C copper oxide superconductor that appeared in the journal *Nature*. Datta was also the team leader in superconductivity and a session chair for the American Physical Society national meeting in Portland, Ore., last March. In November 2009, four members of Datta's team—James Gambrell, Yunjin Wang, Dan Overcash,

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and Ming Yin—accompanied him to the regional APS meeting in Atlanta to make presentations. Also in 2009, Datta was awarded a Key to the City by the then mayor of Columbia Bob Coble.

In spring 2011, Professor Eskil Murat will arrive from Turkey to join Datta's team. Eskil will be at USC as a visiting scientist, studying the quantum Hall effect. Professor Datta is also collaborating with Dr. Mike Osofsky of the Naval Research Laboratory (NRL) on an NRL-supported project in novel magnetic and superconducting materials.

Supercurrents and Superfast Acoustics

Professor Milind Kunchur's research group continues to work in the two areas of superconductivity and psychoacoustics. Currently one graduate student, Manlai Liang, and one undergraduate student, Craig Powers, are working in the group.

In the superconductivity field, recent work has shed light on how quantized magnetic vortices dissipate energy in superconductors. By performing measurements with unprecedented sensitivity and accuracy, it was possible to distinguish for the first time between a long-accepted microscopic theory of the phenomenon and a mean field theory based on the relaxation characteristics of the macroscopic superconducting wave function. Kunchur's group also observed a vortex instability in an amorphous superconductor, which helped elucidate the roles of energy relaxation processes involving quasiparticles and phonons. The superconductivity work was published in 2010 and presented at the 2010 APS March meeting. Kunchur continues to be funded by a grant from the U.S. Department of Energy.

On the psychoacoustics side, Kunchur's investigations into the time resolution of human hearing continue to impact the psychoacoustics, auditory neurophysiology, and audio engineering fields. Kunchur was invited to give an introductory lecture and to serve on the High Resolution Audio Panel at the Audio Engineering Convention in London in 2010. The work continues to generate discussion on numerous Internet forums.

Mechanizing Physics at the Nanoscale

In late December 2009, the Zeiss ULTRA plus field emission scanning electron microscope, whose purchase Professor Richard Webb had coordinated, was delivered to the USC Electron Microscopy Center. The new device has 1.0 nm resolution in the SEM mode and 0.8 nm resolution in the STEM mode. It has charge compensation via gas injection and is capable of electron beam lithography using Nabity software and installed beam blanker and sample analysis using Genesis Apex2-ED for EBSD and WDS. Although Webb used his USC start-up funds to purchase this instrument, it is available for all to use, and the trained Electron Microscopy Center staff can assist new users.

In January, Professors Crawford and Webb established a new partnership with the IBM T.J. Watson Research Center in Yorktown Heights, N.Y., for work on the magnetic tunnel junctions used for information storage. IBM supplies the devices, and the USC group performs the measurements.

Webb has another project with Guiren Wang (USC engineering), Phillip Joe Buckhaults (USC pathology and microbiology), Stephen Morgan (USC chemistry and biochemistry), and Frank Berger (USC Center for Colon Cancer Research) on developing nano-microfluidic structures for the early detection of colorectal cancer. Their first research proposal, "Nano-microfluidic chip for early colorectal cancer diagnosis," requesting $913,000 over three years, got good reviews from the National Institutes of Health but did not get funded. They are continuing the collaboration in an attempt to get future funding.

Professor Webb is also working with Michael Sutton, Ken Reifsnider, Chris Li (USC mechanical engineering), and Hanno zur Loye (USC chemistry and biochemistry) on the purchase of a focused ion beam field emission SEM in an attempt to enhance our University infrastructure. The $2 million proposal received good reviews but also was not funded. Webb is still working on future proposals to get this much-needed equipment for USC.

In April of 2010, Hitachi Global Storage Technologies of San Jose, Calif., hired the Webb group's research assistant professor, Samir Garzon, and the group is now trying to start a new collaboration on magnetic tunnel junctions with Hitachi. The details are still being worked out.

There has been recent success in the group's work on ultra-small tunnel junctions, where it was discovered that small-area magnetic tunnel junctions at 10 K actually had several orders of magnitude lower noise than the standard large-area devices. The small devices had a areas of ~10–100 cm^2, more than ten times smaller than previous devices, and their noise is not well described by a $1/f$ behavior, in contrast to what has been observed for junctions with larger areas. Furthermore, time domain measurements directly confirm the existence of resistance fluctuations, which are strongly dependent on the magnetic state of the junction and on the applied magnetic field. This dependence strongly suggests that the observed fluctuations and noise mainly occur due to pinning of domain walls during the magnetization reversal process, rather than from charge traps within the tunnel barrier. Determining the origin of any excess noise is relevant for the design of sub-micron devices working at low frequency for magnetic field sensing applications.

Webb's group has also fabricated their first NEMS (NanoElectroMechanical System) device using both RIE (Reactive Ion Etching) of Si and wet etching of SiO_2. They are working on making new devices that could be used for the detection of ultra-small changes in electron spin angular momentum at very low temperatures in nanoscale magnetic films.

Building Renovations

By Robert Sproul

The department's main office (Jones Physical Science Center, PSC 404) stripped of asbestos and ready for renovation

The Jones Physical Science Center was completed in 1967 as a state-of-the-art physical science facility to house the Department of Physics and Astronomy, the Department of Chemistry, the USC Science Library, and the newly purchased USC IBM mainframe computer. In the intervening years, chemistry has moved on to be headquartered in their own building (GSRC), the various separate disciplinary libraries have been combined into the Thomas Cooper Library, and computer technology has made the mainframe essentially obsolete. Only the Department of Physics and Astronomy has really bonded with Jones PSC and found it to be a mostly loving and nurturing home for the past 40+ years. But as with all homes that are occupied for a length of time, there have been highs and lows.

At the time that Jones PSC was completed, the prevailing architectural engineering wisdom was to fireproof the steel structure of buildings with sprayed-on fireproofing that contained asbestos. Later, it was determined that this asbestos-containing fireproofing would be a health hazard if the building occupants were to be exposed to it. To this date, there has never been any evidence that the occupants of Jones have ever been exposed to the asbestos-containing material. However, the presence of this material in the ceilings and wall spaces severely limits the extent of any maintenance work and other needed additions. One of the more recent incidents was "the great flood of 2004," when one October weekday, I pulled into the Law School parking lot about 6:30 a.m., got out of my truck, heard an unusual sound, and realized that water was pouring from the seventh floor windows and down the outside of the building! Water cascading through the asbestos-containing ceiling onto lower floors caused many of us to be relocated to the Neutron Generator Building (NGB) for two weeks while a proper cleanup was completed.

This anecdote is just a prelude to the latest saga for the department and our love/hate relationship with Jones PSC. Early in summer 2009, we learned of asbestos abatement plans for the entire basement and the north tower of Jones. The department was relocated to the old purchasing building at 516 Main St., known (very appropriately because of the immediate past occupants) as the Band/Dance Building. Minor improvements were made to 516 Main prior to our occupancy, and we moved from Jones to 516 Main beginning in mid-March 2010. We completely vacated Jones by the afternoon of May 10, 2010. The last couple of weeks of the move were interesting in the sense of the ancient curse, "May you live in interesting times."

Many items from the teaching labs, along with much furniture, were sent to storage, to be returned when they could be moved back. Many more items that had remained unused for years were sent to USC surplus office. Notable items sent to surplus included the original S.H.E. VTS SQUID (superconducting quantum interference device) magnetometer from Professor Timir Datta's lab (purchased in the early '80s) and the Varian EPR (electron paramagnetic resonance) magnet and controls from Professor Haracio Farach's lab. Both of these units were like "old friends" to either Ray Edmonds or myself as we had spent many hours dissecting their problems and repairing them.

The asbestos abatement underway in Jones Physical Science Center

Both the physics labs and the Astronomy Center were relocated to the 5th floor south wing of Jones for the two summer 2010 sessions. Just prior to the beginning of the fall 2010 semester, the basement up through the 3rd floor of the north tower were reoccupied in Jones. We have new telephone and data lines, new ceiling tiles, new lights, new floor coverings, new blinds, and a fresh paint job. The remainder of the north tower (floors 4 through 7) began to move back toward the end of October. The departmental office will have a new look, as both Lisa Saxon and Beth Powell have new offices, and my area has been moved to the fourth floor. Additionally, the conference room has been moved to room 402 and made larger. The 500-level teaching labs have a new home adjacent to one another on the 5th floor to promote an increased motivational spirit of academic excellence among our majors.

It has been said that within the next 5 to 10 years, the north tower of Jones will be gutted and completely renovated. Those of us who have lived and worked and learned in Jones for these last 40-something years know that there is much life and educational opportunities remaining in Jones PSC, and we continue to enjoy our professional life here.

Quantum Leap

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