Carnegie Mellon 2008

INTERACTIONS
DEPARTMENT OF PHYSICS

Small Investment in Promising Student Leads to Major Gift to University

By Manfred Paulini

What do Higgs particles, Duranti's Restaurant, dark energy, the visit of the Physics Advisory Board, Tessera Technologies Inc. and the Large Hadron Collider have in common? Well, they are all ingredients for the latest endeavor of the Physics Department at Carnegie Mellon. The story unfolds as follows.

Bruce and Astrid McWilliams

It all began in 1973, when a young man drafted a solution to a complex mathematical problem and submitted it to a professor of the then Carnegie Institute of Technology. This young man, Bruce Marshall McWilliams, was admitted with a full scholarship, leading to both an undergraduate and a graduate degree in physics. In December 1980, at the age of 23, Bruce McWilliams handed in his physics Ph.D. thesis, entitled "The Phenomenology of Higgs Particles in Gauge Theories of the Electroweak Interaction," which he had worked on under the supervision of Professor Ling-Fong Li. Although he was poised for a career in academia, Bruce went on from Carnegie Mellon to the Lawrence Livermore National Laboratory, where he would lead teams of scientists and engineers to develop electronic systems for satellites and telescopes. After seven years, he decided to take his discoveries into industry, founding his own company in 1989. After some ups and downs in Silicon Valley, about ten years ago Bruce took over as CEO of Tessera Technologies Inc., a San Jose-based company which is the world's leading provider of miniaturizing technologies for the electronics industry. Tessera develops semiconductor packaging, the physical and electrical interface between a semiconductor chip and the system in which it operates. Almost all cell phones contain chips using this technology. But Tessera's products can be found in a broad range of electronics, including computers, PDA's, MP3 players, wireless devices, etc.

Meanwhile, in the Department of Physics at Carnegie Mellon, changes were also taking place. These changes in the research direction of the department went along with global developments in the study of fundamental physics. In the 1950s and 1960s, particle physics was in its infancy and near the beginning of a momentous change in understanding of the universe. The discoveries of six quarks, six leptons, W and Z bosons, gluons, CP violation and the development of the Standard Model of particle physics all lay ahead. The resulting Standard Model links together all of the known fundamental particles and three of the fundamental forces—electromagnetism, as well as the strong and weak forces. But it is not a complete theory, as its explanation of the existence of mass, through the so-called Higgs mechanism, is yet to be proven true. Carnegie Mellon played a significant part in this revolution in understanding the building blocks of matter, with strong contributions to both experimental and theoretical particle physics.

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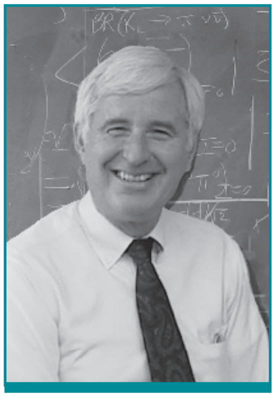
Department Head's Column

By Fred Gilman



The changes in Physics at Carnegie Mellon this past year have been—to use a word from the conversations of our undergraduates—amazing. In some sense it began with the visit of the Physics Advisory Board in February, but of course that was preceded by a year of thinking about where the department is and where we want to go. We first needed to finish up the biological physics initiative that we had begun with the previous Advisory Board with a third hire. Next, we proposed to concentrate for the future along two research thrusts, Quantum Electronics and Dark Cosmology—a combination of astrophysics and particle physics aimed at understanding the 95% of the energy and mass in the universe that is dark. In particular, a Center for Dark Cosmology was put forward as our top research priority, an initiative that leverages the strengths of Carnegie Mellon and Pittsburgh, particularly those in computer science.

The Advisory Board strongly endorsed our plan, followed by the President and Provost. The department's target-size was correspondingly increased for the first time in memory. The third search in biological physics was immediately launched, and a search for new faculty in dark cosmology begun by the summer. In October, Astrid and Bruce McWilliams (who got his Ph.D. working with Ling-Fong Li in 1980) agreed to a major gift to Carnegie Mellon that will establish the Bruce and Astrid McWilliams Center for Cosmology. This allowed the search to be expanded to include the first of the endowed McWilliams Postdoctoral Fellows. The first of the candidates from the search came to visit early in 2008.

One of the other features of the center that has already begun to be realized is closer ties to Computer Science and other departments inside and outside Carnegie Mellon. A first example is a grant from the Moore Foundation to build a computer super-cluster with a special architecture to do physical simulations. It will be shared by researchers in graphics in Computer Science and in the McWilliams Center for Cosmology in Physics. Another example is provided by the Large Synoptic Survey Telescope (LSST) collaboration, which will build and operate the flagship ground-based telescope to study dark matter and dark energy in the next decade. Carnegie Mellon joined the LSST at the beginning of 2008. Our effort will involve faculty from Physics, Computer Science—with new algorithims for doing faster physics simulations and searching huge data bases, and Statistics—with new methods to extract significant signals from massive data as well. The Pittsburgh Supercomputing Center may become an LSST Data Access Center, working with Carnegie Mellon, University of Pittsburgh and Google who are all collaborating institutions in LSST. The Buhl Lecture this past April drew a standing-room-only audience to hear Nobel Prize winner David Gross talk about "The Future of Physics." A more unusual, but also highly attended lecture in the fall, co-sponsored by Physics and Art, was given by Robert Lang, a physicist and origami artist, and titled "From Flapping Birds to Space Telescopes: The Modern Science of Origami."

Having taken on the additional job of acting dean of the Mellon College of Science in September, I have had more opportunity to meet alumni both on campus, at Homecoming and President's Weekend, and off-campus in trips to California and Chicago. With more trips being planned, I hope to get to see many other alumni in person during the coming year. Even if you can't come to campus, please keep in contact, with a brief call or letter to me or email to physics@andrew.cmu.edu.

Fred Gilman Appointed Dean of Mellon College of Science

President Jared Cohon and Provost Mark Kamlet announced on April 1, 2008, that Professor Fred Gilman has been named dean of the Mellon College of Science, effective immediately. Fred had been serving as acting dean of the college since September and has done an outstanding job during this time of transition.

Fred came to Carnegie Mellon in 1995 as the Buhl Professor of Theoretical Physics and was named head of the Department of Physics in 1999. As department head, he oversaw the development of key programs in emerging fields, including biological physics and cosmology.

As dean, Fred will be responsible for overseeing the education provided to 700 graduate and 250 undergraduate students in the college's departments of Biological Sciences, Chemistry, Mathematical Sciences and Physics, as well as the development of the research and educational activities of the college's 200 faculty members.

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Later on, in the 1990s, astrophysics and cosmology provided astonishing insight into the composition of the universe. The discovery that the expansion of the universe is accelerating, together with the fact that dark matter is a much larger fraction of the mass of the universe than ordinary matter, had profound implications. In particular, dark energy, linked to the accelerating expansion of the universe, and dark matter appear to be the dominant parts of the universe, accounting for 95% of its content. However, both are of unknown origin and there is no persuasive theoretical explanation for their existence or magnitude to date. Stated simply, physicists do not understand what 95% of the universe is made of. Recognizing the importance of cosmological studies in fundamental physics, the department had already embarked on building an Astrophysics group in the 1990s.

These and other changes in the Department of Physics, including beginning a Biological Physics Initiative in 2002, bring us to the year 2006, with the department in the process of preparing for the visit of the Physics Advisory Board, scheduled for early 2007. About every five years, the president of Carnegie Mellon reviews each department of the university through an Advisory Board consisting of distinguished academics from other universities, Carnegie Mellon alumni, and members of the Board of Trustees. The planning for the Advisory Board visit culminated in a retreat of the department held at Duranti's Restaurant in Oakland, on a cold Saturday in November 2006. The faculty agreed on "Dark Cosmology" as one research thrust along which to move in the future. Dark Cosmology aims at discovering what makes up the dark part of the universe and how it relates to our understanding of nature at the most fundamental level. In the same way that particle physics was at the beginning of a momentous shift in our understanding of the fundamental forces and particles of nature forty years ago, the efforts of astrophysics, cosmology and particle physics are now combined to face the extraordinarily challenging task of trying to understand the physical nature of the 95% of the universe that is dark.

On April 22, 2008 Carnegie Mellon celebrated the dedication of the Bruce and Astrid McWilliams Center for Cosmology.

To make a long story short, the visit of the Physics Advisory Board was a great success. The department was given approval to establish a "Center for Dark Cosmology." This center will join the department's efforts in astrophysics and particle physics that relate to understanding the dark part of the universe. The initial phase of growth of the center involves an expansion in the target-size of the faculty of the department, including new faculty positions for the center, endowed postdoctoral fellows and graduate students, as well as dedicated large computing facilities and infrastructure. With the Center for Dark Cosmology, particle physics and astrophysics at Carnegie Mellon, leveraging strengths in computer science, statistics and the Pittsburgh Supercomputing Center, will move closer together to unravel the mysteries of the universe. For example, the cosmological puzzle of one quarter of the universe consisting of dark matter could be explained by the existence of yet undiscovered particles. A prime candidate is a particle called a neutralino, which is not part of the Standard Model, but predicted in a theory known as supersymmetry that solves some of the problems of the Standard Model by doubling the number of fundamental particles. Neutralinos are possibly the lightest and most stable of these new particles, which leads some physicists to believe that dark matter could be made largely of neutralinos. Supersymmetric particles may be produced at the Large Hadron Collider (LHC) at CERN which goes into operation later this year. With a strong participation of Carnegie Mellon's high energy group in the CMS experiment at the LHC, particle physics and astrophysics join forces to understand dark cosmology.

Exciting news came to the department and to the university, when in October 2007, Bruce and Astrid McWilliams signed documents pledging a major gift to Carnegie Mellon. This gift provides the core endowment for what is now called the "Bruce and Astrid McWilliams Center for Cosmology." Part of the gift is being used to establish endowed McWilliams Postdoctoral Fellowships in Cosmology. These postdoctoral fellows will be working on research topics of the center in addition to a number of astrophysics and particle physics postdocs supported by grants. A search is underway for at least one new junior faculty member and for the first McWilliams Postdoctoral Fellow.

Furthermore, the first dedicated computational facility for the center will be put in place—a new parallel cluster employing 32 quad-core chips supplied by Intel. In addition, a grant from the Moore Foundation has been received that will fund construction of a much larger cluster with approximately 160 quad-core chips. On April 22, 2008 Carnegie Mellon celebrated the dedication of the Bruce and Astrid McWilliams Center for Cosmology: a joyous event, honoring how our Physics alumni bring good things back to the department.

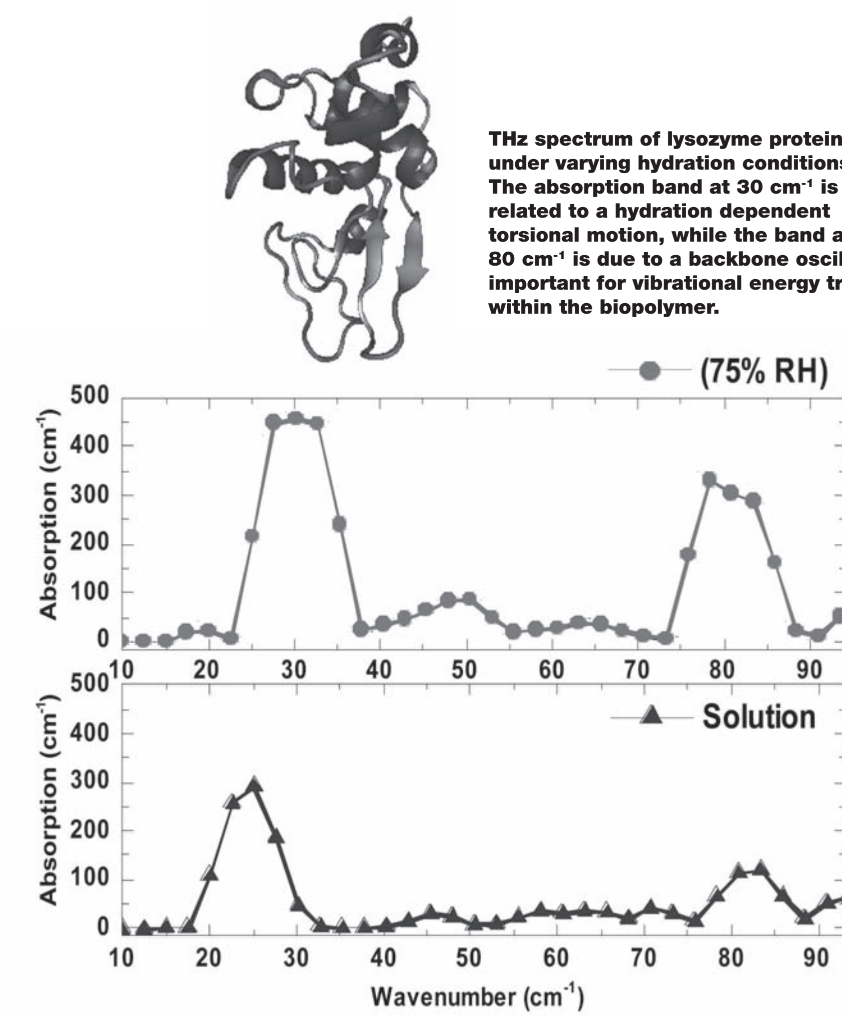
Polymer Physics

By Kristina Woods

THz or far-infrared spectroscopy has seen a huge resurgence in popularity in the last ten years largely due to the number of new, improved coherent THz sources and overall better detection methods. One of the many areas of research that has benefited from this re-emergence of THz spectroscopy as a viable spectroscopy method is polymer physics. Recently, THz spectroscopy has become extremely useful in gaining greater insight into polymer and biopolymer dynamics on a microscopic level. This comprises dynamics on the time scale of a few picoseconds and length scale interactions on the order of tens of nanometers.

My particular research interest is focused on understanding the correlated motions in polymers and biopolymers that take place during the early phase of a chemical or biochemical process. These low energy collective fluctuations and the weak bonding interactions taking place between the individual atoms during the onset of a reaction alter the potential energy landscape associated with a particular process, and ultimately have a strong influence on whether or not the reaction will actually proceed. Both the dynamical fluctuations and structural rearrangements of atoms in the polymer, occurring on this sub-nanosecond time scale, can be studied with THz spectroscopy. This area of research has found tremendous attention in both academic environments as well as in commercial and industrial centers. For instance, changes in the hydrogen bonding and electrostatic interactions in many biopolymer systems, which occur on the timescale of about a few picoseconds, govern the torsional mobility in these molecules that are associated with events such as biomolecule-ligand binding, vibrational energy transfer, and (biomolecule-biomolecule) recognition. These early phase associations taking place in biopolymers, which are responsible for guiding biochemical reactions, is an equally important topic in universities interested in fundamental biology research and pharmaceutical companies with a vested interest in understanding these microscopic interactions for potential drug design. Similarly, picosecond segmental and terminal chain fluctuations, which are believed to trigger phase transitions in many natural and synthetic polymer systems, as well as low energy structural arrangements that are essential for initiating specific chemical reaction pathways are other examples of polymer research topics conducted with THz spectroscopy that have kindled a broad area of interest across a number of different research fields and venues.

One of the most exciting prospects of developing a more fundamental understanding about the early phase dynamics taking place in polymer systems is the ability to use that knowledge to eventually selectively control the outcome of specific processes. Mode selective chemistry or the ability to promote a specific chemical or biochemical pathway with coherent light is an exciting endeavor in the future of polymer physics. In large molecules in the condensed phase, and on the surfaces, there are an extremely large number of low frequency modes (motions) that can accept energy; and hence, can be utilized as a means of selectively exciting or blocking specific pathways. Learning how to manipulate such pathways during the onset of a reaction to promote a desired product may well be an attainable goal in the foreseeable future if a more comprehensive understanding about how energy is managed and distributed during the early phase of biochemical/chemical process is achieved.



THz spectrum of lysozyme protein under varying hydration conditions. The absorption band at 30 cm^{-1} is related to a hydration dependent torsional motion, while the band at 80 cm^{-1} is due to a backbone oscillation important for vibrational energy transfer within the biopolymer.

Biophysical Theory of Lipid Membranes

By Markus Deserno

Life in a Soap Bubble

A lipid envelope surrounds all living cells on our planet. It separates them from their external environment, but it also permits a controlled transport of material and energy. In accord with the second law of thermodynamics internal order can thereby be created and maintained.

The basic structure of these membranes is impressively simple: They mainly consist of lipids, small molecules that unite a water-soluble "head group" with two water-insoluble oily "tails." Dissolved in water, lipids therefore assemble into two-dimensional fluid films, in which the heads screen the tails from the aqueous environment. Such lipid bilayers can close up to form "vesicles," underwater soap bubbles, the rudimental beginnings of a cell envelope. Since membranes self-assemble, they are stable against local injuries: What forms spontaneously can also repair itself spontaneously!

A few billion years ago cell membranes may have been that simple—today they are highly complex structures consisting of hundreds of different lipid species and thousands of embedded proteins. They accomplish countless tasks, from material transport over protein sorting to signal transduction. Yet, their architecture is still the same, and basic physical principles—such as their self-assembled fluid nature or their elastic properties—remain of paramount biological relevance.

How Membranes Transport Forces

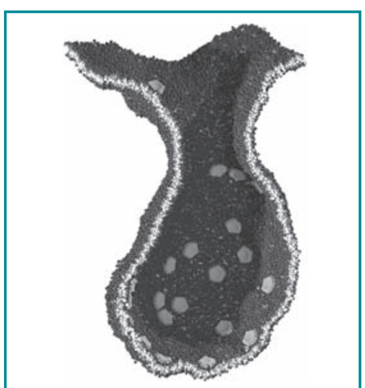
Markus Deserno, who joined the Physics Department in September 2007, studies lipid membrane biophysics using theoretical and computational methods. He is particularly interested in the large-scale interaction of membranes with proteins. If these bind to a bilayer, they locally change its physical properties, such as lipid order, molecular composition, and state of curvature. A disturbance spreads out and is felt far away by other proteins, leading to membrane-mediated interactions between them. Such forces complement specific biological interactions and thus impact the interplay between protein aggregation and the biophysical and biochemical processes dependent on it.

Of Milk, Mattresses and Membranes

Membrane curvature mediates protein interactions. That curved surfaces transmit forces is well known from everyday life: Two cheerios floating on milk attract by capillary forces. Two people lying on the same mattress "attract" since each one rolls into the dent made by the other. Einstein described gravity as a space-time curvature mediated interaction between masses. In all cases the curved geometry of the milk, mattress or space-time is responsible for the interaction, and the same mathematical tool proves useful: differential geometry. Unfortunately, the nonlinearities underlying these theories make them hard to work with, and sometimes not even the sign of the interaction can be predicted with confidence.

Impressionistic Lipids on the Computer

To complement analytical theory, Deserno performs computer simulations of lipid membranes. However, even with modern supercomputers it is impossible to study chemically detailed membrane patches of sufficiently large size for the time required to observe interactions. To overcome this difficulty, Deserno uses the concept of "coarse graining": Throw out as much detail as possible and keep only what is really necessary. He has developed a model in which lipids are represented by just three connected beads. What might look bold at first sight is nevertheless quantitative: It can be checked that these model-lipids properly self-assemble into bilayers displaying correct large-scale behavior. Think of an impressionistic painting that appears perfectly clear if looked at from a sufficient distance, while up close it seems to consist only of blotches of color; however, if one is only interested in the big picture, one can get away with blotches!



Cross-section of a bud in a computer-simulated lipid membrane

Using such coarse-grained simulations, Deserno and his coworkers found that membrane-curving proteins can attract by means of membrane-mediated forces. Even more, sufficiently many of them can cooperatively form a multi-protein aggregate. Since the individual proteins are curved, this aggregate does not just lie flat on the membrane but induces a curved bud, a "bubble" attached to the still overall flat membrane. These observations suggest a physical mechanism by which membrane vesicles are created. These are very important for the functioning of cells, as they accomplish for instance the task of transporting enclosed substances from one region of the cell to another. It is fascinating to see how elementary and unspecific physical principles may lead to their creation; but this poses all the more urgently the question, which biological control mechanisms make sure that these processes only occur when and where commanded by genetically coded necessities. This is a problem we might only be able to answer in a close cooperation of biologists and biophysicists.

Degrees Granted in 2007

Doctor of Philosophy in Applied Physics

Ahmet Kaya
High Frequency Characterization of Magnetic Recording Heads
Advisor: James A. Bain

Doctor of Philosophy in Physics

Daniel Bock
Superconducting Nanowire Bolometers
Advisor: Jeffrey Peterson

Panchapakesan Ganesh
First-Principles Study of Liquid and Amorphous Metals
Advisor: Michael Widom

Rafael Porto
An Effective Field Theory of Gravity for Spinning Extended Objects
Advisor: Ira Rothstein

Kivanc Sabirli
Confirmation of Self-Similar Evolution in the X-ray Luminosity-Temperature Scaling Relation of Clusters of Galaxies
Advisor: Kathy Romer

Madhur Sachan
Magnetostatic Interactions in High Ordered Self-assembled Structures of epsilon-Co Nanoparticles
Advisor: Sara Majetich

Vivek Tiwari
Measurement of the Bs anti-Bs Oscillation Frequency Using Semileptonic Decays
Advisor: Manfred Paulini

Michael Watkins
Inclusive Measurement of Upsilon (1S) Decays to Open Charm Hadrons
Advisor: Roy Briere

Master of Science in Physics

Adam Azarchs
Benjamín Beppler
John Bulava
Ryan Robert Carroll
Lilli Diana Christoph
Christopher M. Hefferan
Charles Robert Hogg III
Yossef Korang-Beheshti
Chao-Hsien Kuo
Chia-Wei Kuo
Shiu Fai Li
Shiang Yong Looi
Luxmi
Elisa Kay Pueschel
Benjamín Adair Sauerwine
Prabhanshu Shekhar
James Charles Thome
Brian James Vernarsky
Peng Zheng

Bachelor of Arts in Physics with an Additional Major in Human-Computer Interaction

Bridget M. Lewis [a, c, d]

Bachelor of Science in Physics

Craig John Bonnoit [a, b, d]
Michael R. Bueti
Siu Kwan Mike Cheng
Olav I. Christianson
Sean T. Conroy [b]
Michael N. Do
Gunnar J. Gissel
Nathaniel Benjamin Greenstein
Philip Daniel Lawson [b]
Geoffrey Overdorff
Jared Andrew Rinehimer [a, b, c, d]
Michael S. Shapiro
Joseph Lawrence Stockhausen
Sukrit Suksombat [a]

Bachelor of Science in Physics with a Minor (as indicated)

Kent E. deVillafranca (Computer Science)
Erica Michelle Krivoy (Hispanic Studies) [b]
Stephanie Pembrook McMahon (Mathematical Sciences)

Bachelor of Science in Physics with an Additional Major (as indicated)

Charles L. Capps (Mathematical Sciences) [a, c, d]
Diana C. Garrity (Professional Writing)

Bachelor of Science in Physics, Astrophysics Track

Jonathan Philip Kaufman [b]
Elijah F. Visbal [a, b, c, d]

Bachelor of Science in Physics, Astrophysics Track with Minors in Mathematical Sciences and Philosophy

Brian D. Newman [a]

Bachelor of Science in Physics, Biophysics Track

Antony Vydrin [a, b]

Bachelor of Science in Physics, Biophysics Track with a Minor in Biological Sciences

Alexander I. Greenwood [a, b, c, d]

Bachelor of Science in Physics, Chemical Physics Track with a Minor in Business Administration

Karl A. Kempe

Double B.S. (second field indicated)

Daniel James DeCapria (Mathematical Sciences)
Ryan McNeive (Mathematical Sciences)
Uchupol Ruangsri (Mathematical Sciences) [a, c]
Robert Ballard Williams (Electrical and Computer Engineering, Computational Physics Track with a Minor in Computer Science) [a]

Bachelor of Science in Materials and Science Engineering with an Additional Major in Physics

Esther P. Yu [a, b, c, d]

Minors in Physics

Benjamin O. Chandler
Brian M. Chin
Ioan T. Ifrim
Gavin C. Kanga
Takuya Kondo
Pauline Law
Alejandro Lince
Mathew D. Nulph
Bharat P. Patel
Christopher S. Pride
Samantha H. Smith
Claire M. Tomesch
Glenn Willen

HONORS CODES:
a: University Honors
b: College Honors
c: Phi Beta Kappa
d: Phi Kappa Phi

Physics Alumnus Appreciates the Gravity of Graduate Studies

By Jared Markowitz (B.S. 2004)

Having just completed my first marathon and being in the midst of yet another arduous semester of graduate school I felt it appropriate to discuss the role of perseverance in physics. In my experience I have found physicists to be single-minded, driven people who will go to incredible lengths to understand the one small piece of nature that strikes their fancy.

One area where the virtue of perseverance has been particularly evident is the study of gravity. It turns out that the problem was not fully solved by a serendipitous apple plunking Newton's noggin; rather it has required years of calculations by the great Albert Einstein and a plethora of tests that continue to this day. Even Einstein had to endure several years struggling through the complexities of differential geometry before producing his famous field equations. His refusal to abandon an unsolved problem was eventually rewarded with experimental support in the form of his explanation of Mercury's orbit and Eddington's observation of light bending around the sun during an eclipse. Despite these triumphs, Einstein's Theory of General Relativity requires further validation and is still being tested extensively today.

One modern experiment that demonstrates the patience necessary for such tests is LIGO (Laser Interferometer Gravitational Wave Observatory). The LIGO project consists of two 4 km and one 2 km Michelson interferometers used to measure incomprehensibly small changes in differential length (10^{-22} and below). These detectors search for radiation of astrophysical origin emitted by the acceleration of asymmetric masses (black holes, neutron stars, etc.) This radiation has only been observed indirectly and is the gravitational analog to the electromagnetic process that produces light. The LIGO detectors were first conceived some 30 years ago and after years of planning were constructed in the late 1990s. After a long period of noise hunting and tuning, the detectors recently gathered a full year of triple coincident data at design sensitivity.

The enormity of this accomplishment can hardly be overstated; locking a laser beam over a 4 km tube is no small feat. Despite this success, however, LIGO is still searching for its first detection and may be years away from the sensitivity required to provide reliable astrophysical interpretations to observed signals. Nonetheless, the collaboration has made incredible strides and will undoubtedly continue to do so until its goals are achieved.

The field of gravity research is just one of many that demonstrate the ability of physicists to stick with a problem until they find the right answer. Whether it's neutrino physicists waiting for the next galactic supernova or high energy physicists seeking the Higgs boson, nuclear physicists trying to control fusion or biophysicists working on human health, our field is full of people who just don't give up. It's that type of perseverance that provides answers to big questions and makes physicists such a special group.

Tell us about yourself!

Mail this form to the
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or email us at physics@andrew.cmu.edu

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INTERACTIONS

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